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WATER PUMP FIELD TESTS IN BOTSWANA

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ACRONYMS

AC	alternating current
AID	U.S. Agency for International Development
ALCC	annualized life-cycle cost
ARD	Associates in Rural Development, Inc.
BHEL	Bobs Harries Engineering, Ltd.
BOS	balance of system
BRET	Botswana Renewable Energy Technology project
BTC	Botswana Technology Centre
CWD	Consulting Services for Wind Energy in Developing Countries
DAS	data acquisition unit
DC	direct current
DWA	Department of Water Affairs
GOB	government of Botswana
IFPP	Integrated Farming Pilot Project
ITDG	Intermediate Technology Development Group
IT Power	Intermediate Technology Power Ltd.
HP	horsepower
kWh	kilowatt-hour
kWp	kilowatts peak
LCC	life-cycle cost
m	meters
Met Services	Department of Meteorological Services
MLGL	Ministry of Local Government and Lands
MMRWA	Ministry of Mineral Resources and Water Affairs
O&M	operation and maintenance
P	pula
PV	photovoltaics
RET	renewable energy technology
RIIC	Rural Industries Innovation Centre
RPM	revolutions per minute
RTI	Research Triangle Institute
SIDA	Swedish International Development Agency
TOOL	Technical Development with Developing Countries
USAID	U.S. Agency for International Development
VITA	Volunteers in Technical Assistance
VSU	variable-speed step-up unit
Wp	watts peak
WTGS	Wind Technology Group Serowe

PREFACE

This report presents the results of a comparative testing and evaluation program for water pumps conducted by the Botswana Renewable Energy Technology (BRET) project. Mr. Richard W. McGowan is senior engineer and Mr. Jonathan Hodgkin, a staff engineer for Associates in Rural Development, Inc. (ARD), the contractor implementing the BRET project for the U.S. Agency for International Development (AID) under contract number 633-0209-C-00-1024-00. This comparative pump testing program was undertaken in coordination with the Government of Botswana's (GOB) Ministry of Mineral Resources and Water Affairs (MMRWA). Substantial contributions to these activities were made by the Department of Water Affairs (DWA), Ministry of Local Government and Lands (MLGL), Botswana Technology Centre (BTC) and Rural Industries Innovation Centre (RIIC).

I. EXECUTIVE SUMMARY

During the second half of the BRET project (1984 to 1985), a comparative testing program for water pumps was designed and implemented. This program utilized comprehensive field testing to assess the technical performance and cost characteristics of a wide range of pumping technologies installed in Botswana. The program's purpose was to make recommendations to both the GOB and a wider audience of water resource specialists in other countries on the technical and economic applicability of pumping options that are currently available in Africa.

While other studies have addressed some of the research issues covered here, this was the most comprehensive pump field-testing program yet conducted. Altogether, over 40 systems were tested, including diesel, grid-electric submersible, hand- and human-traction, bio-gas, animal-traction, wind and solar photovoltaic (PV) pumps. Most of these pumps were small in terms of system size, as that range is where alternative pumping systems are most likely to be competitive with diesel pumps, which are the standard system used in Botswana.

The DWA Village Water Supply program has been very successful in achieving its goal of delivering water to rural villages, particularly in comparison to similar programs in other countries. This success had a considerable effect on the conclusions given below, since proper system installation and periodic maintenance and repair procedures significantly reduce the cost of pumping water with diesel systems. Despite the success of DWA's program, a number of individuals and institutions in Botswana, from both the public and private sectors, have been interested in quantifying the real costs of diesel pumps more precisely and examining alternative systems to determine whether they might complement the widespread use of diesels, particularly for small-scale remote systems.

The most important evaluative criterion calculated in this study was the unit cost of water delivery for the different types of systems. While both financial and economic analyses were performed, economic analysis was emphasized because the largest purchaser of pumps in Botswana is the government, particularly DWA. However, pumping systems are not often chosen purely on the basis of cost. Long-term reliability, system design, ease of installation, spare parts availability and the level of technical skills required for proper operation and maintenance are equally important.

The general conclusions in this section are simplifications, which should be viewed only in terms of the many qualifications and explanations given in the body of the report. While actual measured data were used as much as possible, the analysis was, of necessity, based on many assumptions concerning long-term operation and maintenance costs, technical performance and reliability. Sensitivity analyses on many of these assumptions has shown that the requirement of pump attendants (pumpers) at all government installations is the most sensitive cost-driver. This factor not only dramatically affects costs, but has significant social and institutional impacts as well.

The energy required to pump water is a function of both the volume of water pumped and head (elevation plus friction and velocity losses) through which it is pumped. Thus, the energy costs of pumping are best expressed in terms of both flow (in cubic meters or m^3) and head (in meters). All cost figures in this report are given in Botswana currency, Pula (P), where US$0.57 = P1 = 100 thebe. The unit cost of water delivery was then expressed in terms of cost per volume*head product (P/m^3*m).

The major conclusions reached by the BRET comparative pump testing program are as follows:

- diesel/Mono pumps are clearly the most cost-effective choice for moderate- to large-scale systems, where demand is greater than 1,000 m^3*m/day (i.e., 10 cubic meters per day at 100 meters of head);

- hand-operated systems (including traditional hand and human-traction pumps) are definitely the most cost-effective option for the low end of the demand spectrum (less than 120 m^3*m/day or the equivalent of pumping four cubic meters a day at 30 meters of head), when there are no labor costs for operating the pump;

- based on field tests at only two sites, grid-electric submersible pumps do not appear to be significantly less expensive than diesel/Mono systems, as had been widely assumed--this finding is based on current electricity tariffs, but when the Morupula power plant comes on-line, reduced rates could change this conclusion;

- the applicability of wind pumps is the most site-dependent option, as these systems require both low head (less than about 50 meters) and relatively high wind speeds for Botswana (an average greater than 2.5 meters per second for the worst-case design month) to be cost-competitive with diesel pumps--while a wind resource assessment is underway, the wind speeds in most areas of Botswana are marginal; and

- solar PV pumps are not as site-dependent as wind systems because solar radiation levels are relatively high and uniform throughout Botswana, and PV pumps appear to cost-competitive with diesel systems at sites where demand is between 120 to 1,000 m^3*m/day and the head limited to about 50 meters--the costs of PV equipment are by far the most volatile of any of the systems tested, and continued price decreases will make the costs of PV pumps more favorable compared to diesel (the PV module prices presented here are about 40 percent higher than current market prices).

Considerably more detailed information on several of these renewable energy technologies (RETs) can be found in individual technical reports on wind, solar, hand and human-traction pumps available through MMRWA and ARD. Preliminary reports on tests conducted on animal-traction and bio-gas pumps may be obtained from MMRWA and BTC.

Further research is needed to strengthen and refine the conclusions presented here, and this report should be viewed only as an analysis of the preliminary data collected thus far. The comparative pump testing program has received funding for a 15-month extension, which will allow more detailed examination of many of the issues raised in this report. This includes a more careful study of windmill performance, instrument recalibration, completing the installation and initiating testing of a second group of solar pumps, and examining a wider range of diesel systems (particularly in the smaller size range, where alternatives are most likely to be cost-competitive). Other work that should be undertaken to address unresolved issues and refine the analyses given here are continuation of the wind resource assessment, start-up of a solar resource survey by the GOB's Meteorological (Met) Services, and examining such factors as storage costs, optimal system sizing, and the costs of training and developing infrastructural support networks for alternative pumping options. Finally, the extension of the pump testing program will include continued training for technicians in the installation and maintenance of RET pumps (particularly solar systems), and assistance with the design of RET pumping systems. Both of these activities are essential to successful dissemination of these technologies in the future.

II. INTRODUCTION

In the developing world, small-scale rural water supply systems that do not have access to national electrical grids have traditionally been gravity-fed or powered by human, animal, wind or diesel energy. In most areas of Botswana, surface water is scarce, so groundwater must be pumped. All pumps require outlays of limited financial resources as well as varying degrees of periodic maintenance and repairs to keep them operational. Each type of pump has an optimal application, which is a function of water demand, water source constraints (e.g., borehole yield and water quality), pumping head, amount of capital for purchasing a pump, and local availability of technical skills and spare parts inventories to properly operate and maintain the pump.

The BRET project conducted a comparative testing program to assess a variety of water pumping systems in Botswana. One purpose of the program was to quantify as many pertinent factors as possible, characterizing the various water pumping options from technical, financial/economic, social and infrastructural support perspectives. The study's other goal was to try to determine which of the wide range of available pumping systems are the most appropriate choices under circumstances that are commonly encountered at small-scale rural water development sites in Botswana. The types of pumping systems examined varied widely in terms of their capacity, cost, required level of technical support skills and labor/capital intensiveness. They included solar PV, wind, diesel, hand and human-traction, grid-electric submersible, animal-traction and bio-gas pumps. The last two were not tested directly by the BRET project, but were subcontracted to BTC and RIIC for development and testing.

While a number of previous studies have examined certain types of water pumps,* there has been and remains a dearth of practical field experience with both older technologies (e.g., windmills) and more recent developments (such as PV). Up until this program, no effort had been made to compare so many

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*AN ANALYSIS OF WATER-LIFTING DEVICES IN BOTSWANA, N. Davidson, BTC, Gaborone, Botswana, October, 1984; SMALL-SCALE SOLAR-POWERED PUMPING SYSTEMS--THE TECHNOLOGY, ITS ECONOMICS AND ADVANCEMENT, Sir William Halcrow and Partners and IT Power Ltd., World Bank and UNDP, London, June, 1983; HANDBOOK ON SOLAR WATER PUMPING, Sir William Halcrow and Partners and IT Power Ltd., World Bank and UNDP, London, February, 1984; TRAINING NEEDS ASSESSMENT FOR RENEWABLE ENERGY TECHNOLOGIES, George Burrill, ARD, Burlington, VT, June, 1985; and EVALUATING THE TECHNICAL AND ECONOMIC PERFORMANCE OF PHOTOVOLTAIC PUMPING SYSTEMS: A METHODOLOGY, J. Kenna et al, IT Power and LESO, AID, Washington, DC, May 1985.

alternative systems using the same analytical methodology. While pump manufacturers' data are useful for design estimation, they are often overly optimistic. Their performance curves are typically generated under ideal operating conditions in the laboratory--pumping very clean (i.e., noncorrosive) water with a multitude of researchers nearby to attend to each component. Field-test results are crucial to the sizing and design of real pumping systems. It is hoped that this report will aid other system designers in future projects and give water resources development planners some indication of the real costs of water delivery in Botswana for a wide range of pumps.

The need for comparative pump testing programs such as the BRET effort is becoming more widely recognized as small-scale rural water supplies assume greater importance in development planning. Previously, bigger projects that addressed the needs of larger population concentrations were assigned top priority, partly because they appeared to be more cost-effective, while the needs of small farmers and villagers received less attention from donor agencies. As the need to reduce rural-urban migration became obvious, governments began to examine ways to encourage rural development, and the attention of donor organizations focused on the most critical rural need--a safe, reliable water supply.

Diesel pumps are the most common water delivery system in areas that do not have access to an electrical grid. In some countries, diesel generators drive electric pumps. However, in Botswana, 85 percent of the boreholes in use are equipped with direct, diesel-driven Mono (progressive-cavity) pumps. Botswana has been fortunate in that MMRWA's DWA and District Council maintenance units have implemented a very successful diesel pump maintenance program. This has been largely due to standardization of equipment and a commitment to training. However, DWA is becoming increasingly concerned with the long-term operation, maintenance and repair costs of diesel pumps, which have not been adequately quantified in the past.

In spite of a recent decline in world oil prices, the cost of this scarce and inherently limited commodity is expected to rise again. In many cases--the price of petrol (gasoline) being one example, this slight decrease has not been reflected in retail costs for consumers or local distributors. This has an even greater impact in rural areas of developing countries, where consumers seldom have the opportunity to choose among fuel alternatives to meet their energy needs. In fact, the financial cost of diesel fuel for the end user has not noticeably decreased in many countries, but has continued to rise. Thus, it is important to consider more energy-efficient fossil-fuel engines as well as alternatives to the use of fossil fuels, particularly in developing countries where constraints on scarce available foreign exchange are most critical.

A. Brief Project History

Prompted by the perception of an increasingly acute energy crisis in Africa, AID began to fund a series of 24 renewable energy projects in Africa in the late 1970s. As part of an overall evaluation of the results of this effort, a study funded by AID in late 1982 examined various RETs that were part of donor development programs in seven African countries and reported findings on the technical performance of these systems (TECHNICAL FINDINGS ON THE PERFORMANCE OF RENEWABLE TECHNOLOGIES IN AFRICA: RESULTS FROM FIFTY-FIVE PROJECTS IN SEVEN SAMPLE COUNTRIES, John Ashworth and George Burrill, ARD, Burlington, VT, April, 1984). Among the technologies investigated were various types of RET water pumps, particularly wind and PV systems. Some of the major technical findings regarding RET pumps were:

- long periods of inoperation occurred for all types of pumps due to a shortage or complete lack of adequate spare parts and technical skills;
- insufficient training in proper maintenance and operations skills was characteristic of many RET projects, some of which included water pumps;
- RET pumps were frequently poorly designed in terms of both matching various system components (for example, pump and motor) and using unreliable or unproven components; and
- despite previous problems with RET pumps, many donor agencies still felt that PV had tremendous potential for potable water pumping, even in view of its high capital cost, because it promised high reliability for such a critical load.

Partly due to the findings of this report, the BRET project refocused some of its efforts after a midterm evaluation to develop a comprehensive comparative testing program for a wide range of water pumping systems. Detailed results of the wind, PV, human-traction and hand pump tests are given in separate technical reports available through ARD or the BRET project. Tentative conclusions from the tests of bio-gas and animal-traction systems are provided in separate BTC reports. The results of the grid-electric and diesel pump tests are presented in this overall report.

In addition to the BRET project, several other organizations in Botswana have been involved, to a lesser extent, in testing several types of water pumps. BTC tested a PV water pump (TEST OF MOGONYE PHOTOVOLTAIC PUMPING SYSTEM, G. Jacobs and L. Maseng, BTC, Gaborone, Botswana, September, 1984), worked on the development of bio-gas and animal-traction pumps, and participated in BRET-funded studies of them (TECHNICAL EVALUATION OF THE RIIC BIO-GAS INSTALLATION AT DIPHAWANA, G. Jacobs, BTC, Gaborone, Botswana, 1985; and TWO-DAY TEST OF ANIMAL-DRIVEN PUMP IN GAMAROTSWANA, L. Maseng and G. Jacobs, BTC, Gaborone, Botswana, March, 1985). RIIC was also involved in testing bio-gas and animal-traction pumps, and has been working for several years on developing a windmill that can be manufactured locally, the "Motswedi," which they also tested (FINAL REPORT: RIIC WINDMILL TEST, M. Ewans and J. Allen, RIIC, Kanye, Botswana, 1985). The BRET project partially funded this development work and purchased several RIIC machines for testing.

DWA has been interested in alternatives to diesel pumping systems for some time, and purchased several conventional windmills and hand pumps to supply water at remote cattle posts. While DWA was not involved in testing wind pumps, they made several of their machines available to the BRET testing program. DWA has also begun to use grid-electric submersible pumps as an alternative to their standard Mono/diesel combination system. Consideration of submersibles increased after a World Bank energy sector study was published which recommended their use for some situations in Botswana. Finally, the Swedish International Development Agency (SIDA) has had an interest in hand pump use in Botswana for some time, and District Council Water Unit technicians were also considering the use of hand pumps. Thus, the BRET project decided to include this technology in the testing program.

This report summarizes the findings for each component of the water pump testing program undertaken by the BRET project during 1984 and 1985. Comparative assessments of the pumps monitored by the project are given in terms of economics, technical performance and social acceptability. Detailed results are provided in individual technical reports that are available through ARD.* While this research should not be considered conclusive because of the relatively small number of pumps studied, it is still the most comprehensive, comparative field

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*COMPARATIVE TESTING FOR WATER PUMPING SYSTEMS INSTALLED IN BOTSWANA, Richard McGowan and John Ashworth, ARD, Burlington, VT, July 9, 1984; SOLAR PUMP FIELD TESTS IN BOTSWANA -- PRELIMINARY TECHNICAL AND COST COMPARISONS, Richard McGowan and Jonathan Hodgkin, ARD, Burlington, VT, April, 1986; THE THEBE PUMP -- A HUMAN TRACTION PUMP FOR BOTSWANA, Jack Shields and Richard McGowan, ARD, Burlington, VT, August, 1985; TWO TYPES OF HAND PUMPS -- RESULTS OF FIELD TESTS IN BOTSWANA, Jonathan Hodgkin and Richard McGowan, ARD, Burlington, VT, August, 1985; and WIND PUMP FIELD TESTS IN BOTSWANA -- PRELIMINARY TECHNICAL AND COST COMPRISONS, Jonathan Hodgkin and Richard McGowan, ARD, Burlington, VT, March, 1986.

test of small-scale water pumps ever undertaken. The information base it produced will be significantly strengthened over the next 15 months, as the comparative testing program has received a funding extension, which will permit monitoring and analysis of the performance of a second group of six PV pumps that have been purchased and were being installed as the BRET project drew to a close in September, 1985. The program extension will also allow further examination of pumps that have already been installed and additional testing of conventional pumps.

B. Previous Comparative Evaluations

With the dramatic rise in the cost of energy since 1973, water engineers and economists have become more concerned with the energy-related costs of operating pumping systems. Since the amount of energy used by a pump to deliver water is reflected in its operating efficiency, several studies have sought to quantify the efficiency of various types of pumps.* Given the known (or estimated) costs of different pumps and some estimate of long-term recurrent costs for operation and maintenance, financial and economic analyses can provide useful information about the type of pump that is best for a particular water demand situation. Unfortunately, most of these studies have been based on either laboratory pump tests or information supplied by the manufacturer on their technical performance, rather than actual field tests. Lab tests generally overstate the actual output of pumps operating under field conditions. One of the most important situations that lab tests seldom emulate is the gradual degradation of performance over time, which occurs with any mechanical device. For diesel pumps, this is particularly true when proper maintenance schedules are not followed.

Another difficulty with extrapolating the results of research conducted in other countries to Botswana is the great variation in long-term operation and maintenance costs. Well yields, depths, water-demand profiles (which can dramatically affect water storage costs), local technical skill levels, spare parts availability and government pricing policies can all influence the comparative ranking of various technologies in different countries. While these considerations do not make other studies useless, their results must be carefully examined for country-specific differences so they can be normalized to fit other situations. Because different studies employ varying analytical methodologies, this is not an easy task.

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*AN ANALYSIS OF WATER-LIFTING DEVICES IN BOTSWANA, N. Davidson, BTC, Gaborone, Botswana, October, 1984; and SMALL-SCALE SOLAR-POWERED PUMPING SYSTEMS--THE TECHNOLOGY, ITS ECONOMICS AND ADVANCEMENT, Sir William Halcrow and Partners and IT Power Ltd., World Bank and UNDP, London, June, 1983.

A recent study funded by the World Bank (conducted by Louis Berger International, Inc., but unpublished) gathered considerable data on the field performance of diesel pumps in Kenya. While cost data from that study are not directly applicable to Botswana, the technical performance information could have been useful. However, of the three parameters that characterize diesel pump performance (head, output and fuel consumption), much of the data included information on only two of the parameters, making it necessary to estimate the third from the authors' experience or manufacturers' literature.

Windmill pumping performance has also been examined in considerable detail by a number of researchers. However, most of these assessments have also been laboratory rather than field tests, and thus, do not replicate the often harsh conditions (and frequently, lack of proper maintenance) under which most wind pumps operate. Many new approaches to increasing the efficiency and lowering the cost of windmills are currently being examined, and it is likely that the unit cost of delivering water with these machines will improve in relative terms. Typical windmill design had not changed a great deal since the 1930s until it began to receive increased attention in the 1960s, particularly from the Intermediate Technology Development Group (ITDG) in England, Consulting Services Wind Energy Developing Countries (CWD) which is a Dutch consulting organization, and Volunteers in Technical Assistance (VITA) in the United States. The two types of windmills manufactured locally in Botswana are permutations of ITDG designs, as is the design imported from Kenya, the Kijito.

A very detailed study commissioned by the World Bank in 1978 examined the technical, economic and social performance of the first generation of solar pumps.* Other research since then has analyzed solar, wind and diesel pump performance at different levels of detail under a variety of conditions in Africa and Central America.** Nearly all of these studies have concluded that under certain circumstances, PV and windmill water pumps can be cost-competitive with diesel systems. Other research has extensively analyzed the reliability and financial/economic costs of operating a wide variety of hand pumps for village water

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*SMALL-SCALE SOLAR-POWERED PUMPING SYSTEMS--THE TECHNOLOGY, ITS ECONOMICS AND ADVANCEMENT, Sir William Halcrow and Partners and IT Power Ltd., World Bank and UNDP, London, June, 1983.

**AN ANALYSIS OF WATER-LIFTING DEVICES IN BOTSWANA, N. Davidson, BTC, Gaborone, Botswana, October, 1984; and HANDBOOK ON SOLAR WATER PUMPING, Sir William Halcrow and Partners and IT Power Ltd., World Bank and UNDP, Washington, DC, February, 1984.

supply.* However, these costs were not directly compared with similar data for delivering water using alternative equipment.

These and other studies have analyzed the field performance of water pumps in detail, and found that in the case of PV, there is still considerable room for improvement in the balance of system (BOS) components, such as motors and controllers. As more research and development is done on better matching of components, annualized unit water costs for these systems will continue to improve relative to diesel pumps. Similarly, ongoing research and development on wind pumps has and will probably continue to produce more efficient and more reliable machines with lower unit water costs.

Diesel pumps are a very mature technology, so it is unlikely that significant future technical advances will dramatically alter their cost structure. Since most of the life-cycle cost (LCC) for operating diesel systems is in long-term recurrent costs (for fuel, operators and periodic overhauls), reducing capital equipment costs will have little effect on LCC. However, diesels are the most commonly used type of pump in the developing world. As a result, they have a distinct advantage in that the necessary support infrastructure (for maintenance, spare parts availability, trained mechanics, and fuel transportation and equipment distribution networks) is already in place, although to widely varying degrees in different countries. As time passes, the efficiency of these networks will undoubtedly improve. The use of RETs, such as wind and PV pumping systems, will have to hold significant promise in terms of potential savings to justify the expenditure of scarce resources on establishing similar support infrastructures.

A World Bank-funded study is testing some 2,860 hand pumps at sites in 17 countries.* Much of the initial testing was done in the laboratory, but has now moved into the field. The methodology used by the BRET comparative testing program to evaluate hand pumps was the same as that employed in the World Bank study. In addition, one of the pumps developed as a result of that study proved to be the most successful hand pump tested in Botswana.

The importance of a standardized technology assessment procedure has been noted in many studies. Although much research has compared common water-pumping alternatives, the conclusions of these studies are not directly comparable because of differing technical methodologies, varying techniques used for financial and economic analysis (and different choices of the most

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*HANDPUMPS TESTING AND DEVELOPMENT, PROGRESS REPORT ON FIELD AND LABORATORY TESTING, World Bank, Rural Water Supply Handpumps Project, 1984.

sensitive assumptions), and lack of attention to social, managerial and infrastructural issues, which are often the most compelling reasons for adopting one technology over another. Mechanisms that can dramatically affect the rate of adoption of new technologies are often not readily understood in the abstract and are only rarely quantified.

Comparative testing methodologies must not only measure the pertinent technical and financial/economic performance aspects of each technology, but must also somehow assess constraints that could inhibit the innovation, diffusion and dissemination of devices to potential end users. The results of such assessments should be presented in a form that makes them accessible to public- and private-sector planners and policymakers who are responsible for technology selection. Because of the long-term ramifications of such decisions, accurate, reliable information becomes a critical need. The authors of this report, Mr. McGowan and Mr. Hodgkin, participated in the development of a comprehensive pump testing and evaluation methodology (based largely on the experiences of the BRET project) in conjunction with AID and many other European donor agencies, which will be published in early 1986.

It must be emphasized that although the results of this study apply specifically to water pumps in Botswana, the methodology developed during the program can easily be adapted to fit a wide variety of circumstances in other countries, in Africa and elsewhere. This report attempts to point out the parameters that are most critical to each assessment perspective (e.g., technical, economic, etc.) and are site- or country-specific. As more data are gathered (during the extension of the comparative pump testing program in Botswana as well as by related programs underway in other countries), the statistical significance of the results will increase proportionally, making the conclusions that much more useful.

C. Types of Pumping Systems Examined

Diesel pumps are the standard system used throughout Botswana's rural areas for virtually all water needs. For this reason, the test results for any other pump should be directly comparable to diesel-driven Mono pumps in terms of performance, cost and reliability. The following systems were tested during the first phase of the BRET comparative testing program:

- five standard and six new-design windmill water pumps,
- five solar PV pumps,
- 14 hand pumps,

- five diesel pumps,
- three human-traction pumps,
- two grid-electric pumps,
- one animal-traction pump, and
- one bio-gas pump.

Due to the limited number of each type of pump tested, no claim can be made that this study was a definitive test of water pumping options in Botswana. However, it certainly indicated the approximate technical limits of current commercial technologies, yielded useful information on social and institutional constraints, and quantified all costs associated with their use (except those for infrastructural support, as discussed below). To introduce each of the technologies examined, brief descriptions are given in the following subsections.

1. Windmills

Although wind pumps have been in use worldwide for years, there is remarkably little documentation of their long-term performance and repair histories. This began to change recently, as new wind pump designs are being developed and tested by such groups as Intermediate Technology (IT) Power Ltd., VITA, CWD and Technical Development with Developing Countries (TOOL). However, the testing of older designs has been largely overlooked. Some testing of Dempster windmills has been done in Honduras and Cape Verde, and similar work is beginning in Kenya, but a broad base of reliable field performance data is lacking. As a result, a program for testing both standard wind pumps and newer designs was outlined by BRET project engineers. DWA had already made a commitment to use wind pumps under certain conditions (e.g., along cattle trek routes and for some agricultural purposes), and installed 11 Climax and Southern Cross machines in the early 1980s. One of these systems represented an effort to use a wind pump to augment the village water supply in Serowe, but without much sucess, unfortunately. It became clear that a more organized testing effort was necessary to determine the proper role of wind pumps in Botswana.

DWA's wind pumps were made available to the BRET project for testing, and in some cases, these machines were moved to more suitable test locations. The project was also committed to supporting two wind pump development efforts, one by RIIC and the other by the Wind Technology Group Serowe (WTGS). Both designs use the wind to drive a rotary Mono pump, instead of a standard piston pump, which allowed the BRET project to directly compare several distinctly different wind pump designs. It was felt that the value of the testing program would be increased if several newer (and perhaps more efficient) designs were also evaluated, so two Kenyan Kijitos and two American Wind Barons were purchased. Finally, the test group of windmills was rounded out by three conventional wind pumps, installed by the Ministry of Agriculture at the Integrated Farming Pilot Project (IFPP) area.

2. Photovoltaics

With the advent of lower-cost solar cells, water supply engineers have begun to look at PV as a possible alternative to diesel pumps for small-scale, low-head (lift) systems. Between 2,000 and 5,000 PV water pumps now supply water for human consumption, livestock and irrigation in many areas around the world, including Africa, Asia, the Pacific Islands, and Central, South and North America. These systems range in size from an experimental 25-kWp (kilowatts peak) unit driving a 25-horsepower (HP) pump to irrigate grain fields (installed in the United States in 1978) to 280-Wp (watts peak) arrays with 1/2-HP motors pumping water for small vegetable plots in Botswana, Zimbabwe and many other countries.

Although the technical performance of first-generation PV pumps is well documented,* the rapidly maturing technology and continually decreasing cost of PV modules indicated to BRET project planners and AID advisors that a detailed field comparison of currently available PV pumps could provide valuable information about present costs and reliability. Initially, a decision was made to install five to six PV systems, instead of the two suggested in the original project paper. However, procurement and installation of these pumps was delayed by a lack of agreement between the BRET project and BTC on the types of pumps to be tested. Further delays were caused by DWA's initial reluctance to release boreholes to the project for PV pump installations.

A World Bank mission to Botswana in 1984 warned that previous analyses** of the potential for PV water pumping in Botswana should be viewed with caution, but suggested that PV systems could possibly be competitive with diesel pumps in situations where they were used:

- for village drinking water supply, not irrigation;

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*SMALL-SCALE SOLAR-POWERED PUMPING SYSTEMS--THE TECHNOLOGY, ITS ECONOMICS AND ADVANCEMENT, Sir William Halcrow and Partners and IT Power Ltd., World Bank and UNDP, London, June, 1983.

**AN ANALYSIS OF WATER-LIFTING DEVICES IN BOTSWANA, N. Davidson, BTC, Gaborone, Botswana, October, 1984.

- at sites where diesel pumping recurrent costs are higher than the average; and
- where the static lift is less than 30 meters.*

According to DWA personnel and an examination of borehole drilling records for many areas of Botswana, the average static lift (depth from the surface of the ground to water) is in the 30- to 80-meter range over much of the country. However, along the eastern border (where much of the population lives), static lifts average 40 meters or less. Thus, the BRET project's PV pumps were installed mainly on boreholes in this area.

3. Hand Pumps

Hand pumps have been used throughout the world for several hundred years to provide modest amounts of water (less than about five cubic meters a day) from relatively low pumping heads (less than around 40 meters). Their primary advantages are relative simplicity and low capital cost, which make them more accessible to users than more expensive pumping systems. Over the past few years, MMRWA, district and subdistrict councils, and several donor agencies have been interested in using hand pumps to meet small-scale water demands in Botswana. Two types of hand pumps were tested during the BRET program--one (the India Mark II) was a standard reciprocating-piston pump, developed as part of the World Bank study of hand pumps and now used in many countries, and the other (the Swedish Petropump) is a recently developed model that has shown promise elsewhere. While Mono hand pumps (produced in South Africa) are beginning to be used in Botswana, none were available for testing at the start of the BRET program. However, they should be included in any further testing.

4. Diesel

Diesel pumps have a wide range of applications and are capable of pumping well over 100 cubic meters per day from 50-meter heads. As the Village Water Supply Program under MMRWA and DWA evolved, a decision was made to standardize equipment as much as possible so that extensive training programs and duplication of spare parts supplies involved in the use of many different types of pumps would not be necessary. This was a very positive step in many respects, but did require a trade-off--some systems had to be installed at sites where they were not well matched to load conditions. Maximum efficiency was sacrificed to reduce the

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*BOTSWANA, ISSUES AND OPTIONS IN THE ENERGY SECTOR (draft), World Bank and UNDP, Energy Assessments Division, Washington, DC, March, 1984.

cost of the support infrastructure. Thus, standardization has resulted in a network of fairly reliable pumps throughout Botswana, but has unavoidably increased the unit water cost at some sites due to suboptimal load matching.

The use of diesels also involves a trade-off between relatively low initial capital equipment costs and higher long-term recurrent costs. In many developing countries, recurrent costs are coming under government scrutiny, as they are often hard to meet, and Botswana is no exception. While much of the initial equipment costs are provided by donors, water development agencies must pay for long-term operation, maintenance and training costs, and are finding these to be a growing burden. Since MLGL, rather than DWA, is responsible for the support costs of water systems in the Village Water Supply Program, they are becoming much more interested in addressing the issue of recurrent costs. Up to now, there was a general awareness of the problem, but very little data collection and analysis to adequately quantify these costs. To partially meet this need for cost information, diesel pumps were included in the BRET comparative testing program. The project chose five different models of diesel pumps to cover the typical range of smaller systems, which bracketed the alternative pumping systems with the greatest potential to be cost-competitive.

5. Human-Traction

One of the main constraints to using hand pumps is that they are severely limited in terms of the depth from which they can pump water. Above a certain total head (approximately 30 to 40 meters, depending on the strength of the person pumping), the required force approaches the limits of many users. The human-traction pump extends this maximum to significantly greater depths. Using mechanical advantage, a rocker assembly operates a standard piston pump in the borehole. The assembly is driven by a person walking in a circle, pushing a bar attached to a cam. This is a more effective use of human power, as the much stronger leg muscles provide the push, rather than the arm muscles which power hand pumps.

Two abandoned human-traction pumps were refurbished and reinstalled by BRET technicians. A third redesigned version was also tested. While research and development on the new design is hardly complete, it has shown considerable promise for water delivery in areas with pumping heads of up to 100 meters and low population density, where it would be difficult to justify the much greater expense of other types of pumps. Human-traction pumps could also be used in ecologically fragile areas where the government might not want to install larger systems, which tend to promote settlement and possibly subsequent overgrazing.

6. Grid-Electric

The BRET project was primarily concerned with testing pumps that could be used in rural areas without access to electrical grid power. The national grid in Botswana is not very extensive at present, but there are grids operated by several other governments in some of the larger villages, which are far removed from the main grid (Maun, for example). The electrical energy tariffs of consumers on these separate grids are subsidized by the GOB, so that a common tariff is charged to all electricity consumers throughout the country.

Since the BRET program sought to determine the costs of all types of pump systems commonly used in Botswana, and electric submersibles were widely thought to be the least-cost option where grid electricity was available, two grid-connected electric submersible pumps were tested for several months to gather some minimal base-case data. For similar reasons, the program attempted to include electrically driven Mono pumps. However, the only installations of these systems which were checked had such low water yields that the pumps were partially pumping air. Hence, any measured efficiencies would be far below their potential, so the tests were not continued. It is hoped that other installations of these types of pumps will be found and examined during the extension of the comparative testing program.

7. Animal-Traction and Bio-Gas

Animal-traction (animal-drawn) and bio-gas pumps have been used for many years in some areas of the developing world with considerable success. RIIC and BTC expressed an interest in the development of these pumps and determining their potential for use in Botswana, primarily for livestock watering. These types of pumps are not strictly comparable to the other systems tested by the BRET program, mainly because their operation requires extensive user participation and cooperation, and this extensive labor input means they could only be used in the private sector (i.e., if GOB labor rates were in effect, they would not be cost-effective).

While the intent of the BRET contract with BTC and RIIC was to develop baseline performance and cost data on animal-traction and bio-gas pumps so that comparisons could be made to the other systems tested, the BTC test data were of limited value. The contract stipulated that 30 days of tests were to be conducted on the animal-traction pump, but only one-and-a-half day's data were collected, so their cost and performance figures are necessarily speculative. Further, the bio-gas pump was installed on a very low-yield borehole, which did not permit testing of the system's true potential. However, these tests did raise pertinent issues, particularly in terms of institutional and social factors, which should be addressed in any further testing.

III. ANALYTICAL METHODOLOGY

For RET pumps to be seriously considered for selection by development professionals, water supply specialists must have reason to believe there is a good potential to realize significant cost savings over the life cycle of these pumps, so as to make up for the risk of investment in heretofore unfamiliar technologies. In addition, there must be some assurance that the costs, both social and economic, of building a significant infrastructural support network can be recovered by long-term recurrent cost savings. An accurate determination of costs and technical skills required for the design, installation, operation and routine maintenance of the system, availability of replacement spare parts, and social acceptance of the devices at the user level must be made before reasonable choices of pumping equipment can be made.

The analytical and data collection methodology used by the BRETproject to determine the performance of PV pumps was first outlined in COMPARATIVE TESTING FOR WATER PUMPING SYSTEMS INSTALLED IN BOTSWANA (Richard McGowan and John Ashworth, ARD, Burlington, VT, July, 1984). Both long- and short-term testing procedures are described in detail in that methodology report and hence, will not be repeated here. Revisions of the original methodology were made as field-testing proceeded, reflecting time constraints, skill levels of available technicians, and various equipment malfunctions which occurred during the testing period. These modifications were principally logistic rather than technical in nature, so that the general analytical approach was not significantly modified.

A. Technical Performance

The basic descriptor of technical performance for any pump is how much water it can deliver from a given pumping head. In the case of boreholes (on which most of the pumps tested in Botswana were installed), if borehole depth and yield do not vary, water output will depend on the energy input to drive the pump element (apart from gradual deterioration of the pumping equipment with time and use). For renewable energy systems, this input can vary considerably over time, in daily as well as monthly terms, and is normally seasonally dependent. To adequately describe a pump's technical performance, it is necessary to measure time-dependent energy input, water output, head and degradation of output due to wearing of component parts.

To determine the maximum potential output of a given pump, short-term tests were performed to measure the performance of each of component (e.g., pump element, motor, controls, etc.). Since these tests were undertaken at various points during the overall testing period, it was possible to determine to some extent the degradation due to wear of the various components over time, caused by particles suspended in the water, corrosion, breakage, etc. To determine actual long-term water output which would be required for a proper financial/economic analysis, water output for the life of the system should be measured. Information on the long-term performance of many of the pumps tested here was simply unavailable before this program. Several of the pumps have only recently become commercially available, and others had never been field-tested. Also, because of the seasonal variations in RET pump output, it was necessary to extrapolate from data that have been analyzed to estimate annual outputs, as a full year's data had not yet been gathered by the testing program. Subsequent funding for the extension of the comparative testing program will allow these annual measurements to be made and consequently, more reliable conclusions drawn.

For fossil-fueled pumps such as diesels, it was not so critical to gather long-term annual technical performance data because their output is not contingent on seasonally dependent energy inputs (such as solar radiation and wind). Variations might occur due to changes in the water table over the year, which could change the borehole yield and static water level, thereby increasing overall pumping head. However, this did not seem to be a problem with the diesel pumps monitored by BRET staff. The pumping head was very close to constant over the measurement period. Variations in diesel pump output can also occur when periodic maintenance does not take place, which can dramatically reduce the equipment's overall efficiency. However, this was not the case here due to the good management of DWA and the district-level borehole and pump maintenance program. Most DWA equipment received proper periodic maintenance and parts replacement, so the diesel pumps' efficiency varied little over the maintenance cycle. The important long-term data were required maintenance and repair frequencies, and associated costs. This information was gathered primarily from the records kept by DWAand Council Maintenance Units.

The concept of efficiency is used to describe pump performance. Efficiency is a measure of the losses involved in converting one type of energy to another (for example, changing electrical energy into mechanical energy or heat into electricity). "Overall efficiency" is often used to describe a pumping system. It is the ratio of the hydraulic energy out of the pump (in terms of head and flow) divided by the energy input required (e.g., fuel, solar radiation, wind energy, etc.). Since different kinds of pumps use different power sources, this definition varies according to the pump's power supply. For the pumps tested in this program, the energy inputs were:

- for solar electric pumps, the solar radiation falling on the PV array;

- for wind pumps, the energy of the wind hitting the windmill rotor;
- for diesels, thermal energy from combustion of diesel fuel;
- for hand- and human-traction systems, the energy exerted by the pumper;
- for animal-traction, the energy exerted by animals;
- for bio-gas, thermal energy from combustion of the bio-gas; and
- for grid-electric systems, the electrical energy consumed by the pump (see below).

Since all of the different types of pumps have slightly different definitions of efficiency, it is not particularly useful to compare efficiencies across the range of pumps. For instance, to say that a diesel pump has an average overall efficiency of 10 percent while a solar pump has an overall efficiency of four percent, does not necessarily imply anything about the actual unit water cost from those pumps. However, within a group of the same type of pumps, a higher efficiency normally implies lower unit cost at a given head. Similarly, saying that a grid-electric submersible operating at 50 percent efficiency is better than a wind pump operating at 16 percent does not include the efficiency of the power plant (about 35 percent, at best) used to generate the electricity. Combining the two gives a real overall efficiency for the submersible of (0.5 x 0.35 = 17.5 percent). Thus, efficiency is used to compare pumps within a particular group (e.g., PV to PV), not different types of systems (e.g., wind to PV to diesel).

Efficiencies are measured for two main purposes:

- to compare different pumps of the same type, and
- to help system designers determine the best pump for a given site.

Measuring efficiency can also give information about how well a system is performing over the long run. For hand pumps, if a sudden drop in efficiency (i.e., reduction in water output for constant head) occurs, it is a good indication that the cylinder leathers need replacing. While the determination of relative efficiencies for different pumps and pump types is useful for engineering considerations, the primary concern of this testing program was to measure the actual costs of water delivery. Efficiency affects unit water costs only insofar as a less efficient pump would require more mechanical energy to pump the same volume of water. More mechanical energy output from a diesel, for example, would require running the engine at higher RPM and thus, burn more fuel.

Since the type of prime mover (i.e., the source of mechanical energy delivered to the pump element) was different for each type of pump in the BRET testing program, the parameters measured during the tests differed as well. These parameters are listed in Section IV. Detailed site and equipment descriptions are given in Appendix A.

Other efficiency calculations were of interest in comparing the same types of systems (e.g., wind to wind). These focus on different system components, such as array efficiency for solar pumps (electrical energy output by the PV array divided by solar energy on the array plane), the hydraulic efficiency of all pumps (water volume pumped to a given head divided by the electrical or mechanical energy to the pump element itself, as opposed to the motor driving it), etc. Multiplying the efficiencies of all of a system's components gives the "overall efficiency" described above. Since system-specific efficiencies are not of general interest when comparing the different types of systems to each other, information on them is provided the individual technical reports on each of the different types of systems tested (see the bibliography provided in Appendix E).

One year or less of field tests cannot provide data on the long-term costs of pumping water, which are required for financial and economic comparisons of alternative types of systems. Therefore, after the actual performance of each pump was measured by field tests, approximations of long-term performance were made using simple computer models of pump output. For wind pumps, this was a simulation program that required three inputs--a description of the wind pump, wind speed distribution at the sit, and borehole parameters. The model predicted long-term water output on an annual basis, which was then used in the LCC analysis described below. Details on the procedure are given in the BRETproject's technical report on wind pumps (WIND PUMP FIELD TESTS IN BOTSWANA -- PRELIMINARY TECHNICAL AND COST COMPARISONS, Jonathan Hodgkin and Richard McGowan, ARD, Burlington, VT, March, 1986).

Since the individual performance of PV pumps was measured as a function of varying solar radiation levels, long-term performance could be predicted with some accuracy if solar radiation levels for the site were known. Since solar radiation data have not been collected in Botswana long enough to produce a statistically significant information base (several years at a minimum), approximations were made based on long-term data recorded at nearby locations (in South Africa) and adjusted somewhat given site-specific radiation measurements taken during the pump testing program. These long-term solar radiation approximations were then used to calculate the solar pumps' water output on an annual basis over the amortization period of the system. A detailed description of this analysis is provided in the BRETtechnical report on PVpumps, SOLAR PUMP FIELD TESTS IN BOTSWANA -- PRELIMINARY TECHNICAL AND COST COMPARISONS (Richard McGowan and Jonathan Hodgkin, ARD, Burlington, VT, April, 1986).

Annual water outputs and maintenance and repair costs for the other types of pumps tested--diesel, hand-operated, human- and animal-traction, grid-electric--were based on extrapolations from short-term outputs measured during the program as well as any existing long-term data recorded by DWA (diesel and grid-electric systems).

B. Financial/Economic Selection Criteria

LCC analysis, which calculates the present worth of all costs--capital, operation and maintenance, and replacement parts--over the system's lifetime, is a common method used for financial and economic comparisons of water pumping alternatives. The costs considered in this analysis do not include well drilling or development, the water distribution system or storage tanks, except where specifically noted. In addition, any system components that are common to all systems were not included in the costing.

Economic analysis attempts to place a "true" value (cost to the national economy) on various cost components, which is not necessarily representative of these costs in the marketplace. It tries to quantify such real costs to the overall economy as government subsidies (hidden or otherwise), anomalies in the marketplace, imbalances in exchange rates and availability of foreign exchange. By and large, the cost of diesel fuel and grid electricity (except for isolated generators, as in Maun) are not substantially subsidized in Botswana, but this is not the case in many other African nations. While the real economic cost of subsidies would not be considered by the average consumer, it should be taken into account by government planners who are concerned about the scarcity of foreign exchange, much of which is caused by importing fossil fuels. There are other advantages of using decentralized power systems, which have been adequately discussed elsewhere.

A number of assumptions were made in performing the LCC analysis. Input variables, such as discount and real inflation rates, assumed (or measured) system lifetimes, shadow pricing of labor and foreign exchange, and expectations about the availability of capital, can all dramatically affect the outcome of the analysis, either individually or in combination. Long-term technical performance and cost assumptions are discussed in the appendices and should be reviewed before accepting the graphs of the results at face value. Extensive sensitivity analyses were performed to determine the effects of variations in base-level assumptions on the overall analysis. To clarify what should be used as base-case assumptions, a discussion was held with MMRWA engineers and economists, where most of the reasonable possibilities were reviewed. Some of the decisions reached were as follows.

First, the primary figure of merit to be calculated in the analysis was annualized life-cycle cost (ALCC) per cubic meter of water delivered. This is also referred to as the unit cost per cubic meter of water delivered at a given head. MMRWA requested that the calculation of unit water cost reflect a discounting of the volume of water pumped over the system's lifetime. This calculation was performed in the economic and financial spreadsheets, but since constant annual outputs were assumed in all cases, the relative ranking of the systems is identical for both discounted and undiscounted cases. Although a benefit/cost ratio, net present value or internal rate of return could also be used to evaluate projects, it was agreed that these would not be the main evaluative criterion in this study because the value of a delivered unit of water would have to be assumed.

Second, since the government was assumed to be the primary purchaser of PV pumps, no import duties were assessed against the equipment. DWA (presumed to be the primary client) buys most of its equipment in bulk, so diesel costs were similarly based on bulk tender prices. Costs for other systems assumed purchases would be in bulk, rather than by single system.

Third, unskilled labor for tending pumps, reticulation networks and occasional replacement of piping was shadow-priced at 0.5. Foreign exchange was shadow-priced at 1.1.

Fourth, it is the custom to hire a pump tender (pumper) on a full-time basis for diesel pumps. It was felt necessary for sociopolitical rather than strictly practical reasons to include at least a part-time pumper's salary in the baseline operation and maintenance costs of RET pumps, as some degree of operator interaction is necessary under normal operating conditions. Sensitivity analyses on this assumption were performed (varying pumper labor charges from one day per week to half-time to full-time) for the wind and PV pumps.

Fifth, incremental training costs for PV pump technicians should somehow be factored into the systems' recurrent operation and maintenance (O&M) costs. The magnitude of this incremental cost was difficult to estimate and since it was not part of this research, was not included in this analysis. While the training expenses associated with the diesel pump maintenance infrastructure are indeed sunk costs, they should similarly be included in any comparative evaluation of pumping technologies.

Sixth, salvage values for all equipment were assumed to be zero, in accordance with current DWA practice.

Seventh, while unit water costs are given initially in terms of cubic meters of water (P/m^3), this is an oversimplified formulation. The energy required for pumping water is directly proportional to both the volume of water pumped and head (or lift) through which it is pumped. Pump comparisons should give costs in terms of flow (in cubic meters) times head (in meters) or "m^3*m." This tends to normalize the performance of pumps at different sites and reflects the additional energy input required to pump water from a deeper borehole. Hence, the results are given both in terms of cubic meters of water delivered (P/m^3) as well as volume-head product (P/m^3*m).

Eighth, discount rates and real cost increases of equipment/labor above general inflation rates were taken to be six and zero percent, respectively, reflecting the GOB's standard assumptions for public-sector financing. Private-sector discount rates will be somewhat higher--16 percent interest rates for private-sector financing are common. Assumptions of lower discount rates tend to bias the analysis in favor of technologies with higher initial capital costs and lower long-term recurrent costs (i.e., PV will seem relatively more favorable than diesel because of such an assumption).

IV. DATA COLLECTION REQUIREMENTS AND INSTRUMENTATION

To adequately characterize the financial and economic performance of a given type of pump, its long-term recurrent and initial installed costs must be determined. For renewable energy systems in particular, this meant determining the output of the pump on a monthly basis over the year, because of monthly variations in the strength of the renewable energy resources at the site. Solar radiation levels and wind speeds can vary by an order of magnitude of about 20 percent over the year. To estimate long-term pump performance, it was important to have information on both the actual measured output of the pumps and to know with some assurance what the expected long-term energy resources at the sites would be.

Data collection difficulties were exacerbated by the fact that many of the pumps were installed at relatively remote sites. This significantly increased the effort required not only for installation, but also for assuring that appropriate data collection procedures were being followed and the pumps were working properly during the data collection periods. This did not always turn out to be the case.

Social and institutional data were collected as an adjunct to implementation of the field-testing program, rather than through a formal interview process. Installation crews and, later, local data collectors (who were often hired from nearby villages) were informally interviewed and asked about users' responses to the various systems installed by the BRET project. It might well have been useful to examine in more detail responses to the various technologies that are not easily quantified, but time and personnel limitations did not permit this.

Information on social acceptance of the technologies is summarized in the site histories provided in the individual technical reports, which discuss:

- details of problems encountered during both pump installation and operation;
- a subjective evaluation of the advantages and disadvantages of the particular pump in terms of simplicity of installation, functional complexity (a good indicator of long-term reliability) and probable reliability, based on previous experiences with similar pumps;
- technical skills necessary to design, install and maintain the pump in proper running condition;

- spare parts availability and use of locally manufactured components; and
- probable need for back-up systems, to supplement the output of RET pumps during periods when the renewable energy resource is insufficient to meet water demands (e.g., Mono pumps which can be belted to either diesel, wind or PV power supplies).

Short-term intensive testing of each of the pumps measured instantaneous component and system energy flows at 15-minute intervals during the day. Long-term tests measured monthly and annual energy and water flows, and operation and maintenance requirements and costs were recorded as well. The data necessary to characterize pump operation were somewhat different for each type of system. The most important parameters measured were total head (elevation plus friction and velocity losses), volume of water pumped and energy requirements of the pumping system. Details of the short- and long-term tests are given in the individual technical reports and the overall testing methodology.

For solar PV pumps, the parameters measured were:

- water output;
- PV array electrical energy output;
- electrical energy to the pump (if a controller or battery bank was used);
- solar radiation in the plane of the array;
- experiment elapsed time and pump on-time; and
- static water level and total pumping head.

In addition, during the short-term tests, system voltage, motor current draw, module surface temperature and ambient air temperature were recorded. In the case of the Mono pumps, the pump shaft speed of rotation (revolutions per minute or RPM) was also recorded, which was used to determine the efficiency of the pump element itself. With submersible pumps, this was neither possible nor strictly necessary. The monthly average daily values for solar radiation in the plane of the array (30 degrees tilt above horizontal, facing due north at all sites) were also calculated. These values will aid in the design of future systems by providing refinements to the long-term average values being measured by Met Services in Botswana and the Weather Bureau in South Africa.

For wind pumps, the following parameters were measured:

- water output;
- 16-bin (division) anemometry--wind speed distribution;
- cylinder stroke count, in some cases;
- experiment elapsed time and pump on-time; and
- static water level and total pumping head.

The stroke count was not a critical variable in describing windmill performance for the economic analysis, so its measurement was not emphasized.

The difficulties of measuring the long-term performance of hand pumps are addressed in the BRET technical report on hand pumps (TWO TYPES OF HAND PUMPS -- RESULTS OF FIELD TESTS IN BOTSWANA, Jonathan Hodgkin and Richard McGowan, ARD, Burlington, VT, August 30, 1985). The basic difficulty lay in the fact that hand pump output is directly proportional to the rate of movement of the pump handle and length of the stroke, which can and do vary considerably depending on the person pumping. In the studies which compared the two type of hand pumps to each other, this fact did not prove to be of major importance since one of the two (the India Mark II) was vastly superior to the other (the Swedish Petropump), based simply on survivability. Thus, subtle differences in output per unit of energy input between the two pumps were unimportant. For hand pumps then, the following parameters were measured:

- water output per stroke;
- force required to drive pump handle;
- approximate strokes per minute by "average" pumper; and
- static water level (the discharge head was generally zero, and drawdown and velocity losses very low, so friction losses were estimated by conventional procedure).

The human-traction pumps presented difficulties that were similar to the hand pumps in that the water output per unit time was not constant, but rather a direct function of the walking speed of the pump user. Thus, average use patterns had to be estimated. Otherwise, the parameters measured were the same as for the hand pumps, with the exception of cycles per minute instead of strokes.

Diesel pump water output varied with the operational speed of the engine (and consequently, the speed of rotation of the pump element in revolutions per minute). Water output per unit of fuel input at a given head and RPM were fairly constant over time, so long as proper and timely maintenance procedures were followed. Since this was the case for the diesel pumps examined (which were all DWA pumps and therefore generally well maintained), only the following diesel pump parameters were measured:

- water output,
- fuel consumption rate,
- speed of rotation of the pump shaft (RPM), and
- static water level and total pumping head.

Instantaneous tests of the grid-electric submersible pumps were performed only on an informal basis, as their output was fairly constant over time so long as line voltage and current draw were constant, which was normally the case. Thus, the pump parameters measured were:

- water output,
- electrical energy consumption, and
- static water level and total pumping head.

BTC conducted the testing of the animal-traction and bio-gas pumps. Details of their testing procedures are available in individual reports on those two systems. This report relies on the results of those limited tests as well as observations made in a draft report, WATER DEVELOPMENT AT THE INTEGRATED FARMING PILOT PROJECT (M. Ainley, 1985).

A. Monitoring Instrumentation

Because different parameters had to measured for each type of pump, the instrumentation used for each was somewhat different. Since equipment designed to perform both the short- and long-term tests of the wind and PV pumps was not commercially available, a monitoring unit was developed in conjunction with an electronics equipment maufacturer. This battery-operated equipment measured and accumulated water flow (positive displacement flow meters), pump run time and total elapsed time (on-board clock), solar radiation (pyranometer) or wind speed and pump strokes (anemometer) depending on the type of pump, and in the case of PV pumps, electrical energy flows in the system (watt-hour meters). Head was measured manually during site visits with a standard electronic well dipper.

During the short-term tests of the PV pumps, voltage and current were measured with voltmeters and ammeters to verify the electrical energy measurements made by the integrating watt-hour meters. Module temperature was measured using mercury thermometers, and instantaneous solar radiation was checked with a hand-held analog pyranometer. Pressure gauges installed in the discharge line measured discharge head. RPM for the rotary output windmills and Mono-coupled PV systems were measured with a digital tachometer.

Diesel pump measurements were made using the same type of flow meters and pressure gauges, which had already been installed in the diesel systems as part of DWA's monitoring program. Short-term fuel consumption rates were measured using a graduated cylinder with measured quantities of fuel. Engine and pump RPM were recorded with a digital tachometer. Electric pump performance was monitored entirely with existing in-place kilowatt-hour (electrical energy) meters, flow meters and pressure gauges. A stopwatch was used for time measurements.

Short-term testing of hand and human-traction "Thebe" pumps (named after an individual who contributed substantially to their development) was done using local labor so that typical user stroke rates could be approximated. Calibrated buckets and a stopwatch were used to measure flow rates and a spring balance to determine the force required to drive the pump shafts. Instrumentation used for the animal-traction and bio-gas pump tests is discussed in the BTC reports on those systems. Details on all of the pump testing instrumentation is provided in the individual technical reports.

Calibration of the monitoring equipment is ongoing and will be completed during the extension of the comparative testing program. The instrumentation used has an overall accuracy of about ±15 percent.

B. Collection of Detailed Cost Data

Determining the cost of the pumping equipment used was not as simple as it initially seemed. Since the BRET project was funded by AID, most of the high capital cost items had to be purchased in the United States from U.S. suppliers. This had several implications on the equipment purchased and prices paid. On one hand, the pump testing project had access to state-of-the-art technology, which was and is not yet readily available in most of Africa. In addition, much of the equipment was purchased in bulk quantities, reducing the retail cost below what normally would be paid when purchasing a single system.

On the other hand, questions arose as to whether it was appropriate to use the prices actually paid by the BRET project for the systems or current prices for the same or similar equipment, commercially available in Botswana. As it turned out, the retail price for PV equipment in Botswana is essentially equivalent to bulk U.S. prices. U.S. manufacturers of PV systems are painfully aware of the currently artificially strong U.S. dollar and are vitally interested in maintaining their market share in an extremely competitive industry. Thus, they have chosen to offer their products below cost to foreign buyers, at least in the short run. For this reason, the prices used for this analysis are local market prices. If DWA were to purchase a relatively large number of modules or exchange rates changed, the module price FOB Gaborone could vary significantly. Since module costs alone account for up to 80 percent of the total installed cost of PV pumping systems, it was clear that a sensitivity analysis of varying module prices was necessary. Indeed, module prices decreased significantly between the first and second BRET purchases (a period of one year), and have experienced yet another significant reduction since that time. The impact of these cost reductions was examined in the sensitivity analyses.

The cost of RIIC and WTGS windmills was the contract price paid by the BRET project for the production prototypes and did not necessarily reflect what higher level production costs would be. Presumably, if a commitment were made by either group to increase production, costs would drop due to economies of scale.

For the remainder of the systems, DWA tender prices were used. This was done largely because they are the largest purchaser of pumping equipment in Botswana, the BRET project was working for MMRWA and it was likely that only government groups would financially be in a position to seriously consider widespread purchases of much of this equipment. Every effort was made to be as consistent as possible in assigning costs across various pump types in order that the financial/economic comparisons could be made with as few assumptions and caveats as possible.

V. TECHNICAL AND COST PERFORMANCE BY SYSTEM TYPE

In this section, the technical performance results of the pump tests are used in the economic analysis for each type of system. Comparative results between the different types of systems are given in Section VI. A brief explanation is necessary to understand the financial/economic analysis spread-sheets given in the following sections. At the top of the spread-sheets are six rows which give a summary of several of the most important site parameters. These are site location, average daily water volume pumped over the year, average pumping head over the year, amortization period assumed (20 years is the default value), predicted pump life (time between replacements of the pump element or pump and motor, in the case of electric submersibles) and discount rate used to calculate the values given.

Because of the complexity of comparing wind pumps at different sites to each other, the test results were normalized using the computer model mentioned in Section III.A to predict the machines' outputs for a common head and wind speed condition. The outputs of the PV pumps are extrapolations over a "typical" year from the limited actual measured values for each site. Since solar radiation levels varied little from one site to another, normalization to account for differences in solar radiation across sites was not considered necessary. The results for the other types of pumps are also extrapolations over time from the actual water output values measured during the tests.

The second group of numbers given on the spread-sheets is the actual costs of purchase and installation paid by the BRET project with slight modifications, as explained in Section III.B. Labor charges were broken out so that shadow-costing could be easily applied. The PW (present worth) of recurrent costs was calculated as a series of negative cash flows representing the recurrent charges by year given in Appendix B. These include all costs for operation and maintenance, expected replacement of parts, pump operator (pumper) costs, transportation, etc. The LCC is the summation of all costs incurred in the purchase and operation of the system over its assumed lifetime.

The third group of numbers on the spread-sheets is benefits from the pump. The predicted annual flow was calculated from the tests results obtained so far and will be modified in later reports as additional data become available. The annual flow was then discounted to reflect the time value of water delivery. The annual volume-head product was calculated by multiplying the daily water output by total pumping head. The value of that annual benefit was then calculated based on an assumed value of P0.30/m^3, which is the tariff currently charged by DWA to its customers. Lastly, the PW of the benefit stream was determined and the benefit/cost ratio calculated following the standard procedure.

The final set of figures given are the unit costs calculated for each system. All are forms of the annualized life-cycle cost (ALCC). The first uses the discounted value of the water delivered (P/m^3), the second gives undiscounted flow (P/m^3), and the third and most useful formulation is the ALCC based on the volume-head product (P/m^3*m).

Separate spread-sheets are given for the economic and financial analyses. The only differences between the two are that the economic analysis includes the effects of shadow-pricing local labor at 0.5 times actual cost, and capital costs, which require foreign exchange, at 1.1 times actual cost. The graphs show that these assumptions have a considerable effect.

A. Wind Pumps

This section gives the projected water output and associated unit cost of water delivery using wind pumps operating under identical head and wind regime conditions, typical of some of those encountered in Botswana (average wind speed of 2.5 meters per second at 37 meters of head). The pumps tested included the Climax 10 and 12, Southern Cross, Kijito, Wind Baron, RIIC and WTGS. Baseline costs for these seven wind pumps and assumptions used in the analysis are outlined in Appendix A. The results are shown in tabular form in Tables 1 and 2, and graphically in Figures 1 and 2.

The assumptions and explanations of the various line items in these spread-sheets are given in detail in Appendix B. There are apparently low initial capital cost entries and high installation labor charges for the RIIC and WTGS machines. Since the machines both use local labor in their manufacture, that labor was split out of the capital cost and allocated to the installation labor cost for convenience in shadow-pricing the labor charges in the economic analysis on the following page. This does not affect the unit cost calculations. The high installation charge for the Wind Baron reflects both the relative mechanical complexity of its assembly and the use of a rented crane. A second Wind Baron installation has since been successfully accomplished without using a crane. The reduced installation cost will be reflected in updates of this analysis in later reports.

A general description of the wind machines tested is provided in the table at the top of page 36.

Table 1

FINANCIAL ANALYSIS OF WINDPUMPS

AVERAGE WINDSPEED = 2.5 M/S

Type of Windpump	CMAX10	CMAX12	SC 14	KIJITO	W.BARON	RIIC	WTGS
Avg. Output (m3/dy)	2.1	3.1	5.1	8.3	22.7	6.9	6.3
Total Pump Head (m)	37	37	37	37	37	37	37
Amort. Per. (yrs)	20	20	20	20	20	20	20
Pump Life (yrs)*	20	20	20	20	20	20	20
Discount Rate (%)	6%	6%	6%	6%	6%	6%	6%
COSTS							
Init. Cap. Cost (P)	3457	4683	4479	20156	36708	4343	4754
Installation Cost	246	262	262	460	721	600	600
Install. Cost-Labor	980	980	980	1120	3203	7075	7691
Tot. Installed Cost	4683	5925	5721	21736	40632	12018	13045
Recurrent Costs PW	8165	8199	8327	8717	12591	10848	10848
Life Cycle Cost (P)	12848	14124	14048	30453	53223	22866	23893
BENEFITS (Assumed Water Value = 0.30 Pula/m3)							
Annual Flow (m3/yr)	767	1132	1862	3030	8286	2519	2300
Discount. Ann. Flow	440	649	1068	1737	4752	1444	1319
Head*Flow (m3*m/yr)	28,361	41,866	68,876	112,092	306,564	93,185	85,082
Benefits @P.30/m3	230	339	558	909	2486	756	690
Benefit Stream PW	2638	3893	6405	10424	28510	8666	7914
Benefit/Cost Ratio	0.21	0.28	0.46	0.34	0.54	0.38	0.33
Unit Cost (P/m3) (Water Discounted)	2.55	1.90	1.15	1.53	0.98	1.38	1.58
Unit Cost (P/m3) (Water Undiscount.)	1.46	1.09	0.66	0.88	0.56	0.79	0.91
Unit Cost (P/m3*m)	0.039	0.029	0.018	0.024	0.015	0.021	0.024

Note: This 20 year lifetime is for the windmill head and tower. The actual pump (reciprocating cylinder or Mono pump) is assumed to require replacement every five years (see Appendix).

Table 2

ECONOMIC ANALYSIS OF WINDPUMPS

AVERAGE WINDSPEED = 2.5 M/S

Type of Windpump	CMAX10	CMAX12	SC 14	KIJITO	W.BARON	RIIC	WTGS
Avg. Output (m3/dy)	2.1	3.1	5.1	8.3	22.7	6.9	6.3
Total Pump Head (m)	37	37	37	37	37	37	37
Amort. Per. (yrs)	20	20	20	20	20	20	20
Pump Life (yrs)*	20	20	20	20	20	20	20
Discount Rate (%)	6%	6%	6%	6%	6%	6%	6%
COSTS							
Init. Cap. Cost (P)	3803	5151	4927	22172	40379	4777	5229
Installation Cost	246	262	262	460	721	600	600
Install. Cost-Labor	490	490	490	560	1602	5538	6846
Tot. Installed Cost	4539	5903	5679	23192	42701	10915	12675
Recurrent Costs PW	6013	6047	6175	6565	10349	8654	8654
Life Cycle Cost (P)	10551	11950	11854	29757	53050	19569	21329
BENEFITS (Assumed Water Value = 0.30 Pula/m3)							
Annual Flow (m3/yr)	767	1132	1862	3030	8286	2519	2300
Discount. Ann. Flow	440	649	1068	1737	4752	1444	1319
Head*Flow (m3*m/yr)	28,361	41,866	68,876	112,092	306,564	93,185	85,082
Benefits @P.30/m3	230	339	558	909	2486	756	690
Benefit Stream PW	2638	3893	6405	10424	28510	8666	7913
Benefit/Cost Ratio	0.25	0.33	0.54	0.35	0.54	0.44	0.37
Unit Cost (P/m3) (Water Discounted)	2.09	1.61	0.97	1.49	0.97	1.18	1.41
Unit Cost (P/m3) (Water Undiscount.)	1.20	0.92	0.56	0.86	0.56	0.68	0.81
Unit Cost (P/m3*m)	0.032	0.025	0.015	0.023	0.015	0.018	0.022

Note: This 20 year lifetime is for the windmill head and tower. The actual pump (reciprocating cylinder or Mono pump) is assumed to require replacement every five years (see Appendix A).

Figure 1

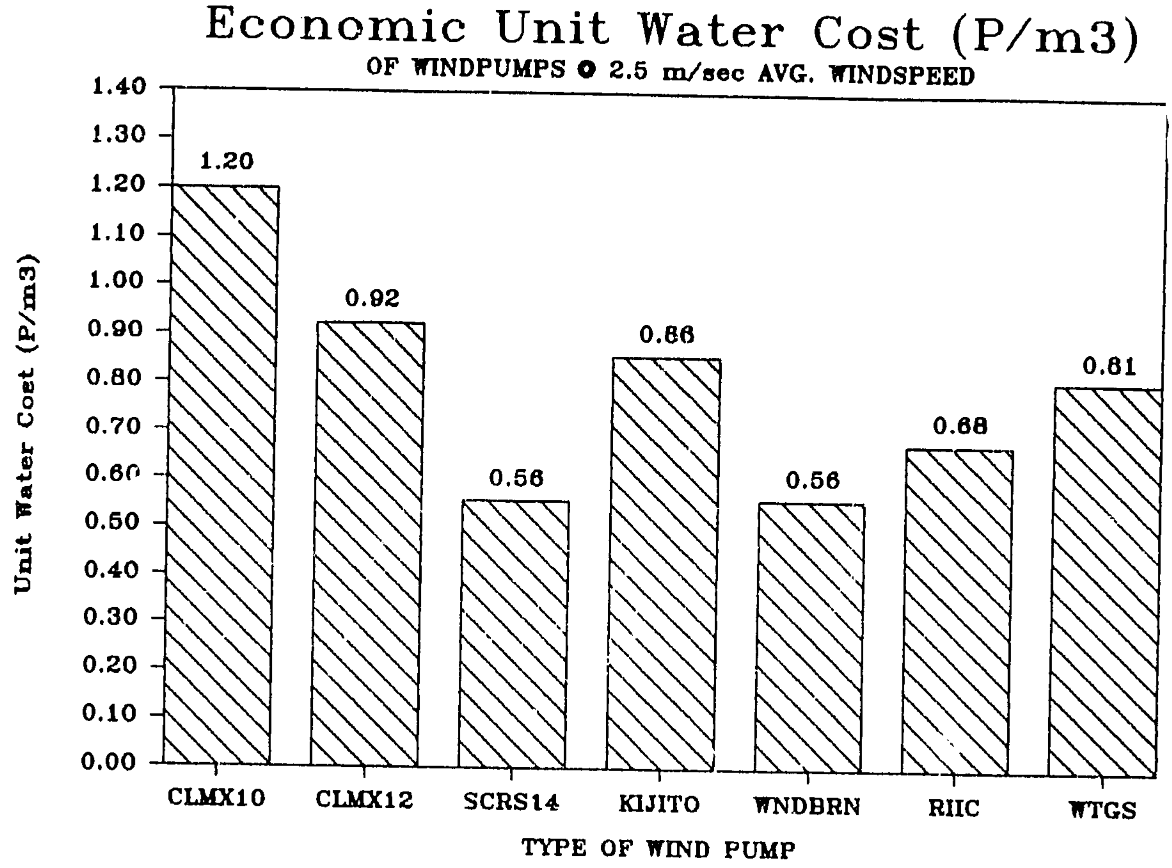
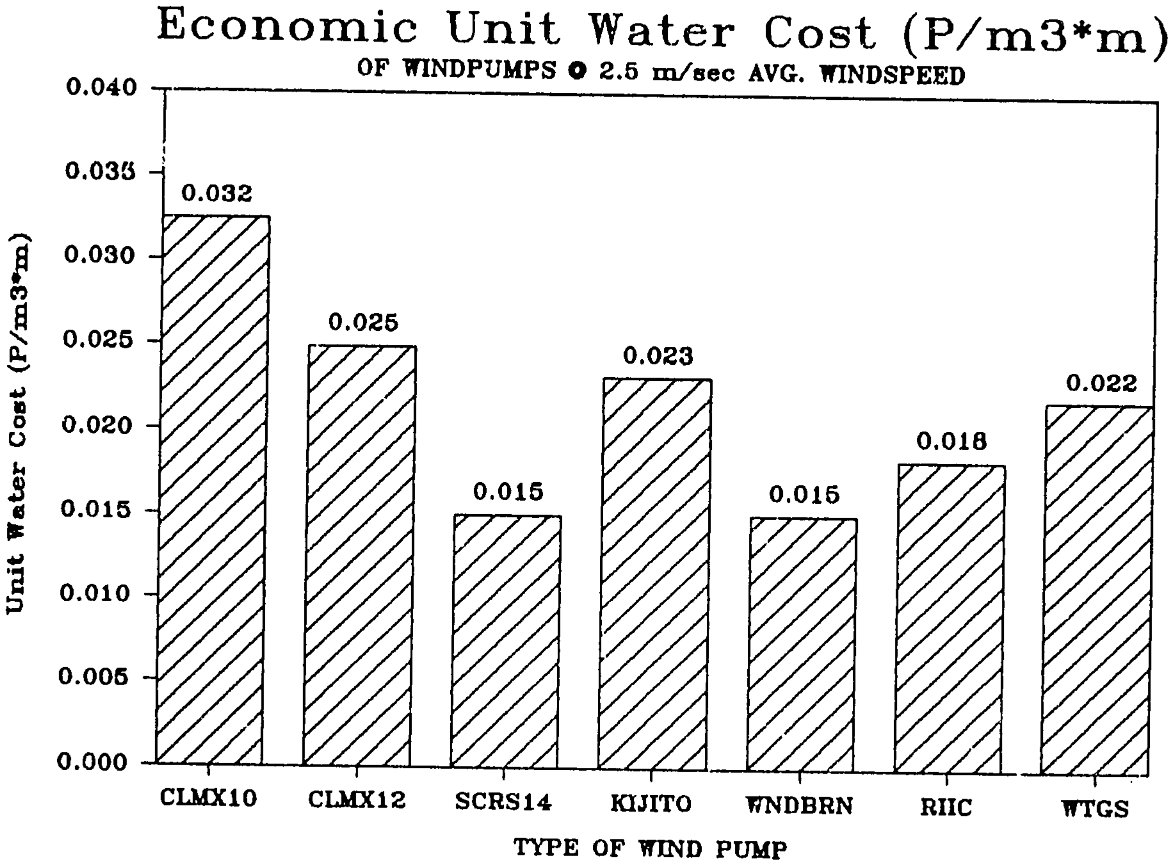


Figure 2



Wind Pump Model	Rotor Diam. (meters)	Type of Pump	Production/Prototype
Climax 10	3.0	Recip. Piston	Production
Climax 12	3.7	Recip. Piston	Production
So. Cross 14	4.3	Recip. Piston	Production
Kijito	6.1	Recip. Piston	Production
Wind Baron	6.4	Recip. Piston	Prod. Prototype
RIIC	6.2	Mono ES-15	Prototype
WTGS	6.2	Mono ES-15	Prototype

In general, since more water is pumped at higher wind speeds, while equipment and operation and maintenance costs remain essentially constant, the unit water costs were lower for higher wind speeds, as expected. This assumes that the wear and tear on the equipment is not significantly greater for these relatively small incremental increases in wind speed. For the standard-design wind pumps (Climax and Southern Cross), unit costs decreased as rotor size increased. This was also expected--the increase in power output normally rises at a greater than linear rate compared to the incremental cost of the larger rotor, since the majority of the other equipment costs (tower, sucker rod, etc.) remain constant.

This relationship was not as clear for the nonstandard machines (i.e., Wind Baron, WTGS, RIIC and Kijito) for several reasons. The cost to import wind pumps from Kenya and the United States was quite high, so delivered capital costs for the imported machines (Wind Baron and Kijito) were much greater than for wind pumps manufactured in Botswana or South Africa. However, these increased costs were largely offset by the superior performance of the imported machines, at least over the short term. Nevertheless, the BRET project has found that the procurement of spare parts may well be a significant deterrent to the use of imported machines, primarily due to unreasonable delays in freight forwarding once equipment arrives in South Africa. If these systems were fabricated in southern Africa (and this appears to be a possibility for both the Kijito and Wind Baron), the results of this analysis could change dramatically.

The indigenous systems coupled to Mono pumps are an interesting and unique development. Compared to the other reciprocating-piston wind pumps, the unit water costs for the WTGS and RIIC systems were considerably less than for the 10- and 12-foot Climax machines (although the former had much larger rotors), and in the same range as the Kijito (with a rotor of the same size) and Southern Cross (smaller rotor). However, the RIIC and WTGS designs do not enjoy the presumed economies of scale associated with the production of standard wind pumps, although higher production levels might well reduce unit costs for the indigenous machines. In addition, it was not clear whether the prices paid for the RIIC and WTGS machines represented actual production costs--i.e., whether implicit subsidies were involved or research and development costs were being recovered over a small number of machines. From a technical perspective, the Mono systems have another distinct advantage over reciprocating-piston machines in that they permit convenient coupling to auxiliary diesel engines for back-up power during periods of low wind speeds, since only the belts need be switched. All in all, the Mono-coupled systems are prototypes that show significant promise.

The Wind Baron has the potential to deliver a lot of water at a relatively low unit cost, if it is assumed (perhaps unjustifiably) that redesign efforts will reduce currently unacceptable maintenance requirements to levels which are characteristic of standard, production-model wind pumps. The Wind Baron's potential is largely a function of its counterbalanced design. Both Kijito and Climax sell counterbalance kits that should have the same effect on performance as the integrated Wind Baron system, but these were not tested by the BRET project, so their potential to reduce the unit cost of water delivery is speculative. Because performance is enhanced by counterbalancing, especially in areas with low wind speeds, such as Botswana, it is a bit misleading to compare counterbalanced to non-counterbalanced systems. However, this is a moot point at present, since the repair record for the Wind Baron was so poor that recommending its use would be inappropriate at its current level of development, regardless of potential performance.

The comparatively high installation cost for the Wind Baron was due to the use of a drop pipe with a considerably larger diameter to accommodate the greater flow of water expected, an imported pump cylinder that was larger than the ones locally available and a rented crane to install the machine on its tower. In a subsequent installation, a gin-pole arrangement was used instead of the crane, and this will greatly decrease installation costs in the future. However, changing the installation cost in the present analysis to reflect this decrease would not affect the ranking of the various wind pumps.

One other major point must be raised. Unlike diesel pumps, a windmill's output depends on the availability of the wind, which is a highly variable energy resource. The estimated performance figures given here are only statistical averages for the conditions cited. A wind pump's output during periods of low wind speed cannot be augmented without incurring the additional costs of a back-up system. If the site under consideration has long periods of low wind speeds (greater than the maximum capacity of a reasonable storage system), a back-up power source, such as a diesel engine, must be included in the system's design. Otherwise, a wind pump is inappropriate for the site.

B. Solar Photovoltaic

Five PV pumps were tested in the first phase of the BRET comparative testing program. Three (at Mahalapye, Malopowabojang and Mochudi) were Jacuzzi submersible direct-current (DC) pumps that were directly coupled to PV arrays. At Mahalapye, the system was also tested using a constant voltage tracking controller to determine whether the incremental water output would offset the additional cost. This was not the case. In general, controllers are not recommended for use with submersible pumps, since they are not strictly required for overcoming starting torque, nor does their extra cost and complexity appear to be balanced by appreciable increases in output.

The other two systems (at Mmathubudukwane and Otse) used Mono pumps. The Mmathubudukwane site also employed a constant voltage tracking (CVT) controller to provide the high current required for start-up of the standard Mono pump. The CVT was the most problematic component in the system. The Otse system used batteries both for energy storage and starting torque. Batteries (because of the need for and cost of proper maintenance as well as expected periodic replacement) and CVTs should be avoided where possible. The newly developed Mono nitrile stator pumps have much less of a problem with starting torque, and their effect on system performance will be examined in more detail during the extension of the project.* Where high starting torque is unavoidable, electronic controllers seem to hold more promise than batteries, as they are relatively inexpensive and long-lasting, at least in principle. There has been considerable improvement in commercially available controllers since these prototypes were designed.

All of the arrays were fixed. Passively controlled sun-tracking array mounts show considerable promise for increasing PV system output for relatively small incremental increases in cost, and should be field-tested if possible during follow-on studies.

The final results for all of the solar pumps are shown in Tables 3 and 4, and graphically in Figures 3 and 4. These results are normalized in that all transportation and labor costs are computed as if the pump sites were equidistant from the water maintenance unit's station.

Each system's water output shown here involves a degree of uncertainty, since it was extrapolated from short-term data collected during the pump tests thus far. Unit water costs were

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*SOLAR PUMP FIELD TESTS IN BOTSWANA -- PRELIMINARY TECHNICAL AND COST COMPARISONS, Richard McGowan and Jonathan Hodgkin, ARD, Burlington, VT, April, 1986.

Table 3

FINANCIAL ANALYSIS OF SOLAR PUMPS

Pump Site	Mahalapye	Mmathab.	Mochudi	Molapow	Otse
Avg. Output (m3/dy)	30	16	16	21	13
Total Pump Head (m)	7	45	36	24	9
Amort. Per. (yrs)	20	20	20	20	20
Array Output (Wp)	516	1548	1376	1376	280
Discount Rate (%)	6%	6%	6%	6%	6%
COSTS					
Init. Cap. Cost (P)	10763	25610	22349	22218	8128
Installation Cost	428	164	140	141	147
Install. Cost-Labor	840	840	700	740	700
Tot. Installed Cost	12031	26614	23189	23099	8975
Recurrent Costs PW	8745	10313	10655	10585	8976
Life Cycle Cost (P)	20776	36927	33844	33684	17951
BENEFITS	(Assumed Water Value =			0.30 Pula/m3)	
Annual Flow (m3/yr)	10950	5877	5694	7592	4745
Discount. Ann. Flow	6280	3370	3265	4354	2721
Head*Flow (m3*m/yr)	76,650	264,443	204,984	182,208	42,705
Benefits @P.30/m3	3285	1763	1708	2278	1424
Benefit Stream PW	37679	20221	19593	26124	16327
Benefit/Cost Ratio	1.81	0.55	0.58	0.78	0.91
Unit Cost (P/m3) (Water Discounted)	0.29	0.96	0.90	0.67	0.58
Unit Cost (P/m3) (Water Undiscount.)	0.17	0.55	0.52	0.39	0.33
Unit Cost (P/m3*m) (Water Undiscount.)	0.024	0.012	0.014	0.016	0.037

Table 4

ECONOMIC ANALYSIS OF SOLAR PUMPS

Pump Site	Mahalapye	Mmathab.	Mochudi	Molapow	Otse
Avg. Output (m3/dy):	30.0	16.1	15.6	20.8	13.0
Total Pump Head (m):	7	45	36	24	9
Amort. Per. (yrs) :	20	20	20	20	20
Array Peak Watts :	516	1548	1376	1376	280
Discount Rate (%) :	6%	6%	6%	6%	6
COSTS					
Init. Cap. Cost (P):	11839	28171	24584	24440	8941
Installation Cost :	428	164	140	141	147
Install. Cost-Labor:	420	420	350	370	350
Tot. Installed Cost:	12687	28755	25074	24951	9438
Recurrent Costs PW :	6756	8317	8578	8511	7008
Life Cycle Cost (P):	19443	37072	33652	33462	16446
BENEFITS	(Assumed Water Value =			0.30 Pula/m3)	
Annual Flow (m3/yr):	10950	5877	5694	7592	4745
Discount. Ann. Flow:	6280	3370	3265	4354	2721
Head*Flow (m3*m/yr):	76,650	264,443	204,984	182,208	42,705
Benefits @P.30/m3 :	3285	1763	1708	2278	1424
Benefit Stream PW :	37679	20221	19593	26124	16327
Benefit/Cost Ratio :	1.94	0.55	0.58	0.78	0.99
Unit Cost (P/m3) : (Water Discounted):	0.27	0.96	0.90	0.67	0.53
Unit Cost (P/m3) : (Water Undiscount.):	0.15	0.55	0.52	0.38	0.30
Unit Cost (P/m3*m) : (Water Undiscount.):	0.022	0.012	0.014	0.016	0.034

Figure 3

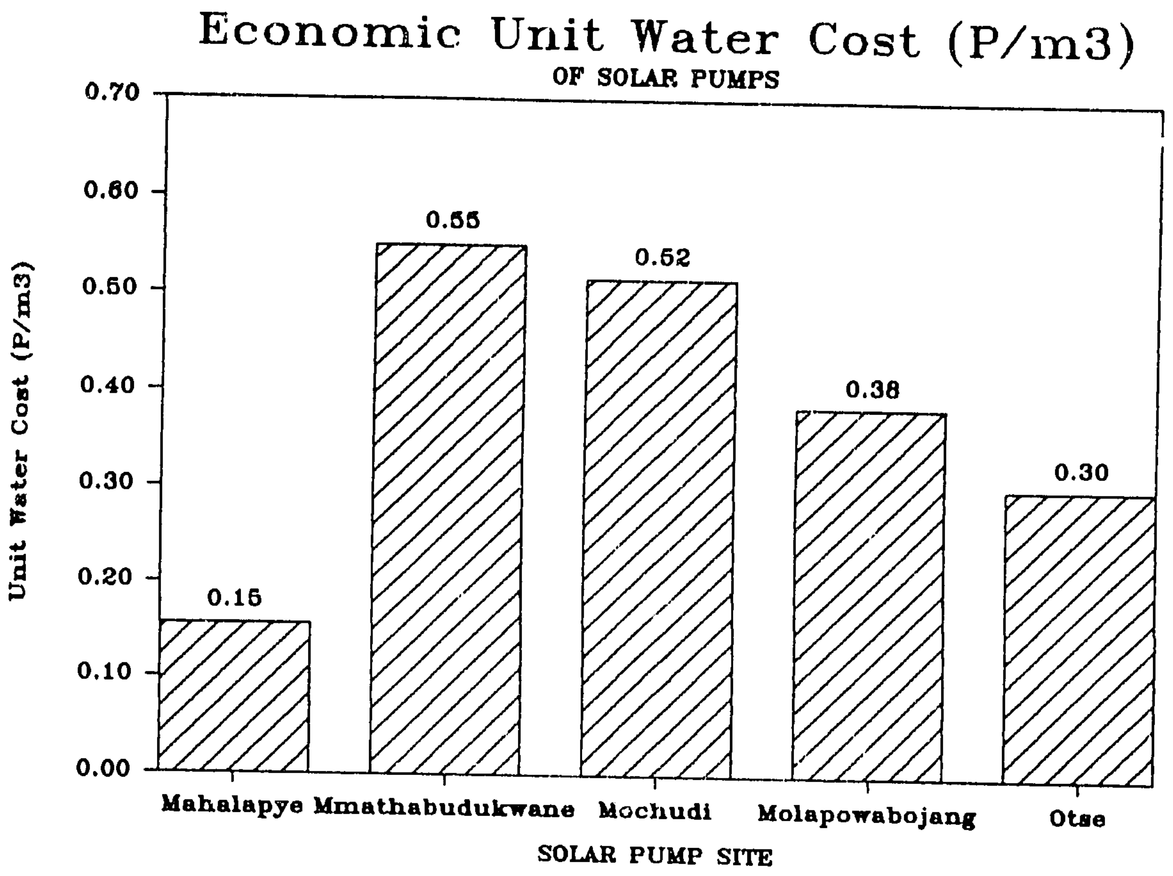
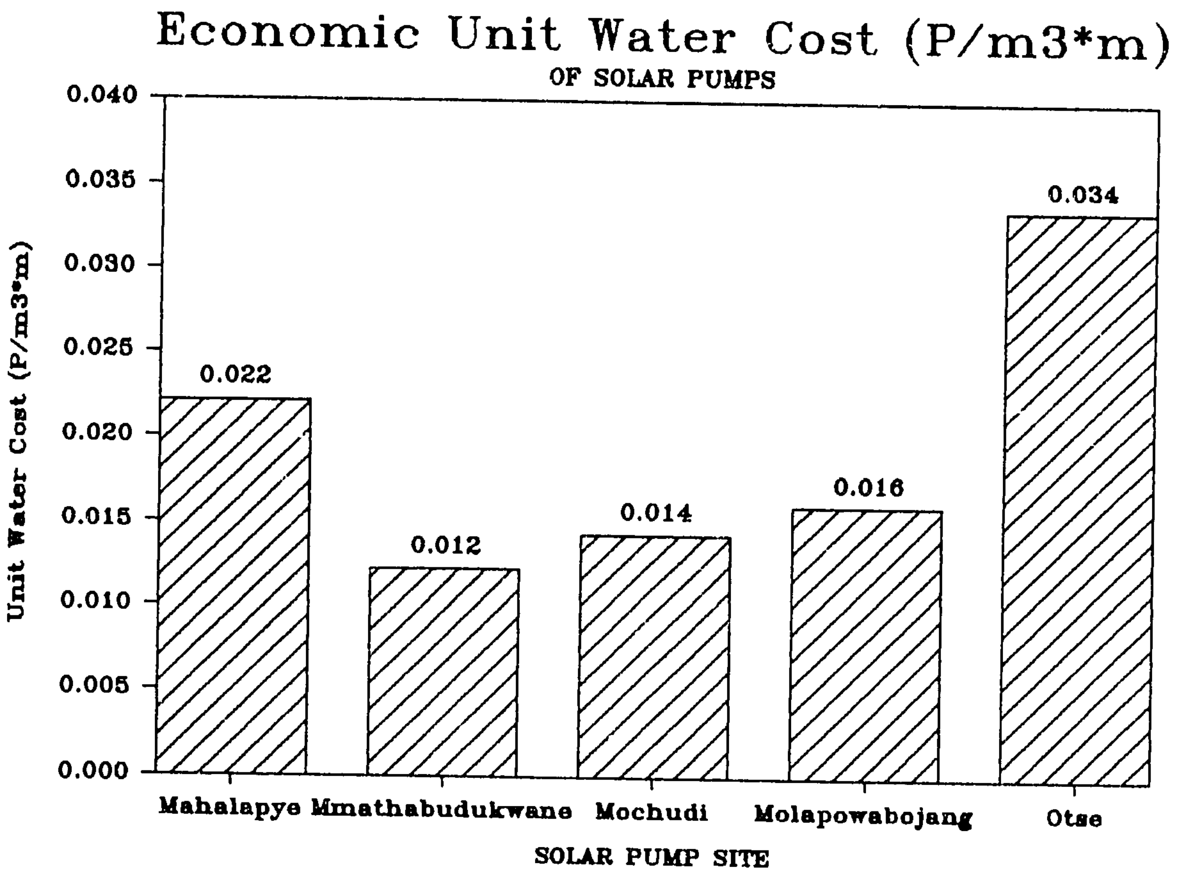


Figure 4



calculated based on certain assumptions about long-term solar radiation levels and somewhat speculative maintenance schedules and costs. The costs of the Mono-coupled systems involve the most extrapolation because of the paucity of data collected at Mmathubudukwane, due to problems with the controller and unexpectedly low borehole yield, and Otse (the pump was not used on a regular basis by the agricultural cooperative there*).

From the first graph, it is clear that the system at Mahalapye delivers water at the lowest cost, based simply on water output. In order of increasing unit cost come Otse, Malopowabojang, Mochudi and finally, Mmathubudukwane. This ranking is directly related to the increasing head at each site--the higher the head, the less water pumped, in spite of the fact that these were different-sized systems. However, the ranking of the systems was very different in the second graph of unit cost/m^3*m. The Mono-coupled system at Mmathubudukwane and two Jacuzzi submersibles at Mochudi and Malopowabojang are in a very close tie for the most cost-effective system, assuming that the controller problems were resolved, which appear to be true.

The Otse system, which had the most poorly matched components and was the only battery system, was by far the poorest performer, largely due to both poorly matched components (pump and motor) and the high recurrent cost associated with the anticipated need for battery replacement every five years. The Mahalapye system was not very cost-effective because of poor matching between the pump and well head (due to a misunderstanding between the user group and the BRET project), and does not reflect the true cost of well-matched systems, such as those at Molapowabojang and Mochudi.

The relative system costs calculated here show that a clear choice between using DC-electric submersibles and Mono-coupled PV systems is not yet possible. Alternating-current (AC) electric submersibles will be tested during the extension of the PV pump evaluation program. The various advantages and disadvantages of submersibles and Monos are discussed at length in Section VI.B.

For the small-scale systems discussed here, the module cost is normally about 80 percent of the entire system cost. While it is likely that the cost of modules will continue to decline (the costs of modules for this program were about P13.2/Wp and current quotes are as low as P10.5/Wp), it is unlikely the balance of system (BOS) costs will decrease at such a rate. While there will be certain economies of scale as the number of units manufactured increases, BOS costs are spread over array

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[*] SOLAR PUMP FIELD TESTS IN BOTSWANA -- PRELIMINARY TECHNICAL AND COST COMPARISONS, Richard McGowan and Jonathan Hodgkin, ARD, Burlington, VT, April, 1986.

structures, pumps motors, and controls. The technology for manufacturing these devices is relatively mature, so their costs are unlikely to drop dramatically. However, due to recent advances in PV cell manufacturing technology, particularly in the area of amorphous silicon cells, system costs will continue to decline in the near future, thus increasing the cost-effectiveness of PV systems relative to the alternatives.

Among the most sensitive assumption made in this analysis is the current government requirement for a pump attendant, which is discussed at greater length in Section VI. Sensitivity analyses of several important assumptions, including the module cost per peak watt (Wp), pump attendent charges, discount rates and amortization periods are given in the Appendix C.

C. Diesel/Mono

The predominant type of pumping system in use in Botswana is a Mono, positive-displacement, progressive-cavity pump coupled to a Lister diesel engine. DWA has standardized on these systems to minimize the necessary parts inventory and training required for their installation and maintenance. These systems are used in almost all village water supply program schemes as well as at DWA boreholes in major villages and other government boreholes.

The BRET project tested five representative diesel pumping systems over short periods of time and examined their operating logs, fuel delivery records and borehole records. The sites were chosen because they represent the overlap between diesel and RET pump applications to some extent. The pumps tested covered the range of smaller Lister engines used by DWA and a cross section of the Mono pump models in use. A range of pumping heads and water demand cases were represented as well. The sites and technical details on them are presented in the following table.

Site Name	Engine Type	Pump Type	Total Head (meters)	Daily Output (m^3/day)
Bonwapitse	Lister ST-1	ES-30S	58	19
Malotwana	Lister SR-1	ES-15S	48	10
Mmankgodi	Lister LT-1	ES-15	82	22*
Mogobane	Lister ST-1	ES-30	74	104
Oodi	Lister 8/1	ES-15	101	39

*This pump normally delivered 22 cubic meters per day, but the other pumps in the village were broken, so it was pumping 24 hours a day (65 cubic meters) at the time of the test.

All of the engines were installed since 1981 as part of the Village Water Supply Program. During the last several years, there has been an emphasis on training and upgrading District Water Departments and Water Units to decrease pump downtime pumps and improve the quality of service that these systems receive. Although service is not yet up to the desired level, great strides have been made in the last several years, resulting in engine-pump sets that are in reasonable operating condition.

The results of the tests corresponded well to the records for each of borehole and expected fuel use, as calculated from information provided by Lister on the fuel consumption of their engines under less than full load conditions. The results are given in the table below.

Site Name	Water Output	--Fuel Use--		Overall Eff.
	(m^3/hr)	ml/hr	ml/m^3	(%)
Bonwapitse	7.66	780	100	15
Malotwana	3.24	520	160	8
Mmankgodi	2.70	405	148	14
Mogobane	8.67	820	95	20
Oodi	3.86	740	192	14

The long-term repair and maintenance records for these pumps are not complete, which is one areas where improvement in the village repair and maintenance system is needed, so it was necessary to estimate many of these costs. These estimates were made by discussing the maintenance and repair needs of the pumps and engines with such individuals as the workshop foreman at DWA, workers associated with the Borehole Repair Service (BRS), Water Unit Technicians, private-sector engine and pump dealers, and manufacturers' representatives. General impressions from these conversations, along with existing records, reveal a number of important points.

The Lister engine appears to be quite robust, but with some marked differences in engine models. The water-cooled models, particularly the 8/1, are favorites as they require less maintenance than the air-cooled models, which must run faster in the hot and dusty conditions found in rural Botswana. The smallest model, the LT series (now replaced with the LV series), appears to be best suited technically to many situations in Botswana, but is not as well liked as the somewhat larger SR and ST series (now replaced by the TS series) because it appears to require more attention than the other engines. In almost all cases, engines are rebuilt rather than replaced, and engine lifetimes are estimated to range from six to eight years for the LT series, and 15 to 20 for the water-cooled models. DWA claims that they are still repairing some Lister 3/1 and 5/1 models, which have not been manufactured for over 25 years.

The Mono pump used in almost all government-sponsored water supply schemes is a well-known, reliable pump. The pump itself is not expensive. However, the installed price is increased significantly by the pump drive shaft, pump head and associated hardware. The pump is easy for a trained crew to install, capable of pumping a certain percentage of silt or sand and will survive pumping air so long as some water is present. Mono pumps are also easy to repair. The most common problem seems to be clogging from too high a sand and grit content in the water.

Appendix B contains all of the assumptions and financial information used in the development of the economic and financial analyses of the diesel pumping systems. Tables 5 and 6, and Figures 5 and 6 summarize the financial and economic analyses for five sites. The costs for delivered water range from P0.31 to P1.83, and it should be noted that this does not include the overhead costs of the maintenance organization.

The unit costs for diesels, based on both head and volume, range from seven to 22 thebe/m^3*m (100 thebe = one Pula). It should be remembered that most of these systems are much larger than the RET systems discussed previously and unit water costs are considerably cheaper for larger systems. A figure of P0.66/liter was used for the cost of diesel fuel in these calculations, since it is the contract price paid by water units for medium-grade diesel fuel. As the volume-head product increases, costs decrease exponentially over the range of heads represented (48 to 101 meters). These results are not very sensitive to head (at least not for the range of heads tested). The implication is that it becomes very expensive to pump smaller quantities of water with diesel pump systems, with costs exceeding P1.00 per cubic meter (water discounted) for volumes of less than 20 cubic meters a day. This is due largely to the fixed cost of the pumper, who must be paid the same full-time wage regardless of how much water is pumped according to GOB industrial-class regulations. This cost approaches half of the unit cost of water delivered in cases where less than 20 cubic meters per day is pumped.

The relatively low unit water costs (particularly for the larger systems) are at least partly due to the well-supported diesel pump operation, maintenance and repair program of DWA in Botswana. Transportation networks are fairly well developed, and anything besides isolated fuel shortages are uncommon. Diesel pumping costs in situations with other than these fortuitous circumstances can be much higher.

Table 5

FINANCIAL ANALYSIS OF DIESEL PUMPING SYSTEMS

Site Location	:BONWAPITSE	MALOTWANA	MMANKGODI	MOGOBANE	OODI
Avg.Water Output (m3/dy):	19	10	22	104	39
Total Pumping Head (m) :	58	48	82	74	101
Amortizatn. Period (yrs):	20	20	20	20	20
Pump life :	20	20	10	10	20
Discount Rate (%) :	6%	6%	6%	6%	6%
COSTS					
Initial Capital Cost :	4423	4075	4650	4970	6085
Installation Cost :	328	328	328	328	328
Installation Cost-labor :	1500	1000	1410	1500	1500
Total Installed Cost :	6251	5403	6388	6798	7913
PW of Recurrent Costs :	41167	39045	48819	73368	68178
Life Cycle Cost (LCC) :	47417	44448	55207	80166	76091
BENEFITS	Cubic meter water value assumed =				0.30
Ann. Flow :	6989.75	3547.8	7884	37974.6	14089
Disc. Ann. flow :	4009	2035	4521	21778	8080
Ann. Head*Flow (m4/year):	405,406	170,294	646,488	2,810,120	1,422,989
Value of Output @P.30/m3:	2097	1064	2365	11392	4227
PW of Benefit Stream :	24052	12208	27129	130670	48480
Benefit/Cost Ratio :	0.51	0.27	0.49	1.63	0.64
:					
Annualized LCC (P/m3) : (Water Discounted) :	1.031	1.905	1.065	0.321	0.821
Annualized LCC (P/m3) : (Water Not Discounted):	0.591	1.092	0.611	0.184	0.471
Annualized LCC (P/m4) : m4 = Volume delivered X Head	0.010	0.023	0.007	0.002	0.005

Table 6

ECONOMIC ANALYSIS OF DIESEL PUMPING SYSTEMS

Site Location	:BONWAPITSE	MALOTWANA	MHANKGODI	MOGOBANE	OODI
Avg.Water Output (m3/dy):	19	10	22	104	39
Total Pumping Head (m) :	58	48	82	74	101
Amortizatn. Period (yrs):	20	20	20	20	20
Pump life :	20	20	10	10	20
Discount Rate (%) :	6%	6%	6%	6%	6%
COSTS					
Initial Capital Cost :	4865	4483	5115	5467	6694
Installation Cost :	328	328	328	328	328
Installation Cost-labor :	750	500	705	750	750
Total Installed Cost :	5943	5311	6148	6545	7772
PW of Recurrent Costs :	27000	25051	33634	58414	53132
Life Cycle Cost (LCC) :	32943	30362	39782	64959	60904
BENEFITS	Cubic meter water value assumed =				0.30
Ann. Flow :	6989.75	3547.8	7884	37974.6	14089
Disc. Ann. flow :	4009	2035	4521	21778	8080
Ann. Head*Flow (m4/year):	405,406	170,294	646,488	2,810,120	1,422,989
Value of Output @P.30/m3:	2097	1064	2365	11392	4227
PW of Benefit Stream :	24052	12208	27129	130670	48480
Benefit/Cost Ratio :	0.73	0.40	0.68	2.01	0.80
Annualized LCC (P/m3) : (Water Discounted) :	0.716	1.301	0.767	0.260	0.657
Annualized LCC (P/m3) : (Water Not Discounted):	0.411	0.746	0.440	0.149	0.377
Annualized LCC (P/m4) :	0.007	0.016	0.005	0.002	0.004

m4 = Volume delivered X Head

Figure 5

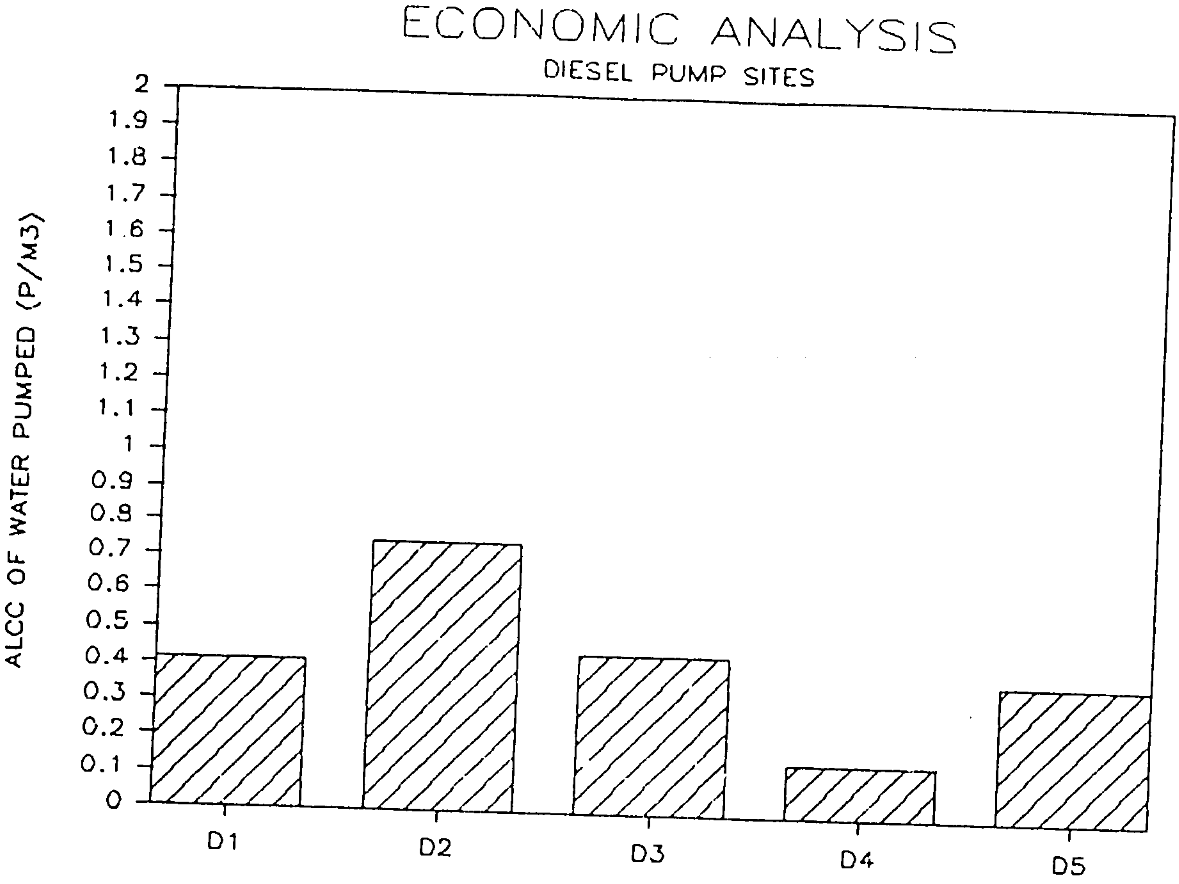
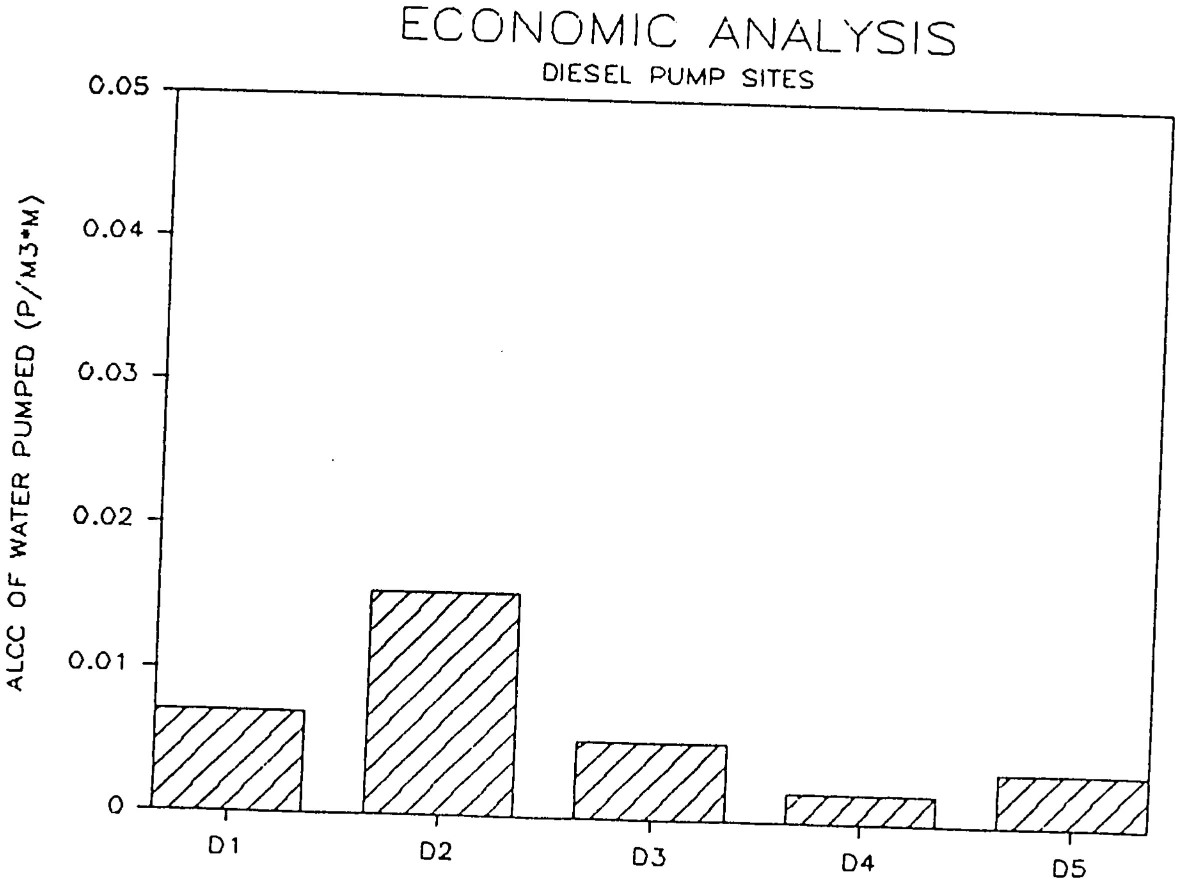


Figure 6



D. Grid-Electric Submersibles

DWA is becomming increasingly interested in the substitution of electric pumps for diesel systems in areas where grid electricity is available. This interest developed as a result of DWA's belief that electric pumping systems can be more cost-effective than diesel pumps, as suggested in the UNDP/World Bank draft report BOTSWANA, ISSUES AND OPTIONS IN THE ENERGY SECTOR (Energy Assessments, Division, Washington, DC, March, 1984). Electric pumps will be even more cost-effective when Botswana begins to generate more of its own power as the Morupula power plant comes on-line. DWA has been operating about a dozen submersibles and electric-driven Mono pumps for major village water supplies for some time and are adding five new submersibles to the Kanye well field. Most of these systems fall well outside the range of interest to this study, as they are larger systems with demands that could not be met cost effectively by renewable energy sources. At this time, there is only one set of grid-connected pumps in the Village Water Supply Program, the sand river extraction units at Mmadinare.

Testing of two electric pumps was undertaken as part of the BRET program. Considerable difficulty was encountered in trying to identify suitable test sites, partly because of the size of most electric pumping systems and technical difficulties at some of the sites. Both submersible and electric-driven Mono pump test sites were sought, but only two suitable submersible pumps were found and tested, and even for these, there is some confusion as to the make and model of the pump and motor. Both were in Mochudi and are identified by borehole number. Site parameters and the results of tests undertaken during a one-month period in June, 1985 are provided in the following table.

Site No.	Total Head (m)	Output (m^3/hr)	Operation (hr/day)	Output (m^3/day)	Energy Use (kW-hr/day)	Energy Eff.(%)
3136	110	9.6	17	163	116	42
3137	94	4.0	16	64	47	35

Although both of these pumps have been in place since the late 1970s, there are no records of their installation or any subsequent repairs or maintenance. Although it appears that they have been relatively trouble- free, there is some evidence that repairs and maintenance have been done. Details concerning these assumptions can be found in Appendix A. The results of the financial and economic analyses are given in Tables 7 through 9 and Figures 7 and 8.

Table 7

FINANCIAL ANALYSIS OF ELECTRIC PUMPING SYSTEMS

SITE:	No.3136	No.3137
Avg.Water Output (m3/dy):	163	64
Total Pumping Head (m) :	110	94
Amortizatn. Period (yrs):	20	20
Pump life :	7	7
Discount Rate (%) :	6%	6%
COSTS		
Initial Capital Cost :	5600	3200
Installation Cost :	66	66
Installation Cost-labor :	1046	1046
Total Installed Cost :	6712	4312
PW of Recurrent Costs :	86978	39340
Life Cycle Cost (LCC) :	93690	42652
BENEFITS	Cubic meter water value =	0.3 Pula
Ann. Flow :	59495	23360
Disc. Ann. flow :	34120	13397
Ann. Head*Flow (m4/year):	6,544,450	2,195,840
Value of Output @P.30/m3:	17849	7008
PW of Benefit Stream :	204721	80381
Benefit/Cost Ratio :	2.19	1.88
Annualized LCC (P/m3) : (Water Discounted) :	0.239	0.278
Annualized LCC (P/m3) : (Water Not Discounted):	0.137	0.159
Annualized LCC (P/m4) : m4 = Volume delivered X Head	0.001	0.002

Table 8

ECONOMIC ANALYSIS OF ELECTRIC PUMPING SYSTEMS

SITE:	No.3136	No.3137
Avg.Water Output (m3/dy):	163	64
Total Pumping Head (m) :	110	94
Amortizatn. Period (yrs):	20	20
Pump life :	7	7
Discount Rate (%) :	6%	6%
COSTS		
Initial Capital Cost :	6160	3520
Installation Cost :	66	66
Installation Cost-labor :	523	523
Total Installed Cost :	6749	4109
PW of Recurrent Costs :	85082	36231
Life Cycle Cost (LCC) :	91831	40340
BENEFITS	Cubic meter water value =	0.3 Pula
Ann. Flow :	59495	23360
Disc. Ann. flow :	34120	13397
Ann. Head*Flow (m4/year):	6,544,450	2,195,840
Value of Output @P.30/m3:	17849	7008
PW of Benefit Stream :	204721	80381
Benefit/Cost Ratio :	2.23	1.99
Annualized LCC (P/m3) : (Water Discounted) :	0.235	0.263
Annualized LCC (P/m3) : (Water Not Discounted):	0.135	0.151
Annualized LCC (P/m4) : m4 = Volume delivered X Head	0.001	0.002

Table 9

ECONOMIC ANALYSIS OF ELECTRIC PUMPING SYSTEMS

SITE:	No.3136	No.3137
Avg.Water Output (m3/dy):	163	64
Total Pumping Head (m) :	110	94
Amortizatn. Period (yrs):	20	20
Pump life :	7	7
Discount Rate (%) :	6%	6%
COSTS		
Initial Capital Cost :	6160	3520
Installation Cost :	66	66
Installation Cost-labor :	523	523
Total Installed Cost :	6749	4109
PW of Recurrent Costs :	31578	14585
Life Cycle Cost (LCC) :	38327	18694
BENEFITS	Cubic meter water value =	0.3 Pula
Ann. Flow :	59495	23360
Disc. Ann. flow :	34120	13397
Ann. Head*Flow (m4/year):	6,544,450	2,195,840
Value of Output @P.30/m3:	17849	7008
PW of Benefit Stream :	204721	80381
Benefit/Cost Ratio :	5.34	4.30
Annualized LCC (P/m3) : (Water Discounted) :	0.098	0.122
Annualized LCC (P/m3) : (Water Not Discounted):	0.056	0.070
Annualized LCC (P/m4) : m4 = Volume delivered X Head	0.001	0.001

Figure 7

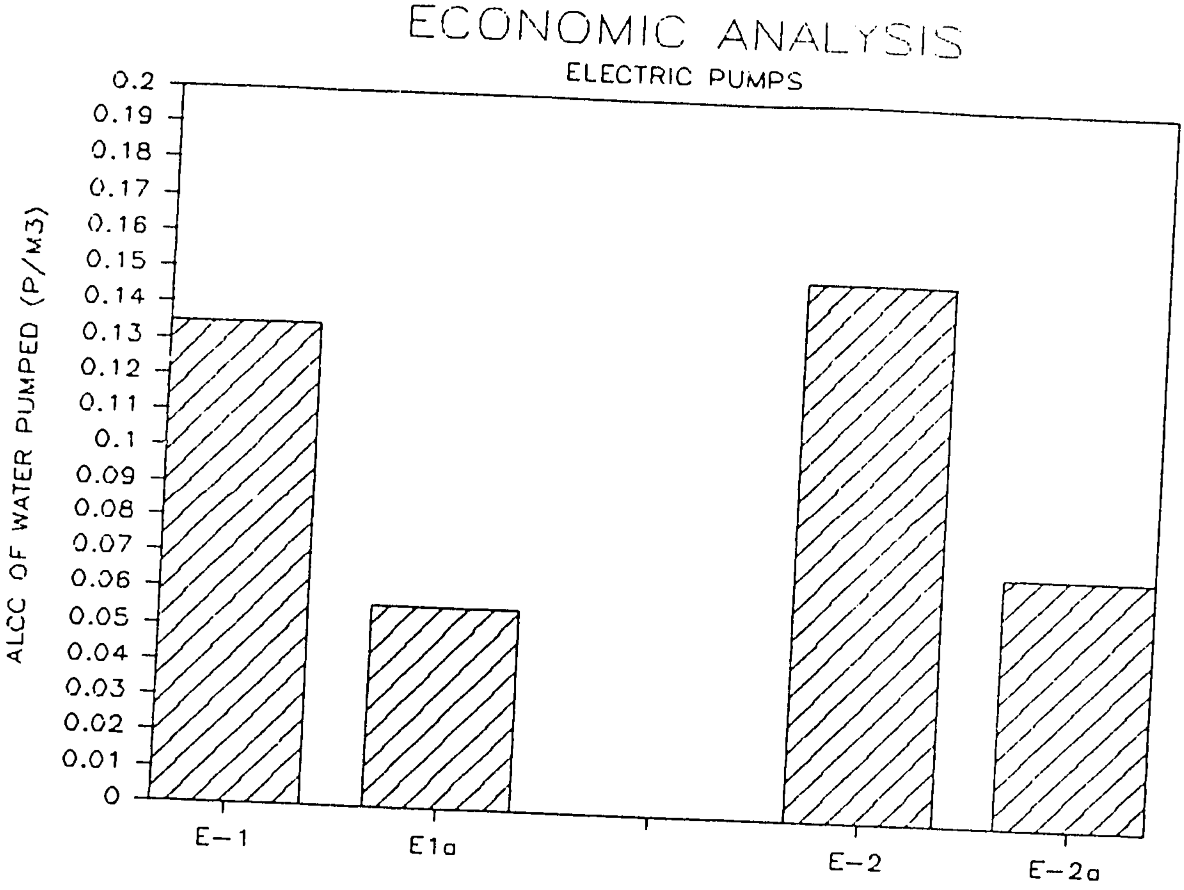
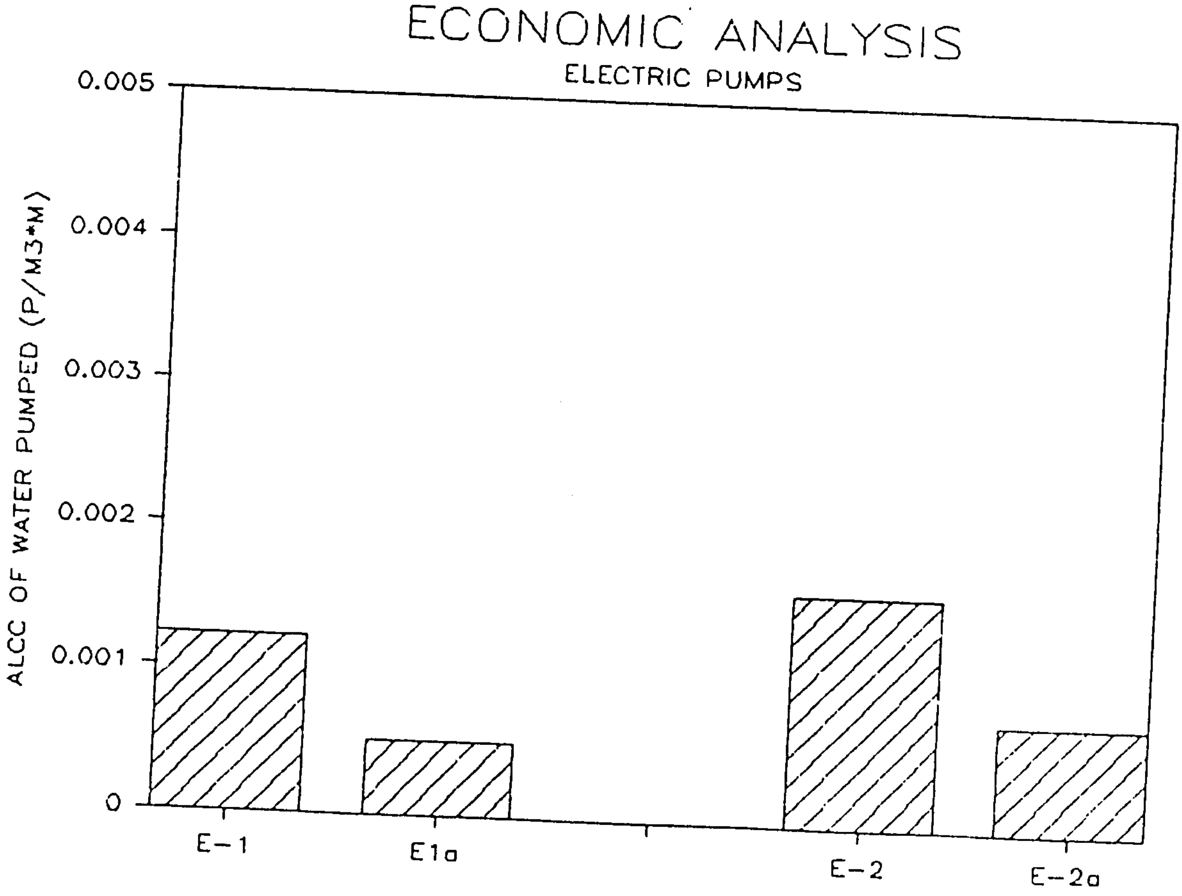


Figure 8



Although these results can hardly be considered conclusive because of the small number of tests conducted thus far, they indicate that electric pumps are approximately in the same cost range as diesel systems. This somewhat unexpected conclusion is largely due to the high electrical energy cost at the water pumping tariff rate of 16.1 thebe per kilowatt-hour (kWh). A World Bank study (not yet published) assumes an economic cost of P0.05 per kWh if the power is generated at the Morupula power plant. This assumption was used in Table 9 and Figures 7 and 8. (The E-1 and E-2 designations on the graphs indicate the economic calculations completed using 16.1 thebe/kWh for the first and second electric pump sites. E-1a and E-2a indicate calculations based on the lower kilowatt-hour charge suggested in the World Bank study).

The graphs show that the unit cost for pumped water using the lower energy cost is about half that diesel systems of similar size. If grid-electric pumps are used in areas where smaller diesel generators supply grid power, the real costs will undoubtedly be higher, as GOB-supplied energy is subsidized in these places (e.g., the smaller grids, as in Maun). Small private diesel generators (in the 10-kilowatt range) deliver energy at costs around P0.80/kWh, which is considerably higher than large grid tariffs.

It is unfortunate that the electric pumps tested were such high-capacity systems. It is difficult to draw any conclusions about the economics of these pumps in the range of interest for RET pumps. However, there are general potential advantages to the use of electric pumps, such as relatively easy installation, and low maintenance and operating costs (other than electricity charged) compared to diesels. Electric pumps can also be more easily controlled automatically to protect the motor, prevent the pump from running dry, turn the pump on and off, and keep the storage tank full. Thus, it is possible to operate the system without a full-time pumper, which is not true of diesel pumps.

It is unfortunate that no operating electric Mono pumps were available for testing, since they have some potential advantages over submersibles, particularly if electric pumps are ever to be used in the Village Water Supply Program. These advantages include a surface-mounted motor that can easily be serviced, a pump whose operation which is familiar to technicians at the district level, and the fact that borehole characteristics (such as static water level and drawdown) are often not well-known, but the performance of Mono pumps is not nearly as sensitive to changes in head as submersibles. Testing this type of pump will be part of the project extension if time permits.

E. Hand-Operated Pumps

Early in the project, a comparison of two designs of hand pumps was undertaken in response to a perceived need by both the BRET project and several GOB agencies to examine hand-operated systems as a water pumping alternative. Hand pumps have been used in Botswana for some time in a rather ad hoc manner. There have been a number of Godwin hand pumps in use, but most are now in disrepair. More recently, a few Mono hand pumps have been installed. The BRET comparative testing program began with a donation of equipment from SIDA and a request for assistance with a test program from DWA. Two models of hand pumps were tested, the India Mark II and Swedish Petropump. The results of this work are described in detail in TWO TYPES OF HAND PUMPS -- RESULTS OF FIELD TESTS IN BOTSWANA (Jonathan Hodgkin and Richard McGowan, ARD, Burlington, VT, August, 1985).

The tests indicated that the India Mark II was a more suitable pump for conditions found in Botswana for several reasons. The Petro pump, which uses an unconventional pump element and anchor assembly, was designed to be installed on boreholes with a smaller casing than is normally found in Botswana. Also, the India Mark II pump had a much better repair record than the Petro.

Human-traction pumps had been used in Botswana in the late 1940s and early 1950s, and several were in operation up until 1981. The pump consists of a capstan, rocker assembly and conventional piston pump. The action of walking around the capstan and pushing an attached arm operates the counterbalanced rocker arm and provides the vertical action necessary to operate the pump. A number of these pumps were located in rural areas in various states of disrepair, and so, it was decided to refurbish several of them. After reinstallation, these pumps were received enthusiastically by their users. This encouraged the BRET project and RIIC technicians to redesign the pump with the idea of increasing both output and long-term reliability. One of the redesigned pumps was installed and tested. This pump has operated quite successfully thus far. The results of this work are presented in the BRET report titled, THE THEBE PUMP -- A HUMAN TRACTION PUMP FOR BOTSWANA (Jack Shields and Richard McGowan, ARD, Burlington, VT, August, 1985).

During the tests, interviews with standard hand pump users showed that the practical acceptable limit for their use is 30 meters. Beyond that depth, users found them difficult to operate and sought out another source of water, if available. The human-traction pump was redesigned to incorporate mechanical advantage to permit pumping water from 100 meters. At this time, none of the pumps are actually pumping from this level, but indications are that this is certainly possible with the current design.

The output of hand-operated pumps is dependent on several factors, principally the number of users and distance that users must carry water. Obviously, if mechanically or electrically driven pumps are easily accessible, users prefer them. The long-term output of the hand pumps was not directly recorded. The expected range of output varied from almost nothing in several cases, where the pumps were unreasonably expected to pump from medium depths (over 40 meters), to more practical installations that delivered three to four cubic meters a day at lower heads. These were usually in more populated areas where reticulated water was not available or the local diesel engine was broken.

Since DWA's centralized activities focus on village water reticulation schemes, District Councils and their water units would be more appropriate agencies for implementation of a hand pump dissemination program. Because of the nature of council activities and their proximity to water users, both physically and in terms of communication, these agencies can be more responsive to local needs, select adequate sites where the need is the greatest, and handle installations, maintenance and repairs more economically. Hand pump technology is simple and straightforward enough so that after some training, District Council Water Units should be able to install these systems as well as perform all of the additional maintenance and repair work.

A financial analysis determined the unit cost of delivered water for these pumping systems, and these results are presented in Tables 10 and 11, and graphically in Figures 9 and 10. One major assumption was that the labor required to pump the water had no value. Experience in other hand pump testing programs has suggested that the life of hand-operated pump is expected to be 10 years. Thus, a replacement was included at 10 years to compute unit water costs in the same way as for the other pumps tested in the overall program. The primary periodic maintenance procedure that was recommended was simply replacement of the pump leathers.

The range of unit costs per cubic meter (water undiscounted) is 20 to 40 thebe (assuming that three cubic meters a day is pumped). Up to the practical head limit of hand pumps, output is largely independent of head. This means that unit cost per m^4 is largely a function of head and perhaps is not such a good indicator. For consistency in comparing hand pumps to the other systems tested, unit water costs were calculated in the same way. They ranged from 1.5 to 2.9 thebe/m^3*m, using the output assumptions noted above.

From both technical and financial/economic perspectives, hand pumps certainly have a role in addressing small-scale water supply needs. They are most applicable under one or more of the following circumstances:

Table 10

FINANCIAL ANALYSIS OF HAND PUMPING SYSTEMS

Site Location	:TLHARESELEELE		HUKUNTSI		DIKGONYE THEBE		SENGWOMA	
Avg.Water Output (m3/dy):	1	3	1	3	1	3	1	3
Total Pumping Head (m) :	14	14	17	17	33	33	16	16
Amortizatn. Period (yrs):	20	20	20	20	20	20	20	20
Pump life :	10	10	10	10	10	10	10	10
Discount Rate (%) :	6%	6%	6%	6%	6%	6%	6%	6%
COSTS								
Initial Capital Cost :	605	605	538	538	2123	2123	539	539
Installation Cost :	176	176	861	861	327	327	274	274
Installation Cost-labor :	560	560	980	980	840	840	540	540
Total Installed Cost :	1341	1341	2379	2379	3290	3290	1353	1353
PW of Recurrent Costs :	3462	3462	1633	1633	3369	3369	1746	1746
Life Cycle Cost (LCC) :	4803	4803	4012	4012	6659	6659	3099	3099
BENEFITS	Cubic Meter Water Value Assumed					0.3 Pula		
Ann. Flow :	365	1095	365	1095	365	1095	365	1095
Disc. Ann. flow :	209	628	209	628	4187	12560	4187	12560
Ann. Head*Flow (m4/year):	5,110	15,330	6,205	18,615	12,045	36,135	5,840	17,520
Value of Output @P.30/m3:	110	329	110	329	110	329	110	329
PW of Benefit Stream :	1256	3768	1256	3768	1256	3768	1256	3768
Benefit/Cost Ratio :	0.26	0.78	0.31	0.94	0.19	0.57	0.41	1.22
Annualized Cost (P/m3) : (Water Discounted) :	2.000	0.667	1.671	0.557	0.139	0.046	0.065	0.022
Annualized Cost (P/m3) : (Water Not Discounted):	1.147	0.382	0.958	0.319	1.591	0.530	0.740	0.247
Annualized Cost (P/m4) :	0.082	0.027	0.056	0.019	0.048	0.016	0.046	0.015

m4 = Volume delivered X Head

Table 11

ECONOMIC ANALYSIS OF HAND PUMPING SYSTEMS

Site Location	:TLHARESELEELE		HUKUNTSI		DIKGONYE THEBE		SENGWOMA	
Avg.Water Output (m3/dy):	1	3	1	3	1	3	1	3
Total Pumping Head (m) :	14	14	17	17	33	33	16	16
Amortizatn. Period (yrs):	20	20	20	20	20	20	20	20
Pump life :	10	10	10	10	10	10	10	10
Discount Rate (%) :	6%	6%	6%	6%	6%	6%	6%	6%
COSTS								
Initial Capital Cost :	666	666	592	592	1885	1885	593	593
Installation Cost :	176	176	861	861	327	327	274	274
Installation Cost-labor :	280	280	490	490	1010	1010	270	270
Total Installed Cost :	1122	1122	1943	1943	3222	3222	1137	1137
PW of Recurrent Costs :	2890	2890	1327	1327	2788	2788	1397	1397
Life Cycle Cost (LCC) :	4012	4012	3270	3270	6010	6010	2534	2534
BENEFITS		Cubic Meter Water Value Assumed				0.3 Pula		
Ann. Flow :	365	1095	365	1095	365	1095	365	1095
Disc. Ann. flow :	209	628	209	628	4187	12560	4187	12560
Ann. Head*Flow (m4/year):	5,110	15,330	6,205	18,615	12,045	36,135	5,840	17,520
Value of Output @P.30/m3:	110	329	110	329	110	329	110	329
PW of Benefit Stream :	1256	3768	1256	3768	1256	3768	1256	3768
Benefit/Cost Ratio :	0.31	0.94	0.38	1.15	0.21	0.63	0.50	1.49
Annualized Cost (P/m3) : (Water Discounted) :	1.671	0.557	1.362	0.454	0.125	0.042	0.053	0.018
Annualized Cost (P/m3) : (Water Not Discounted):	0.958	0.319	0.781	0.260	1.436	0.479	0.605	0.202
Annualized Cost (P/m4) : m4 = Volume delivered X Head	0.068	0.023	0.046	0.015	0.044	0.015	0.038	0.013

Figure 9

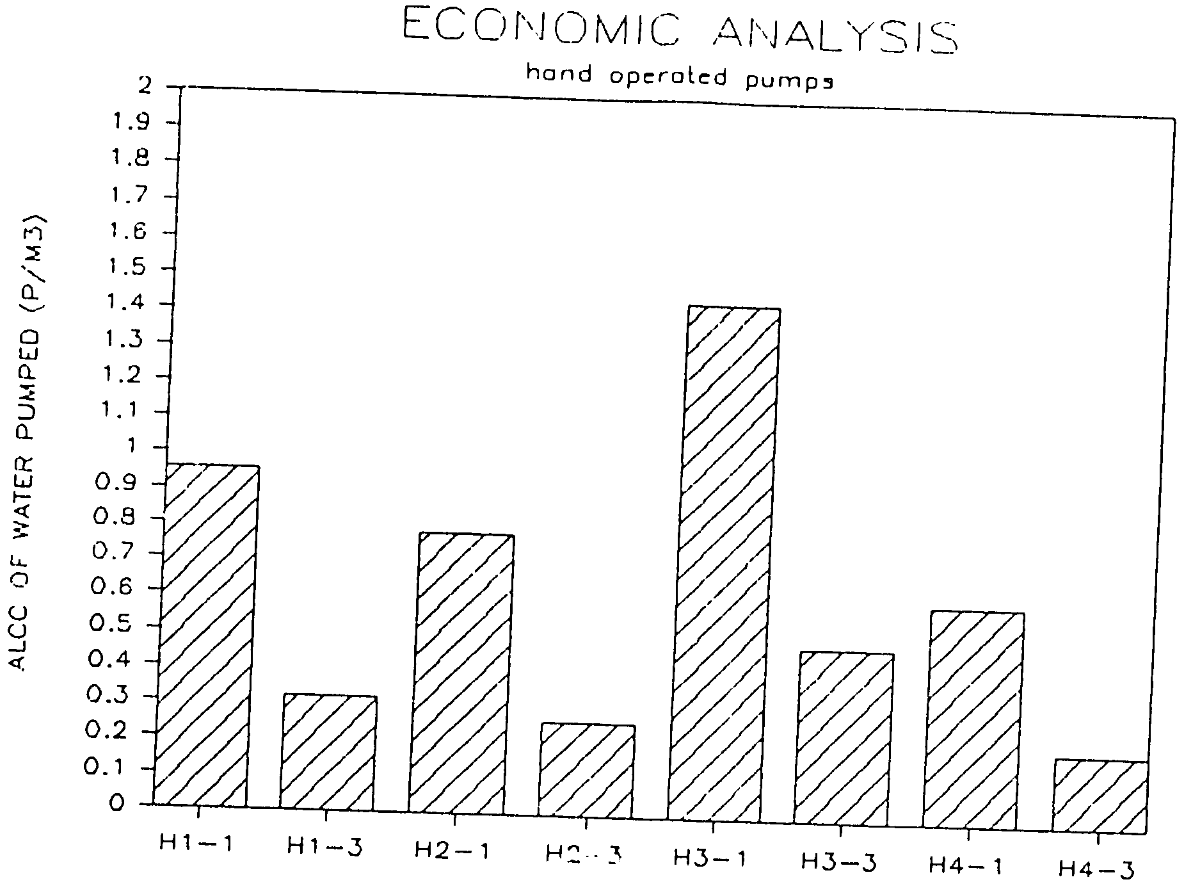
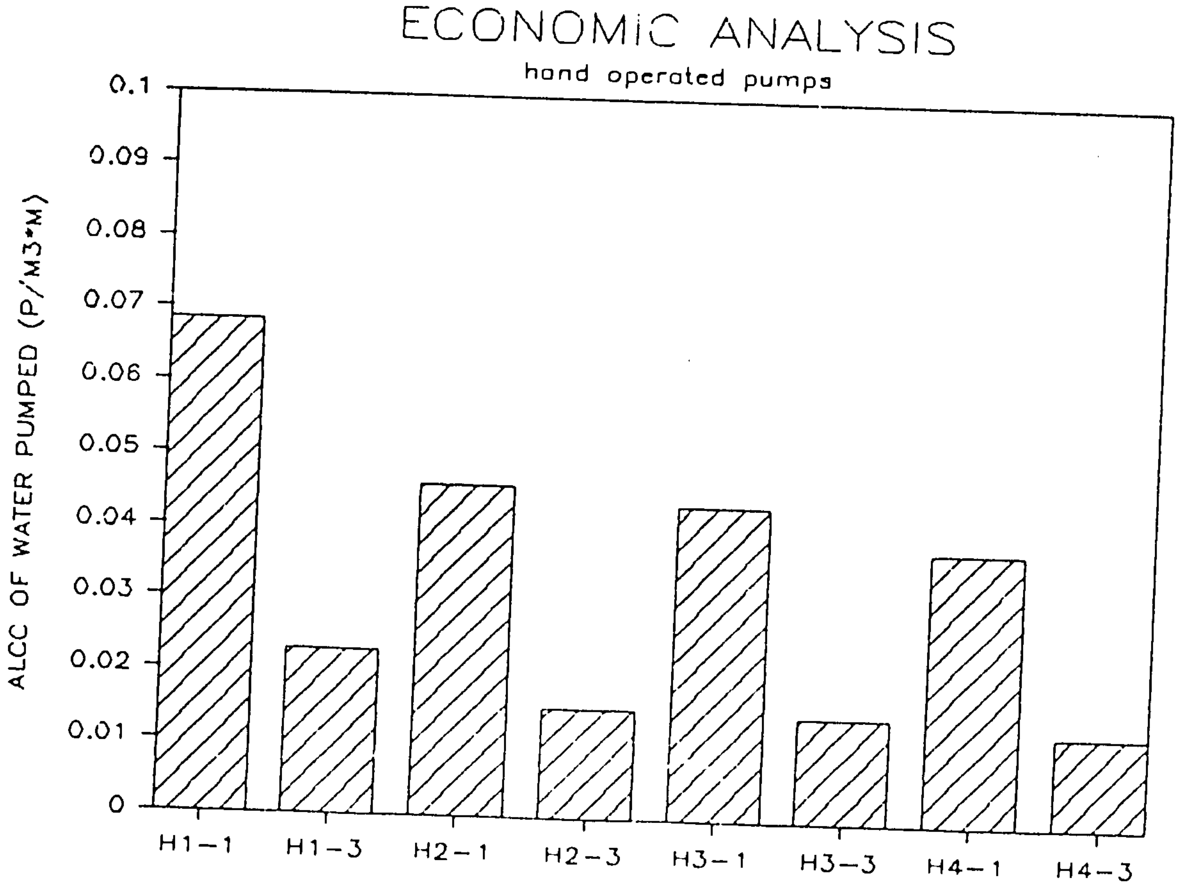


Figure 10



- as back-up systems in villages with reticulation networks;
- in low-yield boreholes;
- in cases where demand is limited, such as lands areas and small settlements; and
- for wells with heads of less than 30 meters.

Hand pumps can also play an important role as back-up pumps at sites with operating pumps that go down for periodic maintenance, lack of fuel or simply breakdowns. Even for sites with medium-level demand, hand pumps can meet immediate emergency needs until the primary system is again delivering water. In or near many villages, suitable boreholes for hand pump installations already exist and could be regarded as an inexpensive, reliable back-up measure.

The cost figures for both hand and human-traction pumps could certainly be improved through local manufacture. While the one redesigned human-traction pump was manufactured by RIIC, it was a one-off unit and was costed accordingly. It is likely that both hand and human-traction pumps could be manufactured in Botswana, either by RIIC, a brigade or Water Maintenance Units, using skills and equipment that already available. This option should be investigated in the future.

F. <u>Animal Traction and Bio-Gas Substitution</u>

During the last several years, RIIC has made a substantial effort to develop appropriate pumping systems. Their wind pump program has been discussed elsewhere in this report. The other two aspects of this effort are animal-traction and bio-gas substitution pumps. As part of the BRET project's involvement in RETs, financial support for development of the animal-traction pump and purchase of a bio-gas system was provided. Testing these pumps, as well as the technical and financial analyses, were contracted to BTC. The results of their work have only recently become available. Unfortunately, they are incomplete and inconclusive for a number of reasons, some of which were unavoidable. For this reason, all of the financial analyses for these systems must be treated with caution. However, this work has raised some important questions and identified a number of issues. A very preliminary financial analysis is presented below. The two systems are covered separately in the following subsections.

1. Animal Traction

The concept of using the draft power of animals to pump water is an ancient one. The RIIC animal-traction pump is a recent effort to use animal draft power to drive a Mono pump. The pump's above-ground components consist of three drawbars connected to a central point so that animals (in this case, donkeys) connected to them walk in a circle and turn the mechanism. This circular motion drives a step-up transmission of gears and chain drives. The output of the transmission is then connected to a standard Mono pump through a standard Mono head by drive belts. The total step-up from the drawbar to the pump is 1:750. At the site where tests were undertaken, the head was about 40 meters, and water delivery was reported to be six cubic meters per hour. In this configuration, the pump appears capable of pumping about 40 cubic meters a day with continuous use. The tests conducted by BTC were incomplete in that only two days of testing were conducted, and during most of this, a tractor was used to turn the pump rather than draft animals. From a purely technical perspective, it appears that the animal-traction pump has the potential to replace smaller diesel engines for some applications.

The issues raised by the work to date are the labor required to collect, feed, care for, harness and drive the animals, the use of supplementary feed, and owership of the donkeys. The operation of this pump is labor-intensive process, requiring at least three men working full-time to drive the donkeys. Beyond that, the animals must be cared for and fed, if grazing is insufficient, collected in the morning, harnessed and then put out to graze when their shift is over. If these men must be paid according to a government scale, it will seriously affect the financial aspects of using an animal-traction pump.

Initial assumptions surrounding the design of the animal-traction pump included the use of donkeys already owned by pump users. Grazing was assumed to be freely available so that no supplementary feed would have been needed. Both of these assumptions have been called into question. Based on experiences thus far, owners of animal-traction pump might be unwilling to use their own donkeys for such strenuous work, so several shifts of donkeys must be owned cooperatively. The strenuous nature of the work would require supplementary feed for at least certain parts of the year. All of this would drive up operating costs. The magnitude of all of these assumptions appear to be sensitive in the financial analysis.

In spite of all these concerns, it appears that the unit price of water can approach diesel pump costs under certain conditions. The most important of these is that labor cost must be minimized. This condition immediately eliminates animal-traction pumps from consideration for any government installations, because of Industrial Class Regulations governing the wages of government employees. An allowance for the purchase and some feed over the dry season is also included. However, the information on annual incremental feed requirements or minimum grazing area required and consequent costs are inadequate. Perhaps the most important assumption is that repair and maintenance requirements will be minimal over the system's lifetime. Based on the minimal testing done thus far, this has not been established.

If labor costs to operate the pump can be kept to about P1,000 per year and supplemental feeding costs to approximately P500 per year, and P1,500 will purchase 30 donkeys or mules to power the animal-traction pump, it could produce water for about 20 thebe per cubic meter or about .5 thebe/m^4. This compares favorably with diesel pumps (with a full-time pumper) in the same output range. The costs for an animal-traction system are about equal when compared to the same diesel with a pumper paid P500 per year. Since the limited test data are inconclusive at this point, these conclusions are tenuous at best. Long-term acceptabilty will be heavily dependent on the technical, social and managerial factors already mentioned.

2. Bio-Gas Substitution

The use of animal waste to create bio-gas that can then be used as a substitute for petroleum-based fuels is not new. The RIIC bio-gas pump effort makes use of this concept. The 75-cubic meter digester at Diphawana produces gas that is used to substitute for a percentage of the diesel fuel required to operate a standard Lister ST-1/Mono pump combination. The tests undertaken by BTC indicate that the bio-gas pump was not operating in a representative way for two reasons. First, borehole yield was so low that air was being pumped, which seriously degraded the pump's potential performance. Second, gas production was low due to the rate of feeding dung to the digester during the period prior to the tests. However, it was anticipated that the pump set was capable of pumping approximately 3.5 cubic meters per hour at 74 meters of head. Under ideal operating conditions, it was expected that bio-gas could replace about 80 percent (by volume) of the diesel fuel.

The bio-gas pump is another technology that requires a substantial commitment from users. With sufficient operating skills, it is possible to drive the pump entirely with diesel fuel. Fuel savings are thus a function of the pump users' commitment to the work required to operate the bio-gas system. This includes collecting the dung input, adding the right amount of water, monitoring gas production and removing accumulated waste. The cost of the digester and ongoing effort involved must be perceived by the operator as worth the savings in fuel. Since the system still requires the purchase of a diesel engine, and hence, will still require at least some fuel and all the maintenance needed for a diesel installation, there is a minimum of infrastucture cost savings. Indeed, these costs may be increased by the training requirements to understand and properly operate the bio-gas portion of the system. Since the pump can be operated entirely with diesel fuel, there are no assurances that the maximum savings obtained from 75 to 80 percent fuel substitution will be accomplished.

The spread-sheets and graphs of the financial and economic analysis of the animal-traction and bio-gas pumps are not included as the output and cost data were not considered adequate. To give a rough estimate of the economics of bio-gas pumping, based on the very limited data analyzed so far, the following should be assumed:

- only half of the diesel fuel is displaced by bio-gas in the long run;
- a pumper can be employed for P500 per year (with no other paid labor required); and
- the long-term costs of operating the system are the same as for a diesel pump alone.

Under these conditions, it appears that bio-gas pumping may be marginally less expensive than a diesel system operated by a pumper paid the same low wage (not GOB standard). Unit water cost would then be in the .40 to .50 thebe per m^4 range. This analysis is very preliminary, as a satisfactory definition of the economic parameters is not yet complete.

These two pumps fall into a different category from the others considered thus far. Neither of show promise as cost-effective alternatives to diesel systems for provision of water under any government scheme. The Industrial Class Regulations stipulate a minimum daily wage that would make both uncompetitive with conventional (or several alternative) pumping systems. Because the data are so inadequate, they will not be discussed further and are omitted from the comparative analysis because of the different nature of these systems and the number of assumptions that must be made.

VI. COMPARATIVE SYSTEM PERFORMANCE

While the previous section discussed each of the pump technologies individually, this section compares the relative advantages and disadvantages of each type of pump and notes their most appropriate applications. Again, pump performance was extrapolated from relatively short-term (several weeks to several months) measured data. All costs used in the analysis reflected commercial pricing of equipment as of July, 1985, and the authors' best estimates of long-term recurrent costs, based on actual costs incurred during the testing program thus far. The testing focused mainly on small-scale applications (less than 75 meters of head and outputs of less than 50 cubic meters a day), where the alternatives to standard diesel pumps have the greatest potential application.

This section is divided into two parts. In Section A, the general conclusions of the tests are given, followed by elaboration of these general conclusions as they apply to each system option. In Section B, issues which directly pertain to the conclusions, but have not yet been satisfactorily resolved, are discussed.

A. Applications and Limitations by System Type

The overall results of the economic analysis of the pumping program are summarized in Figures 11 and 12, which show several unexpected conclusions. Figure 12 is simply an enlarged version of the area of most interest in Figure 11, i.e., the low to moderate head and volume range. The graphs plot unit water cost (Pula/m^3*m) versus the energy required to pump the water. This volume*head product (m^3*m) formulation presents the data in a format which allows direct comparison between the various types of systems. The only information that is not easily included in this graph is technical or practical limits on system output or head, which are discussed in the sections on each system type. The assumptions that had to be made because the data base is not yet complete had a large impact on the results--they are outlined in detail in Appendix B and should be reviewed before accepting the conclusions presented below.

The general conclusions from Figures 11 and 12 include:

- although the RET pumps tested were primarily in the low range for head and flow, it appears that for high-head and moderate- to high-flow situations, diesel pumps are much cheaper than RET systems, given the pricing structure and existing infrastructural support now available in Botswana;

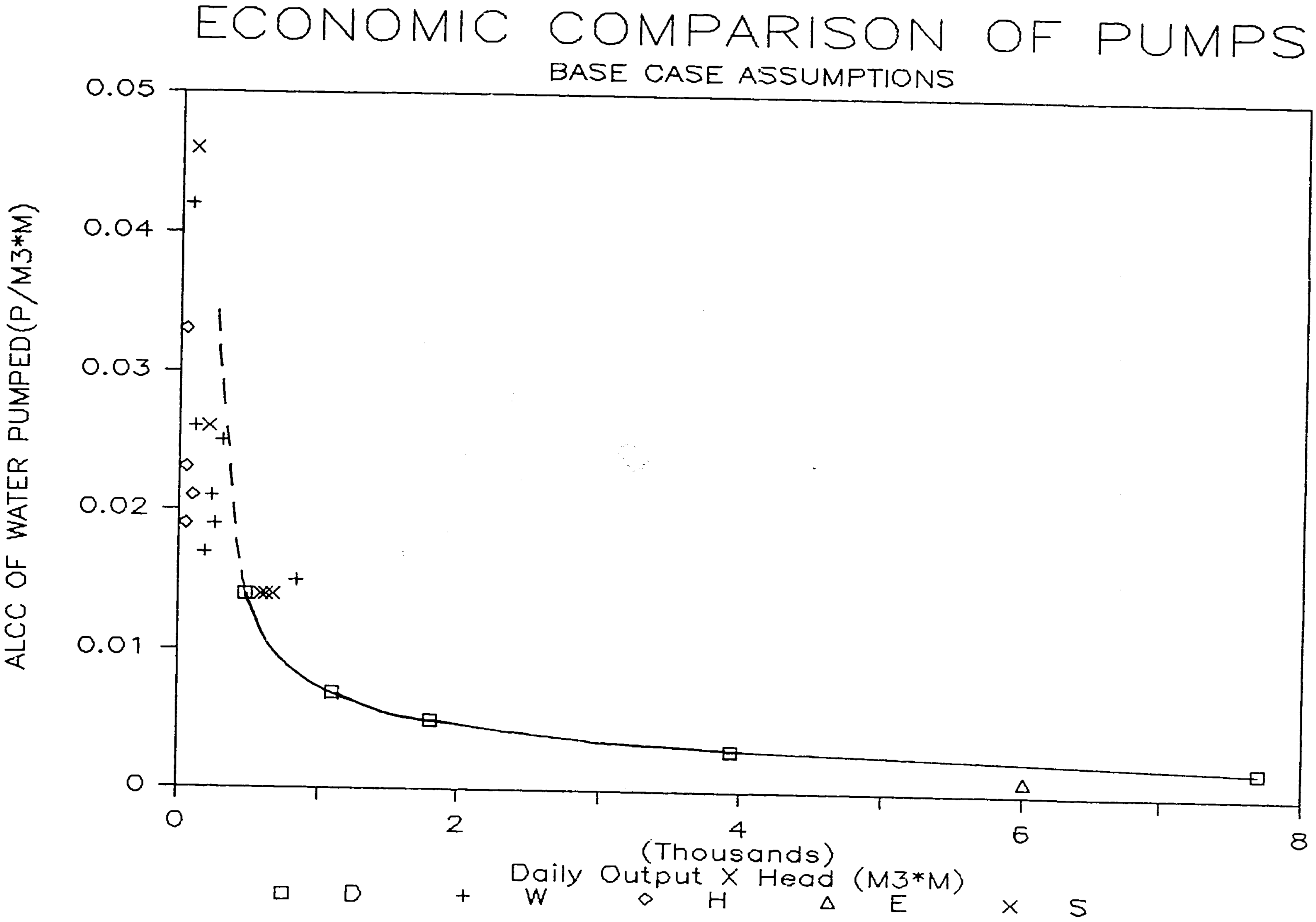

ECONOMIC COMPARISON OF PUMPS
BASE CASE ASSUMPTIONS
ALCC OF WATER PUMPED(P/M3*M)
0.05
0.04
0.03
0.02
0.01
0
0
2
4
6
8
(Thousands)
Daily Output X Head (M3*M)
□ D
+ W
◇ H
△ E
× S

Figure 11

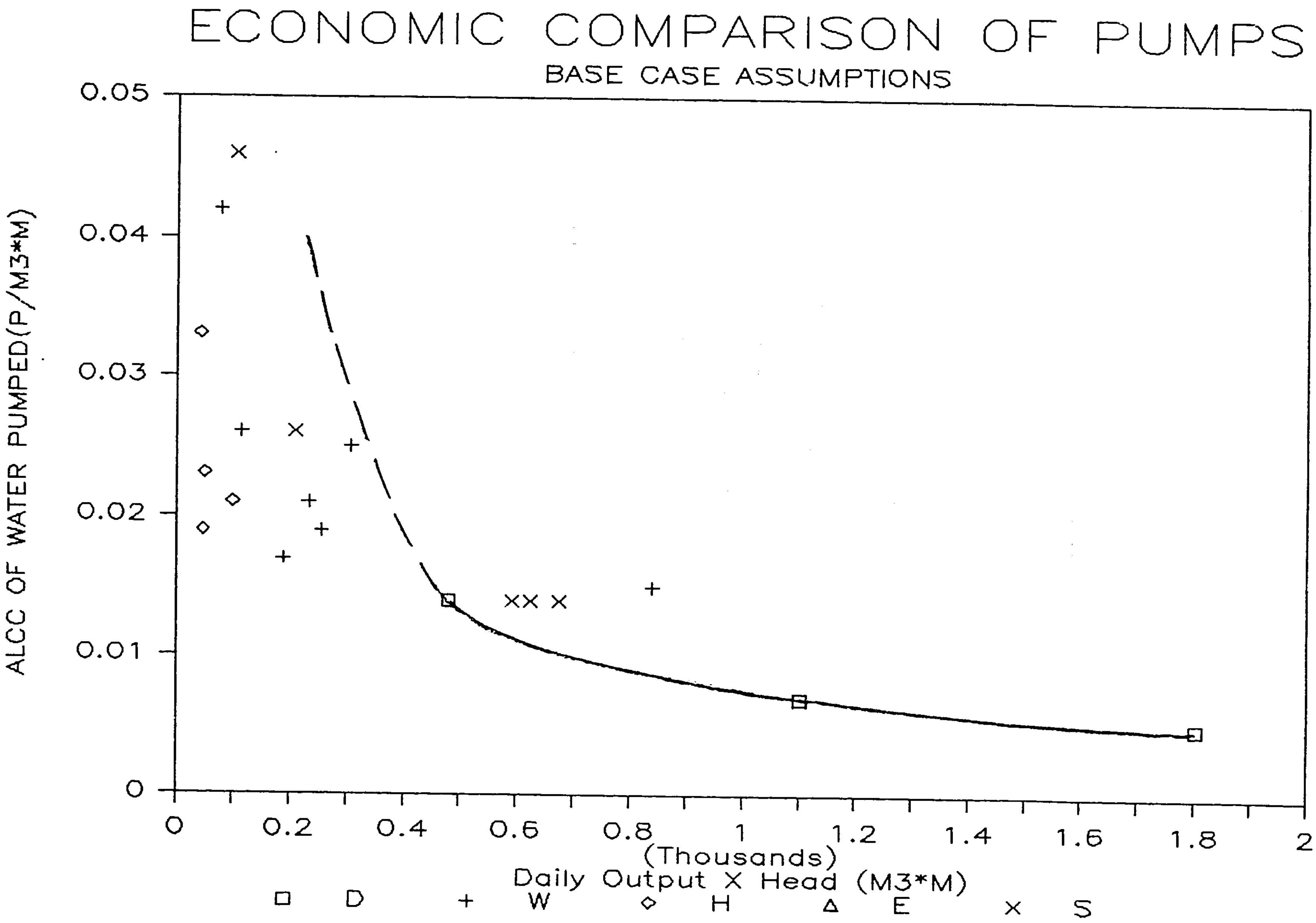

ECONOMIC COMPARISON OF PUMPS
BASE CASE ASSUMPTIONS
ALCC OF WATER PUMPED(P/M3*M)
0.05
0.04
0.03
0.02
0.01
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
(Thousands)
Daily Output X Head (M3*M)
□ D
+ W
◇ H
△ E
× S

Figure 12

- grid-electric pumps are capable of delivering high flows at high heads, but appear to be as expensive as diesel pumps at the current electricity tariff rate--if the economic cost of electricity generated by the Morupula power plant is as inexpensive as promised, electric pumps would become the least-cost option in the high-output range;

- within the technically feasible range for hand-operated pumps (below about 100 m^3*m/day), they are clearly the best choice, <u>assuming that there is no labor cost for pumping water</u>; and

- above 100 and below 1,000 m^3*m/day, the choice of most appropriate system becomes less clear-cut, as this is the range of potential application for wind and PV pumps (see the following subsections on those two technologies).

1. Diesel

Diesel pumps are the standard against which the other pumps must be measured, as they are installed on approximately 85 percent of all boreholes in Botswana. While only a limited sample (five) of these pumps were tested, the unit costs shown in Figure 11 lie on a surprisingly smooth curve and rise very rapidly when output drops below 1,000 m^3*m/day. This corresponds to outputs of 10 to 20 cubic meters a day for common pumping heads in Botswana. Sensitivity analysis of the cost assumptions showed that the high unit cost for low daily output was largely a function of fixed pumper costs, which become a much larger percent of the unit water cost for smaller systems. This raises an interesting policy issue,(which surfaced in sensitivity analyses for virtually all the pumps tested--the importance of pump operators and employment generation in the rural sector.

Diesel fuel is the only energy source used for the pumps examined that will continue to be imported, since grid electric power that is currently imported will soon be displaced by the opening of the Morupula power plant. As such, diesel fuel is the only energy source used for pumping that international market forces have control over.

Water delivery in rural areas of Botswana is remarkably good, compared to other African countries. In large part, this is because DWA has standardized on the Lister-Mono pump combination to reduce spare parts inventory requirements and simplify training of maintenance personnel. The success of this program had a profound impact on the unit water costs for diesel pumps, since reliable and reasonably well-maintained equipment have resulted in lower long-term recurrent costs than in many other countries where standardization and successful technical support infrastructures do not exist. These successes should not be overlooked,* nor should infrastructural support costs for alternative pumping systems be underestimated, as these are not yet in place.

Diesel pumps have the lowest ratio of installed capital costs to total LCC, ranging from 10 to 15 percent, while the values for solar and wind pumps range from 50 to 80 percent. These figures are in line with the general perception of diesel pumps as having a low initial cost, but high recurrent costs, and the reverse for RET systems. This can be an advantage or disadvantage depending on the current availability of financing and future financial constraints.

The advantages of diesel pumping systems are:

- relatively low installed capital cost;
- it is the least expensive option for high-head, high-flow situations;
- the support infrastructure for equipment distribution, maintenance, repair and technical training is currently in place and well developed;
- it provides on-demand water delivery (assuming adequate fuel availability and performance of proper maintenance procedures), so storage costs are less;
- there is no practical size limit on commercially available equipment; and
- it can have electrical as well as mechanical output.

The disadvantages of diesel pumps are:

- from a maintenance perspective, they are fairly complex, requiring periodic overhauls and a pump attendant during operation--skilled labor is needed for periodic overhauls, which in Botswana, require the engine to be temporarily replaced and taken to a central repair shop;
- they are dependent on national (often rural) transportation networks to maintain an adequate fuel supply as well as the vagaries of international distribution and pricing;

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*EVALUATION OF THE VILLAGE WATER SUPPLY PROGRAMME IN BOTSWANA, J. Agrell et al, SIDA, June, 1984.

- normally, all costs, except local labor charges, are in foreign exchange;

- they have relatively high recurrent costs for operation, maintenance and repair;

- while larger, low-speed diesels are quite reliable, the smaller engines used at low-demand sites usually run at higher speeds, thereby requiring more frequent maintenance and replacement because of more rapid wearing of components;

- since small (less than two kW) units are unavailable, engines at low-demand sites often run well off their design point, dramatically reducing efficiency (i.e., increasing fuel consumption per unit of water pumped); and

- they are noisy.

2. Grid Electric

The number of electric pumps tested was very limited. The BRET project had difficulty finding grid-electric pumps that operated in the small-scale output range, which was of primary interest. The two pumps that were selected and tested delivered well over 50 cubic meters a day and thus, were outside the primary range of interest. However, the tests did show that electric pumps were surprisingly expensive to operate, due to the high cost of electrical energy. With electricity costs of 16.1 thebe per kilowatt-hour, the energy cost alone for pumping water is 11 thebe per cubic meter at a typical head of 100 meters, assuming an average system efficiency of 40 percent. This compares with diesel energy costs for a similar system of nine thebe per cubic meter (assuming 66 thebe per liter of fuel and an average system efficiency of 20 percent).

Thus, the main savings in operating grid-electric pumps comes from their ability to run unattended, so that pump attendant costs are much less. Since DWA currently assigns pumpers to these sites, the policy issue of the real need for pump operators is again raised. The World Bank study argues that the economic cost of electric energy produced at the Morupula power plant will be about one-third of the current tariff rate. If this is the case, economic unit water costs for grid-electric pumps will drop dramatically.

While the electricity tariff is not subsidized by the government in many areas, electricity sold by the GOB in remote locations that are on separate grids (such as Ghanzi, Maun and Tsabong) is subsidized by as much as 100 percent--i.e., real electricty costs are twice the tariff rate, and the grids are usually characterized by very low load factors. Hence, the relative costs of grid-electric pumps in these areas are considerably greater.

DWA has become more interested in grid-electric submersibles and thus has begun to build the necessary support infrastructure. For replacement parts, the value of the inventory for submersibles is considerably higher than diesels, as the integral submersible units represent the cost of both motor and pump element. However, the range of pump sizes that must be kept on hand is unlikely to be much greater than for diesels, as a single submersible motor can be used with several different pump elements for different head requirements.

The advantages of grid-electric submersible pumps are:

- relatively low capital equipment costs, excluding grid tie-in costs, such as long-line extensions or step-down transformers;
- they provide on-demand water delivery (assuming adequate energy availability and performance of proper maintenance procedures), so storage costs are less;
- there is no practical size limit on the equipment;
- electronic controls allow for unattended operation, thus reducing pump attendant costs;
- with longer maintenance intervals than most of the alternatives, maintenance costs are expected to be correspondingly less;
- while electricity is currently imported, when Morupula comes on-line, there will be no imported fuel requirements, so they will not be dependent on the vagaries of transportation networks or international petroleum products distribution irregularities; and
- quiet operation.

The disadvantages of grid-electric submersibles are:

- all equipment costs are in foreign exchange;
- relatively high recurrent fuel costs; and
- the support infrastructure for system design, maintenance, parts distribution and training is not

yet extensive, and the costs of developing such a support infrastructure could be substantial.

3. Wind

Initial results from the first phase of the wind testing program indicate that wind pumps are the least-cost pumping option only at sites where the design wind speed condition is 2.5 to 3.0 meters per second, and the average water demand is less than 10 cubic meters a day. If a wind pump can deliver this amount of water (which depends on the head as well), then it is likely to be the least-cost option compared to diesel systems. Not only is it technically more difficult for a wind pump to meet water requirements that are much greater than this, due to the size limits of currently available equipment, but unit water costs for diesel pumps improves with higher demand. Preliminary results indicate that all of the new design wind pumps can meet this criterion for heads of less than 35 meters and wind speeds in the range of 3.0 meters per second (or for lower wind speeds in conjunction with lesser head). Questions do remain about the long-term reliability of some of these machines as they are presently configured.

The next issue is determining the areas where these conditions coincide and the potential market for wind pumps in those areas. These questions cannot yet be answered completely, but from uncompiled information that is currently available, it appears that the number of sites where wind pumps are cost-competitive will likely be limited in Botswana. The areas with the highest wind speeds appear to be the southern and eastern regions of the country, whereas the shallowest boreholes generally occur in the east. These areas remain to be defined more clearly by the ongoing wind resource assessment and DWA survey of water table depths.

The major uses of water in Botswana are for human consumption and cattle, with some irrigation, but very little industrial use outside of one or two areas. DWA's major activities are maintaining water delivery systems in the major villages and at government establishments, and building reticulation systems for the 354 villages in the Village Water Supply Program (many of which are now complete). While most village requirements have been beyond the capacity of wind pumps, they may be applicable in some of the smaller villages.

Livestock watering at Department of Wildlife sites and government-supported and syndicate-owned cattle posts appears to be the area where wind pumps could have the most impact. Storage considerations are not such a problem, as cattle could be moved to a diesel-equipped borehole, if necessary when the winds are calm. However, for syndicates or private users, the interest charges (16 percent is common) on capital equipment costs may be a significant constraint.

A modest support infrastructure in both the public and private sectors currently exists in Botswana for conventional, locally manufactured wind pumps, primarily Climax products. If windmills are to be used at Department of Wildlife sites or by syndicates, DWA's Borehole Repair Service (BRS) also needs to be trained to maintain and repair windmills. For the imported wind pumps (Kijito and Wind Baron), parts procurement and technical support are major problems. Only if these machines are manufactured in southern Africa could substantial use of them in Botswana be justified. The RIIC and, to a lesser degree, WTGS designs are being built in Botswana, so the repair and maintenance skills reside completely within the country. RIIC has also trained a special windmill crew to install and repair their machines.

An interesting note is that at current costs, diesel systems are more cost-effective in the moderate output range (for wind pumps) of the Wind Baron. This is due to the shape of the diesel curve shown in Figure 11. At outputs of less than about 500 to 1,000 m^3*m, diesel systems become very expensive, but at levels in this range or higher, currently available RET pumps will have a difficult time competing. Clearly, the Wind Baron's very high capital cost has a pronounced effect, and it is possible that local manufacture will reduce this impact somewhat, but it will have to be significant to yield a unit cost which is less than a comparable diesel pump.

The advantages of wind pumps are:

- low long-term recurrent costs due to minimal maintenance requirements, and maintenance intervals that are much longer than most alternatives;
- no imported fuel requirements, so they are not dependent on vagaries of transportation networks or international distribution irregularities;
- mechanical controls allow for unattended operation; and
- some locally manufactured units which allow considerable savings in foreign exchange over most pumping methods.

The disadvantages of wind pumps are:

- anticipated low wind speeds in most of Botswana will limit potential applications;

- relatively high installed capital cost;
- size limits on currently available equipment (a rotor with a 6.4-meter diameter delivers about 0.5 kilowatt in three meters per second of wind);
- currently available production models (except RIIC and WTGS) require expenditures of foreign exchange;
- the support infrastructure for system design, maintenance, parts distribution and training is not yet extensive, and the costs of developing this infrastructure could be substantial; and
- they cannot supply water on-demand and thus, require larger hydraulic storage capacity than on-demand units, such as diesel systems, so that water can be accumulated during off-peak periods to satisfy peak demands.

4. Solar Photovoltaic

The two kinds of systems tested were the Mono pump driven by Honeywell surface-mounted motors and Jacuzzi DC electric submersibles with both pump and integral motor submersed in the borehole. While additional PV pumps are being tested during the extension of the program, only these two systems are covered in this report. While solar pumps did not deliver as much water as expected, given borehole yield and head constraints, there still seems to be potential for their deployment in Botswana. Applications should focus on small-scale village drinking supply, livestock watering and garden plot irrigation. Irrigation is a somewhat marginal application due to the large volumes of water that are normally required and high heads usually encountered in boreholes in Botswana. Fields larger than about two hectares would require larger PV pumps than are currently available. Development of larger submersible PV pumps (up to 3.7 kilowatts) to meet larger demands is underway.

From Figure 11, PV is not currently a viable option for heads greater than about 50 meters and water demands of 20 cubic meters a day or conversely, heads of 20 meters with water demands of greater than 50 cubic meters per day. Currently, these limiting cases could only be met with Mono-coupled PV pumps in Botswana. For smaller heads and lower flows, submersibles are equally competitive. The graph also shows that while three of the PV pumps tested are in the cost-competitive range with diesel systems, the performance and cost of the remaining two were marginal. In one case, the pump was not well matched to the site. In the other, the system was an early design, purchased by the BRET project after its installation to include in the testing program. The components were not well matched, and the system relied on batteries, with their associated high recurrent replacement costs. Both of these instances emphasize the importance of careful system design. Due to advances in pump controller technology, the use of batteries is not recommended except in unusual cases (such as very low borehole yields), some of which are being tested during the extensionof the program.

The advantages of PV pumps are:

- low long-term recurrent costs due to minimal maintenance requirements--the maintenance intervals much longer than for the alternatives;
- very high reliability for power supply components (PV modules now have 10-year performance waranties);
- they are a rapidly advancing technology that promise continuing cost reductions (there are about 2,000 PV pumps in use, and module cost has dropped from P13.3/Wp to P10.5/Wp in the two years since the first BRET purchase);
- electronic controls allow for unattended operation, which can significantly reduce operation and maintenance costs;
- they require no imported fuel, so they are not dependent on the vagaries of transportation networks or international distribution irregularities.
- maximum water output is normally coincident with the driest period of the year, since that is when solar radiation levels are usually highest;
- with modular design, they can be precisely matched to site constraints, so water output can be increased by the simple addition of modules, without changing pump and controller (within certain limits); and
- quiet operation.

The disadvantages of PV pumps are:

- relatively high installed capital cost;
- size limits on currently available equipment (2.2 kW);

- most components require the expenditure of foreign exchange, although some controllers are now being manufactured in Botswana;

- the support infrastructure for system design, maintenance, parts distribution and training is not yet in place, and the costs of developing this infrastructure could be substantial;

- they cannot supply water on-demand and hence, require larger storage capacity (either electrical or hydraulic) than on-demand units, such as diesel, so that water or energy can be accumulated during off-peak periods to satisfy peak demand; and

- little, if any, local employment generation, except for system design, installation and maintenance, and little possibility for local manufacture of the main system components.

5. Hand and Human-Traction Pumps

Figure 11 shows that hand and human-traction pumps are the least-cost option for low-head, low-flow sites. Their practical output is limited by the amount of force that a typical pumper can apply to the pump handles. The practical upper limits of delivery appear to be about three to four cubic meters a day at heads of 30 meters for the India Mark II hand pump, which was far superior to the other model tested, and 100 meters for the Thebe human-traction pump. At this extreme low end of the water demand spectrum, no other pumping options are even close to being cost-competitive with these pumps, given the assumption of cost-free labor.

These pumps offer the distinct advantages of local fabrication and repair, district-level installation and maintenance, and are quite reliable pumps when proper maintenance schedules are followed, which usually means annual replacement of the cylinder leathers. Other advantages are:

- very low capital and long-term recurrent costs;

- they are the most cost-effective option for low-head, low-flow situations; and

- they are simple in design for easy installation, operation and maintenance.

The main disadvantage of hand and human-traction pumps is their practical limitation to low-head (less than 30 to 40 meters), low-flow (under five cubic meters a day) sites.

6. Animal Traction and Bio-Gas

Animal traction and bio-gas pumps are not discussed in detail in this report because of the lack of adequate cost and performance data, as discussed in Section V.F. However, several general comments can be made. The tests performed thus far by BTC have very limited value, so no definitive conclusions can be drawn at this point. The most likely constraint to widespread use of these pumps in Botswana is that they require considerable participation and management on the part of end users. It is possible that this may be achieved by by sufficiently motivated private user groups under certain circumstances, but this issue has been the main impediment to testing thus far.

It is unlikely that these pumps will find application in government-operated potable water supply programs because of very high labor charges, when employees are subject to Industrial Class Regulations. Private owners may be able to find sufficiently inexpensive labor to overcome this obstacle. Much more work remains to be done before these pumps can be considered as serious options for small-scale water pumping systems.

B. Unresolved Issues

This section discusses some of the issues that were left unresolved by the analysis of the data collected during the first phase of the comparative pump testing program. In some cases, this is due to the paucity of data collected thus far (for example, the comprehensive examination of borehole yields and static water levels by DWA). In others, it is because no clear resolution of the issue seems possible at present--e.g, the decision to use either submersible or Mono pumps exclusively. Other issues are policy-related, such as the question of pumper costs, which had a dramatic effect on the costs of all the systems tested.

1. Mono versus Electric Submersible Pumps

There have been extensive arguments on the relative merits of Mono versus submersible pump use in Botswana, not only with PV-generated electricity, but with grid or diesel-generated electricity as well. There are several important differences in the operation of Mono and submersible pumps, which result in both advantages and disadvantages for the user. Users and distributors of both types of pumps were given an excellent opportunity to discuss their experiences and impressions during the BRET-sponsored BTC workshop on PV applications in Botswana held in August, 1985. A preliminary version of the PV pumping report* was presented at that workshop, and the authors had an opportunity to discuss their findings with users of several types of pumps, thereby clarifying and refining the conclusions presented below.

Mono pumps have proved to be very robust under conditions encountered in Botswana. In sandy, saline or otherwise corrosive water, Monos tend to last longer than submersibles operating under similar conditions. With the exception of the relatively high starting torque of Monos (discussed in the BRET technical reports PV and wind pumps), their operating characteristics are well-suited to the relatively high pumping heads and variable or uncertain water depths in many boreholes. Mono pump efficiency is not particularly sensitive to total pumping head, as is the case with submersibles. If a submersible is not carefully sized for a particular borehole, system efficiency could be significantly less than designed. Thus, more precise engineering is required in submersible installations, and better borehole information is required than is often available. The accuracy of test-pumping and whether tests were done during the dry or wet season can have an effect on the results. Since the static water level in boreholes can change over time, particularly under excessive drought conditions, this could be a significant constraint.

Monos are manufactured locally in both South Africa (as are some models of the Jacuzzi and other submersibles) and Zimbabwe. As such, distribution and technical support are not generally a problem, people are familiar with their proper application and maintenance, and there is a considerable support infrastructure for marketing, distributing, installing and maintaining the pumps. DWA, councils and the private sector have invested substantial time and effort in training people in the use of Monos. Stocks of new units and spare parts are readily available in many areas of the country.

Submersibles (whether PV-driven or otherwise) are just coming into use in Botswana. DWA has begun to use them on very high-yielding boreholes, although borehole diameter can be a constraint for large-diameter submersible pumps. DWA is now becoming involved in submersible repair (changing impellers to vary head specifications), but they must discard many burned-out sealed motors rather than repair them, although the larger, more expensive motors are sent to South Africa for rewiring. The costs of developing the necessary level of infrastructural support required by widespread use of submersible pumps in Botswana have yet to be adequately quantified.

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*SOLAR PUMP FIELD TESTS IN BOTSWANA -- PRELIMINARY TECHNICAL AND COST COMPARISONS, Richard McGowan and Jonathan Hodgkin, ARD, Burlington, VT, April, 1986.

While grid-electric submersibles have no practical limit on system size, the largest commercially available PV submersibles are nominal one-kilowatt pum psets which can deliver 25 cubic meters per day at 25 meters of head, for example. DC motors of up to 2.2 kilowatts are available for use with PV array output to drive Monos, delivering twice that amount. The capacity of Monos when coupled to surface-mounted AC electric or diesel motors is significantly greater. However, this is changing as submersible pump manufacturers (Grundfos) are currently developing five-horsepower (3.7-kilowatt) units for use with PV which will become available shortly.

Monos are more flexible than submersibles as they do not require electric motors. Several of the wind pumps tested by the BRET project used Mono pumps rather than reciprocating piston pumps (and of course, by far the greatest number of Mono pumps are diesel-driven). This would be a distinct advantage for use with hybrid systems, which might use a combination of PV, wind or diesel energy to drive the pump when the primary renewable energy source is not available. A wind pump driving a Mono could be used with a diesel backup for periods of low wind speeds. The drive belt would simply be switched from the wind pump to the diesel. This would not be possible with a submersible (electric) pump unless mechanical shaft power were used to drive an electrical generator first, which is an impractial arrangement. Electric vertical turbine pumps could be used this way, and several manufacturers make them for PV applications.

Monos have surface-mounted motors which allow for ease of replacement and repair. Depending on water quality in the borehole, surface-mounted motors, which are susceptible to vandalism (human and otherwise), may or may not last longer than down-hole motors. However, submersible motors must be pulled from the borehole occasionally for inspection and brush replacement. This could be an expensive task for deep installations.

Submersibles have certain advantages over Monos as well. It is much simpler to install a submersible pump than a Mono--it requires a smaller crew with fewer technical skills because in addition to the drop pipe which both pumps require, Monos also require installation of the drive shaft and bobbins. Submersibles use no drive shaft or bobbins, so that only the drop pipe with the power cable attached must be installed in the borehole. Submersibles also do not require drive belts, pulleys, or weeping glands adjustment or replacement as do Monos.

Very straight boreholes are not strictly necessary for submersibles, yet the overhaul time for Mono pumps is said to be directly related to the straightness of the borehole. Crooked boreholes rapidly wear out the shaft and bobbins, which can require replacement as often as every three to six months in the worst cases. Installation of a Mono in slightly crooked boreholes, which are not unusual in Botswana, can range from difficult to impossible. After such an installation, the bend in the drive shaft can accelerate wear and decrease mechancial efficiency.

Experience with submersibles in Botswana thus far has indicated that they have less downtime than Monos, but this is probably due more to their diesel power plants than the pump elements themselves. Submersibles used in Botswana and South Africa have been found to last five to 10 years. The pump element components of Monos often require more frequent replacement. Due to corrosive water conditions, replacement costs for shafts and bobbins are greater for Monos than the simple replacement of the drop pipe for submersibles. However, submersibles must be properly coated with corrosion-resistant materials so that the submersed motors do not wear out prematurely. Some pump users claim that diesel-driven Monos are much less susceptible to damage caused by lighting strikes than electric submersibles.

When comparing Monos and submersibles for use with PV, it must be remembered that Monos require the use of some type of controller or battery bank in the system because of their relatively high starting torque, while submersibles do not. Thus, while it is true that a submersible pump (i.e., the integral pump and motor unit) costs more than a Mono system with a DC electric motor, the additional costs of controllers or batteries can negate this initial advantage. The recurrent costs of battery replacement can easily become an major factor in LCC, particularly when the batteries are not properly cared for, thus necessitating more frequent (and more costly) replacement. This was the reason for using controllers rather than batteries with the PV/Mono systems installed by the BRET project.

Submersible pumps are very forgiving of accidently closed valves. The systems simply interprets it as higher head, and water output drops accordingly. However, if a valve is closed on an operating Mono pump, and no pressure relief valve has been installed (or the one in the system is not functioning), the discharge pipeline can be blown out. This is characteristic of all positive displacement pumps.

The greatest source of dispute among the advocates of each type of pump was their hydraulic efficiency. The cost of water delivery for a pump is inversely proportional to its hydraulic efficiency, since a more efficient pump requires less mechanical input to deliver the same quantity of water. From the BRET project's tests, it was found that no generalization about which type of pump was more efficient was possible. Well-designed systems, either Mono or submersible, ran at hydraulic efficiencies of around 30 percent.

2. Pumper Costs

The dramatic effect of pumper costs on the recurrent costs of pump systems has already been mentioned several times. Sensitivity analysis (see Appendix C) indicates that pumper costs are the single most sensitive cost component of all pumping systems. The percentage unit cost change for a pump operator that works one day per week to a full-time pumper ranges from 10 to 30 percent for diesel pumps to 40 to 100 percent for wind and solar pumps. At present, government employees are covered by Industrial Class Regulations, which state that P6 is the minimum daily wage, and pumpers can only be hired on a full-time basis at that wage. Labor wages paid by the private sector in rural areas are often considerably less than P6 per day.

Different pumps require widely varying levels of pump attendant interaction for successful operation. Even diesel installations often do not strictly require the daily presence of a pumper, unless the demand for water is taxing the limits of the equipment, which is sometimes the case. Wind and PV pumps require only occasional user interaction for purposes of periodic (annual or biannual) maintenance. The only other purpose a pump attendant serves at these installations is to inspect any reticulation system and take responsibility for notifying Water Maintenance Units or other appropriate authorities when repairs become necessary. Although this is certainly an important task, it hardly requires a full-time employee.

For these reasons, the base-case assumption for wind and PV systems was that an attendant would be hired to work one day per week. It may well be argued that this results in higher labor charges than are strictly necessary, but it was felt that this would be the minimum acceptable (and indeed, was well below current standards). The GOB should reconsider its position in this regard. Labor charges have been shown to be the most significant cost assumption for all of the pump types tested. If savings can be realized here due to actual reduced labor demand, the relative rankings of unit water cost for the various systems could change substantially. While employment generation in rural areas is certainly a reasonable goal, if the GOB is seriously interested in reducing the cost of water delivery, it should carefully examine its labor policy regarding pump attendants.

3. Storage Costs

The problem of sizing and costing water storage equipment was not specifically addressed in the first phase of this testing program. In the cost comparisons between the different types of pumping systems, variable storage costs were not included in the financial and economic analyses. This may tend to bias the results in favor of systems that cannot deliver water on-demand, such as wind and PV. Costs for water storage can be significant, even to the point of exceeding the capital cost of the pumping equipment. A Braithwaite, sectional-steel, 20,000-liter tank on six-meter stands costs about P20,000 installed, while locally available Hanoya tanks are about half that. The costs of promising approaches, such as ferrocement tanks, should be studied, which BTC has done to some extent.

Wind and PV are obviously dependent on available wind and solar radiation resources at the site. If there is no wind or sun, no water is delivered. To address this problem, these types of systems are generally somewhat oversized to meet average daily demands. The excess water or electricity produced on average days is then stored, either in water tanks or batteries. The larger the system size and storage capacity, the greater the cost. Thus, storage requirements could have a significant impact on system cost. Storage capacity for on-demand systems, such as diesels, is not so critical. If more water is needed, the pump is simply turned on, assuming that sufficient fuel is available and the water level in the borehole has not been drawn down by over-pumping).

There are reasons why the storage issue is not as critical as one might think. First, because of a need to standardize equipment, water storage tanks in Botswana are usually available in only several types (corrugated galvanized iron and sectional steel) and in incremental sizes (nine, 20 and 40 cubic meters for the smaller systems included in this testing program). DWA's policy on storage for diesel pumps dictates that systems will include one day's storage. If a particular site requires 12 cubic meters a day, two nine-cubic-meter tanks or, more likely, one for 20 cubic meters will be installed. If the same site were equipped with a wind pump and required two days' storage (24 cubic meters), it is likely that the same tanks would be used, so the storage costs between the two systems would not differ.

However, this does not avoid the fact that water storage is expensive and will undoubtably have an effect on the economics of pumping systems, particularly for wind and PV pumps. As yet, there is no clear answer to the question of how much water storage is adequate for wind and PV systems, as the necessary information on wind and solar resources is not yet available, and basic research on the relationship between the energy resource level and required storage has only just begun. An additional factor is that ferrocement ground-level tanks are now being used in some places and appear to have some potential for wider use, if the engineering and construction details can be worked out. If this proves feasible, a considerable savings could be realized and at the same time, employment generated through their construction and repair. This potential use of ferrocement tanks could have a substantial effect on both diesel and renewable system costs. Another reason is that the use of ferrocement and local labor to construct water storage tanks could significantly reduce their economic cost, thereby reducing the overall cost differential between diesel and installations that are not on-demand.

4. Low Borehole Yields

DWA has three rough classifications for borehole yields--low or 0.5 to 1.5 cubic meters per hour; normal, 1.5 to 12 cubic meters per hour; and high or 12 to about 24 cubic meters per hour (one borehole yielded 90 cubic meters per hour, which is the highest yielding borehole drilled thus far in Botswana). The average yield for pump-equipped boreholes is five to 12 cubic meters per hour. However, there are many village boreholes in the low-yield range, which presents a difficult problem for two reasons. First, the cost per meter of depth to drill boreholes is completely independent of water yield--a low-yield borehole costs just as much as a high-yield one. Second, as mentioned previously, diesel pumping costs increase exponentially for low-head, low-demand installations. Thus, the costs of delivering water from low-yield boreholes are very high. From an economic perspective, such installations are a bad choice. However, they may also be the only choice for some villages. While the GOB is committed to supplying water to everyone, there must be a cost-imposed limit on implementation of this program at some point.

A partial solution to this problem is the use of hand-operated pumps (standard hand pumps or Thebe pumps for higher head situations) on low-yield boreholes. This would address the problem in two ways. First, the costs of water delivery with hand pumps in this range have been shown to be far less than for any other method. Second, since the water output from hand pumps is much less than the smallest diesels, large drawdowns (which could drop the water level beyond the limit of the pumper's ability) would be unlikely to occur.

Wind pumps have not been seriously considered, as their output depends so heavily on inherently variable wind speeds. The economics of wind pumps depend on their ability to pump a great deal of water during the highest wind speed periods of a day. With low-yield boreholes, this could result in pumping the borehole so low that the increase in total head would reduce output to a trickle or the borehole would simply be pumped beyond its recharge rate and temporarily dry up.

Another possibility which is being explored is the use of PV pumps. An oversized array can be used to charge a large battery bank, so that the pump can run 24 hours a day at a relatively low output level. However, unavoidable battery losses increase unit water costs by about 25 to 30 percent for such a system. While this configuration has been tested by BTC, and a similar installation will be tested during the extension of this program, it does not hold much promise at present as a reasonable cost alternative for pumping from low-yield boreholes.

VII. INSTITUTIONAL AND SOCIOECONOMIC ISSUES

A. Obstacles to Widespread Use of RET Pumps

The are a number of economic, technical, social and institutional constraints that have impeded the widespread dissemination of RET pumping technologies, including high capital costs, local unfamiliarity with the equipment and its potential applications, and a lack of technical and institutional support infrastructures. While technical development has and continues to receive much of the research effort, unless these other constraints are dealt with successfully, they will continue to present major obstacles to the implementation of small-scale RET pumps in rural areas.

It is necessary to overcome a general lack of awareness on the part of both the private and public sectors of the potential benefits of RET water pumping systems. Many people are unaware that such systems exist or view some of them (PV, in particular) as experimental technologies that have yet to be proven under field operating conditions, which are often harsh. Other pumping systems, which are labor- rather than capital-intensive (hand pumps, for example), are sometimes frowned on as technologies for the poor, and their use is shunned by status-conscious groups.

The principal obstacle to the widespread use of RETs for small-scale water supply is their relatively high initial capital cost. Capital cost can be a critical issue in societies where credit is not easily available, particularly for private-sector users. In general, while some RET system costs have shown a downward trend (particularly, PV), many potential users are simply not in a financial position to take advantage of long-term savings in energy costs because of the lack of available financing mechanisms. While the GOB is not so concerned with the availability of financing for capital investments in the private sector, individuals who wish to take advantage of the potential savings of using RETs for water pumping are faced with the difficulties of obtaining financing. At sites where these technologies are a cost-effective choice, it is in the GOB's long-term interest to make financing available, whether through guaranteed loans or perhaps direct subsidies (after careful consideration from a national economic perspective). Alternative sources of financing might include RET equipment manufacturers and distributors, and agricultural cooperatives or syndicates.

Individuals with limited access to or experience with long-term capital financing often expect very short payback periods and implicitly high discount rates. Convincing potential users, in both the public and private sector, of the reasonability of balancing relatively high initial costs by reduced long-term recurrent costs requires a carefully planned public awareness program, perhaps through existing government agricultural extension programs, equipment distributors or government-sponsored educational broadcasting.

Government pricing policies have a significant effect on the comparative economics of pumping systems. Import duties, particularly on high capital cost items, can significantly affect unit water costs. For example, customs duty surcharges on equipment imported from outside the South African Customs Union (for example, from the United States, Kenya or Europe), would certainly reduce the cost-competitiveness of solar, wind or other imported pumping systems. This also points out the advantage of locally manufactured pumps, such as the human-traction pump and certain windmills purchased or made locally by the BRET project. Perhaps the raw materials for locally manufactured products could receive favorable customs treatment as well. In some countries, import duties are levied based on the end-use of the equipment. It is reasonable to assume that equipment for purposes such as water supply would receive similarly favorable treatment. Because the unit cost of pumping with diesels is more dependent on recurrent operation and maintenance costs, rather than initial captial equipment costs, favorable import duty treatment on water pumping equipment would enhance the use of RETs over fossil fuel-fired pumps, all other things being equal. While many of these comments apply mainly to private-sector users, such as large cattle owners or syndicates and cooperatives, the largest buyer of PV pumps in Botswana will remain DWA.

Much of the equipment used for the BRET comparative testing program was of U.S. origin. Since foreign exchange rates over the last several years have not favored U.S. manufacturers, the unit water costs in Pula reflect the imbalance of exchange rates resulting from an unusually strong U.S. dollar. Now that this trend is slowly reversing itself, the cost of several US-manufactured RETs (PV, in particular) should decrease. The Japanese have invested considerable time and effort in PV research and have begun to sell power modules worldwide, increasing competition which has contributed to further decreases in the cost of PV modules. While competition due to increased world production of oil has also resulted in a considerable drop in the price of oil, due to the difficulties of petroleum imports into landlocked Botswana, it is unlikely that the cost of diesel fuel will drop correspondingly.

Local manufacture is frequently suggested as a possible means of reducing the high capital cost of RET pumping equipment. Kenya and Botswana (among other developing nations) manufacture wind pumps. Zimbabwe makes some of the components for solar pumps and also produces Mono pumps. PV battery charge-controllers are manufactured in Botswana by BTC. In other developing countries (India, for example) complete PV pumping systems, including modules, batteries, controllers and small DC jack pumps, are manufactured. However, in spite of generally lower labor rates, it is often difficult for developing countries to successfully compete with technical equipment from the developed world, due to a lack of modern manufacturing facilities, access to credit and/or sufficiently trained technical and managerial personnel as well as a number of other reasons. Thus, local manufacture, which sometimes holds considerable potential (such as RIIC manufacturing hand pumps for both domestic consumption and export) for economic development, is certainly no panacea.

At least one corporation (Spire Corp. in the United States) sells complete turnkey operations for the production of PV modules. Several countries (China, for instance) have purchased these units and are now manufacturing their own modules. As the cost of modules is approximately 25 percent labor, in countries where local labor rates are lower than in the United States, Europe or Japan (which currently manufacture most PV modules), savings can be realized from the local production of modules, both for domestic consumption and export to local areas. An added benefit is the consequent generation of employment opportunities and gross domestic product effects, which in turn affect the gross national product. However, these turnkey operations are not inexpensive (prices start at US$500,000), so careful market studies are necessary before any such investment can be wisely made. A certain minimal level of technical support infrastructure (in terms of available, trained personnel and raw materials supply) should exist before such an undertaking would be profitable in either an economic or financial sense.

Wind pumps have already been manufactured in their entirety in Botswana. The advantages include employment and local knowledge of the equipment, which simplifies installation, repair and spare parts availability, and this is reflected in low economic unit costs for water relative to other wind pumps. The major remaining questions about local manufacture have to do with potential markets and the pumps' long-term repair requirements. In addition to the wind pumps currently being developed in Botswana and standard wind pumps manufactured in the Republic of South Africa, at least two other wind pump manufacturers (Kijito and Wind Baron) have had tentative discussions with Zimbabwe regarding possible joint ventures or licensing arrangements to manufacture those designs locally. Since both production costs (due to reduced labor costs) and shipping charges would likely be significantly reduced, these technically advanced machines would become much more cost-competitive for use in Botswana. Hand and human-traction pumps could also be manufactured locally in greater quantities, which could lead to significant savgins on capital costs.

B. Technical Support Infrastructure

When the BRET testing program began, there was one distributor of solar modules in Botswana--now there are several. At the start, very few technicians had any experience with PV system design, installation or troubleshooting problems that arose in the few systems installed at that time. Only the Department of Telecommunications had given any attention to PV and has since increased its use of PV dramatically. In addition to BRET-trained personnel, staff from BTC, the Department of Electrical Engineering, DWA and several private-sector groups have begun to accumulate considerable experience in the use of PV, and this trend is likely to continue.

Standard design wind pumps have been in use in Botswana for many years. However, the market has been small, due partly to less-than-ideal wind regimes and also a lack of aggressive marketing by South African manufacturers. The Climax line of wind pumps is represented by Stewarts and Lloyds, but Southern Cross (the only other standard wind pump in use in Botswana) has no representative at all. In addition, tunThere are only a few people who are able to repair these pumps. Recently, with both RIIC and WTGS becoming interested and involved in wind pump manufacture, more people have become knowledgeable about windmills. Even still, this cadre remains small and except for DWA's windmill crew, outside the public water supply infrastructure.

However, to provide infrastructural support for any widespread use of RET systems throughout Botswana, significant investments in manpower training will be necessary. As noted, these costs have not been included in the financial/economic analysis, as they have yet to be carefully examined and quantified. However, actual training needs have been examined in a qualitative fashion (TRAINING NEEDS ASSESSMENT FOR RENEWABLE ENERGY TECHNOLOGIES, George Burrill, ARD, Burlington, VT, June, 1985). This assessment focused on both the short-term needs of various GOB agencies, which will continue to deal directly with RETs, and longer-term needs for supporting the dissemination of the various technologies. It was recommended that at least one graduate engineer with specific training in mechanical/electrical engineering and experience with PV installations would be needed to simply continue the PV program at its present level.

Similar recommendations were made for wind pumps. A pump installation crew and separate maintenance unit would be required to provide an installation capability of approximately 10 to 20 pumps per year at sites around the country. Increasing the scope of government activities beyond this would require a similar increase in the number of support technicians and engineers. Similar technical staff have been trained and are currently maintaining more than 60 solar pumps in Mali, a program which has met with considerable success.

Taurus Batteries was the sole distributor of PV modules in Botswana for several years, and the proprietors strongly support continued development and dissemination of the technology. It is likely that they would be willing and quite capable of providing support in terms of new equipment and spare parts stock for the continued and increased use of PV for water pumping and other applications. Several manufacturers of PV-related pumping equipment, such as Mono and Jacuzzi, have already invested in South African manufacturing facilities for their pumps, which were designed for use with PV. Mono is in the midst of a development program for a new, low-cost, PV pump controller. As the market increases, it is likely that other entrepreneurs, as well as established companies, will find it profitable to become further involved in PV activities, and increased competition in the field will prove favorable to consumers.

RIIC and WTGS are interested in continuing their work with wind pumps, although both groups are making changes in their wind-related activities. The Climax division of Stewarts and Lloyds is becoming more interested in Botswana as a potential market because extensions to the grid in South Africa are hurting markets there. Once the wind resource assessment is complete and areas for potential wind pump use become more clear, all these groups will undoubtedly provide support to further the use of wind pumps in these areas.

If the RET water-pumping sector were to expand due to increased private- or public-sector purchases, a significant private-sector technical support capability in Botswana would be needed, so that reliable inventories of new equipment and spare parts, a continuing awareness of new technical advances and constant upgrading of skill levels through training would occur. Financial incentives for development of this capability might include favorable import duty treatment, waivers of sales tax (or tax rebates, where appropriate) and conceivably, outright subsidies, depending on the magnitude of the benefits that the GOB perceives in the increased dissemination of these technologies. Since it is neither necessary nor desirable for the government to increase expenditures unnecessarily (especially when competing with the developing private sector), the GOB should encourage establishment of these support functions in the private sector, rather than absorbing them into existing government agencies.

VIII. CONCLUSIONS AND RECOMMENDATIONS

While a substantial amount of field data on a wide variety of water pumps has been collected and analyzed in considerble detail, the conclusions thus far must be considered tentative. It is still necessary to examine a somewhat wider range of systems more closely, and collect and analyze longer-term data (particularly on reliability and maintenance) for systems currently being tested (especially small diesels). Much of this work will be undertaken during the extension of this testing program. As much as possible, the conclusions below are grouped by renewable and conventional energy technologies, with general conclusions presented in Section B.

A. Renewable Energy Technologies

- Hand pumps are clearly the best solution for low-demand (less than four cubic meters per day) and low-head (under 30 meters) installations, where labor charges for pump operation are taken as zero. Thebe human-traction pumps can cost-effectively extend this range of applicability to higher heads, up to 100 meters.

- The range of cost-effective application for wind and PV pumps is for demands between four and 30 cubic meters a day (below which hand pumps should be used) in the 15- to 40-meter head range, and slightly greater demand for lower head applications. This assumes average wind speeds of 2.5 meters per second at the site.

- For sites with demands of less than 1,000 m^3*m/day, but greater than four cubic meters a day (in which case, hand pumps should probably be used), if the site has a moderate to good wind regime (greater than 2.5 to three meters per second for the average wind speed), wind pumps should be given careful consideration. For low wind speed sites, PV pumps will probably be more appropriate.

- PV pumps are cost-competitive with diesels in the 0.4 to 1.5 kW range. Below that range, hand pumps are the system of choice. Above that range, the unit cost of diesel pumps drops faster than PV as pump size increases, although PV pumps are commercially available up to 2.2 kW.

- Because of generally low wind regimes and the pumping heads found in much of Botswana, it is unlikely that wind pumps will find wide application. However, there are areas of the country where wind speeds average nearly three meters per second, with pumping heads of less than 35 meters. If water demand is in the range of cubic meters a day, wind pumps appear to be the most economical solution. The results thus far indicate that the larger the wind pump's rotor diameter, the more cost-effective it is.

- Because the RIIC and WTGS wind pumps, are manufactured locally, they appear to be more cost-effective from an economic standpoint than most other wind pumps tested. However, their long-term recurrent costs and reliability have yet to be adequately determined.

- The Kijito and Wind Baron wind pumps are technically superior to the others tested (although note the next conclusion below). However, their high initial capital cost must be reduced (perhaps by local manufacture in a joint-venture arrangement with Bobs Harries Engineering, Ltd. or Wind Baron) before they will be cost-competitive in Botswana.

- While the Wind Baron is technically a very promising machine in terms of water output, the system tested could not be considered a commercial production model. Considerable work in strengthening and modifying the current design is required before its widespread use should be seriously considered.

- The unit water cost of all pumps is very sensitive to assumptions about requirements for pump attendants. This is especially true for PV and wind pumps.

- The highest output RET pumps in each category (wind, PV, etc.) are generally the most cost-effective system within that particular category. However, because of their high volume-head product (m^3*m), they often fall into the range where diesel is a more cost-effective option across all categories. This anomaly can best be understood by looking at Figure 11. While the Wind Baron has the lowest unit water cost among the wind pumps (P0.015/m^3*m), its high output (840 m^3*m/day) puts it in the range where diesel is cheaper. On the other hand, the RIIC wind pump, which has a slightly higher unit cost (P0.021/m^3*m) than the Wind Baron, is in the output range (255 m^3*m/day) where it _is_ cost-competitive with a diesel system of similar size.

- While there is insufficient data to make definitive conclusions on the applicability of animal-traction and bio-gas pumps, it seems that they are inappropriate choices for village water supply because of the participatory nature of their operation, as well as high labor costs (particularly if contingent on the Industrial Class Regulations).

- Better information is needed on the magnitude of both solar and wind resources in Botswana. The wind resource survey and map of depths to the water table, planned as part of the wind survey work, should be completed. The MET Services solar radiation monitoring effort is now underway to help address this need.

B. Conventional Energy Technologies

- For sites where demand is greater than 1,000 m^3*m/day, diesel pumps are clearly a more cost-effective choice than RET systems.

- Better data on borehole yields and static water levels (including seasonal and annual variations) are required, particularly when using submersible pumps because of their sensitivity to variations in pumping head.

- Grid-electric pumps appear to be more expensive, compared to diesel, than previously thought, largely due to recurrent electrical energy costs. If the predicted lower tariff rate for the new Morupula power plant is assumed in the economic cost calculations, grid-electric pumps will be cheaper to run than diesels (not including power line extensions and power conversion equipment). However, in many places, Morupula energy will not be available. Due to the potential advantages of electric pumps, they should be considered where grid electricity already exists. More testing of smaller electric pumps should also be conducted.

- More care should be taken in choosing the type of pump for a particular site. While there are significant differences between existing Mono-coupled and submersible pumps, both types have certain advantages (and disadvantages) which would make them an appropriate option under certain sets of circumstances. Although the advantages of standardizing equipment are significant, neither type of pump should be dismissed as inappropriate for use in Botswana at this point.

- While DWA knows what is needed in terms of the Village Water Supply Program, before any widespread dissemination efforts for new types of pumps are undertaken, a careful needs assessment among potential end-users should be carried out to assess current and future water requirements. It will be necessary to educate the public, media, schools, pump operators and water unit personnel about the potential advantages and disadvantages of new types of pumps if they are to be successfully disseminated.

- Due to the GOB's commitment to supply drinking water under the Village Water Supply Program, smaller and smaller village systems are being built (there are more than two dozen villages of less than 300 inhabitants in the design year, so demand is under 10 cubic meters a day). Since diesel unit costs increase dramatically with decreased system size, system designers should carefully examine the alternatives recommended here for smaller systems.

- A more comprehensive comparative analysis should include detailed cost estimates for the development of support infrastructures (including training for technicians and engineers, parts distribution networks, etc.) for all RET and grid-electric submersible pumps.

- Designers and users of all types of pumping systems would gain much from better records of borehole yields, depths, straightness and water quality. In this regard, the efforts currently being made by DWA should be further strengthened.

C. Recommendations

The following recommendations are made to give some specific direction for both the extension of the BRET pumping program as well as to public- and private-sector groups who are dealing with water supply issues. They are:

- continue to collect data on the pumps currently being tested, begin data collection on the second set of PV pumps that have been purchased, but not yet installed, and broaden the program somewhat to expand the limited data base on diesel and grid-electric submersible pumps;

- focus attention on any new systems being tested to sites where the demand is less than 1,000 m^3*m/day, i.e., the range in which alternatives are potentially most cost-competitive with diesel;

- continue to collect and analyze data on solar radiation levels and wind regimes throughout the country, and make that information available to system designers as soon as possible;

- long-term operation and maintenance costs for all of the pumps being tested should be closely examined--these costs involved the most estimation in this preliminary report and should be determined as precisely as possible before the conclusion of the testing program;

- infrastructural support requirements should be studied carefully, including the costs of developing equipment supply networks, public awareness information systems, and the technical skills required for proper system design, installation, operation and maintenance;

- the storage sizing and cost issue for the different types of pumps must be examined to determine its effect on unit water cost; and

- attempt to assess the size of the market for RET pumps by means of a study to determine the number of existing boreholes or future sites where water demand would be less than 50 cubic meters per day at heads of less than 50 meters.

D. Further Research

While the BRET comparative testing program for water pumps, added significantly to the increasing body of knowledge about the field performance of this promising technology, it was by no means an exhaustive study of the existing range of RET pumps. Manufacturers' research is continually yielding new refinements of the equipment, which to some extent reflect the results of field tests, such as those conducted by the BRET project. These refinements tend to decrease equipment costs, while increasing component and overall system efficiency and reliablity. This is clearly true for the windmills built in Botswana, which are still in a development stage, even though great strides in reliability and simplified fabrication have already been made. Indications are that costs can still be cut substantially, possibly by private-sector fabrication in the case of the RIIC Motswedi.

Technical developments, especially for rapidly changing technologies, such as PV, can and do alter relative cost structures. For example, one U.S. PV manufacturer recently achieved a 12.4 percent cell efficiency in certain types of their production models. While this may not seem like much, it represents a 10 percent increase in efficiency over the PV modules currently being used in Botswana. Since prices per peak watt are dropping as well (Japanese manufacturers have just begun to quote P10.5/Wp on any quantity of PV modules, a 20 percent drop from BRET's purchase prices one year ago), the net result is that the market for PV for a variety of applications in addition to water pumping is growing rapidly.

Long-term field-testing yields information on the most elusive equipment operating characteristics (reliability and long-term operation, maintenance and repair costs), which can dramatically affect unit water costs. To refine LCC analysis input parameters, detailed cost estimates for training skilled technicians must be determined. While these training needs have been ascertained, their costs remain to be adequately quantified. Successful widespread dissemination of RET pumping systems is dependent on the creation of the necessary technical support infrastructure. Further research in this area is certainly warranted.

RET-driven pumps normally have seasonally dependent variations in their power supplies. While design tools have been developed which can aid system designers in estimating the output of these pumps for each month of the year,* they are merely estimates, the validity of which is dependent on the accuracy of the energy resource inputs. The water output of solar pumps is directly proportional to the amount of solar radiation incident on the array, and for wind pumps, is proportional to wind speed. As yet, reliable, long-term solar radiation and wind speed data have not been processed for most of Botswana. The data collection effort under this testing program has added to the data base needed to make accurate predictions of pump output. The BRET-funded Met Services solar radiation monitoring equipment and SIDA-financed anemometry work will add significantly to this effort. However, these studies are far from complete.

Year-round monitoring of RET pumps is necessary to validate design tools. Fortunately, the extension of the BRET comparative pump testing program will allow more detailed annual data to be collected on a larger number of systems, resulting in more

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*SOLAR PUMP FIELD TESTS IN BOTSWANA -- PRELIMINARY TECHNICAL AND COST COMPARISONS, Richard McGowan and Jonathan Hodgkin, ARD, Burlington, VT, April, 1986; and WIND PUMP FIELD TESTS IN BOTSWANA -- PRELIMINARY TECHNICAL AND COST COMPARISONS, Jonathan Hodgkin and Richard McGowan, ARD, Burlington, VT, March, 1986.

comprehensive and reliable design tools. This extension will also provide more reliable data on long-term operation and maintenance costs, which critically effect the unit water costs of a pumping system.

Water storage requirements and differences in their magnitude for different types of pumps (diesel, wind, PV) were not addressed in this study. Since the cost of incremental storage can affect overall system costs, this factor should be examined in some detail during further research. Since diesel pumps can deliver water on-demand, diesels or gird-electric submersibles would likely require less storage than PV or wind systems. However, the solar resource in Botswana is, relatively speaking, so uniform that it has not been found necessary to have to include more than one day of storage in the systems installed thus far. Since the output of these systems usually was more than adequate for the water demand at the sites, storage was not a critical issue. In countries where solar radiation levels are neither so high nor so uniform, the costs of increased storage would be more of a concern. This argument cannot be made about wind pumps, due to the greater variability of this energy resource, but the state of research on water storage requirements for windmills is not conclusive. Clearly, a more careful look at this issue is needed.

In addition to these general needs for further research on technical and economic performance, there are several pieces of information which could be collected by DWA that would prove very useful in terms of both the use and evaluation of pumps. Improved data on borehole characteristics would be of particular value in sizing submersible pumps, given that their performance is especially dependent on pumping head. In the BEET testing program, borehole yields were frequently found to be considerably less than specified in the drilling records, resulting in the installation of pumps that were oversized for the borehole. It would be desirable, though expensive, to test-pump boreholes before installation, particularly if considerable time has elapsed since the initial drilling.

While much of the information produced by this study can be directly applied to situations in other countries (particularly in Africa), many of the cost assumptions and institutional comments on which the conclusions are based are not transferable. For example, the price of diesel fuel varies considerably acorss nations, due to both international political events as well as that particular government's policy stance on subsidies, investment in transportation networks, fuel allocation, private- and public-sector development, and a number of related issues from the national to the local level. Similarly, the level of locally available technical skills to support pumping equipment varies tremendously, as do site-specific renewable energy resource levels. The figures in this report were gathered from an area that has relatively low wind speeds, but very high and uniform solar radiation. In another country, this situation might well be reversed. Thus, it is advisable to be wary of simply extending the site-specific conclusions presented here to situations with dissimilar conditions.

The approach taken in this study attempted to incorporate field research methodologies used by other researchers and improve on those methodologies, so when all these studies are put in a common analytical format, such as that presented here, intercomparison of their technical and economic conclusions will be easy. A common methodology and format for the presentation of results would be very useful for the integration of all this information and would make it more accessible to decision-makers with different backgrounds (e.g., economics, engineering or administration). The authors, Mr. McGowan and Mr. Hodgkin, recently coauthored (with IT Power and CWD engineers, and several social scientists and economists) a comprehensive pump testing and evaluation methodology, based on their experiences with this and other related testing programs. This methodology will be used by a multi-donor community in a number of countries throughout the world. Interested parties should review this methodology prior to embarking on pump testing programs. In this way, all of the data that is collected, at considerable effort and cost, is presented in a standardized format which is useful to all.

APPENDIX A

Site Descriptions

BRET DIESEL PUMP TEST SITES

SITE:	BONWAPITSE
DISTRICT:	CENTRAL, MAHALAPYE SUB.
B.H. NO.:	4226
WATER REST LEVEL	17 METERS
TOTAL PUMPING HEAD	58 METERS
PUMP TYPE:	MONO ES-30S
MOTOR TYPE:	LISTER ST-1
WATER OUTPUT	7.5 M3/HR
WATER USE	ABT 19 M3/DAY

SITE:	MALOTWANA
DISTRICT:	KGATLENG
B.H. NO.:	3514
WATER REST LEVEL	20 METERS
TOTAL PUMPING HEAD	48 METERS
PUMP TYPE:	MONO ES-15S
MOTOR TYPE:	LISTER SR-1
WATER OUTPUT	3.4 M3/HR
WATER USE	ABT 10 M3/DAY

SITE:	MMANKODI
DISTRICT:	KWENENG
B.H. NO.:	2611
WATER REST LEVEL	30 METERS
TOTAL PUMPING HEAD	82 METERS
PUMP TYPE:	MONO ES-15
MOTOR TYPE:	LISTER LT-1
WATER OUTPUT	4.9 M3/HR
WATER USE	ABT 29 M3/DAY

SITE:	MOGOBANE
DISTRICT:	SOUTH-EAST
B.H. NO.:	3816
WATER REST LEVEL	30 METERS
TOTAL PUMPING HEAD	74 METERS
PUMP TYPE:	MONO ES-30
MOTOR TYPE:	LISTER ST-1
WATER OUTPUT	9.0 M3/HR
WATER USE	ABT 104 M3/DAY

SITE:	OODI
DISTRICT:	KGATLENG
B.H. NO.:	1507
WATER REST LEVEL	28 METERS
TOTAL PUMPING HEAD	101 METERS
PUMP TYPE:	MONO ES-15
MOTOR TYPE:	LISTER 8/1
WATER OUTPUT	3.6 M3/HR
WATER USE	ABT 39 M3/DAY

BRET PHOTOVOLTAIC PUMP INSTALLATIONS

SITE:	MAHALAPYE
DISTRICT:	CENTRAL
B.H. NO.:	NONE, DUG WELL
TOTAL HEAD:	7 METERS
WATER USE:	COOP GARDEN
ARRAY SIZE:	12 ARCO-SOLAR M-53
ARRAY OUTPUT:	516 WATTS PEAK
PUMP TYPE:	JACUZZI SUBMERSIBLE Model XP-3
MOTOR TYPE:	JACUZZI DC Model S4
CONTROLLER	CONSTANT VOLTAGE TRACKER
SYSTEM COST:	11,839 PULA

SITE:	MMATHUBUDUKWANE
DISTRICT:	KGATLENG
B.H. NO.:	977
TOTAL HEAD:	45 METERS
WATER USE:	AUGMENT VILLAGE SUPPLY
ARRAY SIZE:	36 ARCO-SOLAR M-53
ARRAY OUTPUT:	1548 WATTS PEAK
PUMP TYPE:	MONO, ES-10
MOTOR TYPE:	HONEYWELL 1.5 HP DC
CONTROLLER:	CONSTANT VOLTAGE TRACKER
SYSTEM COST:	28,171 PULA

SITE:	MOLAPOWABAJANG
DISTRICT:	SOUTHERN
B.H. NO.:	3327
TOTAL HEAD:	23 METERS
WATER USE:	VILLAGE SUPPLY
ARRAY SIZE:	32 ARCO-SOLAR M-53
ARRAY OUTPUT:	1376 WATTS PEAK
PUMP TYPE:	JACUZZI SUBMERSIBLE Model E7
MOTOR TYPE:	JACUZZI DC Model SJ-1
CONTROLLER:	N/A
SYSTEM COST:	24,440 PULA

SITE:	MOTHEBE(MOCHUDI)
DISTRICT:	KGATLENG
B.H. NO.:	4234
TOTAL HEAD:	38 METERS
WATER USE:	COOP GARDEN (INTENDED)
ARRAY SIZE:	32 ARCO-SOLAR M-53
ARRAY OUTPUT:	1376 WATTS PEAK
PUMP TYPE:	JACUZZI SUBMERSIBLE Model E7
MOTOR TYPE:	JACUZZI DC Model SJ-1
CONTROLLER:	N/A
SYSTEM COST:	24,584 PULA

BRET WIND PUMP INSTALLATIONS (NEW DESIGNS)

SITE:	MOCHUDI
DISTRICT:	KGATLENG
B.H. NO.:	#4205
MANUFACTURER:	KIJITO
DIAMETER:	20 FEET
TOWER:	9 METERS
PUMP TYPE:	3.25" PISTON PUMP
GEAR RATIO:	1:1 (DIRECT STROKE)
TOTAL HEAD:	37 METERS

SITE:	PITSANE-BOTLOKO
DISTRICT:	SOUTHERN
B.H. NO.:	UNKNOWN
MANUFACTURER:	KIJITO
DIAMETER:	20 FEET
TOWER:	9 METER
PUMP TYPE:	3.25" PISTON PUMP
GEAR RATIO:	1:1 (DIRECT STROKE)
TOTAL HEAD:	23 METERS

SITE:	MOCHUDI
DISTRICT:	KGATLENG
B.H. NO.:	#4202
MANUFACTURER:	RIIC (MOTSWEDI)
DIAMETER:	6 METERS
TOWER:	9 METERS
PUMP TYPE:	ES-15S MONOPUMP
GEAR RATIO:	VARIABLE (.9:1 TO 1:6.2)
TOTAL HEAD:	37 METERS

SITE:	MALAU
DISTRICT:	SOUTHERN
B.H. NO.:	#617
MANUFACTURER:	RIIC (MOTSWEDI)
DIAMETER:	6 METERS
TOWER:	9 METERS
PUMP TYPE:	ES-10 MONOPUMP
GEAR RATIO:	VARIABLE BY VSU
TOTAL HEAD:	53 METERS
SYSTEM INSTALLED COST:	11,267 PULA

BRET WIND PUMP INSTALLATIONS (NEW DESIGNS) CONTINUED

SITE:	MOCHUDI
DISTRICT:	KGATLENG
B.H. NO.:	#4232
MANUFACTURER:	WIND BARON MK4
DIAMETER:	21 FEET
PUMP TYPE:	4.0" PISTON PUMP
GEAR RATIO:	1.5:1
TOWER:	12.5 METERS
TOTAL HEAD:	33 METERS

SITE:	MOCHUDI
DISTRICT:	KGATLENG
B.H. NO.:	#4220
MANUFACTURER:	MOMOSO ENGINEERING (WTGS)
DIAMETER:	6.1 METERS
PUMP TYPE:	ES-15S MONOPUMP W/ CLUTCH
TOWER:	9 METERS
GEAR RATIO:	1:8.5
TOTAL HEAD:	37 METERS

SITE:	SHOSHONG
DISTRICT:	CENTRAL, MAHALAPYE SUB.
B.H. NO.:	118
MANUFACTURER:	SWANENG HILL SCHOOL (WTGS)
DIAMETER:	6.1 METERS
PUMP TYPE:	ES-15 MONOPUMP
GEAR RATIO:	
TOWER:	9 METERS
TOTAL LIFT:	40 METERS

BRET WIND PUMP INSTALLATIONS (STANDARD DESIGNS)

SITE:	DIPOTSANA
DISTRICT:	SOUTHERN
B.H. NO.:	#821
MANUFACTURER:	CLIMAX
DIAMETER:	12 FEET
TOWER:	9 METER
PUMP TYPE:	3.0" PISTON PUMP
GEAR RATIO:	3:1
TOTAL HEAD:	30 METERS

SITE:	KGORO
DISTRICT:	SOUTHERN
B.H. NO.:	#806
MANUFACTURER:	CLIMAX
DIAMETER:	10 FEET
TOWER:	9 METER
PUMP TYPE:	2.75" PISTON PUMP
GEAR RATIO:	3.18:1
TOTAL HEAD:	35 METERS

SITE:	MALESANE
DISTRICT:	SOUTHERN
B.H. NO.:	#810
MANUFACTURER:	SOUTHERN CROSS
DIAMETER:	14 FEET
TOWER:	12 METER
PUMP TYPE:	3.0" PISTON PUMP
GEAR RATIO:	2.33:1
TOTAL HEAD:	35 METERS

SITE:	SEDIBENG
DISTRICT:	SOUTHERN
B.H. NO.:	#3815
MANUFACTURER:	CLIMAX
DIAMETER:	12 FEET
TOWER:	12 METER
PUMP TYPE:	2.75" PISTON PUMP
GEAR RATIO:	3:1
TOTAL HEAD:	27 METERS

SITE:	THARESELEELE
DISTRICT:	SOUTHERN
B.H. NO.:	UNKNOWN
MANUFACTURER:	CLIMAX
DIAMETER:	12 FEET
TOWER:	9 METER
PUMP TYPE:	3.5" PISTON PUMP
GEAR RATIO:	3:1
TOTAL HEAD:	19 METERS

ELECTRIC PUMP INSTALLATIONS

SITE:	MOCHUDI
DISTRICT:	KGATLENG
B.H. NO.:	# 3136
PUMPING WATER LEVEL:	36 METERS
TOTAL PUMPING HEAD:	110 METERS
PUMP TYPE:	SUBMERSIBLE
MANUFACTURER:	FILJO
PUMPING RATE:	8.9 M3/HR
AVE. OUTPUT PER DAY:	163 CUBIC METERS

SITE:	MOCHUDI
DISTRICT:	KGATLENG
B.H. NO.:	# 3137
PUMPING WATER LEVEL:	42 METERS
TOTAL PUMPING HEAD:	94 METERS
PUMP TYPE:	SUBMERSIBLE
MANUFACTURER:	FILJO
PUMPING RATE:	4.0 M3/HR
AVE. OUTPUT PER DAY:	64 CUBIC METERS

HAND PUMP INSTALLATIONS

SITE:	TLHARESEELE
DISTRICT:	SOUTHERN
B.H. NO.:	UNK.
PUMPING WATER LEVEL:	14 METERS
PUMP TYPE:	INDIA MK II
CYLINDER SIZE:	2.25"
PUMP STROKE:	4.0"

SITE:	HUKUNTSI
DISTRICT:	KALAGADI
B.H. NO.:	# 4429
PUMPING WATER LEVEL:	17 METERS
PUMP TYPE:	INDIA MK II
CYLINDER SIZE:	2.25"
PUMP STROKE:	4.0"

SITE:	DIKGONYE
DISTRICT:	KGATLENG
B.H. NO.:	# 3982
PUMPING WATER LEVEL:	33 METERS
PUMP TYPE:	"THEBE" HUMAN TRACTION
CYLINDER SIZE:	2.25"
PUMP STROKE:	30"

SITE:	SENGWOMA
DISTRICT:	SOUTH-EAST
B.H. NO.:	# 4153
PUMPING WATER LEVEL:	16 METERS
PUMP TYPE:	INDIA MK II
CYLINDER SIZE:	2.25"
PUMP STROKE:	4.0"

APPENDIX B

Detailed System Costs

The following pages describe in detail the rationale for assigning costs to each line item in the financial and economic analysis given on the spread-sheets in Section V. The two major types of costs--initial capital equipment and installation costs, and all recurrent costs for operation, maintenance and repair--are separated for convenience.

Capital Equipment and Installation Costs

In calculating the costs for the pumps, every effort has been made to reflect the actual costs on a site-specific basis. The costs include all the necessary hardware to pump water out of the ground at the site in question. Also included are such aboveground components as water meters, non-return valves and gate valves, so that with connection of piping to the storage or reticulation system, the entire water delivery system would be complete. Storage and reticulation systems are not included, due to insufficient information about water storage needs, particularly for the renewable systems. Borehole drilling and well preparation are not included either, because these costs do not vary when different pumping systems are used. General comments about components common to more than one type of pump are discussed first. A more detailed discussion by pump type follows.

Piping is common to all systems. For the purpose of this discussion, it can be broken down into two categories: aboveground and below-ground. This is done for two reasons. First, below-ground piping costs are fixed by the required pump installation depth, which is directly related to the site-specific borehole rest water level and draw-down. Second, below-ground components corrode much more quickly than those aboveground; therefore, they must be replaced more frequently than the rest of the piping system, and it is convenient to view these costs separately. In the case of Mono-coupled systems, the Mono drive head (gearbox) is included in the aboveground components. In all cases, the current DWA tender prices are used when they are quoted, and the least expensive commercial figure is used when they are not. A complete list of the current prices of components used in these installations is included as a part of this appendix.

All items that required purchase in foreign currency, notably the imported windmills and the solar pumps, were handled by obtaining a current quote. This figure was then translated into pula at the current rate of exchange (P0.57 = US$1.00). The two exceptions to this are pointed out as they are discussed under the separate pump types. Shipping was included where it was necessary. In many cases, any shipping costs have already been included as part of the purchase price of the equipment.

Also included for each system are all other capital costs. Included are the costs of cement, crushed stone and sand to make the necessary foundations, as well as reinforcing steel, foundation bolts and borehole clamps. Since fencing is considered an integral part of a complete PV or wind pumping system, it is included. For diesel and electrical pumps, the cost of the pump house is included.

The standard construction crew used by DWA is from six to 10 people, with a driver and driver's assistant. The crew generally camps at the construction site on installation jobs and gets a per diem allowance in addition to regular pay. The crew that was available to the BRET project was a very capable crew of eight, plus a driver and a helper. The cost of keeping this crew in the field is P140 per day, of which approximately 40 percent is wages and the rest is the allowance. The crew comes supplied with a seven-ton truck. In some cases (particularly with diesel and electric pumps), an estimate for the time required for installation was necessary. The figures used were derived from discussion with DWA personnel and examination of the records for similar installations.

Transport costs are calculated by the kilometer, at different rates, depending on the type of vehicle used. During installation, a seven-ton truck is used to ferry supplies to the site, carry the crew and its camping equipment, and haul stone and sand as required. In each case, the mileage is calculated as if the pump were 50 kilometers from the nearest maintenance point and 100 kilometers from the DWA depot that oversees the installation.

Recurrent Costs

Given that the comparative testing program has yet to run long enough for any normal major repairs to have become necessary, and that it is by nature a testing program, no sense of the true long-term operation and maintenance for many of the pumps has been definitively established. Because of the data collection procedure established, the number of visits to each of the test sites has been far in excess of those required for smooth operation of the pumps. Manufacturers' claims for the lifetimes of the solar and wind pumps far exceed the actual operation time of any pump thus far. Therefore, it has been necessary to estimate the recurrent cost schedules. The inherent uncertainty involved in this estimation is reduced somewhat by a knowledge of how these maintenance functions should be accomplished, based on experience thus far in Botswana.

The base-case assumption is that DWA will be the primary purchaser of these pumps, and the pumps would be installed as part of the village water supply program. This means that the installation would be done by DWA, and all recurrent costs would be borne by the District Councils and their respective water maintenance units or water departments. These underlying assumptions are the basis on which the baseline recurrent maintenance and repair schedules were developed. All transport costs are calculated from the site to the location of the Water Maintenance Unit responsible for the pump.

The recurrent costs break down into several broad categories. The first of these is annual recurrent cost, which includes site visits for inspection, replacement of drive belts or cup leathers, delivery of fuel, and other related work done on an annual basis. The type of vehicle normally used for this type of activity at the council level is a four-wheel-drive Toyota or Land Rover. Two people would normally go on light maintenance or inspection trips. The major question was how many such trips to include in a given year for each of the pump types. The Water Maintenance Units are responsible for about 20 to 70 boreholes and pumps each. It appears that each diesel pump site is visited between one and four times a month, depending on location. These visits are often part of a tour of several sites that includes major work at one of them. The number of chargeable visits to each site is based on this knowledge and on the requirements of the pumps.

The other major annual recurrent cost is that of a pumper. One of the advantages of PV and wind pumping installations is that they can be operated without an attendant. However, for village systems, there are other tasks that a pumper performs, such as taking care of the storage tanks and the piping system, keeping records, and reporting any problems to the Water Unit. In short, it is felt that someone must be responsible at the local level for the system's operation. Therefore, except for the hand pumps, a pumper is assumed to be required at least one day a week, at a rate of six pula per day. Since the diesel systems need an operator for starting and stopping the pump on a daily basis, a full-time pumper is assumed. The financial and economic viability of RET pumps is strongly affected by the use of pumpers. A sensitivity study indicating the extent of this effect is included in the Appendix C.

For all pumps, it was assumed that at five years, most below-ground piping components were replaced. This figure will vary widely based on water quality, depth and borehole alignment (especially with Mono pumps). Although there are scant records of time between replacement, it is generally felt that a five-year replacement period is reasonable. It was assumed that all piping and, in the case of Mono pumps, all bobbins and half of the shafts would need replacement. This assumption will make little difference accept to bias the results toward submersibles if the replacement period is too short, or towards Mono pump systems if the period is too long. Most other repair and maintenance requirements are dependent on pump type and are covered in the following pages.

Solar Pumps

For solar pumps, the cost of the array includes the costs of ARCO Solar M-53 modules used on all of the BRET installations. It also includes the costs of manufacturer-supplied interconnects and support structures. In the case of Otse, the ARCO 16-2000 modules originally used are no longer available. Today's replacement is the ARCO Solar 701, and the current price of this module is used. In all cases, the current prices for these components supplied by the Gaborone dealer (Taraus Batteries) are used. These prices seem to compare favorably with the international market prices at this time.

The cost of the pump/motor includes the costs of the pump, motor and gearboxes or belt/pulley units used to connect them. These are an integal unit in the submersible systems. However, for the Mono-coupled systems, this figure includes the costs of the motor, the Mono pump and the discharge head. Not all PV pumping systems have major electrical components, such as controllers and/or batteries, but for those that do, the costs are are included. Also included are the costs of wiring (including submersible pump wire as appropriate), ground rods, switch boxes, switches and circuit breakers or fuses as necessary.

At the five-year mark, along with the pipe replacement mentioned above, any batteries used in the systems would have to be replaced. However, one five-year expense that applies to all of these systems is perhaps a controversial assumption that there will be some module breakage, and some replacement will be necessary. Based on experience thus far, a reasonable assumption is that the replacement of two modules every five years for 30- to 40-module arrays, and one module every five years for arrays with fewer than 20 modules, will be required.

DC electric submersible motor brushes are expected to last from 5,000 to 10,000 hours, according to the manufacturers. At this point, having little else to go on, it is assumed that the lifetime of the motor itself will be about 25,000 hours, or seven years at six hours run-time per day. The same assumption was made about surface-mounted DC motors for at least the base case.

It was assumed that the controllers, whether battery-charged controllers or other power conditioning units, would be replaced at 10-year intervals. Except for breakage, the lifetime of the PV modules was placed at 20 years. This is based on numerous accelerated testing programs conducted by manufacturers, and reinforced by the fact that manufacturers are now giving module warranties based on a less-than-10 percent reduction of module power output over 10 years. The Mono pumps themselves were assumed also to last the full assumed 20-year system lifetime.

Although a pumper is not normally required for the day-to-day operation of a solar pump, the base-case assumption is that a pumper will be hired for one day per week. Annual recurrent costs also include the cost of an annual maintenance trip to the site from the nearest Water Maintenance Unit to check the pump, controller, batteries and array. The general assumption is that two chargeable trips per year will be made, but that the machine will be visited more often by crews passing by.

Wind Systems

For the Climax and Southern Cross machines, a current price quote was obtained. The Kijito price was obtained by requesting a current price quote and using the prevailing rate of currency exchange. Note that the price increase in the period since BRET purchased its two machines is due in part to a price increase of the machine in Kenya and in part to a change in the exchange rate. For the Wind Baron, the original U.S. dollar cost is used, and the pula cost was calculated using the current exchange rate. This was done because no current price quote was obtained. The cost of the Wind Baron has increased by about 40 percent as a result of exchange rate fluctuation alone. For the RIIC and WTGS designs, the project's purchase price is used.

In the cases where the BRET project installed the wind pumps, the actual costs are used. However, there are several cases where others performed the installation. First is the case where BRET was charged for the installation. This case includes the WTGS and the RIIC (indirectly). The cost of the RIIC machine includes installation (hence, no installation cost on the financial analysis summary). Momoso Engineering installed the WTGS and charged the project an amount used in the analysis. The cost for installing the Wind Baron is much higher than for the others for two reasons. The wind pump is more complex than the others tested, and the installation required the use of a crane.

Although the longer-term reliability of the traditional wind pumps is historically well established (providing that the installation is done correctly), this is not yet true of the newer designs. In several cases, the wind pumps must be considered as production prototypes, and the process of minor repair and system refinement do not reflect the longer-term recurrent costs to operate a fully developed machine. Since this is the case, it has been necessary to estimate the recurrent cost schedules. This is, of course, an area open for intense discussion. For the present study, an estimate is made based on the projected requirements for operation and maintenance of production machines installed correctly. As this is certainly an optimistic assumption, an additional inspection and site visit are included each year.

Although a pumper is not normally required for the day-to-day operation of a wind pump, the base-case assumption is that a pumper will be hired for one day per week. Annual recurrent costs also include the cost of an annual maintenance trip to the site from the nearest Water Maintenance Unit to grease the machine, change the oil, change the cup leathers (in the case of reciprocating pumps), and replace drive belts (in the case of Mono-coupled systems). The general assumption is, again, that two chargeable trips per year will be made, but that the machine will be visited more often by crews passing by.

Diesels

For diesel systems, the capital costs are known with some precision, but the recurrent costs have not been recorded over any longer period of time, so, again, much of this must be estimated. The fuel costs for operating the engine can be estimated with some accuracy, and the cost of employing a pumper is well documented. It is the repair, replacement and transportation costs to and from the borehole to deliver fuel and make the necessary repairs that must be estimated. These costs are very much a function of the organizational ability of those who oversee the repair and fuel delivery as well as the skill of the repair crews. Scheduled maintenance of the equipment is being done in an increasingly efficient manner by many of the maintenance crews, but in almost all cases the manufacturers' schedules for maintenance are not being met. Also, the mechanism for accomplishing the repair tasks varies from unit to unit, as some do engine overhauls themselves and some send the engine in to DWA for repair.

Experience with the Lister engines in use in Botswana indicates wide differences in the maintenance and repair schedules for different models of pump. In all cases, it was assumed that the engines would be rebuilt rather than replaced at least once, as this is the current practice at both DWA and at the district level. It is uncertain how many times this rebuilding will be a cost-effective choice. It is assumed that after one complete rebuilding, the engine would be replaced. Based on information from DWA personel, the overhaul intervals assumed were 3,000 hours for the LT-1; 10,000 hours for the ST-1;

and 20,000 hours for the 8/1 models. These figures are widely variable depending on the level of maintenance during the overhaul intervals, but seem reasonable for the conditions under which many of the engines must operate. Decarbonizing, cleaning or replacing injectors and changing filters are the major maintenance functions done by Water Unit technicians (oil changes are done in most cases by the pumpers). Indications are that this maintenance is not done strictly on schedule, but it does appear to get done in a reasonable manner, not usually going beyond twice the scheduled interval. This variable also is dependent on the site, and the operation of the maintenance units. It is assumed that these tasks would be done by the maintenance unit (and thus require a chargeable trip) at intervals slightly longer than those scheduled.

The fuel costs for operating the engines are not well documented over the long term. The Water Units are just beginning to institute a logbook system that will yield useful long-term information. Short-term tests of fuel consumption were performed, and in several cases where records were available, the figures agreed very closely. Also, Lister provided formulas for computing fuel consumption as a function of engine model, derated condition, and partial load conditions. These figures also agreed closely with the test figures. Indications are that theft is not a significant problem. Fuel delivery seems to be a major point of contention, as each Water Unit approaches this problem differently. Some (North-East District, for example) deliver fuel only when necessary. This can be done reasonably in some of the smaller districts, but clearly not everywhere. Most units are instituting a regular fuel delivery schedule that allows more than one site to be visited per delivery trip. Usually, delivery takes the form of one or two 200-liter drums, depending on the site, so that deliveries take place at intervals of one month or longer. It is assumed that four chargeable fuel deliveries will be made each year, with other deliveries being made as part of another chargeable trip or as part of a trip chargeable to a different site.

In most cases, a full-time pumper, complete with relief operator for the weekends, is hired to operate pumps in rural areas. This is the baseline assumption for this study (P2400 per year including relief and benefits). There are sites where this is not the case, and no relief is hired. Another case is where there is more than one pump in a village, and one pumper is responsible for two or perhaps three pumps. There are clearly cases for some of the smaller schemes where a half-time pumper would suffice, but the regulations do not yet allow for hiring part-time employees.

Grid-Electric Pumps

Only two electric pumps were tested under this program. There has been some confusion about what model of pump is installed in the two boreholes in question. Some detective work has been required to determine the most likely pumps installed, and current prices for replacement pumps have been used (the original models are no longer available). It appears that the pumps are functioning at acceptable efficiencies, and the LCCs are not heavily influenced by the pump cost, so this does not seem to be a poor assumption. The cost of pumping water with electric pumps is largely a function of the electricity cost. Botswana has a special water pumping tarriff of 16.1 thebe per kWh (Botswana Power Corporation, April 1985). The number of kWh used was recorded from the power company meter, which has limits of acceptability of 2.5 percent fast and 3.5 percent slow. There is a tarriff study currently underway that may well result in a change in the tariff for water pumping. It is unlikely that any off-peak tariff will be instituted, as the demand curve is very flat.

In addition to the cost of the pumps themselves, the costs of protection equipment, transformers, distribution lines, if necessary, and interconnect charges must be considered. Interconnect charges and estimates for the cost of the protection equipment (based on replacement) are included in the analysis. The cost for additional wiring and transformers are not included, not because they are not important, but because time did not permit an accurate determination of their cost. As the electrical pumps tested are outside the range of interest for RET pumps, they received lower priority at every stage of the program. This will be corrected during the second phase of the program.

As with the other pumps, the assumption about a pumper is one of the most important. For the electrical pumps, the ALCC of the water pumped is not affected so greatly, as the pumper cost is defrayed over such a large volume. For this analysis, a one-day-a-week pumper was assumed, based on the sorts of sites where electric pumps are found; at least for the near term, this is in the major villages where the pumper will have many responsibilities other than turning the pump on and off.

Hand-Operated Pumps

Several years' experience have given a reasonable idea of the costs for installation of the India Mark II hand pumps. Although it is believed that the installation and maintenance of these pumps should be done from the district level, the cost estimates included here are for installation by the crew assigned to BRET for the purpose. A brief examination of the costs reveals that some savings can be realized by installation by district-level crews. The major reason for district-level control is the ability to be responsive to local needs and the increased contact that allows necessary O&M to be accomplished. It was assumed that only one chargeable trip per year to replace the cup leathers would be necessary. This would be done with a heavy truck in order to carry all the crew and the equipment to the site. Although it is too early to tell, the same maintenance assumptions were made about the "thebe" human-traction pump.

In all the hand-operated pump cases, the capital costs used are recent figures. A second shipment of Mark II pumps was received during 1985, and the invoice cost is used in the analysis. The redesigned "thebe" pump was purchased and built during the middle part of the year. A lifetime of 10 years was assumed, so a replacement pump is necessary at the 10-year mark to allow comparison with the 20-year lifetime assumed in other cases.

PRICES in PULA (P 1.00 = $0.57)
JUNE 1985

	Tender	Haskins	Asso. Eng.	Taurus	Sharps	Other
-ELECTRICAL COMPONENTS-						
100 A-HR BATTERIES				90.00		
12 MODULE SUPPORT ST.				300.00		
4mm ELEC. WIRE (100 M)					29.99	
6mm ELEC. WIRE (100 M)					43.62	
8 MODULE SUPPORT ST.				150.00		
ARCO M-53 MODULES				570.00		
ARCO M-63 MODULES				500.00		
ARRAY INTRCONECTS				10.00		
BATT. TERMINALS				0.80		
GROUND ROD					17.60	
GROUND WIRE PER METER					1.71	
JACUZZI PUMP						2275.00
KNIFE SWITCH						
MODULE INTERCONNECTS				6.00		
SUBMERSIBLE PUMP CABLE(PER M)					3.74	
-WIND PUMPS-						
12mm ROD 3M		5.95				
16mm ROD 3M	8.16	10.85	16.75			
20mm ROD 3M	11.85	15.90	20.94			
CLIMAX 10						
CLIMAX 12						
CLIMAX 18						
CYLINDER (2.75*18 BALL)	281.75	322.00				378.75
CYLINDER (3*18 POPPET)	101.47					147.60
CYLINDER (3.25*18 BALL)	362.25	414.00				480.00
CYLINDER (3.5*18 POPPET)						173.30
CYLINDER (3.75*18 BALL)	409.50	465.00	444.30			585.00
CYLINDER (4*18 POPPET)	147.90					214.00
CUP LEATHERS	1.50					
FORCE HEAD (3")		155.61				
KIJITO 20 FT.						
SOUTHERN CROSS 14						2184.00
30' TOWER FOR 14'IZ						670.00
SOUTHERN CROSS 25						11838.00
55' TOWER FOR 25'R						2981.00
WIND BARON (INCL SHIPPING)						
D-9 NATIONAL PUMP HEAD			740.00			
-GENERAL-						
100-50mm REDUCER		19.34				
100-80mm REDUCER	13.09	20.29				
100mm ELBOW	31.30	33.54	33.54			
100mm GS PIPE 3M	33.62	56.40	61.48			
100mm NIPPLE	3.28	4.25	6.39			
100mm TEE	20.23	46.76	46.76			
100mm UNION	48.36					

12mm FOUNDATION BOLTS		0.60				
20mm BRASS TAP	6.92					
20mm ELBOW	0.94					
20mm EQUAL TEE	1.34					
20mm GS PIPE 3M	4.32					
20mm NIPPLE	0.19					
20mm PLUG	0.32					
25mm ELBOW	1.77	2.30	2.30			
25mm GS PIPE 3M	6.45	11.10				
25mm NIPPLE	0.28	0.32	0.46			
25mm TEE	2.24	3.20	3.20			
25mm UNION	3.65	5.63	5.63			
32mm BARREL NIPPLE		0.69	0.77			
32mm ELBOW		4.34	4.34			
32mm GS PIPE 3M		14.10	16.21			
32mm TEE		5.68	5.68			
32mm UNION		7.62	7.62			
40-20mm REDUCER	3.57					
40-25mm REDUCER	1.96	3.00	2.27			
40-32mm REDUCER		3.45	1.91			
40mm BARREL NIPPLE	0.46	0.77	0.86			20.00
40mm ELBOW	3.92	5.42	5.42			
40mm FLANGE	4.53					
40mm GATE VALVE	6.92					
40mm GATE VALVE		9.50				
40mm GS PIPE 3M	8.13	15.90	18.42			
40mm KENT WATER METER	231.00					
40mm NON-RETURN VALVE	14.48					
40mm TEE	4.56	7.04	7.04			
40mm UNION	6.16	9.50	9.50			
50 Kg CEMENT		4.05				
50-20mm REDUCER	5.57					
50-40mm REDUCER	3.35	5.17				
50mm BARREL NIPPLE	0.68	1.12	1.24			
50mm FLANGE	5.20					
50mm GATE VALVE	10.13					
50mm GATE VALVE		14.20				
50mm GS PIPE 3M	13.95	22.95	26.67			
50mm KENT WATER METER	234.00					
50mm NON-RETURN VALVE	22.16					
50mm TEE	6.83	10.56	9.75			
50mm UNION	10.14	15.64	15.64			
50mm ELBOW	6.27	7.70	8.63			
5mm ANGLE STEEL (6M)		2.15				
65mm ELBOW	12.76	13.70	13.70			
65mm GS PIPE 3M	17.67	30.15	34.32			
65mm NIPPLE	1.56	2.75	1.65			
65mm TEE	11.82	18.25	18.24			
65mm UNION	15.37	23.95	23.94			
6mm ANGLE STEEL (6M)		3.10				
6mm STEEL WIRE ROPE		2.45				
80-50mm REDUCER	6.62	10.26				
80mm ELBOW	15.12	17.40	17.40			
80mm FLANGE	7.68					
80mm GS PIPE 3M	21.44	38.10	43.63			
80mm KENT WATER METER	279.00					

80mm NIPPLE	2.05	3.37	2.79			
63mm TEE	18.99	29.30	29.30			
80mm UNION	19.25	29.98	29.98			
BOREHOLE CLAMP 2"		27.08				
CRUSHED STONE (M3)						
ENGINE MOUNTING FRAME 8/1	200.00		205.00			
ENGINE MOUNTING FRAME ST-1	200.00		195.00			
PRESSURE RELIEF VALVE(1000KPA)	27.30					
PRESSURE RELIEF VALVE(700KPA)	27.30					
TEFLON TAPE		0.43				
-PUMPS AND ACC.-						
13mm MONO ROD (1.5M)	4.36	6.00				
16mm MONO ROD (1.5M)	6.48	8.10				
BOBBINS (40mm)	5.08	6.35	5.72			
BOBBINS (50mm)	6.72	8.40	7.29			
MONO ES-10	291.20	364.00	327.60			
MONO ES-10S	291.20	291.00	234.90			
MONO ES-15	423.20	529.00	476.10			
MONO ES-15S	291.20	364.00	327.60			
MONO ES-30	505.40	633.00	569.67			
MONO ES-30S	400.00	500.00	450.00			
MONO ES-4	208.80	261.00	234.00			
MONO COLUMN (50mm)	44.55					
MONO COLUMN (40mm)	31.77					
MONOSTROOM (250*50*28)	280.80	213.00	278.91			
MONOSTROOM (250*40*28)	268.80	213.00	270.90			
STABILISERS (40*152)	6.20	9.45	8.96			
STABILISERS (50*152)	7.56	7.75	6.68			
16mm TOP SHAFT	22.40	28.00	20.50			
MONO COL ADAPTER		23.00				
-FENCING AND FOUNDATIONS-						
1.6mm WIRE	37.85	44.70				44.30
4mm WIRE	39.60	42.50				38.15
CORNER BRACES (1.2)	5.62	6.95				5.62
CORNER POSTS 91.2)	9.13	15.75				9.13
DIAMOND MESH (1.2)	37.90	36.45				32.42
GATE (HOMESTEAD)	41.58	71.25				45.48
STANDARDS (1.2)	3.90	3.25				3.39
TALL CORNER BRACES (1.8M)	10.23					7.39
TALL CORNER POSTS (1.8M)	13.04					11.90
TALL DIAMOND MESH (30 M LENGTH	58.20	54.70				50.59
TALL STANDARDS (1.8M)	4.85					4.60
-DIESEL ENGINES & ACCESSORIES-						
LT-1 (BLD 11)	1104.00	1187.00				1268.75
ST-1C	1324.00	2394.00				2094.75
ST-1C W/CLUTCH	2268.00					2996.00
8/1	2660.00	3954.00				3459.75
V BELTS 17*2500	10.16					
V BELTS 17*4060	11.72					
V BELTS 17*5000	14.44					
V GROOVE PULLEY 160mm	47.50					

V GROOVE PULLEY 200mm	66.00					
PUMPHOUSE (3M*4M)	890.00					890.00
PUMPHOUSE (2.4M*3.6M)	786.00					
PULLEY 140mm DIA	41.30					
PULLEY 160mm DIA	47.50					
PULLEY 180mm DIA	58.00					
PULLEY 200mm DIA	66.00					

APPENDIX C

Sensitivity Analysis

This section contains an analysis of the effect of certain assumptions used to define the base case for each of the technologies. The method of analysis used was a series of sensitivity studies examining a number of the assumptions one at a time. The parameters investigated included the pumper cost, the discount rate, and the amortization period (and lifetime). In these studies, the assumed lifetimes for the various technologies were increased or decreased by the same ratio as the assumed change in the amortization period. For the conventional technologies (diesel and electrical), the effects of a real increase in the price of energy (diesel fuel or kWh cost) were also examined. The effect of a decrease in the cost of solar modules was also examined, as was the effect of various average wind speeds. The tables on the following pages summarize these effects in both an absolute sense and a relative sense (by comparison to the base-case condition).

The tables require some explanation. The studies are divided by technology, and the assumptions used in each case are defined at the top of each sheet. It should be noted that the base-case condition is not necessarily the first case listed. All the studied sites are included by number, and the daily output and head are listed to help interpret the results. The site numbers correspond to the sites across the tops of Tables 4.1 through 4.11 in the main body of the report. For each case, the figures calculated are the financial cost per unit volume (F-M3) and the financial cost per unit volume per unit head (F-M4). Similarly, economic unit costs are given as E-M3 and E-M4. The figures given are the unit costs in thebe. Below these figures, in a corresponding block, are the percentage difference from the base-case conditions. For the base case, the percent difference is obviously zero. A brief discussion of each case follows.

Diesel Pumps

Note that Case #1 is the base case. As is true for all technologies, the assumption about pumpers makes the greatest difference. From an economic standpoint, the unit cost of delivered water for diesel could be reduced by 20 to 40 percent if pumpers could be used for only one day per week. This is not a realistic assumption. However, if one pumper were responsible for two pumps, or if a pumper could be employed half time (a definite possibility for some of the smaller village systems), then a unit cost saving of 10 to 20 percent could be realized.

No other assumption makes nearly as big a difference. Surprisingly, projecting a real increase in the price of fuel made very little difference in the unit cost of delivered water over the range of assumed cases. This is because the labor, maintenance and repair costs are a much larger percentage of the recurrent cost than the fuel cost.

Electrical Pumps

Note that Case #7 is the base case. For electric pumps, an additional two conditions are included. These make the assumption that the economic cost of the electricity from the Morupula Power Plant is five thebe/kWh. These cases also show that the pumper assumption is the most critical one, and not much else seems to make a major difference. Some caution about this set of cases is in order--there is considerable round-off error, as the numbers being compared to the base case are so small. The clearest conclusion about the electric cases is how much difference it will make when Botswana begins to generate its own power, and what an effect that will have on cases where this power can be used for pumping water.

Solar Pumps

Note that Case #7 is the base case (pumper one day a week). As stated, the assumption about pumpers has more impact than any other assumption. If a full-time pumper were needed, the unit cost of water would rise by 35 to 70 percent. It has not been felt that a full-time pumper is required from an operations standpoint, but there may be other forces that require it, such as a commitment to rural employment or an inability or unwillingness to reexamine the Industrial Class Regulations. A look at the tables will also indicate that the effects of most of the parameters examined are significant, ranging above 10 percent. Beyond indicating the importance of these parameters, this shows the need to continue the work to gain more confidence in the base-case assumptions, particularly of lifetime, output and recurrent costs. With PV costs declining to a recently quoted low of US$6 (as compared to the as-paid cost of over US$7.50), the unit cost savings would be in the range of eight to 15 percent. As the reader will note, no assumption other than that about pumpers made as much difference for diesel systems.

Wind Pumps

Note that the base case is #7 (pumper one day a week). The assumption about pumpers still has the greatest impact on the analysis. However, in this case, the assumption about wind speed (and the increase or decrease in output) also has a large effect on the unit water cost, in effect halving or doubling the cost in some cases by a decrease or increase of a half meter per second in average wind speed. This indicates the importance of good siting for wind pumps and the wind resource survey currently underway. As is to be expected, the discount rate, amortization and lifetime assumptions have more effect on the imported wind pumps (#4 and #5).

Hand-Operated Pumps

Note Case #1 is the base case. Each case is divided into two cases assuming different outputs. As none of the parameters studied is dependent on output, there is no difference in the values in these two cases for any of the pumps. Since no pumper is currently being paid to care for the hand pumps, none has been included. The only sensitivity parameters analyzed were discount rate, amortization period and lifetime. These analyses indicate the importance of a good maintenance schedule for hand pumps.

DIESEL SENSITIVITY STUDY

CASE # 1 :PUMPER FULL TIME, 6% DISC RATE, 20 YEAR AMORT., 0% REAL FUEL INFLATION
CASE # 2 :PUMPER FULL TIME, 9% DISC RATE, 20 YEAR AMORT., 0% REAL FUEL INFLATION
CASE # 3 :PUMPER FULL TIME, 12% DISC RATE, 20 YEAR AMORT., 0% REAL FUEL INFLATION
CASE # 4 :PUMPER FULL TIME, 6% DISC RATE, 20 YEAR AMORT., 2% REAL FUEL INFLATION
CASE # 5 :PUMPER FULL TIME, 6% DISC RATE, 20 YEAR AMORT., 1% REAL FUEL INFLATION
CASE # 6 :PUMPER HALF TIME, 6% DISC RATE, 20 YEAR AMORT., 0% REAL FUEL INFLATION
CASE # 7 :PUMPER 1 DAY/WK, 6% DISC RATE, 20 YEAR AMORT., 0% REAL FUEL INFLATION
CASE # 8 :PUMPER FULL TIME, 6% DISC RATE, 15 YEAR AMORT., 0% REAL FUEL INFLATION
CASE # 9 :PUMPER FULL TIME, 6% DISC RATE, 25 YEAR AMORT., 0% REAL FUEL INFLATION

:				CASE 1 (Base Case)				CASE 2				CASE 3			
	M3/DAY	HEAD	M4	F-M3	F-M4	E-M3	E-M4	F-M3	F-M4	E-M3	E-M4	F-M3	F-M4	E-M3	E M4
DIESEL #1	19	58	1102	59.14	1.02	41.09	0.71	61.08	1.05	42.93	0.74	63.15	1.09	44.9	0.77
DIESEL #2	10	48	480	109.23	2.28	74.61	1.55	112.52	2.34	77.85	1.62	116.04	2.42	81.32	1.69
DIESEL #3	22	82	1804	61.05	0.74	43.99	0.54	62.79	0.77	45.66	0.56	64.63	0.79	47.42	0.58
DIESEL #4	104	74	7696	18.4	0.25	14.91	0.2	18.79	0.25	15.28	0.21	19.2	0.26	15.67	0.21
DIESEL #5	39	101	3939	47.09	0.47	37.69	0.37	48.28	0.48	38.87	0.38	49.56	0.49	40.12	0.4
Percent different from Base Case				0	0	0	0	3	3	4	4	7	7	9	8
				0	0	0	0	3	3	4	5	6	6	9	9
				0	0	0	0	3	4	4	4	6	7	8	7
				0	0	0	0	2	0	2	5	4	4	5	5
				0	0	0	0	3	2	3	3	5	4	6	8

	CASE 4				CASE 5				CASE 6			
	F-M3	F-M4	E-M3	E-M4	F-M3	F-M4	E-M3	E-M4	F-M3	F-M4	E-M3	E-M4
DIESEL #1	59.27	1.02	41.21	0.71	59.4	1.02	41.35	0.71	29.26	0.5	26.14	0.45
DIESEL #2	109.44	2.28	74.83	1.56	109.66	2.28	75.04	1.56	50.37	1.05	45.19	0.94
DIESEL #3	61.25	0.75	44.19	0.54	61.45	0.75	44.39	0.54	34.57	0.42	30.75	0.38
DIESEL #4	10.53	0.25	15.04	0.2	18.66	0.25	15.16	0.2	12.91	0.17	12.16	0.16
DIESEL #5	47.34	0.47	37.94	0.38	47.55	0.47	38.19	0.38	32.27	0.32	30.28	0.3
	0	0	0	0	0	0	1	0	-51	-51	-36	-37
	0	0	0	1	0	0	1	1	-54	-54	-39	-39
	0	1	0	0	1	1	1	0	-43	-43	-30	-30
	1	0	1	0	1	0	2	0	-30	-32	-18	-20
	1	0	1	3	1	0	1	3	-31	-32	-20	-19

	CASE 7				CASE 8				CASE 9			
	F-M3	F-M4	E-M3	E-M4	F-M3	F-M4	E-M3	E-M4	F-M3	F-M4	E-M3	E-M4
DIESEL #1	41.96	0.72	33.49	0.56	62.18	1.07	44.19	0.76	57.52	0.99	39.68	0.68
DIESEL #2	75.4	1.57	57.7	1.2	114.65	2.39	80.26	1.67	106.4	2.22	72.18	1.5
DIESEL #3	45.83	0.56	36.38	0.44	64.65	0.79	47.4	0.58	59.5	0.73	42.51	0.52
DIESEL #4	15.24	0.21	13.33	0.18	19.17	0.26	15.65	0.21	18.08	0.24	14.6	0.2
DIESEL #5	38.57	0.38	33.43	0.33	49.25	0.49	39.88	0.39	45.89	0.45	36.58	0.36
	-29	-29	-18	-21	5	5	8	7	-3	-3	-3	-4
	-31	-31	-23	-23	5	5	8	8	-3	-3	-3	-3
	-25	-24	-17	-19	6	7	8	7	-3	-1	-3	-4
	-17	-16	-11	-10	4	4	5	5	-2	-4	-2	0
	-18	-19	-11	-11	5	4	6	5	-3	-4	-3	-3

ECTRIC PUMP SENSITIVITY

ASE #1 :PUMPER FULL TIME, 6% DISC RATE, 20 YR AMORT., 0% KW-HR COST INFL.
CASE #2 :PUMPER 1 DAY/WK, 9% DISC RATE, 20 YR AMORT., 0% KW-HR COST INFL.
CASE #3 :PUMPER 1 DAY/WK, 12% DISC RATE, 20 YR AMORT., 0% KW-HR COST INFL.
CASE #4 :PUMPER 1 DAY/WK, 6% DISC RATE, 20 YR AMORT., 2% KW-HR COST INFL.
CASE #5 :PUMPER 1 DAY/WK, 6% DISC RATE, 20 YR AMORT., 4% KW-HR COST INFL.
CASE #6 :PUMPER HALF TIME, 6% DISC RATE, 20 YR AMORT., 0% KW-HR COST INFL.
CASE #7 :PUMPER 1 DAY/WK, 6% DISC RATE, 20 YR AMORT., 0% KW-HR COST INFL.
CASE #8 :PUMPER 1 DAY/WK, 6% DISC RATE, 15 YR AMORT., 0% KW-HR COST INFL.
CASE #9 :PUMPER 1 DAY/WK, 6% DISC RATE, 25 YR AMORT., 0% KW-HR COST INFL.

				CASE 1						CASE 2					
	M3/DAY	HEAD	M4	F-M3	F-M4	E-M3	E-M4	E-M3a	E-M4a	F-M3	F-M4	E-M3	E-M4	E-M3a	E-M4a
ELEC # 1	163	110	17930	17.23	0.16	15.28	0.14	7.44	0.07	13.95	0.12	13.52	0.12	5.68	0.05
ELEC # 2	64	94	6016	24.86	0.26	19.71	0.21	11.63	0.12	16.31	0.17	15.65	0.17	7.57	0.08
	Percent difference from base case			26	33	13	17	35	40	2	0	0	0	3	0
				56	53	29	31	62	50	2	0	3	6	6	0

	CASE 3						CASE 4					
	F-M3	F-M4	E-M3	E-M4	E-M3a	E-M4a	F-M3	F-M4	E-M3	E-M4	E-M3a	E-M4a
ELEC # 1	14.02	0.13	14.04	0.13	6.19	0.06	13.95	0.13	13.75	0.13	5.75	0.05
ELEC # 2	16.72	0.18	16.1	0.17	8.01	0.09	16.16	0.17	15.24	0.16	7.16	0.08
	2	8	4	8	12	20	2	8	2	8	4	0
	5	6	6	6	12	12	2	0	0	0	0	0

	CASE 5						CASE 6					
	F-M3	F-M4	E-M3	E-M4	E-M3a	E-M4a	F-M3	F-M4	E-M3	E-M4	E-M3a	E-M4a
ELEC # 1	14.18	0.13	13.98	0.13	5.82	0.05	15.22	0.14	14.27	0.13	6.43	0.06
ELEC # 2	16.39	0.17	15.24	0.16	7.16	0.08	19.72	0.21	17.14	0.18	9.06	0.1
	3	8	3	8	5	0	11	17	6	8	16	20
	3	0	0	0	0	0	24	24	12	12	27	25

	CASE 7 (Base Case)						CASE 8					
	F-M3	F-M4	E-M3	E-M4	E-M3a	E-M4a	F-M3	F-M4	E-M3	E-M4	E-M3a	E-M4a
ELEC # 1	13.72	0.12	13.52	0.12	5.52	0.05	14.05	0.13	13.87	0.13	6.05	0.05
ELEC # 2	15.92	0.17	15.24	0.16	7.16	0.08	16.34	0.17	15.69	0.17	7.62	0.08
	0	0	0	0	0	0	2	8	3	8	10	0
	0	0	0	0	0	0	3	0	3	6	6	0

	CASE 9					
	F-M3	F-M4	E-M3	E-M4	E-M3a	E-M4a
ELEC # 1	13.3	0.12	13.09	0.12	5.38	0.05
ELEC # 2	15.42	0.16	14.74	0.16	6.8	0.07
	-3	0	-3	0	-3	0
	-3	-6	-3	0	-5	-12

SOLAR SENSITIVITY STUDY

CASE # 1 :PUMPER FULL TIME, 6% DISC RATE, 20 YEAR AMORT., PV COST AS PAID
CASE # 2 :PUMPER 1 DAY/WK, 9% DISC RATE, 20 YEAR AMORT., PV COST AS PAID
CASE # 3 :PUMPER 1 DAY/WK, 12% DISC RATE, 20 YEAR AMORT., PV COST AS PAID
CASE # 4 :PUMPER 1 DAY/WK, 6% DISC RATE, 20 YEAR AMORT., PV AT $6.00/PEAK WATT
CASE # 5 :PUMPER 1 DAY/WK, 6% DISC RATE, 20 YEAR AMORT., PV AT $4.00/PEAK WATT
CASE # 6 :PUMPER HALF TIME, 6% DISC RATE, 20 YEAR AMORT., PV COST AS PAID
CASE # 7 :PUMPER 1 DAY/WK, 6% DISC RATE, 20 YEAR AMORT., PV COST AS PAID
CASE # 8 :PUMPER 1 DAY/WK, 6% DISC RATE, 15 YEAR AMORT., PV COST AS PAID
CASE # 9 :PUMPER 1 DAY/WK, 6% DISC RATE, 25 YEAR AMORT., PV COST AS PAID

				CASE 1				CASE 2				CASE 3			
	Q/DAY	HEAD	M4	F-M3	F-M4	E-M3	E-M4	F-M3	F-M4	E-M3	E-M4	F-M3	F-M4	E-M3	E-M4
SOLAR # 1	30	7	210	35	5	24.74	3.53	18.29	2.61	17.69	2.53	20.83	2.98	20.37	2.91
SOLAR # 2	15	45	675	96.55	2.15	78.19	1.74	69.08	1.54	70.66	1.57	80.63	1.79	83.16	1.85
SOLAR # 3	16	37	592	84.14	2.27	66.74	1.8	57.15	1.54	58.34	1.58	66.61	1.8	68.58	1.85
SOLAR # 4	26	24	624	52.59	2.19	41.94	1.75	35.89	1.5	36.67	1.53	41.63	1.73	42.88	1.79
SOLAR # 5	13	8	104	74.74	9.34	51.25	6.41	36.08	4.51	34.17	4.27	40.5	5.06	38.81	4.85
Percent different from Base Case				119	119	63	63	15	14	16	17	31	31	34	34
				65	65	32	33	18	18	20	20	38	38	41	41
				74	73	37	36	18	18	19	20	38	37	40	40
				72	72	36	36	17	18	19	19	36	36	39	39
				134	134	72	72	13	13	14	14	27	27	30	30

	CASE 4				CASE 5				CASE 6			
	F-M3	F-M4	E-M3	E-M4	F-M3	F-M4	E-M3	E-M4	F-M3	F-M4	E-M3	E-M4
SOLAR # 1	12.71	1.82	11.66	1.67	14.36	2.05	13.48	1.93	24.04	3.34	19.26	2.75
SOLAR # 2	41.55	0.92	40.57	0.9	51.02	1.13	50.99	1.13	74.63	1.66	67.23	1.49
SOLAR # 3	34.84	0.94	33.96	0.92	42.82	1.16	42.74	1.16	63.59	1.72	56.46	1.53
SOLAR # 4	21.85	0.91	21.32	0.89	26.76	1.11	26.72	1.11	39.94	1.66	35.62	1.48
SOLAR # 5	27.13	3.39	24.57	3.07	29.83	3.44	27.53	3.44	50.14	6.27	38.95	4.87
	-20	-20	-23	-23	-10	-10	-11	-11	51	46	27	27
	-29	-29	-31	-31	-13	-13	-14	-14	28	28	14	14
	-28	-28	-30	-30	-11	-11	-13	-12	31	31	16	16
	-29	-28	-31	-31	-13	-13	-14	-14	31	31	15	15
	-15	-15	-18	-18	-7	-14	-8	-8	57	57	39	31

	CASE 7 (Base Case)				CASE 8				CASE 9			
	F-M3	F-M4	E-M3	E-M4	F-M3	F-M4	E-M3	E-M4	F-M3	F-M4	E-M3	E-M4
SOLAR # 1	15.96	2.28	15.21	2.17	17.08	2.44	16.41	2.34	14.92	2.13	14.13	2.02
SOLAR # 2	58.41	1.3	59.12	1.31	65.08	1.45	66.42	1.48	54.89	1.22	55.28	1.23
SOLAR # 3	48.38	1.31	48.86	1.32	53.83	1.45	54.79	1.48	46.22	1.25	46.52	1.26
SOLAR # 4	30.59	1.27	30.94	1.29	33.49	1.4	34.09	1.42	28.87	1.2	29.08	1.21
SOLAR # 5	31.93	3.99	29.85	3.73	34.16	4.27	32.08	4.01	30.99	3.87	28.76	3.59
	0	0	0	0	7	7	8	8	-7	-7	-7	-7
	0	0	0	0	11	12	12	13	-6	-6	-6	-6
	0	0	0	0	11	11	12	12	-4	-5	-5	-5
	0	0	0	0	9	10	10	10	-6	-6	-6	-6
	0	0	0	0	7	7	7	8	-3	-3	-4	-4

WIND SENSITIVITY STUDY

CASE # 1 :PUMPER FULL TIME, 6% DISC RATE, 20 YEAR AMORT., 2.5 M/S AVE. WINDSPEED
CASE # 2 :PUMPER 1 DAY/WK, 9% DISC RATE, 20 YEAR AMORT., 2.5 M/S AVE. WINDSPEED
CASE # 3 :PUMPER 1 DAY/WK, 12% DISC RATE, 20 YEAR AMORT., 2.5 M/S AVE. WINDSPEED
CASE # 4 :PUMPER 1 DAY/WK, 6% DISC RATE, 20 YEAR AMORT., 2.0 M/S AVE. WINDSPEED
CASE # 5 :PUMPER 1 DAY/WK, 6% DISC RATE, 20 YEAR AMORT., 3.5 M/S AVE. WINDSPEED
CASE # 6 :PUMPER HALF TIME, 6% DISC RATE, 20 YEAR AMORT., 2.5 M/S AVE. WINDSPEED
CASE # 7 :PUMPER 1 DAY/WK, 6% DISC RATE, 20 YEAR AMORT., 2.5 M/S AVE. WINDSPEED
CASE # 8 :PUMPER 1 DAY/WK, 6% DISC RATE, 15 YEAR AMORT., 2.5 M/S AVE. WINDSPEED
CASE # 9 :PUMPER 1 DAY/WK, 6% DISC RATE, 25 YEAR AMORT., 2.5 M/S AVE. WINDSPEED

				CASE 1				CASE 2				CASE 3			
	Q/DAY	HEAD	M4	F-M3	F-M4	E-M3	E-M4	F-M3	F-M4	E-M3	E-M4	F-M3	F-M4	E-M3	E-M4
WIND # 1	2.1	37	77.7	425.89	11.51	225.93	6.92	168.08	4.54	132.28	3.58	183.8	4.97	145.08	3.94
WIND # 2	3.1	37	114.7	298.02	8.05	183.89	4.97	125.73	3.4	102.82	2.78	139.02	3.76	114.97	3.11
WIND # 3	5.1	37	188.7	180.19	4.87	111.42	2.99	75.23	2.03	61.18	1.65	83.03	2.24	68.27	1.85
WIND # 4	8.3	37	307.1	157.58	4.26	120.06	3.24	104.7	2.83	102.52	2.77	122.12	3.3	120.9	3.27
WIND # 5	22.7	37	839.9	80.15	2.17	67	1.81	65.81	1.78	65.83	1.78	77.66	2.1	78.23	2.11
WIND # 6	6.9	37	255.3	169.59	4.58	118.37	3.2	96.88	2.62	86.11	2.33	107.83	2.91	95.98	2.59
WIND # 7	7	37	259	189.64	5.13	136.31	3.68	111	3	102.7	2.78	124.08	3.35	115.37	3.12
	Percent different			186	186	89	114	13	13	10	10	23	24	22	22
	From Base Case			163	162	101	100	11	11	12	12	23	22	25	25
				165	165	104	102	11	10	12	11	22	22	25	25
				78	78	40	40	18	18	20	20	38	38	41	42
				46	46	23	23	20	19	21	21	41	41	44	44
				96	96	54	54	12	12	12	12	24	24	25	25
				92	92	50	50	12	12	13	13	26	25	27	27

	CASE 4				CASE 5				CASE 6			
	F-M3	F-M4	E-M3	E-M4	F-M3	F-M4	E-M3	E-M4	F-M3	F-M4	E-M3	E-M4
WIND # 1	289.81	7.83	225.18	6.09	91.08	2.46	71.77	1.91	269.43	7.28	177.65	4.8
WIND # 2	232.05	6.27	186.86	5.05	71.04	1.92	57.2	1.55	191.96	5.19	130.86	3.54
WIND # 3	137.28	3.71	109.97	2.97	34.32	0.93	27.49	0.74	115.73	3.13	78.49	2.12
WIND # 4	183.04	4.95	176.7	4.78	58.11	1.57	56.09	1.52	117.97	3.19	100.26	2.71
WIND # 5	79.72	2.15	78.92	2.13	41.87	1.13	41.45	1.12	65.67	1.77	59.76	1.62
WIND # 6	152.41	4.12	136.08	3.68	56.08	1.52	50.07	1.35	121.95	3.3	94.54	2.56
WIND # 7	119.03	3.22	110.14	2.98	71.97	1.95	66.6	1.8	137.45	3.71	110.22	2.98
	95	95	88	88	-39	-39	-40	-41	81	81	48	48
	104	104	104	104	-37	-37	-38	-38	69	69	43	43
	102	102	101	101	-50	-49	-50	-50	70	70	44	43
	106	106	106	107	-34	-35	-34	-34	33	33	17	17
	45	44	45	45	-24	-24	-24	-24	20	19	10	10
	76	76	77	77	-35	-35	-35	-35	41	41	23	23
	20	21	21	21	-27	-27	-27	-27	39	39	21	21

	CASE 7 (Base Case)				CASE 8				CASE 9			
	F-M3	F-M4	E-M3	E-M4	F-M3	F-M4	E-M3	E-M4	F-M3	F-M4	E-M3	E-M4
WIND # 1	148.88	4.02	119.72	3.24	162.59	4.39	127.49	3.45	148.46	4.01	115.31	3.12
WIND # 2	113.48	3.07	91.62	2.48	121.3	3.28	98.78	2.67	109.05	2.98	87.55	2.37
WIND # 3	68.02	1.84	54.64	1.48	72.6	1.96	58.8	1.59	65.43	1.77	52.27	1.41
WIND # 4	88.66	2.4	85.6	2.31	99.53	2.69	97.11	2.62	82.49	2.23	79.07	2.14
WIND # 5	54.95	1.49	54.4	1.47	62.21	1.68	62.06	1.68	50.83	1.37	50.05	1.35
WIND # 6	86.68	2.34	76.91	2.08	92.09	2.49	81.55	2.2	83.62	2.26	74.28	2.01
WIND # 7	98.84	2.67	90.91	2.46	105.45	2.85	97.2	2.63	95.08	2.57	87.34	2.36
	0	0	0	0	9	9	6	6	0	0	-4	-4
	0	0	0	0	7	7	8	8	-4	-3	-4	-4
	0	0	0	0	7	7	8	7	-4	-4	-4	-5
	0	0	0	0	12	12	13	13	-7	-7	-8	-7
	0	0	0	0	13	13	14	14	-7	-8	-8	-8
	0	0	0	0	6	6	6	6	-4	-3	-3	-3
	0	0	0	0	7	7	7	7	-4	-4	-4	-4

HAND OPERATED PUMP SENSITIVITY

CASE #1 ¦ 6% DISCOUNT RATE, 20 YEAR AMORT.
CASE #2 ¦ 9% DISCOUNT RATE, 20 YEAR AMORT.
CASE #3 ¦12% DISCOUNT RATE, 20 YEAR AMORT.
CASE #4 ¦ 6% DISCOUNT RATE, 15 YEAR AMORT.
CASE #5 ¦ 6% DISCOUNT RATE, 25 YEAR AMORT.

				CASE 1 (Base Case)				CASE 2			
	M3/DAY	HEAD	M4	F-M3	F-M4	E-M3	E-M4	F-M3	F-M4	E-M3	E-M4
HAND #1	1	14	14	114.72	8.19	95.03	6.84	121.14	8.65	101.18	7.23
	3	14	42	38.24	2.73	31.94	2.28	40.38	2.88	33.73	2.41
HAND #2	1	17	17	95.03	5.64	78.1	4.59	109.4	6.44	89.17	5.25
	3	17	51	31.94	1.88	26.03	1.53	36.47	2.15	29.72	1.75
HAND #3	1	33	33	159.07	4.82	143.57	4.35	176.84	5.36	161.14	4.88
	3	33	99	53.02	1.61	47.86	1.45	58.95	1.79	53.71	1.63
HAND #4	1	16	16	74.02	4.63	60.53	3.78	81.27	5.08	66.65	4.17
	3	16	48	24.67	1.54	20.18	1.26	27.09	1.69	22.22	1.39
	Percent difference from base case			0	0	0	0	6	6	6	6
				0	0	0	0	6	5	6	6
				0	0	0	0	14	14	14	14
				0	0	0	0	14	14	14	14
				0	0	0	0	11	11	12	12
				0	0	0	0	11	11	12	12
				0	0	0	0	10	10	10	10
				0	0	0	0	10	10	10	10

	CASE 4				CASE 5			
	F-M3	F-M4	E-M3	E-M4	F-M3	F-M4	E-M3	E-M4
HAND #1	126.06	9	106.79	7.63	108.48	7.75	89.8	6.41
	42.02	3	35.6	2.54	36.16	2.58	29.93	2.14
HAND #2	113.46	6.67	94.17	5.54	86.1	5.06	69.25	4.07
	37.82	2.22	31.39	1.85	28.7	1.69	23.08	1.36
HAND #3	188.4	5.71	174.14	5.28	143.25	4.43	127.11	3.85
	62.8	1.9	58.05	1.76	47.75	1.45	42.37	1.28
HAND #4	87.29	5.46	73.26	4.58	66.74	4.17	53.55	3.35
	29.1	1.82	24.24	1.53	22.25	1.39	17.85	1.12
	10	10	11	12	-5	-5	-6	-6
	10	10	11	11	-5	-5	-6	-6
	18	18	21	21	-10	-10	-11	-11
	18	18	21	21	-10	-10	-11	-11
	18	18	21	21	-10	-8	-11	-11
	18	18	21	21	-10	-10	-11	-12
	18	18	21	21	-10	-10	-12	-11
	18	18	20	21	-10	-10	-12	-11

APPENDIX D

Water-Related Institutions in Botswana

Institutional water delivery systems in Botswana are divided by user group. The major user groups are:

- towns;
- major villages (currently 17);
- villages included in the Village Water Supply Program (354 villages are now a part of this program, but not all schemes are due to be completed until the early 1990s);
- villages not included in the Village Water Supply Program;
- government installations (police stations, border posts, secondary schools, etc.);
- agricultural lands and cattle areas;
- freehold farms; and
- agricultural cooperatives and syndicates.

Water is delivered to users in these areas by different groups and by different mechanisms. These groups are the Water Utilities Corporation (WUC), Department of Water Affairs (DWA), District Water Units and Water Departments, and the private sector. The first two fall under the jurisdiction of the Ministry of Mineral Resources and Water Affairs (MMRWA), the WUC being a parastatal. The district-level activities fall within the jurisdiction of the Ministry of Local Government and Lands (MLGL) and the District Councils. The activities of each of these organizations overlap to a certain degree and are defined broadly below.

Water Utilities Corporation: This parastatal organization has responsibility for water supply in the towns where the population density makes it possible for public water supplies to be financially self-supporting. In the towns of Gaborone, Francistown, Lobatse and Selibe-Phikwe, the WUC runs the operations. In the diamond-mining towns of Jwaneng and Orapa, the mining concern operates the system. The largest water users in the country, the mining and industrial sector, are provided with water by this mechanism.

Department of Water Affairs: DWA has extensive responsibilities in the water supply sector, including borehole drilling and maintenance, operation of the water supply systems in the 17 major villages, operation and maintenance of government boreholes, implementation of the Village Water Supply Program, and operation of the Borehole Repair Service (BRS). The drilling section drills and test-pumps boreholes in major villages, and in rural areas for the Village Water Supply Program. Boreholes are numbered, and the information is catalogued in the borehole files kept at DWA and at the Geological Survey in Lobatse. DWA has complete responsibility for water supply in the 17 major villages. This includes drilling and equipping boreholes and maintaining the systems. Most of the water in these villages is supplied by public standpipe, but private connections are available. The water tarriff is currently P0.30/m^3 for private connections. Government boreholes include those at secondary schools, police posts, border posts, veterinary quarantine areas, wildlife stations and other such stations. These total about 200 boreholes, mostly supplying small amounts of water. Currently, one of the major efforts of DWA is the completion of water systems for rural villages. This program, begun in the late 70s, currently includes 354 villages. The program is ongoing and not due to be completed until the end of the decade. DWA is only responsible for the installation of these systems. The District Councils are responsible for ongoing operation and maintenance. The BRS is a service of the DWA offered to any public or private borehole users. The service includes borehole cleaning, engine repair and pump maintenance. The users of this service include District Water Units, cooperatives and syndicates, and the private sector.

District Water Units and Water Departments: Thirteen of these district-level organizations answer formally to the District Councils. They operate at the district and subdistrict level, and their main responsibility is maintenance and repair of the water supply systems installed as part of the Village Water Supply Program. They have other duties, including installation and maintenance of some village schemes that fall outside the village program. Some of these other systems were already in existence, and some were installed more recently as part of the drought relief program. These district-level organizations can also call upon the water engineer at MLGL, who distributes some of the drought relief monies and acts as consultant to the district water technicians. The presence and current upgrading of these district offices has greatly increased the reliability of rural water supplies. Also, they are often more in touch than DWA with the water needs of the people in their districts, particularly in more remote areas. The district-level operations maintain about 500 boreholes nationwide.

Private Sector: The private sector includes consultants, drilling contractors, borehole mechanics and equipment suppliers.

These individuals and organizations provide services to private-sector users as well as to the government. The private-sector users are the freehold landowners, as well as cooperatives and syndicates. Cooperatves and syndicates are usually formed by a group of people for the specific purpose of operating a borehole to supply water for cooperative gardening groups or for stock watering. It has been estimated that there are as many as 2,000 such sites in Botswana. These users can call for assistance from BRS as well. Many also qualify for financial assistance from the National Development Bank. Some government assistance is also provided through the Ministry of Agriculture and various extension activities.

APPENDIX E

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