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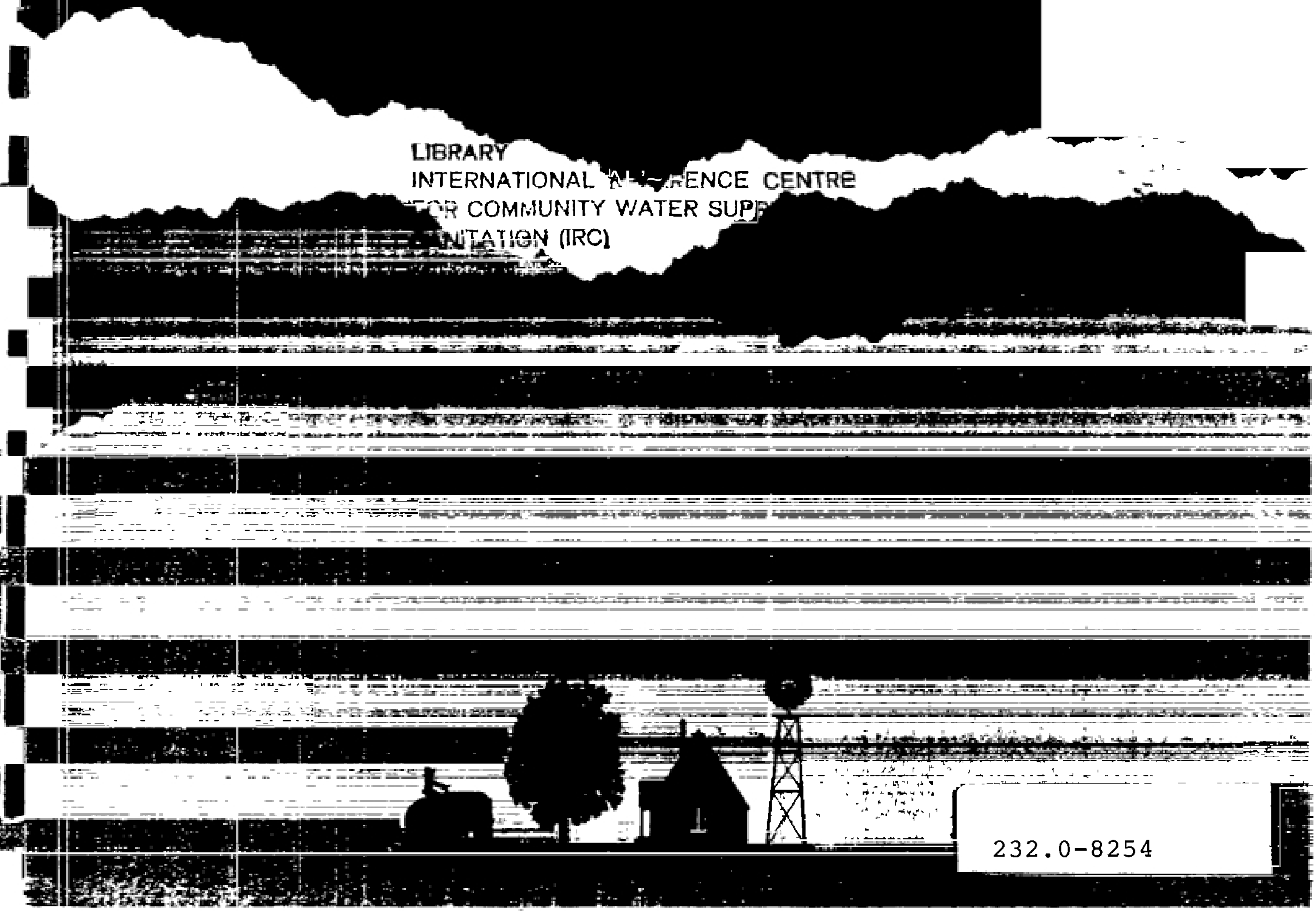

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Meeting Rural Pumping Needs in Sudan:
An Analysis of Pumping System Choice

(Diesel, Wind, or Solar)

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ABBREVIATIONS AND ACRONYMS

ABS	Agricultural Bank of Sudan
ADRA	Adventist Development Relief Agency
ARD	Associates in Rural Development
BP	British Petroleum
CWD	Consulting Services Wind Energy Developing Countries
ERC	Energy Research Council
GPC	General Petroleum Corporation
GTZ	Deutsche Gesellschaft für Technische Zusammenarbeit (Fed. Rep. of Germany Agency for Technical Assistance)
HP	horsepower
kWh	kilowatt-hour
kWh/m^2/day	kilowatt-hour per square meter per day
LCC	life cycle cost
m	meter
MFEP	Ministry of Finance and Economic Planning
m/s	meter per second
MoA	Ministry of Agriculture
MT	metric ton
NCR	National Council for Research
NCRWRD	National Corporation for Rural Water ResourcesDevelopment
NGO	nongovernmental organization
O&M	Operation and Maintenance
ODA	Overseas Development Agency
PV	photovoltaic
RERI	Renewable Energy Research Institute
RETs	renewable energy technologies
RPM	revolutions per minute
SCF	Save the Children Foundation
SEP	Special Energy Program (GTZ-funded)
SMD	Sudan Meteorological Department
S£	Sudanese Pound*
SREP	Sudan Renewable Energy Project
UNDP	United Nations Development Program
UNICEF	United Nations Children's Fund
USAID	U.S. Agency for International Development
W	Watt (unit of power)
W_p	peak Watts (PV module output at 1000 W/m^2 irradiance)
W/m^2	Watts per square meter (a measure of solar irradiance)
WSDP	Western Savannah Development Project
WUSC	World University Services of Canada

* The exchange rates for the Sudanese pounds (S£) in late 1989 were as follows:

Official rate:	US$ 4.50 = S£ 1.00
Regulated commercial rate:	US$12 20 = S£ 1.00
Free market rate	US$20.00 = S£ 1.00

PREFACE

The second phase of the Sudan Renewable Energy Project (SREP) was a technical assistance project funded by USAID (contract number 650-0041-C-00-8014). Technical assistance was provided by Associates in Rural Development Inc. (ARD) from January 1988 until the project was prematurely terminated in February 1990 due to the overthrow of the Sudanese Government by a military coup, and the subsequent invocation of sub-section 513 of the US Foreign Assistance Act. The project was implemented under the auspices of the Energy Research Council (ERC), a division of the National Council for Research. Project field staff included Dr. Martin Bush, Chief of Party, and Fred Swartzendruber, Small Business Development Advisor. The pump testing and evaluation program, one of the project's four technical components, was initially designed in January 1987 by Rick McGowan and Dr. Russell Delucia. The program was subsequently revised, implemented, and managed by Jonathan Hodgkin. The ERC Pumping Team was led by Engineer Siddig Omer Adam and included Ali Abdelrahman Hamza, Nourella Yassin Ahmed and Ali Omer Eltayeb. Technical assistance was also provided by Dr. Philip Lebel and Ron White. This report covers the work of the pumping team during the second phase of the SREP project.

The project team wishes to acknowledge the support and assistance of Dr. El Tayeb Idris Eisa, Director of the ERC and SREP Coordinator until July 1989, and Gaafar El Faki Ali who became the ERC director thereafter. We would also like to mention our appreciation of assistance provided by the GTZ-funded Special Energy Program (SEP), and in particular the counsel of Dr. Edgar Koepsell, as well as the windmill crew established by the Dutch government-funded Sudan Wind Energy Project. Thanks should also be extended to USAID Project Officer Tony Pryor, who provided much of the initial inspiration for SREP's water pumping activities and offered encouragement, support and insight throughout the project. The team would also like to thank the many Sudanese working in both the government and private sector who provided information and assistance in testing and evaluating the pumps. These people also performed the survey work necessary to complete this report. Finally, the team wishes to thank the organizations, agencies, their staffs, and villagers and farmers who allowed us to test pumping equipment for which they were responsible. These include the National Corporation for Rural Water Resources Development (NCRWRD), University of Gezira, the Hodieba Research Station, the Swedish-Sudanese Friendship Association, World University Services of Canada project (WUSC), Save the Children Foundation (SCF), and a number of private farmers and rural villagers. We hope they have also benefitted from our work.

1.0 Executive Summary

In the early 1980s, the Renewable Energy Research Institute (RERI) was established as part of the Government of Sudan's Energy Research Council (ERC). Its mandate was to identify, test, evaluate and disseminate renewable energy technologies (RETs). The Sudan Renewable Energy Project (SREP), begun in 1982 and funded by USAID, was designed to help strengthen ERC/RERI. The second phase of the project began in 1988 with technical assistance provided by Associates in Rural Development, Inc. (ARD) of Burlington, Vermont. Among other project tasks, this phase undertook a testing and evaluation program for diesel, wind, and solar water pumps. Renewable energy pumping systems address many of the problems associated with conventional diesel pumps, including:

- variable diesel fuel cost and availability;
- spare parts scarcity and procurement difficulty;
- lack of skilled technicians, especially in rural areas;
- lack of adequate transportation;
- poor communication; and
- aging facilities.

The objective of the ERC/SREP water pumping program was to develop within RERI the capability to assess the technical, non-technical and economic issues related to meeting rural water pumping needs in Sudan. This capability enables the ERC to respond to government and nongovernment requests for assistance in choosing appropriate water pumping technologies. The specific goal of the water pumping program was to field test a number of operating pumping systems (including diesel, solar and wind pumps) in order to determine their performance, comparative cost and socio-institutional feasibility under typical operating conditions in Sudan. These activities were guided by the report *Water Pump Testing and Evaluation in Sudan - Project Design* (Reference 11). The testing and evaluation methodology was based on the *Handbook for Comparative Evaluation of Technical and Economic Performance of Water Pumping Systems* (Reference 19). The methodology was modified and adapted to the particular resource and transportation constraints in Sudan. The four main tasks outlined for the pump program were:

- technical data collection for operating pumping systems;
- data analysis and pump output modeling;
- collection of information on operation and maintenance (O&M) requirements and costs through surveys; and
- financial and economic analysis of pumping systems using the technical, financial and economic data collected.

Performance tests were conducted for 15 diesel pumps, 5 solar pumps and 3 wind pumps. Data collection for solar and wind pumps was facilitated by the use of Omnidata Copyloggers, from which data was transferred to computers for subsequent analysis. Diesel pump testing was performed on-site during short visits to pump installations. Addressing institutional, social and economic issues required developing a base of information on O&M and repair costs for diesel, wind and solar pumps. A review of all currently available information, data collection at the test sites, and selected surveys of village water supplies, small farmers, and local equipment suppliers gave the information necessary to complete the basic analysis. Financial and economic analyses using life cycle costing yielded comparative unit water costs (cost in Sudanese Pounds per cubic meter of water pumped at a given head, or S£/m^3) for each system. Spreadsheets developed for this analysis permit the rapid identification of performance and cost factors which have the most impact on unit water costs. Given the currently highly variable condition of Sudan's economy, this approach provides the flexibility that analysts and planners need to review water pumping system choices as cost parameters continue to change.

During the testing and evaluation period from mid-1989 to early 1990, a series of difficulties ranging from floods to severe fuel shortages to a military coup made a comprehensive country-wide pumping system evaluation impossible. Nevertheless, a considerable data base of performance and cost information was assembled and analyzed. The following major conclusions, grouped first by technology type and then end-use application, are based on conditions in Sudan as of early 1990. A set of recommended actions concludes this chapter.

Diesel

Diesels are by far the most common type of pumping system in Sudan. Enduring and generally worsening difficulties in operating and maintaining reliable diesel water systems have generated considerable interest in developing alternatives. To determine the potential for displacing diesel systems, first their performance and costs must be quantified. Diesel system operating efficiencies vary widely among systems tested. A well-designed and properly maintained system will have an efficiency of 17 percent or better. Higher efficiency means lower specific fuel consumption, reduced engine wear, and lower O&M costs. Systems monitored by the project had efficiencies ranging between 2-15 percent. Systems recently installed by the NCRWRD for rural village water supplies in the west are reasonably well-designed, and efficiencies of 12-15 percent were measured at several wateryards. However, lack of proper maintenance and repair procedures typically reduces operating efficiency at many sites over time. Much can be done to improve diesel system design procedures and system efficiency, and thereby reduce operation and maintenance costs.

For small-scale irrigation, efficiencies of all privately owned pumpsets tested were very low (only around 5 percent). This is in part the result of the low power output and high fuel consumption characteristics of the very inexpensive "Indian Lister" engines (engines resembling the ubiquitous Lister 8/1, but manufactured in India) and cheap imported pumps used. Whether used for high quality Listers in village water systems or their cheaper counterparts in irrigation, the scarcity and increasing cost of diesel spare parts and fuel are becoming increasingly problematic, especially over the last year.

Solar

The solar radiation regime in Sudan is very good (averaging 6.0 $kWh/m^2/day$ annually), particularly north of Khartoum. Solar pumps used in Sudan have proven in most cases to be very reliable systems. The Grundfos solar pumps installed in 1983 at the University of Gezira and the Hodieba Research Center have experienced no failures after over seven years in service. However, the KSB floating solar pumps, which at one site monitored during the project required replacement twice in the last two years, have not proven as reliable. The performance of all solar pumps tested was 10-25 percent less than predicted by manufacturer's literature. Installation and maintenance (minimal though it is) of solar pumps are not always properly performed. Solar arrays are not always tilted at the proper angle to take full advantage of available radiation, arrays are sometimes partly shaded, loose wiring and connections dissipate otherwise usable energy, and modules are not often kept clean. Proper attention paid to simple installation and maintenance procedures could do much to improve solar pump performance at some sites.

There are a number of technically suitable applications for solar pumps in low head and low water demand sites in Sudan. In general, the product of the daily water demand (cubic meters per day) and the total pumping head (meters) should not exceed 750 m^4 for areas with good solar radiation. For example, this is equivalent to 50 m^3/day at 15 meters head. Areas and applications which meet these criteria are located mainly in the Northern Region near the Nile and its tributaries, where water can be found close to the surface and the water demand is moderate. Scattered areas near seasonal streams and wadis are found in the other areas of Sudan. The market potential for solar pumps is therefore fairly limited, since such sites represent less than about 5 percent of the total villages in Sudan.

Wind

Wind pumps monitored during the program did not fare so well. The three wind systems monitored during the program, all of which were CWD 5000 windmills, had considerable maintenance and repair problems which were serious enough to bring into question the long term reliability of these particular machines. In addition, the water output predictions made by the machine's designers overestimate output (when compared to tested performance) by as much as 30-45 percent. The obvious design weaknesses in this machine must be rectified before any further dissemination is worth consideration.

The water output from a wind pump is dependent in part on the daily average wind speed and distribution. A precise estimation of wind energy potential is not possible from the limited data now available in Sudan, so it is difficult to give a precise estimation of the market potential for windmill pumping. To help correct this situation, wind speed measuring instrumentation currently used by the Sudan Meteorological Services should be replaced with lower maintenance, higher resolution instrumentation. Wind data collected as part of this and other on-going programs suggest that the wind resource may be better than previously anticipated (based on older, fairly limited data) at locations along the Nile north of Khartoum.

Nevertheless, on the basis of available wind speed data and monitored windmill performance, wind pumps are a viable pumping option at sites where the demand*head product does not exceed about 750 m^4, for areas with site average wind speeds of 4 meters per second (m/s) or greater. Areas and applications which meet these criteria are mostly the same as those appropriate for solar pump applications, located in the Northern Region near the Nile and its tributaries and in the Eastern Region in coastal areas, where water can be found close to the surface and the water demand is low to moderate. Scattered areas near seasonal streams and wadis are found in the other areas of northern Sudan. Other proven windmills, such as the Kenyan-made Kijito, could likely be used in Sudan where higher site wind speeds might justify its higher cost.

Village Water Supply vs. Small-Scale Irrigation

The common practices for equipment selection, installation, operation, and maintenance of pumping systems vary so much (depending on whether the pump is for village water supply or irrigation), that comparative system cost for the two applications must be analyzed separately. Financial and economic unit water costs are much higher for rural village water supplies than for small farmers. Much of this difference is due to equipment used for village water supply which is not necessary for irrigation systems, such as higher quality (hence more expensive) engines and pumps, elevated storage tanks, distribution piping and taps. Because of these great cost differences, it is highly unlikely that solar or wind pumps will attain any significant market share in irrigation pumping applications in the near future.

Given the current economic situation in Sudan, National Corporation for Rural Water Resources Development (NCRWRD) rural village water supplies are largely dependent on donor support for construction and rehabilitation. When donors are willing to provide capital equipment, the recurrent cost considerations become important for the NCRWRD and system beneficiaries, who pay water fees in order to support their systems. On the other hand, for small irrigated farms, cash flow considerations force farmers to weigh up-front capital costs much more heavily than any potential life cycle savings when it comes to making decisions about what pump to buy. Even with all of the problems evident in the use of diesel pumpsets, analysis shows that they are still much more economical than solar and wind pumps in nearly all small-scale irrigation applications within the capacity range for solar and wind pumps. For applications beyond the very limited capacity of commercially available solar and wind pumps, diesel is the only reasonable option (unless mains electric pumps could be used).

Recommendations

Energy policy in Sudan is currently weighted towards the use of diesel fuel as an energy source for pumping. If it is truly in the national interest to promote renewable energy technology (RET) use in general and renewable energy sources for pumping in particular (which we believe it is, but only with a good understanding of the significant limitations of RET pumps), then the following actions should be considered:

- set a more realistic (i.e., less subsidized) price for diesel fuel;
- set water tariffs to fully reflect the life cycle cost of developing, operating and maintaining village water systems, and use fees collected to directly support wateryard O&M at the local district level;
- equalize incentives for using renewable energy technologies by expanding existing credit programs to include these technologies, and pricing all equipment based on an unregulated foreign exchange rate;
- develop viable institutional plans for commercializing proven, reliable wind and solar systems, including a program for financing the development of the necessary infrastructure to support these systems over the long term; and
- reduce general inflationary pressures, which will foster longer term resource allocation decisions based on life cycle costing, rather than the capital cost-driven decisions of today.

However, these actions alone are not sufficient to take advantage of the limited potential for using solar and wind pumps to partially displace diesels. Users must understand and appreciate the advantages these technologies offer, while being fully aware of their inherent capacity limitations.

Increasing the cost effectiveness of investments in the water sector requires a closer examination of traditional technologies as well. The NCRWRD should develop and follow improved design procedures which ensure that diesel engines and pumps are more properly matched to the water resource and the demand profile. More careful design and better maintenance of diesel systems will reduce fuel consumption, lengthen engine life, and reduce recurrent O&M costs. Donors must be responsive to standardized NCRWRD designs when providing village water supply equipment. If "tied-aid" is politically necessary, donors should consider using local currency reserves to support water sector development efforts, and using tied hard currency to buy equipment in another sector which is not so dependent upon standardization.

There is potential for using solar pumps in small village water systems. Broader long term experience is needed to more fully evaluate the appropriate niche for solar pump use, and to promote the development of the necessary technical skills to support solar photovoltaic applications, including pumping, cold chain vaccine refrigeration, and telecommunications. Additional solar pump sites should be identified, particularly in the Northern Region. Equipment for 5-10 village sites should be procured (although some is already available through GTZ, as yet uninstalled). Installation and performance monitoring should include the active participation of village beneficiaries, ERC, and the NCRWRD.

Although the use of wind pumps appears attractive from a financial and economic perspective, the CWD 5000 has shown little promise. There has been no evaluation of other wind machines in Sudan. This should be corrected by monitoring and evaluating already available Kijito wind pumps. A more detailed market study for wind pumps should be conducted before committing further resources to wider scale dissemination of wind pumps. The areas that appear most suitable for wind pumping will be in the north or along the Red Sea coast--but do not anticipate quick acceptance.

Technical training organizations, including the Sudan Technical University, the technical training institutes, and the professional mechanical training schools, should introduce energy efficiency into the curriculum focusing on practical applications of PV, wind, and diesel. It is only through these initiatives that a trained cadre of technicians will be available not only for photovoltaic pumping utilization but also for other cost-effective photovoltaic applications, such as cold chain vaccine storage and telecommunications.

ERC's Pumping Team should continue its on-going evaluation of small-scale pumping systems. Detailed monitoring for all solar and wind pump sites should continue until a full year of data is collected. After that, since little additional cost will be incurred beyond labor and transportation, additional wind and solar sites should be sought for monitoring. The ERC Pumping Team should continue to update information on RET pump feasibility, and provide consulting services to interested government and nongovernmental organizations. The SREP Village Water Survey should be continued to include the remaining regions of Sudan beyond the Khartoum Commissionerate and Central Region. The Small Farmers' Survey, begun with the assistance of the National Extension Administration, should be continued to include an examination of more remote small irrigated farms.

2.0 Introduction

In the early part of this decade, the Renewable Energy Research Institute (RERI) was established as part of the Energy Research Council (ERC); its mandate was to identify, test, evaluate, and disseminate renewable energy technologies. The Institute began by collecting renewable energy data and establishing an applied research facility at Soba. The work has since expanded to include applied research efforts, development of renewable technologies, and promotion of viable renewable energy technologies. RERI had begun to work with wind and solar pumping systems prior to the establishment of ERC. However, it is only within the last several years that bilateral donor support has led to a series of related water pumping projects. During the energy crisis in the 1970s, concerns about energy costs and availability led to the creation of the USAID-funded Sudan Renewable Energy Project (SREP). The project began in 1982; the current phase got underway in 1988. This second phase, completed with technical assistance from Associates in Rural Development (ARD) of Burlington, Vermont, explored the possibility of wind and solar energy for water pumping, an activity initiated during the end of the first phase.

2.1 Pumping Activity Background

The ERC and RERI first established their water pumping program in response to serious water supply problems; these problems were highlighted at the Water Resources Supply Seminar in 1982, and reiterated at the National Economic Conference in 1986. ERC/RERI's assumption was that renewable energy pumping systems could provide a cost effective alternative to many of the problems associated with conventional diesel driven water systems. These problems included:

- fuel shortages and high fuel cost;
- availability of spare parts and procurement difficulties;
- lack of skilled technicians to maintain pumping systems, especially in rural areas;
- lack of adequate transportation;
- poor communication; and
- aging facilities.

Similar concerns were expressed in the irrigated agriculture sector. Unfortunately, the needs of large, public sector, pumped irrigation schemes along the Nile cannot be met with currently available small-scale wind and solar pumping technologies. However, it may be possible to meet the water resource needs of small private farmers performing low head irrigation from the Nile and shallow aquifers.

In the aftermath of the high prices of the 1970s and early 1980s, anxiety among western nations about the international price of oil has somewhat receded. However, in Sudan, the concern about local fuel prices, their effect on the balance of payments and, in many areas of Sudan, the availability of fuel for water pumping remains. The Sudanese government is concerned about the implicit cost of fuel oil as measured in terms of import dependence. Therefore government agencies, private farmers, and villages are interested in the use of wind and solar pumping as a means of reducing energy dependence, and the operation and maintenance burden incurred by the use of oil.

2.2 Goals and Activities of the Program

The objective of the ERC/SREP water pumping program is to develop, within RERI, the capability to assess the technical, social, institutional, and economic issues related to meeting rural water pumping needs in Sudan. This will enable the ERC to respond to government and nongovernment requests for assistance in choosing the appropriate water pumping technology.

The specific goal of the water pumping program was to field test a number of currently operating pumping technologies (including diesel, solar and wind pumps) to determine their technical feasibility and comparative cost under typical operating conditions. Although handpumps are used extensively in some areas in Sudan, they were not included in the current study; the decision was based largely on time and resource constraints. This work equips the ERC Pumping Team with the capability to design diesel, solar and wind systems and make appropriate recommendations for their use. It also furnishes data on factors which effect water pumping cost and sustainable operation. These factors include reliability, technical capacity, costs, and the institutional arrangements necessary to provide service economically.

The activities of the pumping component of the ERC/SREP project have been guided by the report *Water Pump Testing and Evaluation in Sudan - Project Design* by Richard McGowan and Russell DeLucia (Reference 11). The testing and evaluation methodology was based on the *Handbook for Comparative Evaluation of Technical and Economic Performance of Water Pumping Systems* (Reference 19). This methodology was modified and adapted to the constraints of resources and transportation in Sudan.

The ERC/SREP Phase One activities included an initial outline of the necessary program steps, a series of preparatory studies to assemble a geographical data base, an explanation of the petroleum and electricity distribution systems, and a description of the renewable energy and groundwater resources in Sudan. In early 1988 Phase Two set the following tasks:

- technical data collection for pumping systems;
- data analysis and pump output modeling;
- collection of information on operation and maintenance requirements and costs;
- inventory of pumping equipment available in Sudan and its costs; and
- financial and economic analyses of pumping systems using the technical, financial and economic data collected.

The primary purpose of the technical data collection was to assemble pump performance data as a function of the energy resource. For diesel pumps, this means fuel consumption and water delivery as functions of engine size, pumping head, and operating conditions. For wind and solar pumps, water delivery is a function of wind speed and solar radiation levels. Data collection for wind and solar pumps benefited from the use of microprocessor based data loggers. Diesel pump testing was performed during short visits to pumping sites. The SREP project has not purchased any new water pumping equipment. The focus of the program has been in evaluating existing systems and the analysis of system choice.

Data analysis included plotting pump performance and checking measured performance against manufacturers' specifications. Theoretical models for pump performance were verified or developed, and used to predict pump performance under other conditions of head, average wind speed or solar radiation levels. The results were then used to design pumping systems or to identify pumping systems which were operating properly. The effort to address the social, institutional and economic issues required a base of information on maintenance and repair costs for diesel, wind and solar pumps. This work included a review of currently available information, data collection at the test sites, and selected surveys of villages, farmers, and pumping equipment dealers. The information is critical to the estimation of long-term O&M requirements.

The financial and economic analyses calculate present value unit water cost derived from life cycle analysis techniques. The use of computer models for these analyses allows for the rapid identification of financial and economic factors which have the most impact on water cost. Given the current rate of change of many financial and economic parameters, this approach provides the flexibility that analysts and planners need in exploring water pumping choices. The information collected and the analyses performed should guide government and NGOs in the choice of pumping equipment, the energy efficiency of various equipment tested, cost issues, and larger national energy and economic planning issues.

2.3 Related Renewable Energy Pumping Activities

Within both government agencies and the donor community there has been considerable interest and activity in renewable energy pumping. During the last several years a number of different wind and solar pumping systems have been installed in the Sudan. So far these systems have been provided to the government of the Sudan as gifts and grants from international multi-lateral and bilateral donors to help demonstrate the potential for alternative technologies. To date, neither wind nor solar pumps have been purchased at full cost by the government or the private sector.

2.3.1 Wind Energy Utilization

Perhaps the most well-known effort in wind energy utilization in Sudan took place in the early 1950s with the installation of more than 150 Southern Cross windmills in the Gezira area. As demand outgrew the ability of windmills to provide the needed water and as problems began to occur, most of the windmills were abandoned or replaced by diesel engines. All of these units were replaced by diesel pumps in the 1960s when energy was readily available and relatively inexpensive. Other makes of windmills including Dempster and Blake have been installed in scattered locations from Zelengi in the west, Atbara and Wadi Halfa in the north and also in the east. Although a few of these windmills continue to operate, the lack of adequate maintenance and spare parts has limited their usefulness and acceptance.

The potential financial and economic benefits of local fabrication along with the benefits of available, locally made spares and service capability led to the Sudan Wind Energy Project, a bilateral Dutch-funded project, begun in 1985. The goal of this project was to establish, within a local firm, the capacity to build and service the CWD 5000 windmill (see Figure 1); its primary application was to be for small-scale irrigation. Ten machines were imported in 1986 and several machines were commissioned for local manufacture; one of these was subsequently built and installed. The ten imported machines are currently installed in and around Khartoum. Although there is currently no long-term Dutch staff in Sudan, nor has there been any recent technical assistance, the project is still active. Technical training in installation and maintenance was provided to ERC technicians and they continue to maintain and repair a number of the windmills. Records are being kept of crops produced and areas irrigated for a demonstration farm at the Soba Research Station. The program is now ready to begin a second phase with the local private sector fabrication of several windmills for sale to private purchasers. The plan includes technical assistance to one or more private sector manufacturing firms. Programmatic delays have hampered the initiation of this phase.

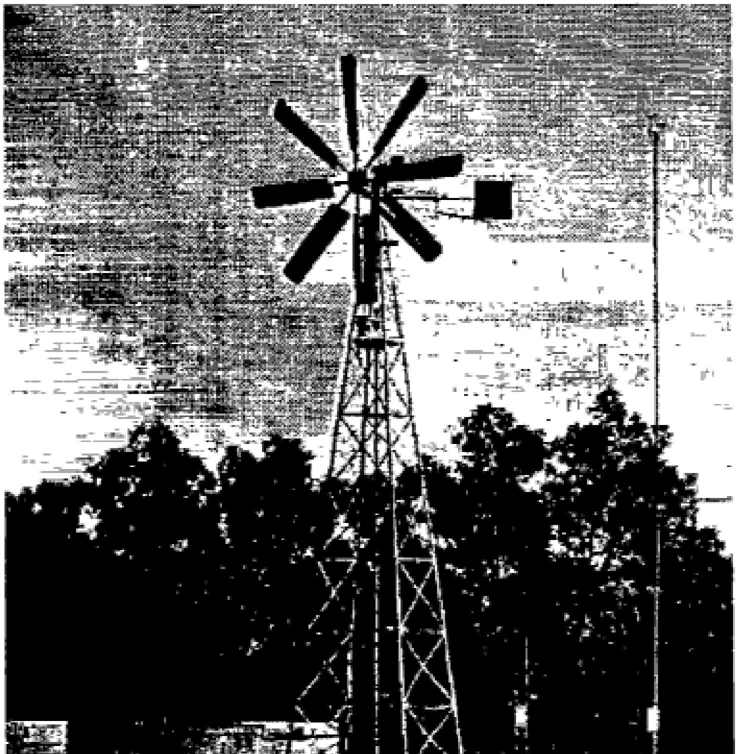


Figure 2.1. CWD 5000 wind pump (with anemometer tower) at ERC's Soba Research Station.

The Special Energy Project (SEP), funded by Gesellschaft für Technische Zusammenarbeit (GTZ–the Technical Assistance Agency of the Federal Republic of Germany), is a sister project to SREP. This project (begun in 1984) includes a water pumping demonstration component. The SEP initiated its wind energy activities with the repair of three Southern Cross windmills. One was installed at Soba and two in Wadi Halfa. The one at Soba was taken down in order to deepen the well and has not yet been re-installed. The two in Wadi Halfa have not been visited for more than a year as a result, at least in part, of the transportation difficulties. The project also imported two Kijito wind pumps (8- and 12-foot diameters). These machines were intended for demonstration prior to arranging licensing agreements with a local manufacturing firm. To date the two Kijitos have not been installed because a number of parts were lost in transit. In addition, disagreements have arisen between the project and the intended licensee, and other project activities have usurped time and energy from these efforts.

Three Kijito wind pumps (two 20-foot and one 16-foot) have recently been installed (mid-1989) at Kelli, a small village on the west side of the Nile and north of Shendi. This project is part of the forestry component of the Northern Region Agricultural Production project funded by the British Overseas Development Administration (ODA). All are installed on shallow wells with pumping heads of under 20 meters. Plans are in place to monitor these pumps independently using Dulas monitoring equipment. It now appears, however, that the Kijitos over-pump the existing wells causing excessive pump wear and raising the possibility of longer term damage to the wind pumps. Possible solutions to this situation are now underway.

The Adventist Development Relief Agency (ADRA) has considered the use of windmills in a project in the Karima area of Northern Region. Both the Kijito and the Southern Cross were studied for possible use in an area with average annual wind speeds in the 5.5 m/s range. No final decisions have been made yet.

2.3.2 Solar Energy

The ERC has been involved in efforts to utilize Sudan's significant solar resource for pumping water. Two Sofretes solar thermal pumps were installed in 1977 at ERC's Soba Research Station and Hillat-Hamedi. These did not prove to be reliable and were abandoned in 1979. In 1978, Sudan participated in early field tests of solar photovoltaic (PV) pumping technology through a UNDP international evaluation program. Two PV pumps were installed at Butri 30 km south of Khartoum in 1981. One of these pumps was eventually removed and reinstalled at ERC's Soba test site. The results of this series of tests and the demonstrations of these small irrigation pumps indicated a promising future for some PV pumping system designs in Sudan.

Grundfos donated two solar pumps to the ERC which in 1983 were installed at the University of Gezira (near Wad Medani) and the Hodieba Research Station (near Ed Damer). Both pumps have operated without major difficulties and both have been evaluated as part of the ERC/SREP pumping program. The pump at the University of Gezira has been the subject of several performance tests by the students and faculty; these test results can be found in Chapter 5.

In addition to the wind energy activities mentioned above, the SEP is actively involved in installing and demonstrating PV pumping systems. Ten low head, floating, KSB Aquasol pumps were purchased in 1987. One of these was located at Shambat in Khartoum North and is providing water for a small irrigated plot (see Figure 2.2). The remainder of these pumps have not been installed yet. More recently, three Grundfos solar pumps were purchased. One of these was originally operating at the Soba site. The pump was damaged by particulate matter in the water. The well has now been rehabilitated and deepened; a new pump has been installed. The ERC pumping team recently (February 1990) installed monitoring equipment at this site to measure the pump's performance. Other solar pumps are scheduled for installation at locations around Khartoum. At least one of these will be part of a collaboration with ADRA to provide water for displaced people. ADRA is also planning to include several solar pumps as part of an agricultural project located mid-way between Khartoum and Karima.

As part of the Western Savannah Development Project (WSDP), the Overseas Development Agency (ODA) is funding a water supply rehabilitation project in collaboration with the NCRWRD. A feature of this project is the installation and monitoring of PV pumps to augment water supplies in the wateryards of Southern Darfur Province. Eight systems including Grundfos pumps, Mono pumps with electronic controllers, and jack pumps have been planned. The two Grundfos systems have been placed on deep boreholes (greater than 80 meters) identified by the NCRWRD office in Nyala. Local sentiment concerning the pumps, which deliver less than ten percent of the necessary water, is that they should be removed and replaced with diesel units. A re-assessment of the project has just been completed with plans to use some innovative techniques to increase the solar pump output. These include the use of two pumps on one borehole and increased array sizes for several other systems. Project planners hope that this will increase pump output to 20 to 25 percent of the water requirement and satisfy local solar pump detractors. The ERC is planning to become involved in the monitoring and evaluation of these pumps. Also at the ODA Northern Agricultural Project site at Kelli, a BP Solar/Grundfos solar pump has been installed for irrigating shelterbelts (see Figure 3).

The Swedish-Sudanese Friendship Association, a small NGO, has purchased four Grundfos solar pumps. Two of these are installed in villages northeast of Bara with two more planned for installation as soon as wells and storage tanks are in place. The pumps are to be used for village gardening and to support the establishment of shelterbelts. A fifth solar pump is planned. The ERC Pumping Team has been active in monitoring the performance of two of these pumps (see Chapter 5) and has provided valuable information to project personnel on the use patterns for these pumps.

Other recent demonstrations with PV pumps included a 4,000 peak watt inverted AC pump donated by the Japanese and installed at NCRWRD headquarters just south of Khartoum. This system, designed to provide 100 cubic meters per day through a 100 meter head, overpumps the well (because the total head is in reality only 40 meters) and is not in continuous operation. Three PV pumps were given by the French Embassy through Total Energie Development; two were installed in the Gezira and one near Karima in Northern Region. These were designed for low head application, but have been out of operation for extended periods as a result of problems with the control systems. A BP/Grundfos pump was purchased and installed, along with the three Kijitos as part of the Northern Region Agricultural Production project mentioned above. The pump was located on a shallow, hand dug well which recently collapsed. The pump was not operating at the time; as yet it has not been removed, cleaned, and inspected for damage.

Planning is underway for a series of area development schemes, managed and funded through a five-year UNDP program. These projects are planned for five areas (two in Darfur and one each in Kordofan, Northern and Eastern Regions). The program will be initiated in the El Obeid Area Council. Activities will be focused in two areas of community managed development: income generating and environmental management. As water is a major limiting factor to development in the area, the demonstration and introduction of PV pumps is suggested as one of the 11 sub-projects. The current budget allows for the purchase of 15 to 20 pumps.

These and other activities make it clear that there is considerable interest in finding workable solutions to small–scale water pumping problems.

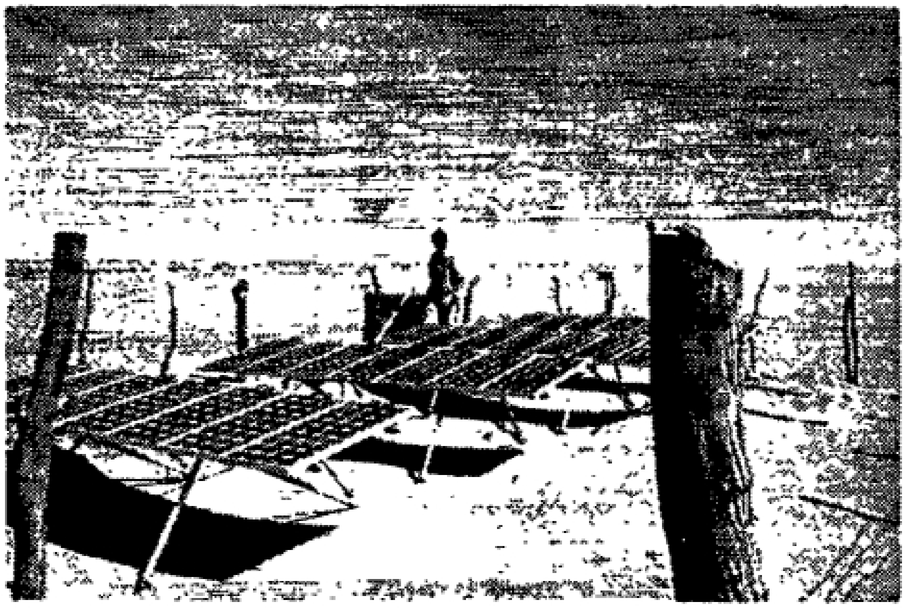


Figure 2.2. Solar pump at Kelli across the Nile from Shendi.

3.0 Water Pumping Sector Organization and Institutions

This chapter briefly reviews the organization of the small-scale water pumping sector. The capacity limits of wind and solar pumps preclude their consideration for large-scale water pumping such as urban water supplies or major irrigation schemes. Although some of the following discussion may apply to larger pumping systems, they will not be formally considered. This section examines the current NCRWRD structure, private sector pump and equipment suppliers, and the small farm irrigation pump user.

3.1 National Corporation for Rural Water Resources Development

In colonial times (prior to 1956), responsibility for rural water supplies was divided among a number of agencies including the Department of Agriculture, the Soil Conservation Committee, Rural Water Supply and Soil Conservation Board, the Rural District Councils, the Hydrological Section of the Department of Irrigation, and finally the Land Use and Rural Water Supply Department. This organizational development proceeded, partly in response to concerns about soil erosion and degradation of the environment. This Department supported construction of water points and also provided supervision, with operation and maintenance budgets allocated by the local government. During this period, the first wateryards were established, mostly in the Darfur and Kordofan regions. A wateryard typically consists of one or more boreholes equipped with diesel pumpsets supplying a storage tank and a distribution system to taps, all enclosed in a fenced yard (see Figure 3.1). A clerk collects fees and monitors water use by humans and animals. An operator runs the engine and provides minor maintenance. Sometimes a guard is employed as well. The term "wateryard" has come to mean any centrally operated water point utilizing diesel or electric pumps.

Political changes caused the organizational evolution of responsibility for rural water supplies to move from the Land Use and Rural Water Supply Department to the Rural Water Development Corporation and finally to the Rural Water Corporation (RWC) within the Ministry of Rural Development over the years prior to 1976. At this time, RWC took over the operation and maintenance of rural water supplies except for guards and operators who were still paid by local governments. During the decentralization efforts of the early 1980s, all responsibility was handed over to regional governments. However, with the establishment of the National Corporation for Rural Water Resources Development (NCRWRD) in 1985, operations were again centralized; construction, operation and maintenance became the responsibility of the NCRWRD. Funds are collected from village water users and remitted to the Ministry of Finance and Economic Planning (MFEP). Operational budgets are agreed to and approved by MFEP.

Until the mid-1960s, the major geographical area of formal government activity in rural water supplies was the installation of about 450 wateryards in the western regions. The decade following the initiation of the Anti-Thirst Campaign in 1967 saw heavy investment in the

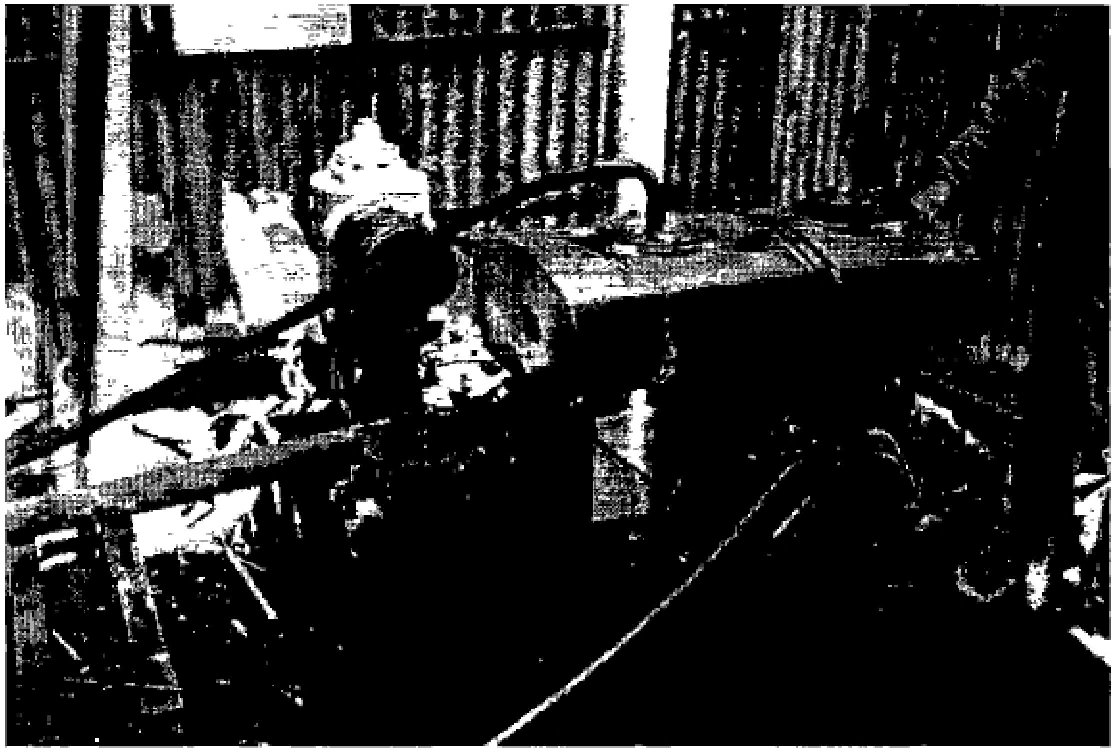


Figure 3.1. Typical village system with Andoria diesel and Grundfos vertical turbine pump at El Sundudab.

rural water sector. By 1977 there were about 2,400 rural wateryards. Investment in the sector has been much slower in recent years. There are now approximately 3,600 rural wateryards. Other water systems installed by the NCRWRD in areas where surface water is available include approximately 170 slow sand filters and about 1,100 hafirs. Hafirs are man-made, protected catchments with pumping systems for water distribution. Recently, with the assistance of UNICEF, the NCRWRD has embarked on a program to utilize handpumps. There are now about 5,000 India Mark II handpumps installed in 3 main project areas: Bahr El Ghazal, South Kordofan, and Red Sea provinces.

The Khartoum headquarters of the NCRWRD is responsible for policy planning and design. It is organized into 5 departments: Research and Water Resources; Supply; Workshop and Manufacturing; Operation and Maintenance; and Finance and Administration. The Research and Water Resources department is responsible for groundwater and surface water investigations, drilling, and design and construction. Major activities are supported by Italian, Yugoslavian, West German, British and Dutch bilateral aid, and Arab Fund, World Bank and UNICEF multi-lateral contributions. A wide range of smaller NGO rehabilitation and construction programs are also working in collaboration with NCRWRD headquarters and regional offices.

The 9 NCRWRD regional offices are directly linked to headquarters; their responsibilities include planning and design. The regional and provincial offices (19) carry out wateryard construction activities and are responsible for operation and maintenance support. Most construction is managed at this level with planning and design approval from Khartoum headquarters. There is little or no NCRWRD activity in the 3 southern regions as a result of the present security situation in these areas. In addition to the regional and provincial offices, there are district offices, many of which also maintain workshops. Construction and improvement of these workshops have been supported by the Yugoslavian program. The workshops were originally equipped with machinery such as lathes, drill presses etc., and some spare parts for pumps and engines. Adequate spares, technical staffing, transportation, and funding are major problems at this level. It appears that in many cases these workshops are not able to offer adequate operations and maintenance support to village wateryards.

At the village level, the NCRWRD maintains a presence with operators, clerks and guards. This arrangement is not universal. Some villages do not have a guard or, where fees are not collected, a clerk. The equipment used in the wateryards varies by wateryard type, pumping requirement, and geographical region. In the western regions (Kordofan and Darfur), the engine and pump of choice appear to be Lister engines and Edeco jack pumps. The Yugoslavian Torpedo engine and Shoeller jack pump are also widely used. Larger engines, mainly Andoria and Bukh, drive vertical turbine pumps (Grundfos, Cato, Rotos and others) in the regions along the Nile. In fact there are more than 10 makes of engines and pumps in use. Many of these pumpsets are old, dating to wateryard construction in the sixties. In addition to applying local pressure to construct new wateryards, NCRWRD is currently collaborating with a number of bilateral donors and NGOs to rehabilitate the old wateryards. Several of these projects have expressed interest in solar pumps.

In the western regions of Kordofan and Darfur, wateryards are for the most part configured as described above. Wateryard clerks collect user fees of about 5 piasters per jerrican (18 liters), 25 piasters per camel, 10 piasters for small stock. The fee level and the use of the collected fees have been a source of much controversy in recent years. In areas where villagers pay NCRWRD clerks, a circuit rider system for collecting these fees and forwarding them to the MFEP is in place. NCRWRD depends entirely on MFEP for capital and operating fund allocations. Villagers contend that the fees they pay should be used for the operation and maintenance of their wateryard, and believe that the money goes to pay salaries and overheads at regional and central levels. There is some truth to this argument; as approved budgets at the national level are not adequate to cover all of NCRWRD costs, activity at the local levels suffers.

In Central Region and Khartoum Commissionerate, villagers often have private connections and community standpipes. Many villages with government- or donor-financed systems do not pay fees to the NCRWRD because, as the NCRWRD explains, if water costs money, then people will use water from irrigation ditches and the Nile. In Northern Region, many of the systems were financed largely by villagers, and this provides the village with considerably more leverage to operate the water systems as they choose. In these areas, fees to cover operation and maintenance costs are often assessed per household and paid to a water committee. A sense of village ownership and local operations' management are much more evident in these villages. In all regions, NCRWRD district workshops are available to assist in repairs.

3.2 Village Participation in Water Supplies

As mentioned above, NCRWRD as an organization has formal responsibility for the operation and maintenance of rural water systems. In recent years budgetary constraints, transportation problems, and lack of skilled labor and spares have severely restricted NCRWRD's ability to fulfill this obligation. In many cases, villagers, in their need to obtain water, have been contributing directly to the operation of village water supplies. Villagers participate in several ways; their level and type of participation vary regionally. The area exhibiting the greatest village participation is the Northern Region along the Nile. Villagers in this area are relatively wealthy, have a history of cooperation, have broad familiarity with technology, and have family connections in Khartoum and abroad. NCRWRD reports that in a number of cases villages have raised and contributed a major share of the installation cost of their water systems. This places the NCRWRD under some pressure to be responsive to the villagers' desires. It appears that villagers continue to feel an ownership of the systems and manage them through a local water committee, collecting their own fees and arranging their own maintenance and repair. The NCRWRD workshops are used as a first response when problems occur, but often villagers will resort to the private sector for maintenance and repair when the NCRWRD is unable to provide these services.

In Kordofan and Darfur, the NCRWRD maintains much tighter control of the wateryards. They believe that villagers cannot or will not maintain equipment properly and that this will result in an increased burden on the organization when eventually the villagers come to them for assistance. The NCRWRD points to earlier times when villagers had more control of their water supplies and many fell into disrepair and disuse. Ownership of water supply systems has always resided with government agencies and as such, villagers seem to believe that the government should be responsive to their needs. The NCRWRD argues that it has the mandate and necessary skills to maintain and repair engines and pumps in these areas. However, they lack the resources to perform the job. In response, villagers, sometimes with the approval and assistance of donors but often on their own, have organized to assist in the operation and maintenance of the engines and pumps in their villages.

In Kordofan and Darfur, it has become quite common for villagers to assess a surcharge on the water fees paid to the NCRWRD; the villagers use these monies to fund fuel and spares for wateryard operation. Fuel is particularly a problem as the NCRWRD does not get a sufficient allocation to meet wateryard pumping needs and is forbidden to purchase fuel on the black market. This leaves the villagers responsible for obtaining fuel in order to keep their systems operational. Village committees also arrange for the purchase of spares for repair of equipment. NCRWRD argues that any maintenance and repair done by private mechanics voids NCRWRD responsibility for the system, so villages often come to NCRWRD to get a mechanic to complete the repairs. Often the village arranges transportation to and from the wateryard for the mechanic. In spite of NCRWRD statements about responsibilities, some villages find it more expedient to work directly with the private sector.

3.3 Private farmers

In addition to the larger government and cooperative gravity and pumped irrigation systems in Sudan, many private farmers use diesel pumps, particularly along the Blue and White Niles and sections of the Atbara river. These systems pump directly from the river or from large diameter wells nearby (see Figure 3.2). There are also a number of areas away from the Nile where small-scale irrigated agriculture is practiced. There are roughly 60,000 privately owned small farms in Sudan. This does not include small plots in government irrigation schemes or farms that are leased or sharecropped by the farmer. Many other privately owned small farms are found in areas near El Obeid, Dilling, En Nahud, Kassala, Doka, Nyala, El Fasher, and other towns where the water table is 10 meters or less and a ready market for high value crops exists. About 3,000 of these farms are under 5 feddans (1 feddan = 1.03 acres) with an estimated 1,000 under 3 feddans.

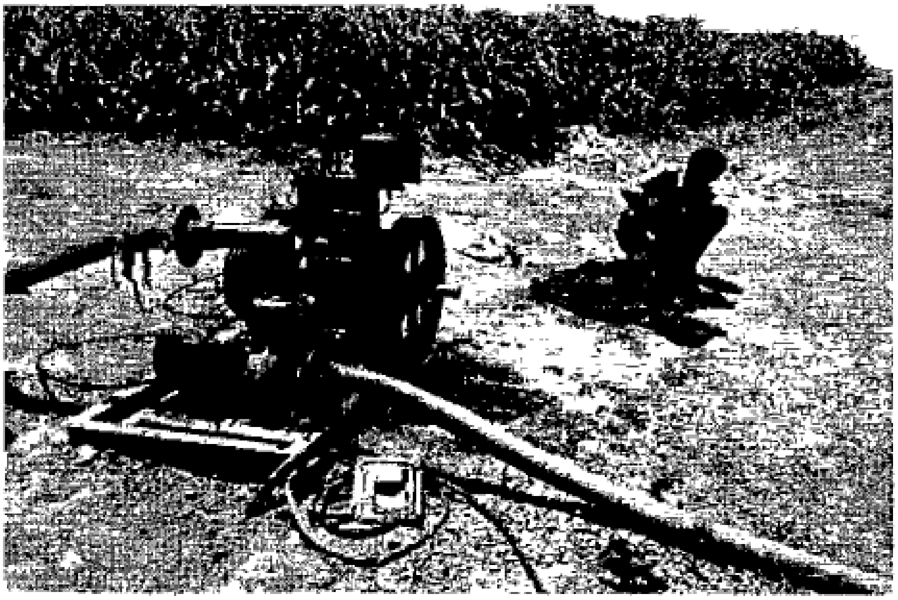


Figure 3.2. Field maintenance of a typical small-scale irrigation pumpset along the Nile.

Incomes reported per irrigated feddan range from S£1,000 to S£7,000 depending on crop and market location. Small-scale diesel pumping from the Nile in the areas around Khartoum began during the mid-1940s. Engines gradually replaced traditional animal lifting methods until the 1950s when the use of diesel engines or electric pumps was almost universal. Now, most small farmers without ready access to electricity are utilizing 2- to 4-inch surface centrifugal pumps. The engine pump units are placed on skids so they can be moved as the river rises and falls. When the water source is a dug well, the pump is often placed in the well and driven by belts with an engine on the surface. Occasionally the entire pumpset is placed in the well. Almost all farmers are using Indian-made Lister engines (i.e., Indian–built copies of the slow running, water-cooled, single cylinder 6/1 or 8/1 Lister design originally built in the U.K.). It is estimated that there are 600,000 small engine pumps of this type in Sudan.

The Agricultural Bank of Sudan (ABS) provides loans to small farmers to purchase diesel pumps on 3-year installment loans currently at 19 percent interest. The ABS imports diesel pumpsets through donor hard currency grants and provides the equipment to farmers at a price based on the official exchange rate. This policy results in a pumpset price well below the market value of the equipment. Similar purchase arrangements are not currently available for either PV or wind driven pumping equipment. However, the availability of these ABS loans is limited and many farmers have purchased their equipment outright. Fuel allocations are available for farmers with diesel pumps. When fuel is available, farmers take advantage of the controlled price of the allocation. Otherwise, they purchase fuel on the open market. Maintenance and repair of small engines are usually performed by local mechanics. The Indian Lister engine is forgiving and relatively easy to keep operating. Parts are usually available in the marketplace.

3.4 Private Sector Support

Both farmers and villages rely heavily on the private sector for spare parts and fuel. There are 10 to 12 major licensed importers for engines and pumps; they represent major European and Asian makes of engines and pumps. These agents have offices in Khartoum and 3 have branches in other towns in Sudan. Equipment and spares are often sold to traders who then take these to other towns and villages for resale. Current restrictions on imports (as a result of foreign exchange concerns and the difficulty of obtaining import licenses) severely limit their capacity to provide both new equipment and spares. Also government mandated pricing policies reduce the incentive for some suppliers to part with their stock. However, particularly for the Indian Listers, there is an active secondary market in reconditioned equipment and possibly in smuggled spares. Profit mark-ups of 25 to 30 percent are considered acceptable. Recent changes in the import licensing procedure have virtually stopped all legal importation of engines, pumps and spare parts. This means that virtually all of the equipment acquired by farmers comes through the Agricultural Development Bank. Under this arrangement, the ABS requests tenders from local firms for the supply of pumpsets and spare parts. The ABS, with foreign currency supplied by a donor, arranges for the off-shore purchase of equipment through the successful firm. The local firm merely arranges the transaction for a fee paid in local currency.

Fuel distribution, previously controlled by a government parastatal (General Petroleum Corporation), is at present controlled by the military at fixed subsidized prices. Although formal allocations are mandated for NCRWRD for vehicle requirements and wateryard operation and for farmers for irrigation pumps, often these supplies are not available. However, fuel is almost always available on the open market, often at considerably above the official price. The NCRWRD concern about fuel availability reflects the availability of allocations to them and not necessarily availability on the open market (in which they are forbidden to participate).

The private sector is also active in the renewable energy area. There is currently a representative for BP Solar, and for Arco Solar and Grundfos in Khartoum. There is also a KSB dealer in Sudan. These cover the range of tested equipment and all of the currently installed and operating solar pumps. These dealers also have the expertise to assist in equipment choice, installation, and repair. However, there is no supply of spare parts in the country as a result of the difficulty in obtaining import licenses and the limited demand for items that may be inventoried for some time. Also there are several manufacturers considering the local production of wind pumps, either the CWD 5000 or the Kijito. These firms have limited raw materials and are not likely to produce any significant number of windmills unless the situation changes radically.

In these now uncertain economic times, concern about the continued availability of spare parts at reasonable cost and the availability of fuel for conventional pumps, particularly in more rural areas, is justified. These concerns lead directly to interest in alternative technologies which hold the promise of reduced maintenance, fewer spare parts, and freedom from conventional fuel sources.

4.0 Water and Energy Resources

4.1 Water Resources

The most prominent feature of Sudan's geography (see maps in Appendix B) is the Nile river system (including the White and Blue Niles) which bisects the country north to south. In northern Sudan away from the Nile system and its few tributaries, the land is dry semi-desert to desert. The population density is highest along the Nile and its tributaries. The surface water of these rivers is utilized for village water supplies and irrigation. Near the rivers, the water table level normally remains high with large diameter hand dug wells in use both for water supply and irrigation.

Groundwater sources include the vast Nubian and Um Rwaaba aquifers, the Gezira formation, several significant areas of basement complex, and numerous smaller superficial deposits. The sedimentary deposits of the Nubian aquifer underlie 28 percent of Sudan's area, largely in the north and west, northwest of Khartoum. This aquifer is divided into six major basins which cover much of the area of northern Sudan from the Red Sea hills west and from the middle of Central Region north (except for the basement complex areas of central Kordofan and the Jebel Marra plateau). The groundwater water levels range from 5 to 120 meters; the levels even flow to the surface at the oases El Natrun and Nukheila in the northwestern part of Sudan. In these aquifers, well yields tend to be good, often in the range of 25 m^3/hour or more.

The Um Rwaaba sedimentary formation underlies a large area in Kordofan, east of Bara towards Um Rwaaba and south into the Sudd region as far as Juba, then west and north to Wau and Nyala. This area is generally to the south of the Nubian aquifer. Water table depths range from 10 to 70 meters. This aquifer lies under about 20 percent of the country. Well yields tend to be good but water quality (salinity and sulfates) is a problem in isolated areas.

There are several major areas where groundwater availability is complicated by basement complexes. These include the lateritic ironstones of southwest Sudan in Bharal-Gazal and West Equatoria, the Aeolean Goz sands of central Kordofan from Kadugali and Dilling north through El Obeid and then to the northwest, and the Red Sea hills, Jebel Marra plateau and the Ingasana hills east of White Nile south of Ed Dueim and Kosti. Roughly 45 percent of Sudan is underlain by basement complexes. In these locations, the groundwater resource is generally limited but exists in deeply weathered and fractured areas where recharge is from rain and run-off. Productive wells are possible in some areas but deep boreholes are often required. Low yields and greater drawdowns are characteristics of many of these wells.

There are low yield hand dug wells of 20 to 40 meters in some areas of North Kordofan. Wells of 30 to 50 meters exist in Bahr El Gazal and West Equatoria. UNICEF has been or is active in these areas as well as the Red Sea hills in support of handpump installation.

Alluvial basins and seasonal streams, the traditional sources of water, have been of special importance in many places; they provide shallow water from 5 to 20 meters. Drainage from hill areas generates seasonal streams and wadis which in turn create farming opportunities. Water is often available from temporary or permanent hand dug wells of 5 to 10 meters. Traditional travel routes and older villages depended on these sources until modern well drilling equipment allowed the tapping of water in other areas.

Wind and solar pumps are economically most viable in areas where the water tables are high. These areas include most of the land along the Nile and a number of scattered locations around Sudan where water can be pumped from shallow boreholes and hand dug wells in the range of 30 to 40 meters or less.

4.2 Energy Resources

The energy sources of interest are diesel fuel, solar radiation, and wind. These energy resources and the characteristics of their use are discussed in the following sections.

4.2.1 Diesel

Diesel fuel has a constant energy content (about 38 MJ/liter). Diesel engines running at fixed speeds deliver water at fixed flow rates. This makes the design of diesel pumping systems relatively straightforward. The energy density of diesel fuel is high and, except for transportation, it is easy to store and use. In Sudan, however, petrochemical fuels including diesel are sometimes hard to obtain. Although the official price is controlled (and subsidized), in practice fuel is not always readily available at the official price, and a black market develops. During these periods, fuel prices vary considerably, often doubling the official price. These uncertainties make diesel fuel a less than fully reliable energy source in much of the country.

The Government of Sudan's General Petroleum Corporation (GPC) controls distribution, allocation, and pricing of oil products. At present, the military also has a hand in distribution and allocation. With the Bank of Sudan, GPC determines the amount of crude oil and petroleum products to be imported. Crude oil is refined under contract to the GPC by the Port Sudan Refinery. The refinery is operated to maximize the production of middle distillate fuels, including kerosene and gasoil (common diesel fuels). However, Sudan still must import two thirds of its diesel fuel needs which in the most recent year for which records are available amounted to 809,513 metric tons (536,992 MT imported and 271,521 MT refined at Port Sudan). Over the last decade the diesel fuel share of total petrochemical consumption has been roughly 50 percent, with the transportation sector accounting for 60 percent of consumption. Water sector diesel fuel use is included as part of agricultural use, and separate data are not available. For several years now, petroleum products have been rationed, thereby creating a scarcity. The GPC uses an allocation system to provide fuel for essential public and private sector use. A percentage of this fuel finds its way into private hands and is available on the black market at higher than GPC official prices.

Official GPC diesel fuel prices in late 1989 ranged from S£3.34 per gallon (Imp.) at Port Sudan to S£4.07 at Nyala. The Khartoum price is S£3.52/gallon. The differences in prices are in part a reflection of the cost to deliver the fuel to these locations. Retailers are permitted to charge slightly more (12 to 18 percent depending on location) than this rate to cover their costs. The Government prefers to subsidize prices for most petrochemical products rather than to allow market price increases. Gasoline and Jet A-1 fuels are sold at higher than their refined costs in order to offset some of this subsidy. If crude and refined products are purchased at the official 4.5 exchange rate, the subsidy to diesel fuel is about 12 percent. At a 12.2 exchange rate, the subsidy amounts to nearly 150 percent.

A substantial black market trade in diesel fuel (as well as other petroleum products) has developed as a result of the current allocation system and fuel scarcity. The black market price of fuel reflects the current availability of fuel through official sources. This depends on the ability of the GPC to provide adequate fuel and to transport it to allocation depots around the country. Sometimes black market fuel prices are approximately the same as the official price; more often prices are much higher, frequently reaching 3 to 5 times the official price, and occasionally much higher. Especially in some of the more remote areas, there are periods when fuel is not available at any price. This may be the result of inadequate allocations or an inability to transport fuel because of rains or flooding or other occurrences such as the breakdown of ferry services. However, it appears that in most cases and in most places diesel fuel can be obtained if one is willing and able to pay the prevailing price.

An important factor for the NCRWRD is that, as a public agency, it is prohibited from purchasing fuel on the open market. The agency must rely solely on the fuel resources provided by the GPC. As the allocations are often inadequate, this severely limits the ability of the NCRWRD to fulfil its obligations in construction programs and in the operation and maintenance of wateryards. Concerns about fuel availability have prompted NCRWRD interest in use of renewable energy.

4.2.2 Solar Radiation

There are 16 meteorological stations throughout the country which collect solar radiation data. The first of these began collecting data in 1967. The Sudan Meteorological Department (SMD) is using Eppley pyranometers and Speedomax recorders to calculate hourly solar radiation totals. These data are used to determine the monthly average total radiation.

These data (Table 4.1) show that Sudan enjoys high solar radiation levels in all areas north of 12 degrees latitude except the eastern part of Eastern Region which reports annual average radiation levels above 5.6 kWhr/m^2/day on a horizontal surface. Areas of the world with solar radiation levels as high as 6 kWh/m^2/day are rare. Half of the 16 stations report annual average figures above 6.1 kWh/m^2/day.

The monthly data show that the lowest solar radiation levels occur in most locations during December when the day length is shortest, and highest values occur during the spring (April to June). Hours of bright sunshine data (recorded by Campbell-Stokes instruments) indicate lower levels of sunshine during the late spring and summer months. This is caused by cloud cover and larger amounts of dust and particulate matter in the air during these periods. In southern regions (which might normally be expected to have higher solar radiation levels because of their proximity to the equator) and along the Red Sea coast, the levels are actually lower than in the north. This is a result of a much greater cloud cover in these areas, especially during the rainy season (May to September). More northerly areas experience much less rainfall and much lower cloud cover, causing higher average solar radiation levels. These data indicate that northern Sudan is a more favorable location for the use of solar energy than the south or east.

Table 4.1. Solar Radiation at Selected Sites in Sudan (kWhr/m^2/day)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	AVG
Abu Na'ama:	5.7	6.3	6.7	6.8	6.7	6.2	5.8	6.2	6.5	5.3	6.1	5.4	6.1
Aroma:	5.4	5.7	6.2	6.2	6.2	6.1	6.2	6.9	6.6	5.9	5.2	4.7	5.9
Babanousa:	5.7	6.3	6.7	6.8	6.6	6.3	5.7	5.8	6.0	5.7	5.5	5.4	6.0
Dongola:	5.6	6.4	7.1	7.5	7.7	7.6	7.2	7.0	6.7	6.4	5.8	5.3	6.7
El Fasher:	5.4	6.4	6.9	7.0	7.0	6.6	6.3	6.3	6.2	6.3	5.7	5.4	6.3
Showak:	5.6	6.5	7.1	7.3	7.1	7.5	6.2	6.2	6.4	6.1	5.8	5.4	6.4
G.Gawazat:	5.7	6.2	6.5	6.6	6.3	6.0	5.7	5.7	6.0	6.0	5.9	5.7	6.0
Hodieba:	5.4	6.0	6.8	7.1	6.8	6.4	6.3	6.5	6.3	6.0	5.6	5 3	6.2
Juba:	5.4	5.4	5.4	5.8	5.7	5.4	5.0	4.9	5.9	5.6	5.4	5.3	5.4
Kadugali:	6.0	6.4	6.6	6.7	6.4	5.8	5.2	5.1	5.2	2.8	6.0	5.9	5.7
Malakal:	5.6	6.0	6.2	6.2	5.6	5.0	5.0	5.4	5.3	5.4	5.6	5.5	5.6
Port Sudan:	4.2	5.2	6.3	4.2	7.1	6.6	6.3	6.3	6.2	5.7	4.6	4.0	5.6
Shambat:	5.6	6.3	6.8	7.1	6.8	6.5	6.3	6.3	6.3	6.0	5.7	5.4	6.3
Wad Medani:	5.8	6.4	6.9	7.0	6.8	6.6	6.2	6.2	6.5	6.2	5.9	5.6	6.3
Tokar:	4.7	3.8	4.7	6.0	6.1	5.4	4.8	4.7	4.9	4.6	6.0	4.6	5.0
Zalengi:	6.1	6.6	7.1	7.1	7.0	5.8	5.8	5.9	6.0	6.3	6.3	6.0	6.2

*Source: **Climatological Normals 1951-1980**, Sudan Meteorological Department*

4.2.3 Wind Speed

The SMD has collected and reported wind data for many years. Sixty-six stations around the country report wind speed and wind direction information. Twenty-three stations record these data using Dines pressure plate anemometers (located at a height of 15.2 meters). The remaining stations report Beaufort scale estimates several times each day. Reduction of even the best of the SMD's wind speed data is fraught with uncertainty. The SMD reports that many of the anemometers are not well sited, particularly in Kosti, Kassala, Wau and Juba (Ref 8). In addition to siting difficulties, the accuracy of the instruments and the reduction of data are difficult. The Dines instruments must be carefully and regularly adjusted, and calibrated by SMD technicians. Also the reduction of the data is time consuming as the data are recorded on daily charts and wind speed resolution is lacking on these charts. This means that the data cannot be considered a fully accurate reflection of the wind speeds at each location.

SMD publications, which include wind speed data, are *Wind Energy for Windmills in Sudan* by Y.P.R. Bhalotra, Sudan Meteorological Service (ref 8) and *Climatological Normals 1951-1980* (ref 9). Even considering the differences in the periods of record, these data are not fully consistent with some stations reporting well over ten percent differences in annual average wind speed.

However, the data do indicate that wind speeds are generally lower in the south (Juba and Wau) and increase to the north (from Khartoum to Wadi Halfa). Higher wind speeds are also reported along the Red Sea coast (Port Sudan). A wind power density map is shown in Appendix B for illustrative purposes. The information given should only be used as a general indication of wind energy availability.

Table 4.2. Average Daily Wind Speeds at Selected Sites (m/s)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	AVG
Atbara:	4.5	4.6	4.6	3.4	3.0	2.9	4.0	3.5	2.9	3.0	4.2	4.7	3.8
El Fasher:	2.2	2.8	3.0	2.5	2.6	2.3	2.3	1.6	1.3	1.9	2.1	1.9	2.2
El Geneina:	3.3	3.9	3.4	3.5	2.6	2.5	2.8	2.1	1.7	2.5	3.8	3.9	3.0
El Obeid:	4.1	4.2	4.5	3.2	3.1	3.9	4.6	3.5	2.5	2.9	3.5	3.9	3.7
Juba:	1.5	1.3	1.6	1.7	1.5	1.3	1.1	1.1	1.3	1.3	1.3	1.3	1.3
Karima:	3.5	4.2	4.4	3.9	3.6	3.5	3.4	2.7	3.3	3.5	3.8	3.7	3.6
Kassala:	2.3	2.2	2.5	1.9	1.9	3.0	3.2	2.6	2.4	1.7	1.8	2.0	2.3
Khartoum:	4.2	5.0	5.1	4.0	4.2	4.2	5.3	4.8	4.0	3.1	3.7	4.0	4.3
Kosti:	3.1	3.5	3.8	3.0	3.1	3.9	4.0	3.1	2.5	2.3	3.3	3.8	3.3
Malakal:	3.9	4.0	3.4	2.8	2.5	2.5	2.5	2.0	1.7	1.8	2.6	4.0	2.8
Port Sudan:	5.0	5.1	4.7	3.7	3.2	3.4	3.8	3.2	2.6	3.0	4.2	4.8	3.9
Wadi Halfa:	4.1	4.6	4.6	3.8	4.6	4.2	4.1	3.7	3.6	4.3	4.5	4.3	4.2
Wau:	1.7	2.0	2.0	2.1	1.6	1.4	1.5	1.3	1.4	1.4	1.9	2.3	1.7

Source: ***Wind Energy for Windmills in Sudan*** *by Y.P.R. Bhalotra Sudan Meteorological Service; Memoire No. 7, March 1964.*

In addition to the SMD data reported above, there are several additional sources for wind energy data at isolated locations. These data were either based on analysis of selected SMD data not reported in the climatological summaries or collected by projects interested in the wind energy potential at particular locations.

Consulting Services Wind Energy Developing Countries (CWD) analyzed data for Khartoum. These data included selected SMD records not analyzed or reported elsewhere. These data indicate an average annual wind speed of about 12 percent less than reported by the

Table 4.3. Average Daily Wind Speeds at Windmill Sites (m/s)

Khartoum(1):	4.2	4.2	4.1	4.0	3.0	4.0	4.0	4.0	3.5	3.0	3.8	4.0	3.8
Khartoum (2)·						3.7		4.5	3.9	3.3	4.2		
Karima (3):	5.3	4.8	5.7	5.4	6.7	4.5	4.1	4.7	5.0	5.0	4.5	5.6	5.1
CWD Kelli (4):		5.2	4.8	5.9	4.6	3.6		6.5				3.7	5.1

Sources: 1- Consulting Services Wind Energy Developing Countries (CWD)
2- SREP
3- see Reference 49
4- Unpublished data, Barbara Sexon, ODA Project

SMD records. However, in most cases recently collected data indicate higher wind speeds than reported by the SMD.

The SEP has collected one year of data at Karima in the Northern Region using a wind totalizer. Their one year of data indicates an average annual wind speed of 5.1 m/s (at 10 meters), whereas the SMD reported 3.6 m/s (more than a 40 percent difference).

Also at Shendi, the Northern Region Irrigation Rehabilitation project, using a data logger, has reported an average monthly wind speed for selected months at Kelli just north of Shendi. This figure is 85 percent higher than the SMD wind readings from across the river at Shendi (2.7 m/s measured as wind force on the Beaufort scale several times a day). The SMD agrees that these Beaufort scale wind speed figures are not accurate. However if one assumes that the average annual wind speed at Kelli is between the values for Atbara and Khartoum (since Kelli lies between these two towns), the data collected at Kelli is still 14 percent higher than one would expect based on SMD data for the months of record.

Data collected by the SREP project in and around Khartoum (only partial year's data collected so far) indicate that the data reported by the SMD for Khartoum may be higher than actual values. This would tend to confirm the results of the analysis conducted by CWD at the commencement of their wind pump project.

It is now generally accepted that Sudan, particularly in the north and along the coast, has good wind energy potential. However, without accurate wind speed data, it is impossible to calculate the energy that could be generated or the amount of water that could be pumped. Wind energy availability is a function of the cube of the wind speed, and the water delivery from windmills is greatly effected by relatively small changes in wind speed. It is clear that a better understanding of the prevailing wind regimes is necessary to accurately predict the performance of wind energy devices. Continued data collection by the ERC will assist in this process. The greatest improvement would be achieved if the SMD upgraded its equipment.

5.0 Pump Field Tests

Background

In order to evaluate reasonably the technical performance of wind and photovoltaic (PV) pumping technologies, it is necessary to understand system performance as a function of solar radiation levels and wind regimes in Sudan. In addition, to evaluate the solar and wind pumps in relation to diesel pumps, the field performance of diesel systems must be known. Sixteen diesel pumps, 5 solar pumps and 3 wind pumps were included in the test program. The following chapter summarizes the results of field tests conducted by SREP.

The diesels tested included the most common engine and pump configurations used in Sudan. These are the diesel driven jack pumps (including Adler, Shoeller, and Edeco), surface centrifugal pumps (largely Indian made and used in small-scale irrigation), and vertical turbine pumps from a variety of manufacturers. Although diesel driven Mono pump systems are not common, several of these were also tested.

Several configurations of PV pumps have been used in Sudan. By far the most common is the Grundfos pump with Arco-Solar, Siemens, or BP modules. There are at least eight now installed with several more planned. Four of these pumps were included in the test program. A KSB floating pump was also tested. SEP has imported ten more of these pumps for inclusion in their pumping program.

Windmill evaluations were limited to the CWD 5000, as it was the only type of windmill in operation during the test period. There is considerable interest in the Kenyan Kijito. Five of these have been imported. Three Kijitos have recently been installed near Shendi on the west bank of the Nile. ODA is supporting an independent evaluation of these machines. The other two, which have been provided by GTZ, have not yet been sited.

5.1 Approach and Test Methodology

The overall goals for the technical monitoring of diesel, solar and wind pumps were:

- to characterize the day to day performance of solar and wind pumps as a function of energy resource levels;
- to determine pumping rates as a function of power input; and
- to monitor the maintenance and repair requirements, for which little data exists in Sudan.

The testing methodology was based on the *Handbook for Comparative Technical and Economic Performance of Water Pumping Systems* (Reference 19) and adapted to conditions in Sudan. Solar and wind pumps were tested on both a short-term (10 minute report intervals) and longer term (one-hour report intervals). The longer term data were also compiled to provide daily performance figures for the machines. Diesel pumps were tested over shorter intervals since their output is constant at constant engine speed. Detailed test methodologies are included in Appendix C.

5.2 Diesel Pumpsets

Four different configurations of diesel engine pumpsets were tested; they were the surface centrifugal, Mono, Edeco, and vertical turbine pumps. The results of testing these pumpsets appear in the following 4 sections.

5.2.1 Surface Centrifugal Pumps

By far the most common configuration of pump and engine in use for small-scale irrigation is the Indian Lister engine belt-coupled to a surface centrifugal pump. Three examples of this configuration were tested. The Indian Lister is a copy of the water-cooled, slow-speed 6/1 design first introduced by Lister in 1962. Lister-Petter has now discontinued the model. The 6/1 engine is a nominal 6 HP (4.5 kW) unit at 650 RPM. The 8/1 is fully rated at 8 HP (6 kW) at 850 RPM. In Sudan there are at least a dozen makes of these Indian Lister engines. Several makes of surface-mounted centrifugal pumps are used as irrigation pumps. Most of these have such similar output characteristics that they are commonly referred to as 2-, 3-, or 4-inch pumps (the size of their discharge pipe in inches). Tests were conducted at three sites. These were in Bara, Wad Medani and Ed Damer. Brief descriptions of these and other test sites are given in Appendix D. Table 5.1 below summarizes field test results of surface-mounted centrifugal pumps.

Table 5.1. Diesel Performance: Surface Pumps

Name of Site	Pumping Head (m)	Pumping Rate (m^3/hr)	Fuel - Consump. (liters/hr)	System Efficiency (%)	Engine/Pump Speed (RPM)
Bara	11	7.6	.53	4.1	361/ -
Wad Medani	5	54.6	1.66	4.3	573/1110
Ed Damer	9	26.2	.86	7.1	537/1080

The relatively high fuel consumption per unit of water pumped and the low system efficiencies for these pumpsets reflect poor matching of equipment to pumping function and the poor condition of the equipment. The engine at Bara is running well below the recommended speed (600 RPM) and the pumpset at Wad Medani was in particularly poor condition with engine vibration and oil leaks. The range of overall efficiencies for these engines are low by the standards of a high quality, well designed pumping systems (which can approach 20 percent). However, the lower quality materials and less rigid tolerances of the Indian Lister engines reduce power output and increase fuel consumption as compared with the genuine Lister engine. The Bara and Ed Damer test results are consistent with engine power output reduced by ten percent and fuel consumptions increased by 25 percent which indicate the price paid for using equipment in poor condition. As expected, lower pumping rates were measured at Bara where a 2-inch pump is being used. Three-inch pumps are being used at the other two sites. Fuel consumption per hour at Wad Medani is higher than at Ed Damer because the pumping rate is greater and the pumpset is in poor condition. The average system efficiency for the three sites tested is five percent. Estimates of the maximum system efficiencies which could be expected for these pumpsets is in the range of 10 to 12 percent.

5.2.2 Edeco Jack Pumps

The Lister-Edeco pumpset is the most common configuration for deep-well pumping by the NCRWRD in the western regions of Darfur and Kordofan. This pumpset used to be common even in Central Region and Khartoum Commissionerate, but most have now been replaced with engines driving vertical turbine pumps. Historically, the Lister engine is the same slow-speed, water-cooled model used by small-scale farmers, although normally the NCRWRD does not install the Indian built Lister copies. Since Lister discontinued this engine model, the Lister PHW-1 has been used. The Edeco is a long-stroke piston or jack pump utilizing a 3.75 to 4.25 inch cylinder and an 18- or 24-inch stroke. Adler and Schoeller pumps are also in use. At one time these pumps were relatively inexpensive, and NCRWRD technicians and pump operators learned how to keep them operating, often without proper spares. In recent years, these models have become obsolete and are no longer being manufactured except on special order (and so are quite expensive). Seven systems were tested in North Kordofan Province. Wad Sabeel, Obeid Mahdi, Malaga, Abu Auwa, and Abu Hamra are villages with new or recently rehabilitated pumping systems. Um Kharain and Sheraim El Karamsha are sites with older equipment in poorer condition. The results of testing are summarized in Table 5.2.

Table 5.2. Diesel Performance: Jack Pumps

Name of Site	Pumping Head (m)	Pumping Rate (m^3/hr)	Fuel - Consump. (liters/hr)	System Efficiency (%)	Engine/Pump Speed (RPM)
Wad Sabeel[1]	95	4.0	.57	17	530/23
Obeid Mahdi	92	4.0	.63	15	512/22
Malaga	81	4.0	.61	14	535/22
Abu Auwa	95	3.6	.68	13	519/20
Abu Hamra	72	3.6	.80	8	510/20
Um Kharain	96	5.1	1.13	11	631/26
Sh. ElKaramsha	17	3.5	.72	2.2	550/20

[1] results are questioned for this site

The efficiencies for Lister-Edeco pumps were higher than expected, partly because many of the systems have only recently been installed. As is to be expected, the tests of older installations reflect the poor condition of these pumpsets. The lowest efficiency, measured at Sheraim El Karamsha, is the result of a very poor choice of the Edeco on a shallow well. The piston pump is much better suited to deep well applications. Overall efficiency at Abu Hamra, the other pumpset operating at less than 75 meters, is also under 10 percent. Note that the efficiency of the older site at Um Kharain is above 10 percent. The pumping rate of 26 strokes a minute is higher than at other sites and the use of a larger cylinder increases pumping rate and hence the load on the engine. However, analysis shows that much of the engine's power is used in overcoming losses in a very poorly maintained and unbalanced pump. A 20 percent fuel savings could probably be achieved if the engine and pump were in good condition. Analysis also shows that the test results at Wad-Sabeel are not consistent with other new or rehabilitated installations. It is unclear why these results were obtained, but a defective water meter may be the reason. For deep well applications, the Lister-Edeco is suitable from a technical standpoint. Overall, these efficiencies are quite good especially when compared to the vertical turbine and surface centrifugal pumpset efficiencies.

5.2.3 Vertical Turbine Pumps

A variety of engines and vertical turbine pumps are in use in Central and Northern Regions and Khartoum Commissionerate. These have gradually replaced the older Lister-Edeco pumpers. The vertical turbine pump is more suitable for the moderate pumping heads of these areas. Common configurations include Bukh engines with Grundfos pumps, and Andoria or Yanmar engines with Kato pumps. The pumps are usually belt driven. Single cylinder engines in the range of 10 to 20 kW are the norm. Pumping rates (normally 20 to-30 m^3/hr) vary depending on pump characteristics, engine power output, and transmission type.

Discussions with NCRWRD officials indicate a rather haphazard design procedure for pumpsets. This situation arises because the stock of equipment is limited and donors provide equipment before site designs are formalized. The design process is reduced to identifying an available engine and pump which will be capable of pumping water at the wateryard. Rules of thumb, such as one pump stage can deliver 18 to 27 m^3/hr from a 20 meter deep well, are used. Accurate technical specifications are apparently unavailable locally for many of the pumps, and no effort is made to optimize system design by the proper selection of pump speed or engine operating conditions. Only two vertical turbine pump sites were tested by project staff. Shortages of fuel curtailed further vertical turbine pump testing. The sites tested were at El Mugdab and El Sundudab (see Figure 5.1); both are near the Nile and south of Khartoum. Test results for the two sites are given in Table 5.3 below.

Table 5.3. Diesel Performance: Vertical Turbines

Name of Site	Pumping Head (m)	Pumping Rate (m^3/hr)	Fuel - Consump. (liters/hr)	System Efficiency (%)	Engine/Pump Speed (RPM)
El Mugdab	21[1]	11.7	1.25	5[1]	1740/2225
El Sundudab	19[1]	21.9	1.52	7[1]	1145/2210

[1] estimated only

The calculated efficiencies given in the above table depend on the pumping head. Because the pumps are installed so that the well head is completely covered by the pump head, it was impossible to measure the pumping water level. Static water level information was available for these sites and the pressure head was measured. The well drawdown was assumed to be three meters. This figure is the maximum value typically found in wells on the west side of the Nile near Jebel Aulia. Any increases in head will increase system efficiencies. However, at El Mugdab, the drawdown would have to reach 12 meters and at El Sundudab 25 meters (both very unlikely) before system efficiencies reached ten percent. Given the design procedures used for these sites, efficiencies of well under ten percent should be expected. Proper selection of engines and pumps should enable pumpset efficiencies of more than ten percent.

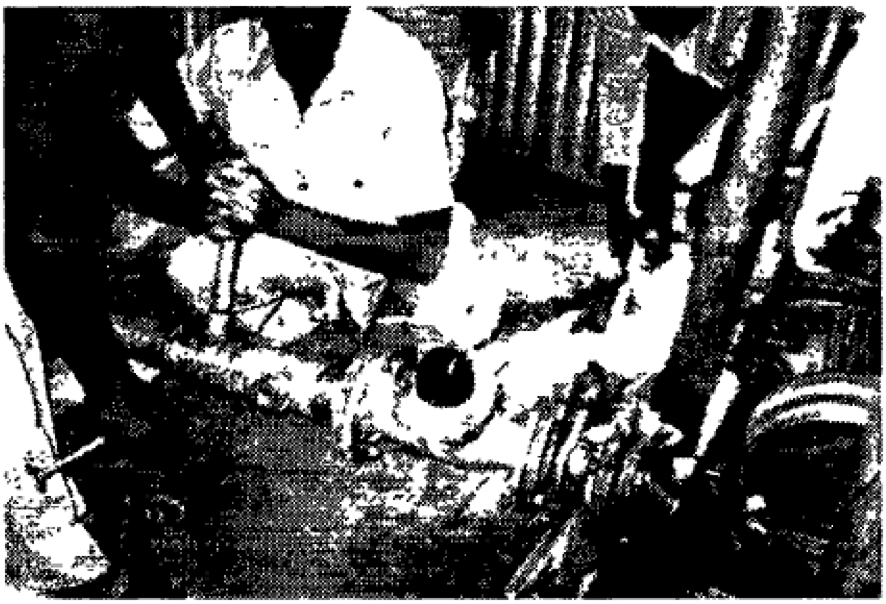


Figure 5.1. Preparations for diesel pump testing: El Mugdab

5.2.4 Mono Pumps

The positive displacement, progressive cavity Mono pump is designed with deep well applications in mind. Pump efficiencies are good at pumping heads in excess of 30 meters and the pumps can be used efficiently to 100 meters. Pumping rates depend on the pump and the pump speed; they can easily exceed the 3 to 4 m^3/hr of the Edeco pumps. In Sudan Mono pumps are used in scattered locations. They have been installed on the livestock route through Kordofan and Darfur. The four sites tested in Northern Darfur Province are part of a wateryard rehabilitation project sponsored by World University Services of Canada (WUSC).

All the sites are near El Fasher and use Lister-Petter water-cooled engines and belt-driven Mono pumps. This configuration is being suggested to NCRWRD by WUSC as a replacement for the jack pumps. A summary of test results is given in Table 5.4.

Table 5.4. Diesel Performance: Mono Pumps

Name of Site	Pumping Head (m)	Pumping Rate (m^3/hr)	Fuel - Consump. (liters/hr)	System Efficiency (%)	Engine/Pump Speed (RPM)
Sharafa (#1)	77	7.4	1.02	14	1440/1000
Shangeltobai	66	6.2	0.79	13	1240/860
Musco	60	7.1	0.86	13	1350/950
Tabit	52	7.1	0.81	12	1380/960

These test results of the Mono pump systems compare favorably with theoretical values based on the power output of the engine at its measured operating speed, the published efficiencies of the Mono pumps under their operating conditions, and the full load fuel consumption of the engines (see Diesel Pump Field Tests in Northern Darfur, SREP). The average efficiency of 13 percent for these sites is quite acceptable.

It is interesting to compare the results of the deep well Mono pump and Edeco pump. Although both can be designed to operate at above 10 percent efficiency, the Mono pump systems are pumping at roughly twice the rate of the Edeco. This means that the water need at a specific site can be met in half the pumping hours if a Mono pump is used. Although this does not cut the fuel savings in half, considerable fuel can be saved. Higher pumping rates should result in considerably reduced maintenance costs as the engines and pump operate far fewer hours. In addition, the Mono pump is not a special order item, spares can be obtained, and it is cheaper than the Edeco.

5.3 Solar Pump Sites

The solar pumps tested included Grundfos submersible pumping systems and KSB floating pumping systems. The test results are summarized in Table 5.5 at the end of this section.

5.3.1 Grundfos Pumps

The Grundfos is the most common PV solar pump in Sudan. The system consists of an array of modules, a DC-AC inverter and a submersible motor/pump. The DC power output of the array is inverted to 3-phase variable voltage and frequency AC power. The SA 1000 inverter in use on all systems tested limits the array size that can be employed with the pump to 1000 watts of continuous output. A recently introduced SA 1500 inverter can be utilized with arrays of up to 1500 watts continuous. Pump testing took place at Gezira, Hodieba, Foja and Sheraim El Karamsha. Site descriptions can be found in Appendix D. At all locations test equipment included sensors to measure water delivery, solar radiation levels, water delivery pressure, ambient temperature, and array voltage (see Figure 5.2). The pumps were continuously monitored with hourly values of all parameters measured. Short-term tests were also conducted on several occasions. The results of these tests are summarized below.

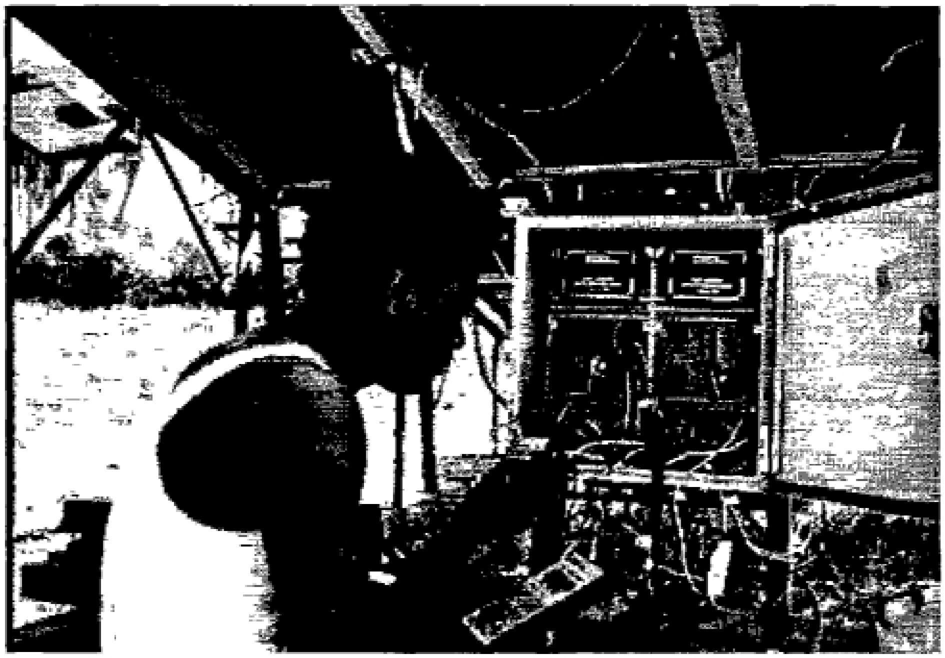


Figure 5.2. SREP pumping team member downloading Datalogger on PV pump.

University of Gezira

During the test period for this pump (April to November 1989), solar radiation ranged from 3.5 to 6.4 kilowatt-hours per square meter per day (kW/m^2/day) in the plane of the solar array. Water delivery by the Grundfos pump driven by a 1,120 W_p (watts peak) array ranged from 21.1 to 36.0 m^3/day through a pumping head of 21 meters. Figure 5.3 shows the relationship of daily pump performance to solar radiation level during this summer period. The average solar radiation over the test period was 5.4 kW/m^2/day; the average water delivery was 31.8 m^3/day. Short-term test results shown in Figures 5.4 and 5.5 indicate water delivery rates and sub-system efficiencies as a function of radiation levels. The peak pumping rate was 82 liters per minute at 820 W/m^2. Figure 5.6 gives the pumping rate as a function of DC power from the PV array. The radiation level at which the pump starts (the cut-in radiation) is 160 W/m^2.

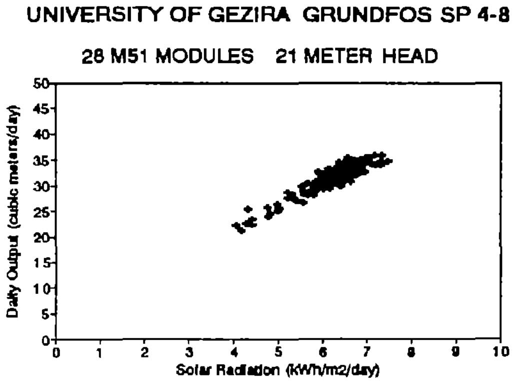


Figure 5.3

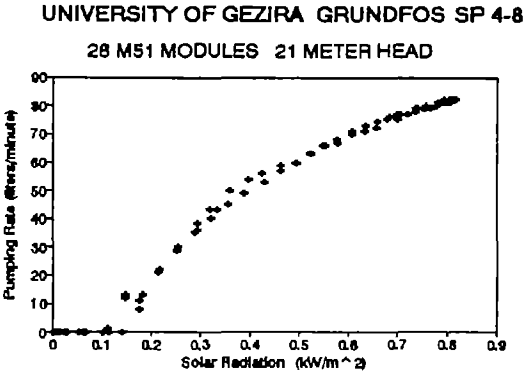


Figure 5.4

The manufacturer's pump curve is given in Appendix E. A comparison of this pump curve with test results indicates that the pump performs as expected or better than expected on some days but on average does not pump as much as predicted. Differences in average day length and ambient temperatures throughout the test period do not fully account for the differences between the test results and the Grundfos pump curve. The average daily water delivery is about 10 percent less than predicted by the manufacturer. This is within anticipated limits for the pump, given that it has been in place and operating for more than six years.

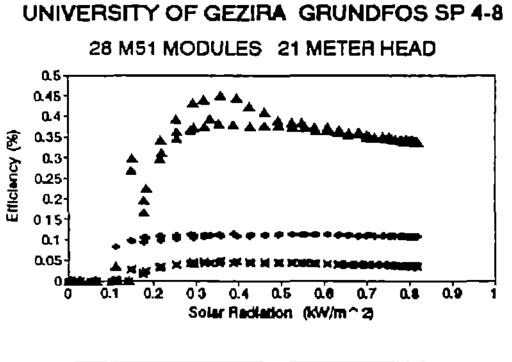


Figure 5.5

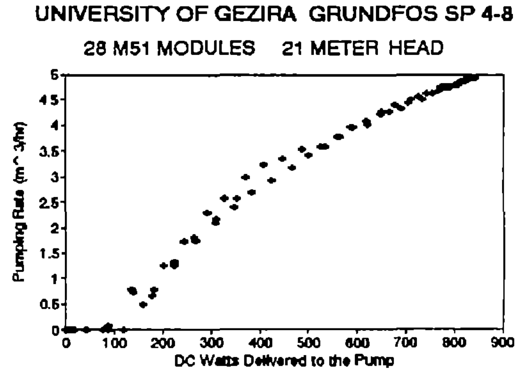


Figure 5.6

As of early 1990, the pump was still operating, and had experienced no breakdowns. There also has been no module breakage. Early in 1989, the on-off switch was replaced (US$80) but the pump could have continued to operate without this replacement. There seems to be no effort to keep the array clean although it would maximize pump performance. The pump continues to be monitored by the ERC in collaboration with faculty and students at the University.

Hodieba Research Center

The 840 W_p Grundfos pump at the Forestry Department's Hodieba Research Station was monitored from June to November 1989. During this period the solar radiation level ranged from 3.2 to 6.5 $kWh/m^2/day$ in the plane of the array. Daily pump output ranged from 20.1 to 43.6 m^3/day, the average daily solar radiation was 5.7 $kWh/m^2/day$, and the average daily pump delivery was 38.6 m^3. Figure 5.7 shows the daily pump output as a function of solar radiation level over this time span. Short-term test results are shown in Figure 5.8 where water delivery rate is given as a function of radiation level. Peak flow rates of 94 l/min. were observed at a 885 W/m^2. Throughout the short-term testing, array shading was observed until 8:30 to 9:00 A.M. during the winter months. The shading is caused by a stand of Eucalyptus trees that have grown up to the east of the pump, resulting in reduced water output. As expected, the pump does not deliver as much water as the Grundfos pump curves given in the appendix suggest it should.

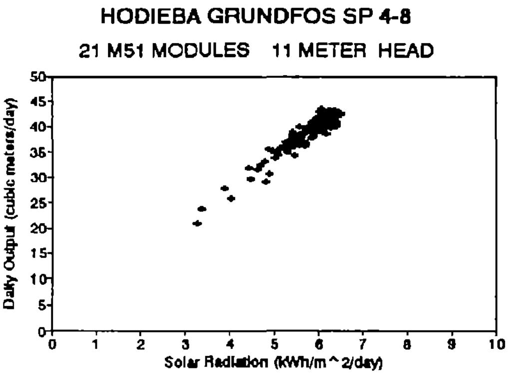


Figure 5.7

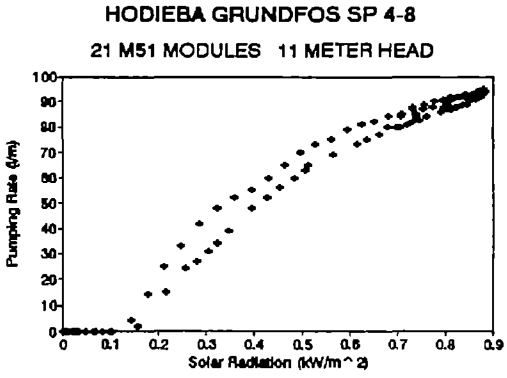


Figure 5.8

This pump has not experienced any breakdown during the more than six years since it was installed. No modules have been broken. The pump is currently operating, although as at other sites, there does not seem to be any effort to maximize performance by keeping the array clean. As a result of the cost and logistical difficulty in visiting this site, the ERC may discontinue intensive monitoring.

Foja

Monitoring of the new 903 W_p Grundfos pump at Foja began in August 1989. Two water meters were used because the pump delivers water to two locations. The total pumping head is 24 meters to a community garden and 33 meters to the shelterbelt storage tank. Less water is pumped at the greater head because of the greater energy requirement. Since at a given solar radiation level, the energy to the pump is constant, less water can be pumped through the greater head. The graph of pump output as a function of solar radiation level (shown in Figure 5.9) reflects this. The scatter in the results arises from the fact that the pump users pump to the garden for part of the day and to the shelterbelt for part of the day. The pumping patterns are not consistent; instead, they depend on the water need at each location. For this reason, it is impossible to provide a daily pump performance curve for each condition. From August to November 1989, the daily total solar radiation ranged from 2.9 to 6.4 kWh/m^2/day. Water delivery varied from 7.5 to 33.1 m^3/day, with water delivered to both the garden and the shelterbelt during parts of each day. The average solar radiation level was 5.6 kWh/m^2/day with an average water delivery of 21.0 m^3/day.

The short-term test results shown in Figure 5.10 provide a more meaningful measure of the pump when operating under the two pumping head conditions. The upper curve, indicating a maximum pumping rate of 75 l/min., reflects water pumped to the lower tank at the garden site. The lower curve, indicating a maximum pumping rate of 40 l/min., shows water delivery to the shelterbelt at the elevated site. Figure 5.11 shows that the subsystem efficiency (measured as the ratio of DC power delivered to pumping rate) is relatively independent of the pumping head.

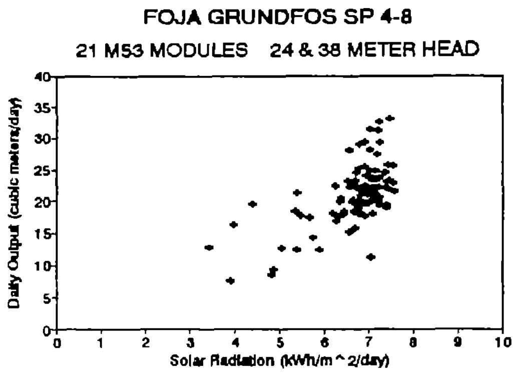


Figure 5.9

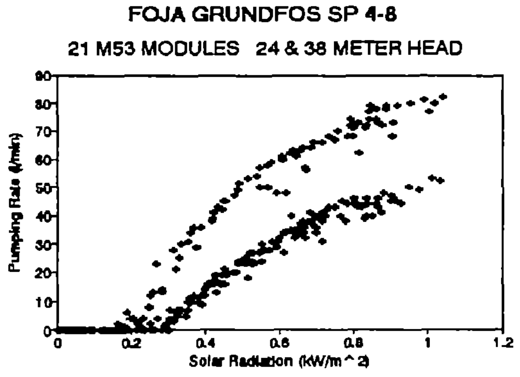


Figure 5.10

The pump is currently operating and being maintained by villagers and the Swedish- Sudanese Friendship Association. There has been no module breakage, and the array appears to be cleaned regularly. Monitoring is continuing at the site.

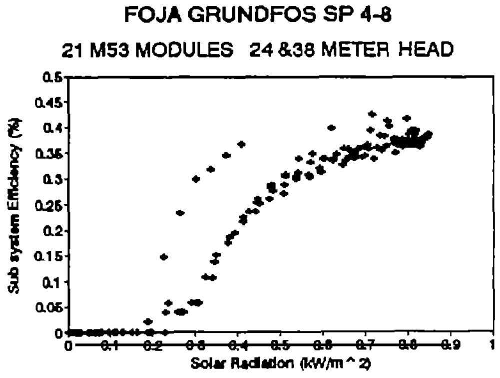


Figure 5.11

Sheraim El Karamsha

The solar pump installed at Sheraim El Karamsha has the same configuration as the one at Foja. The solar pump is currently operational. Pump monitoring instrumentation was installed at the site in August 1989. Unfortunately the villagers do not use the pump continuously, and it has been switched off for long periods of time. The reason for this is unknown, but there is a diesel pump in the village (see 5.2.2) and the villagers may see little need to use the solar pump. Also the trees were planted at least one season before those at Foja; they have grown and the watering interval has been increased.

The array is cleaned and cared for although recently the glass surface was slightly scratched during the cleaning process. Two modules have been broken during the three years since this pump was installed. The fact that the pump is not used on a continuous basis has limited the amount of useful data available from the site. An average of under 5 m^3/day was pumped over the three-month period from September to November. Since the site characteristics are similar to those at Foja, intensive testing will likely be discontinued. However, the site will continue to be visited when trips to Foja are made.

The test results from these four sites, as well as testing conducted in other countries, indicate that the Grundfos solar pump is reliable for low to moderate pumping heads (up to 50 meters). The systems at two of the sites--University of Gezira and Hodieba--have been operating for more than six years now. Application of the Grundfos solar pumps to deeper wells are not common and have not been adequately tested. Planned testing near Nyala at sites of 70 to 100 meters will provide information on high head applications. The recent introduction of the larger capacity SA 1500 inverter allows the use of larger arrays and hence will increase the water output of the pumping system.

5.3.2 KSB Pump

The KSB Aquasol solar pump is among the most common low head floating pumps. The system consists of an array of modules directly coupled to a brushless DC motor and pump. The pump is designed for use in open wells, lakes, and rivers. The model 50M is suitable for heads up to 11.5 meters, and the 100M for lower heads to 5 meters. Maximum pumping rates are 5 and 12 liters per second (respectively) with a 450 peak watt array (12 BMC Solartechnik modules). Tests were conducted at Shambat where the only KSB in Sudan is currently operating (see Figure 5.12). The tested configuration was an Aquasol model 50M. Technical specifications for this pump are provided in Appendix E.

The pump was tested from June 1989 to January 1990. However, the farmer who was to use the pump did so sporadically and rarely for a whole day. During the test period the daily total solar radiation ranged from 2.6 to 7.8 kWh/m^2/day. No meaningful measure of the potential long-term water delivery was recorded as the pump was seldom used. Daily performance data were collected in December and January when the farmer operated the pump more often. Figure 5.13 shows the daily pump output as a function of solar radiation level for selected days when the pump was utilized during all available daylight hours. Within this period the solar radiation levels ranged from 2.6 to 7.8 kWh/m^2/day with water delivery ranging from 6.3 to 45.9 m^3/day. Short-term test results are shown in Figures 5.14, 5.15, and

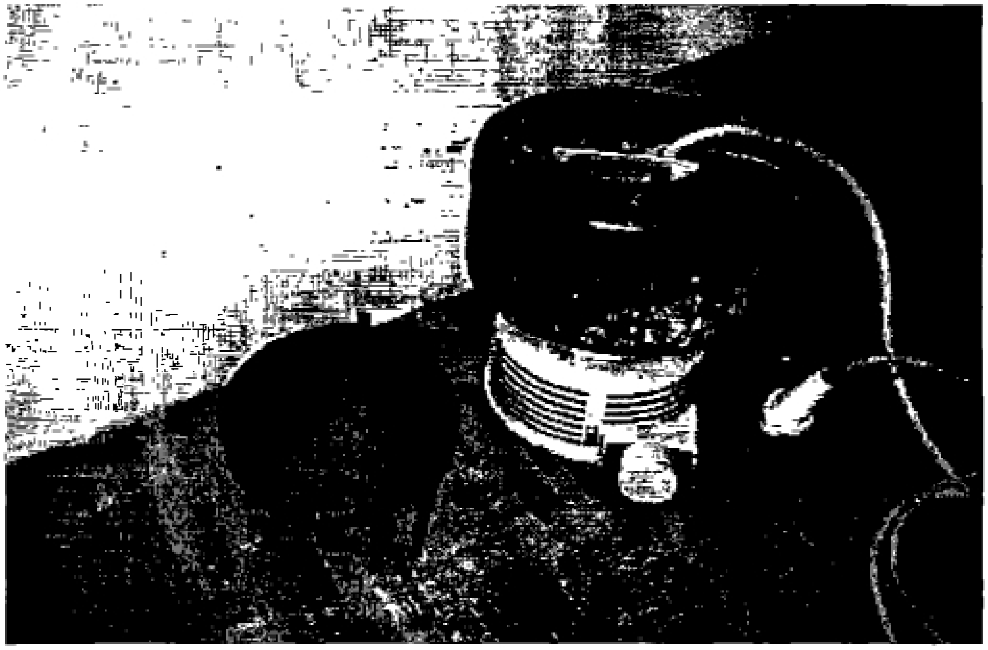


Figure 5.12. Aquasol solar pump showing pump foot removed. Note discoloration from silt accumulation.

5.16. These graphs show water delivery as a function of solar array power and water flow rate and sub-system efficiency as a function of radiation levels.

It is difficult to determine the expected performance of the pump with the information given by KSB. However, it appears that water delivery is about 10 percent less than predicted for the solar radiation, ambient temperature, and pumping head at the Shambat site. This low output is partly the result of voltage losses in the very long power cable used from the array up on the river bank down to the floating pump.

The system at Shambat has had several significant problems. Dirt and debris have gradually filled the bottom of the flexible pump foot (see diagram in the Appendix E). Occasionally,

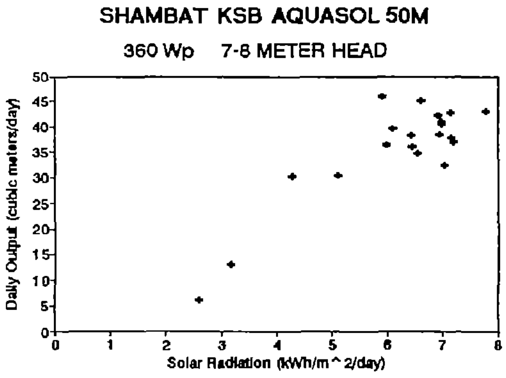


Figure 5.13

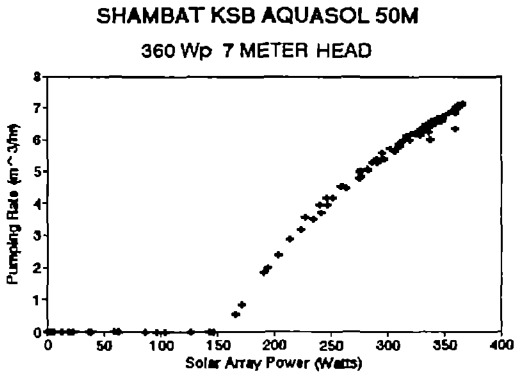


Figure 5.14

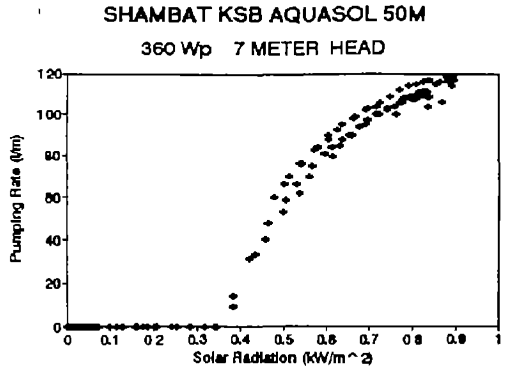


Figure 5.15

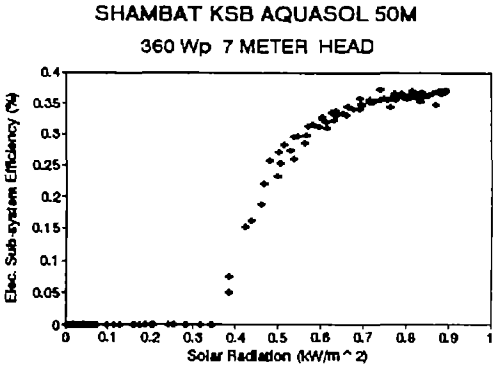


Figure 5.16

the heavy pump foot became detached from the pump, allowing the pump to rest directly on the bottom of the river. Debris entered the pump and clogged it causing the motor to overheat and become damaged. The pump was replaced in May 1989. In January 1990 the pump stopped operating. Pump electronic components drove the voltage to between 5 and 15 volts and the peak current to 8 amps. The pump would not operate at this power. The most likely cause for this behavior is a malfunction in the switching circuit used in starting the pump. This may be caused by heavy cycling in periods of lower insolation early and late in the day and also during cloudy or rainy periods. Apparently, the same problem has surfaced elsewhere as KSB now recommends turning the pump on and off each day. A new pump with an on-off switch is now installed and the pump is currently operating. Although the proper use and care of the pump has been explained to the farmer, the array does not appear to be kept clean. Now that the farmer is beginning to work more diligently on the farm and is depending more heavily on the pump, his care of the equipment may improve. The pump continues to be monitored by the ERC.

The test results at one site are not sufficient to draw too many conclusions about this pump. There have been several design problems related to the siting of the pump in the Nile, with its flow velocity and sediment content. The total water delivery is limited by the small maximum array size that can be used. This reduces the cost of the system but also reduces the water that can be pumped.

A brief summary of solar pump testing is given in Table 5.5.

5.4 Wind Pump Sites CWD 5000 Wind Pump

The CWD 5000 was first designed in 1982-83 by Consulting Services Wind Energy Developing Countries (CWD). Early versions of the machine were installed in Mauritania and Cape Verde. The design was modified after field experiences at these sites. As part of the Sudan Wind Energy Project, a bilateral project funded by the Dutch, Ten CWD 5000 wind pumps were imported for demonstration and test by the ERC. Another two machines were commissioned for fabrication by local machine shops. The CWD design philosophy was to produce a wind pump for low head pumping applications which could be built in developing coun-

Table 5.5 Summary of Solar Pump Tests

Site Name	Array (W_p)	Head (meters)	Avg. Solar Rad. (kWh/m^2/day)	Avg. Output (m^3/day)
University of Gezira	1200	21	5.4	31.8
Hodieba Research Ctr.	840	11	5.7	38.6
Foja	903	38/24	5.6	21.0
Sheraim El Karamsha	903	38/24	–[1]	–[1]
Shambat	360	7	6.2	35.7

[1] Insufficient data available at this time.

tries. A low solidity, eight-bladed rotor is direct coupled to a specially designed piston pump. This pump is fabricated with a small leak-hole to facilitate starting and a continuously replenished air chamber (by a small air pump driven by the windmill). This air chamber design is necessary to dampen the shock loadings inherent in the high speed reciprocating pump cylinder used in the design. Detailed specifications appear in Appendix F. The ten CWD 5000 wind pumps were installed in and around Khartoum prior to 1987. One of the locally made machines was also installed. One of these 11 machines has since been dismantled. Most of the wind pumps are pumping from about 20 meters head and utilize the model 108-D pump (4.25-inch diameter) with an 8-inch stroke. Several pumps on shallower wells are fitted with a different pump, but none of these was suitable as a test site. Three sites were chosen by ERC/SREP for testing and monitoring--Soba, Shambat, and Jebel Aulia, since they were considered the most reliable windmills in operation when testing was initiated. Site descriptions can be found in Appendix D. The test results and a discussion of these results follow in the next paragraphs.

5.4.1 Wind Pump at Soba

During the test period (from April to November 1989), daily average wind speeds ranged from 1.6 to 5.5 meters/second (m/s) at ERC's Soba Research Center, the location of the machine. Daily water delivery during this period ranged from 1 to 57 m^3/day pumped through a 19 meter head. Figures 5.17 and 5.18 show the relationship of daily pump performance and daily overall efficiency to average daily wind speeds during the period. Note that at an average wind speed of 4.3 m/s, the pump delivers about 40 m^3/day; in October, with an average monthly wind speed of 3.1 m/s, the pump delivered about 17 m^3/day. The scatter seen in Figure 5.18 is the result of the differing wind speed patterns throughout each day. The curve shows that peak efficiencies on a daily basis are in the range of 12 to 13 percent at about a daily wind speed of 4 m/s. The short-term test results (10 minute data) shown in Figure 5.19 indicate water flow rates as a function of wind speed. Note the consistency and predictability of wind pump performance at each wind speed.

These test results are at considerable variance with those predicted by CWD. The test data show that this machine's performance is only 40 to 50 percent of that predicted by CWD

(Reference 14). Differences of this magnitude are not explained easily by the more common problems associated with worn pump leathers or inadequate care. The pump leathers were less than 6 months old and the windmill has been maintained by the windmill pump team of ERC who were trained by CWD as part of the project. Correspondence with CWD suggested several possible cases for low performance such as low pump efficiency or high start-up wind speed. Low cylinder efficiency appears to be the problem. At Soba the pump volumetric efficiency is 75 percent at 5.5 m/s and falls off to 40 percent and less at 4.8 m/s and below. The volumetric efficiencies should remain at 90 percent or higher over the full range of wind pump operation. CWD advised that these efficiencies should be checked and the valves and seats treated on a lathe, if necessary. This work has not yet been completed.

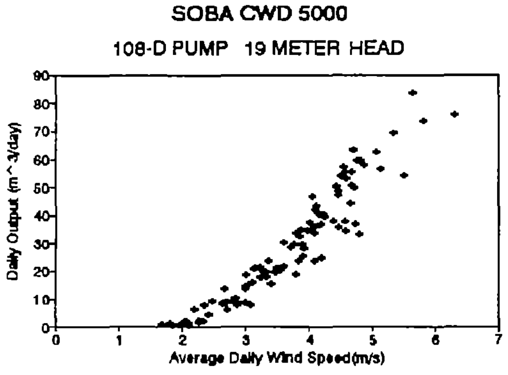


Figure 5.17

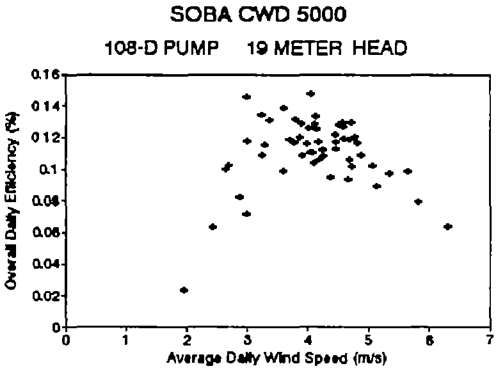


Figure 5.18

The installation and maintenance history of the CWD wind pumps indicates initial difficulties in appropriate wind pump siting, well yield, and logistics which were beyond the control of CWD and ERC. Later problems appear to be related to the design of the prototype machine. Difficulties with the piston pump and the furling cable, which seemed to plague all of the machines, were sorted out before the beginning of 1988. During the two-year period of the SREP project, this machine at Soba has not operated; on several occasions it has operated in damaged condition. In March 1988, with the machine unfurled and operating, the head frame was discovered to be broken. It took a month for the technicians to make the necessary repairs. Analysis of the first several months of test data showed that the performance was well below CWD predictions. When the causes for poor performance were investigated, the rotor shaft bearing was found to have disintegrated. The data reported above were taken subsequent to this last repair. The windmill has reportedly been greased regularly, four times a year. After early problems with the pump, the leathers have been replaced about once a year. At the time of the short-term tests, the leathers had been in place for seven months. Poor performance in spite of regular maintenance and regular repair suggests that the wind pump requires some strengthening and redesign.

5.4.2 Wind Pump at Shambat

The pump monitoring instrumentation was installed at the Shambat wind pump site in August 1989. The pump has been continuously monitored since that time with hourly values of all parameters measured. Unfortunately, very limited useful long- term pump performance data were collected as the land was not cultivated during the past growing season in spite of the farmer's promise to use the wind pump. Short-term tests have been conducted in order to characterize short-term pump performance. These results, shown in Figure 5.20, indicate pumping rates as a function of wind speed. The figures can be compared to the short-term test results at the Soba site since the wind pump configuration is the same and the pumping head differs by only 5 percent. These measured results at the Shambat site indicate performance similar to the Soba site, with wind pump start-up at about 3 m/s and a pumping rate of about 50 l/min. at 5 m/s. At this site volumetric efficiency was 81 percent at 6.5 m/s, and dropped to only 67 percent at 3 m/s, which supports the conclusion that the wind pump is not performing as it should.

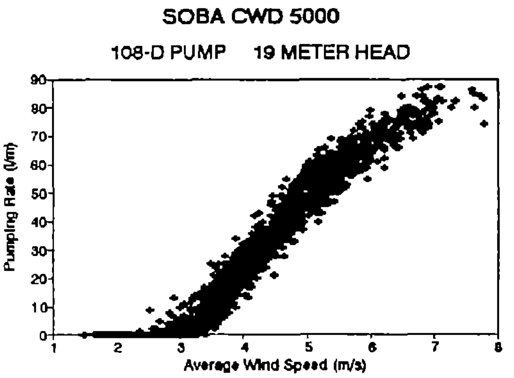


Figure 5.19

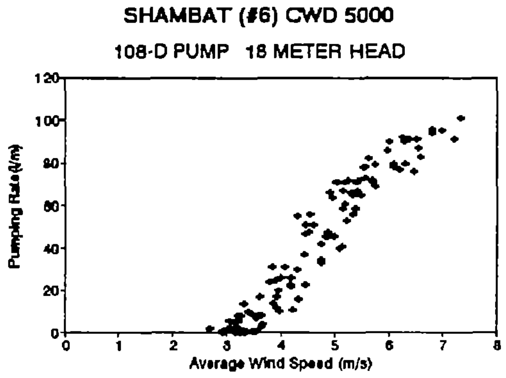


Figure 5.20

This windmill did not experience any breakdowns during the test period. The early piston problems reported at the Soba site were also experienced here and in early 1987 the piston was changed to the new air pump design.

5.4.3 Wind Pump at Jebel Aulia

The pump monitoring instrumentation was installed at Jebel Aulia in August 1989. The pump has been continuously monitored since that time. Due to a sensor problem incorrect wind speeds were recorded during the early part of the test period. Once this was corrected, the windmill tail vane broke (although the windmill continued to run) and the data collected during this period did not represent the true potential performance of the windmill. After the tail was repaired and several months of long-term data were collected and analyzed, questions again arose concerning the windmill's performance. An inspection showed that the brake was dragging and reducing output.

Short-term data were collected for several days before and after the brake failure. These test results, shown in Figure 5.21, show pumping rate as a function of wind speed. Note the scatter in the data especially above 5 m/s. These data were taken before and after the brake began to drag. The upper curve represents performance of the machine before this failure. The lower curve represents the degradation in performance as a result of this failure. Since the total pumping head is similar (21 m) and the windmill and pump design are the same as at Soba, the short-term pumping curves can be compared. Note that the cut-in wind speed is greater than 3 m/s and that the pump delivers about 35 l/min. at 5 m/s wind speeds. This indicates lower performance than at either Shambat or Soba. These results can largely be explained by the very low pump volumetric efficiency at this site. The measured pump volumetric efficiency was under 40 percent at 5.3 m/s.

This site has been plagued with difficulties. As with many of the CWD windmills, the pump has been replaced (on two occasions) and the furling mechanism needed repair. The windmill was out of service for nine weeks in early 1987 with a damaged crank and a broken head frame assembly. In late 1988, the weld on the end of the crank arm broke. This has happened at least at one other site. In late 1989, the tail assembly was damaged and the windmill was out of order for three weeks while it was being repaired. This repair history supports the conclusion that the CWD wind pump needs redesign.

The CWD windmills have been in place in Sudan for about three years. There were initial problems with the air chambers and the pumps used to supply them which caused excessive piston wear. A design problem with the furling mechanism was also discovered and corrected. In addition, the weld at the end of the crank arm had broken at two sites and the head frame assembly has been damaged at three sites. In these cases, repairs have taken up to two months. More importantly, the fact that these problems have occurred at several sites indicates that there continues to be design deficiencies with the machine. Even when installed by the CWD trained wind pump technicians, the CWD 5000 does not meet the output predictions of the CWD. If a lathe is required to improve performance, then the machine cannot easily be maintained by farmers. Considerable effort remains before the CWD 5000 could be considered a commercially viable machine.

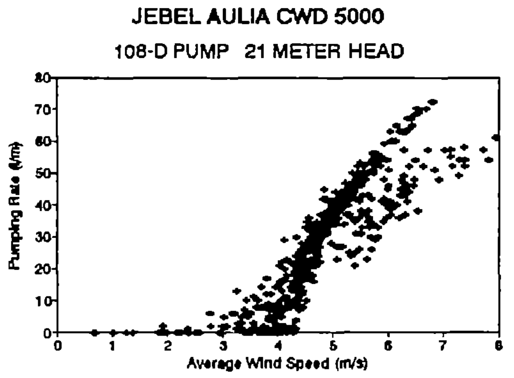


Figure 5.21

6.0 Pumping Practices and Survey Results

An understanding of current design, operation, and maintenance (O & M) practices and costs for diesel driven pumps used for village water supply and small-scale irrigation is important to the analysis of water pumping. This information has been assembled from surveys, interviews, and literature research. Since solar and wind systems have not been used extensively in Sudan to date, their longer-term O & M characteristics must be projected from available information from this program. The following sections discuss operation and maintenance aspects of diesel, solar and wind pumping systems based on a series of surveys conducted by ERC, ARD, and local consultants on:

- village water supply;
- small farm irrigation; and
- local pump and engine suppliers.

6.1 Village Water Supply

Information concerning the operation and maintenance of village water supplies was collected from several sources. The effort was initiated by commissioning a report on the overall activities and practices of the NCRWRD (Reference 5) A series of more focused surveys in selected villages in each region was planned, but project and logistical constraints prevented the series from being completed. However over 50 villages in two regions were surveyed in detail (including site visits and interviews with villagers and pump operators).

In addition to these surveys, ERC staff met with NCRWRD officials, private voluntary organizations, and donor project managers and staff. The ERC staff also conducted several informal village visits to round out their understanding of village water supplies. All available documentation on village water supply practice and cost (see Bibliography) was also studied.

6.1.1 Equipment and Installation

The installation of most village water supplies is the work of the NCRWRD. Wateryards with diesel engines are categorized by type. Type A wateryards are designed for nomadic populations with large animal watering spaces and tanks on 12-foot stands. Type B wateryards are for semi-nomadic populations. These wateryards have smaller animal watering areas, better water provisions for humans, and 24-foot stands. In areas with no nomadic population, type C wateryards are built. These are smaller than the other two with no animal watering troughs, and tanks on 33-foot stands (if possible) to allow for standpipes and/or private connections away from the wateryard. NCRWRD considers that the cost for these differing types of wateryards are nearly the same. The decrease in animal watering capability offsets the increase in the tank height.

The choice of engines and pumps used for these wateryards depends on the location, the pumping head, and the equipment supplier. As donors are currently funding most new construction, they often dictate the equipment used. There are eight to ten makes of engines in use at this point. The engine of choice for the high head cases found in western Sudan is the 6 to 8 kW Lister, preferably water cooled. There are also many Torpedo (Yugoslav), Deutz (German) and other makes in use. Eighteen to 20 horsepower Andoria (Polish), Bukh (Danish), Petter (British), and Yanmar (Japanese) are the leading engines used in Central and Northern Regions along with a smattering of Kubotas (Japanese), Lombardinis (Italian) and others. There are two major types of pumps in use. The jack pump (such as the Edeco, Adler, and Shoeller) is the most common pump in Eastern, Kordofan, and Darfur regions and is driven by the smaller 6 to 8 kW engines. Vertical turbines (such as the Grundfos, Rotos, Nemitsas, and Kato) driven by bigger engines are common in Central and Northern Regions. There are some Mono pumps in use in Central Region and more recently in the Western Region as well. The Lister-Edeco, the Torpedo-Shoeller, and the Bukh-Grundfos are common pumpset combinations. Costs for these pumpsets depend on the source (local purchase or offshore purchase by donors), make and model of engine and pump, and the depth setting of the pump. Current local prices range from 120,000 to 200,000 Sudanese pounds (S£). Elevated storage tanks, usually 11,000 Imp. gallons (50 cubic meters) are used for most village water supplies. These are round or rectangular steel tanks. Locally manufactured tanks (either made in NCRWRD shops or by the private sector) cost about S£100,000. Imported sectional steel tanks are roughly twice the cost.

The pipes, fittings, and construction materials (cement, steel re-enforcing bar, fencing, pump-house, etc.) are often bought locally. The costs for these items (particularly when imported) have increased considerably over the last year. As of the end of 1989, the estimated cost for these items was in the range of S£65,000 to S£140,000.

Labor for installation is provided by a crew of 20 (when fully staffed). Installation takes about a month to a month and a half per site. This does not include the drilling, development, and testing of the borehole. It does include the installation of the engine, pump and all piping within the wateryard; erection of the water storage tank; building taps, animal watering troughs and soak-aways as appropriate; building the pump-house and other structures for the wateryard clerk and pump operator; and fencing the wateryard. Any water distribution outside of the wateryard perimeter is not included. The labor cost breakdown for a one month installation is roughly S£7,000 skilled labor and S£4,000 unskilled.

Transportation requirements for installation are calculated from the nearest installation center. There are 12 such centers located in the Northern Sudan at the provincial level. Transportation needs include the use of: a big truck (15 to 18 tons) to carry the tank and major materials (3 trips at roughly S£20 per kilometer), a seven- to eight-ton truck (six to eight trips at about S£12 per kilometer) to bring the remaining supplies, work crew, and a smaller land cruiser-type vehicle (three trips equivalent at S£6 per kilometer). These figures have been confirmed by NCRWRD offices in four provinces.

6.1.2 Operation, Maintenance, and Repair

The operation of village water supplies depends on a number of factors, including location and configuration. Village water supplies are operated in several ways. Most commonly (particularly in the western areas) an operator is paid by the NCRWRD. In the past, operators were hired, trained, and assigned to a village without much concern about the operator's home village or region.

Currently, potential operators are identified from within the village population, sent to Khartoum for training, and returned to their villages to work. Operators are paid in the range of S£1000 per month (including roughly S£300 of allowances). In locations where the NCRWRD collects fees, a clerk is also hired at the same salary level as the operator. In some villages guards are also hired at the rate of S£800 per month (including S£300 of allowances). In the Northern Region and in some areas in Khartoum Commissionarate and Central Region only an operator and perhaps a guard are hired. Salaries are paid by NCRWRD. Fees are collected, often per household, by the treasurer for the water committee or a hired fee collector.

Wateryard operation requires that the operator run the engine and perform normal maintenance (changing oil, etc.). Normally, more complex maintenance and repair are supposed to be performed by mechanics from one of the 35 rural maintenance workshops. These workshops are supposed to be equipped with facilities to perform engine and pump overhaul, and to send mechanical crews for on site engine and pump servicing. In fact, these workshops are not capable of fulfilling their role. They lack adequate vehicles; have few spares; and without the necessary spares, much of the major workshop equipment does not function properly. In practice the workshops provide skilled mechanics with an array of hand tools.

At the village level, very little maintenance is performed. When breakdowns occur (three times per year on average as defined by the villagers), assistance may be requested from the rural workshop. However, villagers recognize that they must often arrange transportation and obtain the needed spare parts on their own. In order to do this, many villages have organized themselves and collect a surcharge above the amount collected by the clerk. This provides a fund for purchasing items not available from the NCRWRD.

When a breakdown occurs, the normal sequence of events is for the villagers to go to the workshop and ask for assistance, whereupon a mechanic goes to assess the situation and tell the villagers what parts are needed. These will be obtained in the local market or a regional town, if possible, and the mechanic will return to make the repair. This process takes an average of eight days, but occasionally may take weeks or months depending on the availability of the required spares. The NCRWRD survey results indicate a fairly high percentage of equipment operating (80 to 90 percent) given this maintenance and repair process. However, a visit to a rural workshop revealed that 40 percent of the pumpsets were out of order at the time. About half of these needed what was termed minor work; the remainder had been abandoned, needed new pumps, or needed major engine work that could not be accomplished for lack of specialized spares or tools. It appears that those out of order for longer periods are not considered by NCRWRD in the determination of operating wateryard percentages.

Engines last 10 to 12 years which is somewhat longer than expected given operating conditions. Many are certainly old and beyond what would normally be considered their working life, but these engines remain in use because there are no replacements. One of the arguments used to defend the Edeco pumps is that they will last 20 years. This may be so, but observation of operating pumps reveals that long before this many were badly in need of major overhaul and replacement.

Obtaining and paying for diesel fuel and lubricants are particular problems in the operation of village water systems. The "average" village (pumping 50 m^3/day) uses 1,500 to 2,000 liters of fuel annually. Under ideal circumstances, the NCRWRD regional or provincial offices would provide fuel as part of the service rendered for the fees paid by villagers. However, fuel allocations are often late and are insufficient for the overhead and construction activities of the regional offices. Villagers are almost always left on their own to obtain fuel. The surcharge funds collected by the clerk or the villagers themselves are used to pay for fuel and lubricants. It appears that fuel is almost always available, but sometimes difficult to find, and the cost may be as much as ten times the official price.

During late 1989 and early 1990, a period of extreme diesel shortage in Sudan (SREP had no fuel for its field activities during this time), reports from rural areas showed that most wateryards continued to operate albeit with grave concern about where the next fuel would come from. During this period, lubricants appeared to be a greater problem, and scheduled oil changes were delayed or cancelled.

Although the NCRWRD does procure spare parts locally and abroad to meet the needs of the wateryards, it is unable to purchase and distribute enough to meet demand. This leaves many villages with the responsibility of purchasing their own spare parts in the marketplace. Fast moving spares (even pistons and cylinders are so considered) for engines and pumps common to the area are usually available. Occasionally spares will be fabricated; frequently more complex arrangements are necessary to obtain spares from Khartoum or even overseas. This, at least partly, accounts for long delays in repairs. The spares situation is not likely to improve in the near future as the government continues to restrict imports. There are reports that some spares are being smuggled in larger quantities from across the Red Sea. The annual cost of spare parts is a function of the engine and pump make and model as well as the age of the pumpset. Older pumpsets are likely to have more breakdowns and higher spare parts costs. The NCRWRD estimate of S£10,000 annually for wateryard spares is considered a reasonable estimate for a wateryard of average age. Skilled mechanics are available from NCRWRD workshops. In most cases, villagers will solicit assistance from them after they have made an attempt to remedy the problem themselves. However, in some areas the workshops are far from the villages and local mechanics are pressed into service. The NCRWRD says that once all other avenues are exhausted and the problem often exacerbated by local attempts at repair, the villagers arrive and expect service from NCRWRD mechanics. This is undoubtedly true in some cases, but it may also be NCRWRD's belief that villagers do not understand engines and pumps and only make the situation worse with their meddling.

The NCRWRD has severely limited transportation capability. Typically, a rural workshop will have three or four vehicles, only one of which is working at any one time and that one is not reliable enough to send cross-country to service a wateryard. This leaves villagers to arrange transportation to and from the village, and to the workshop and market (to get spares or fuel).

Transportation costs vary considerably depending on the distance and mode of transport. In some cases, a villager with a vehicle is willing to provide transportation at little or no cost in the interest of helping the village. In other cases, a bus or even a privately hired car is necessary. Costs vary from S£25 to S£1500 per trip (average about S£300), typically with three to five trips necessary to effect one repair.

Total maintenance costs include spares, transportation, and labor. The annual spares cost has been variously estimated from S£6,000 to S£10,000. Transportation costs are variable. A reasonable average annual transportation cost is about S£3,600. Labor costs, assuming that NCRWRD mechanics are used, are in the range of S£3,000 to S£5,000 annually assuming that two trips are required for each repair. Including overhaul costs of S£1,700 annually (which are not a part of the above figures), the annual maintenance costs per pumpset is in the range of S£14,300 to S£20,300, (roughly ten percent of the original pumpset cost). This is not an unexpected figure given the age and condition of most wateryard equipment.

6.2 Small-Scale Irrigation by Private Farmers

Information on the operation and maintenance of diesel pumps used by farmers for irrigating small plots was assembled from a number of sources. The effort was begun by commissioning a report on the activities and practices of small-farmer irrigation and their geographical locations (Reference 17). This report identified areas where follow-up surveys of individual farmers were to be conducted.

More than 100 farmers in several areas were surveyed in greater detail to determine how they operated their engines to provide the irrigation water they required. In addition to these surveys, ERC staff met with Ministry of Agriculture staff, private providers of equipment and maintenance, donor project managers and staff; ERC staff also conducted several informal visits to farms to confirm certain points. In addition, all available documentation about small-scale irrigation in Sudan was studied. These documents are referenced in the bibliography.

6.2.1 Equipment and Installation

Most small diesel irrigation systems are purchased by the farmer and installed with the help of a more skilled mechanic. Small petrol pumpsets are not in common use although they are available. The engine, pump, and several lengths of distribution pipe are often purchased as a package. The farmers refer to their pumpsets by the size of the discharge pipe, hence irrigation pumps are 2-, 3-, 4-inch, and larger. Many of these pumps are used along the Nile (both White and Blue). They are bolted to metal or wooden skids along with the surface centrifugal pump they drive (with short belts); this allows them to be moved with the seasonal rise and fall of the river. The intake to the pump is often a length of flexible hose with a large strainer on the end which is placed in a hollowed out location in the river bank. The water conveyance system is usually a series of open channels with openings leading to fields or small plots. Water is pumped through several lengths of pipe from the pump location to the main channel. The number of sections vary as the pump is moved with the level of the river. In some areas with higher banks, the engine is more permanently placed, sometimes with a solid pipe arrangement on the suction side of the pump.

In areas slightly away from the river and in other more scattered areas, water is pumped from open wells to irrigate small plots. In these cases the pump and engine are likely to be separated, with the engine located on the surface near the top of the well and the pump at the bottom. The pump is then driven by a series of long belts (see Figures 6.1 and 6.2).

Figures 6.1 & 2. Diesel pump on shallow open well monitoring site near Wad Medani

Occasionally, both the pump and engine are placed at the bottom of a large diameter well. Water distribution is similar to that described above.

Engines and pumps used for small-scale irrigation are almost universally the Indian Lister type. These engines are copies of the slow-speed, water-cooled British Lister engine. They are either 6 or 8 horsepower running at 500-800 RPM and manufactured by Mercury, Lovson, Alfa, Kumar, Ameer and others. There must be more than a dozen makes of these engines in use. Some are better than others with higher quality bearings and closer tolerances. These engines are widely available on the open market for S£10,000 to S£12,000 as compared to S£45,000 for the Lister-Petter PHW-1. A few other engines makes, including a Chinese model, are in use as well. About 40 percent of the engines used for small-scale irrigation are being supplied through Agricultural Bank of Sudan programs and other bilateral and multi-lateral rural development projects.

The surface centrifugal pumps in common use originate in Italy, Cyprus, and many other countries. It has been reported that a few of these pumps are also made in Sudan. These surface centrifugal pumps are inexpensive at S£1,500 to S£2,000 each. Water storage tanks are not commonly used as part of these irrigation systems.

The pipes and fittings cost from S£2,000 to S£10,000 depending on the complexity and length of the piping systems. More complex irrigation distribution systems with extensive branched pipe networks are even more expensive. No effort has been made in this study to quantify the cost of channel construction. Installation is usually completed by a mechanic working directly for the farmer and assisted by the farmer himself. The installation usually takes several days. The labor costs quoted in the farmers' survey for installation averaged S£1,800. The quoted costs varied widely depending on the complexity of the piping systems and the labor contribution of the farmer.

Transportation requirements for a small pumpset are minimal. A light duty pickup truck is often used if the roads are adequate. Shipping from a larger town is likely to be arranged by suq lorry and costs anywhere from S£0.50 to S£2.00/kilometer/kg. The pumpset weighs about 200 kg so they can be transported in a smaller pickup truck if the truck can reach the site.

6.2.2 Operation, Maintenance, and Repair

Farmers usually operate their pumpsets themselves without a pump operator. The pump is not used regularly. During the growing period, water is pumped every second or third day; the engine is used from four to six hours each time depending on the water requirements and the area under irrigation.

The farmer usually performs whatever normal maintenance (e.g., changing oil) is done. From the observed condition of most of these pumpsets, farmers do very little maintenance and have little or no training in proper operation. Typically both the exhaust and the air filters are removed. Cooling is accomplished with a straight-through system (rather than with a recirculating coolant) which causes high temperature gradients in the engine, leading to short component life. Even pistons and cylinder blocks are considered fast moving spares. This provides some understanding of the treatment these engines get. Farmers also perform what minor repairs they are able to, often using bits of rag, wire, or string to hold components in place and keep the engine and pump operating.

When more serious problems occur, the farmer will seek a mechanic (Figure 6.3). Minor overhauls are often performed in the field with pistons, valves, or cylinder heads being replaced by the mechanic with a set of tools which includes a hammer, several screwdrivers and a couple of wrenches. The ingenuity of these mechanics and their ability to get an engine running again cannot be questioned. However their formal training is often inadequate to the task of making proper repairs to the engine. Spare parts for the Indian Lister appear to be readily available. Specialized spare parts dealers in large towns are usually well stocked and small merchants in rural areas stock some of the most commonly needed parts. Even in the far reaches of the Nile in the Northern Region, the availability of spares for these Lister copies was not cited by farmers as a problem. However, they did complain about price. The charges of S£40 for an injector nozzle, S£80 for a piston (including rings), and S£385 for a cylinder block are still 20 percent of the cost of equivalent genuine Lister parts.

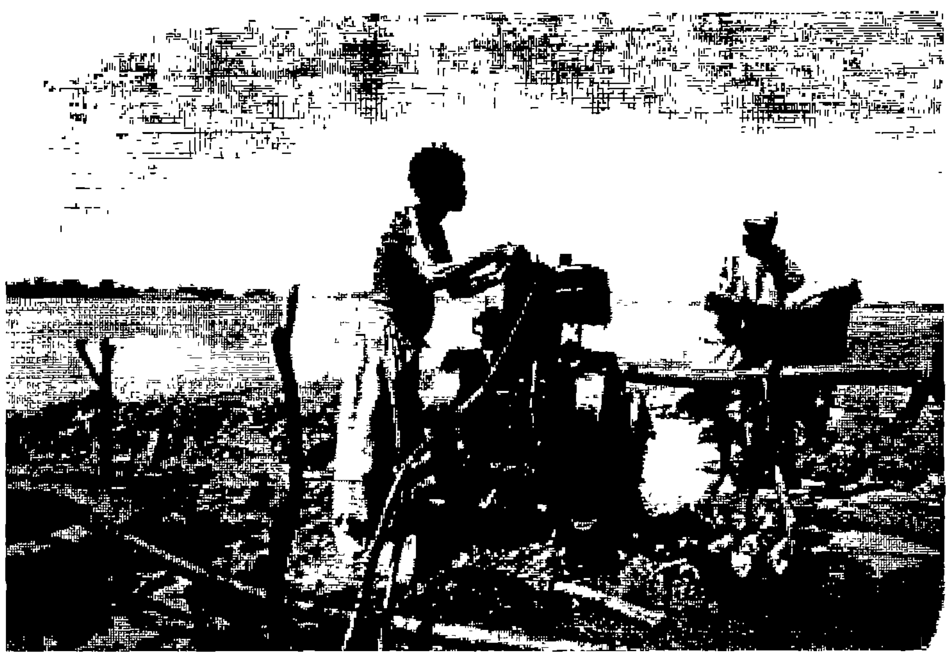


Figure 6.3. Diesel pump mechanic making repairs on Indian-made diesel engine at Um Dum.

According to survey results, the breakdown rate for pumpsets averages 1.5 per year with a standard deviation of 1.5. The average outage period was quoted at eight days. These results indicate that farmers probably do not consider minor breakdowns that can be fixed on the spot or within a day to be breakdowns. The survey indicates that farmers spend S£1,050 annually on spares (including "overhauls" done in the field). The figure is roughly twice this in areas outside major settled areas. Annual labor costs for maintenance and repair were given as S£400, and transportation costs were given as S£125. The total maintenance cost reported is then about 14 percent annually of the cost of the pumpset. Given the care the engines receive, this is not a surprising finding.

As with engines used for village water supplies, these engines last about 10 to 12 years, somewhat longer than expected given operating conditions. Many are certainly old and beyond what would normally be considered their working life, but lack of replacement engines requires their continued use.

6.3 Suppliers' Surveys

The purpose of the supplier's survey was to determine what pumping equipment (including engines, pumps, spares, and related piping and fittings) were available; how pump users obtained these items; and what these items cost. This was accomplished by visiting suppliers, requesting current prices, and asking about current availability of equipment and spares. Other sources of information were several NGOs working in the water sector that could provide recent quotes, and NCRWRD officials who are involved in budgeting and equipment purchase. A supplier's survey report, *Water Pumping Equipment Suppliers Survey* (Reference 45), is available.

There are less than ten active importing agents for pumps and small diesel engines in Sudan. Currently, the most active are Dal Engineering Co. Ltd. (Lister-Petter), Ibrahim Abu Hussain Co. Ltd. (Indian Lister), Hussain Abu Musa Co. Ltd. (Andoria), and Kurdi Engineering Ltd. (Indian Lister). These four agents are the only ones with sub-agents in the larger towns outside Khartoum (in the Kordofan, Northern and Central Regions). Foreign currency restrictions continue to be a pressing problem for most agents. Those who handle Indian and some European brands appear to cope more easily with the situation. This seems to be the result of demand from the private sector and Agricultural Bank of Sudan (ABS) activity. Donor funds support the offshore purchase of pumping sets and spares. This support includes concessions to the local agents for the makes and models of equipment purchased by the ABS. A number of agents are currently inactive (Lombardini, Yanmar, Kubota, and several others) as they have no ability to obtain the hard currency required to import equipment or spare parts. Even the active agents (except the Indian Lister dealers) do not report a large stock of spares.

Engine spare parts, particularly for the Indian Listers, are available outside Khartoum. Merchants in towns and villages will carry some these items (purchased from an agent or subagent) if they believe that there will be a demand. Prices are considerably higher than in Khartoum. For example, prices in Atbara for pistons, cylinder blocks, and injectors for Indian Listers were 50 to 60 percent more than in Khartoum. The availability of engines and pumps depends on the ability of agents to import these items. During 1988, the agents surveyed reported sales of single cylinder engines at 9,500 units. The current inventory for these agents is less than 600 units or less than one month's demand at 1988 levels. The current estimated delivery time is three months if import permits and hard currency are available. This indicates a significant reduction in capability to meet demand. As to be expected, prices are increasing quite rapidly.

Two factors complicated efforts to determine prices of equipment. These were the recent rapid escalation of inflation rates and the lack of current inventory. Consequently agents provide only rough price estimates, which vary according to when the next consignment of equipment arrives and what the cost turns out to be, including duties, taxes, and handling charges. Firm quotes can be obtained, but will often be higher as a result of the businessman's need to protect himself financially.

There are a number of agents handling the Indian Lister makes in Khartoum and elsewhere. These engines and the pumps they drive are readily available in the marketplace. There is a ready market for them, and they are popular with farmers who are often able to pay cash to the supplier. Farmers are also more confident than with other makes that spare parts will continue to be available at cheap prices.

The current economic and business climate in Sudan results in very variable engine and pump pricing, and pump availability. The ABS now appears to be the main suppliers of these engines as the supply of equipment in the private sector is limited. The pumpsets available through the ABS are also very inexpensive; they are priced in local currency at the official exchange rate. This amounts to a subsidy to the buyer of the difference between the official and market exchange rates. Estimates are that 90 percent of the equipment currently being supplied to small farmers comes through the ABS. The major equipment suppliers have provided equipment (including spares) to the government (including the NCRWRD) through the local tender process. However, the current major source is donor projects which procure equipment overseas, often with source requirements (i.e., "tied-aid") which cause longer term problems for the government as a result of incompatibility with existing equipment, spares unavailability, and additional training needs.

6.4 Wind Pumps

No firm figures for the manufacturing of the CWD 5000 or its operation and maintenance costs exist. No larger scale manufacturing effort has been initiated so the purchase price of a Sudanese-built machine is unknown. To date, all ten machines initially installed in Sudan have been maintained by the ERC Pumping Team. Although these windmills have been in place for more than three years and maintenance records are in good order, not enough information is available to estimate the longer term, steady state maintenance cost of a reliable wind pump. The following sections discuss of windmill manufacturing and maintenance costs.

6.4.1 Manufacture and Installation

The ERC has been involved with the Dutch program for promoting the local manufacture of the CWD 5000 since its inception in 1986. As the initial goal for the program was local manufacture of the windmill, the ERC/CWD program developed production and cost estimates of the manufactured product. In 1986, the Sudan Wind Energy Project estimated that the manufacture of the windmill would require 223 hours, with the manufacture of the pump taking roughly 20 hours. At current rates, the labor component of windmill manufacture would be about S£6,000.

In 1986, the materials' cost for the fabrication of the windmill was roughly US$2,500. At an estimated ten percent inflation in the international price of steel, the late 1989 off-shore price would be US$3,500. At the official exchange rate, the local materials' price would be S£15,750. At the commercial exchange rate of S£12.2 = US$1.00, the cost would be over S£42,000. Allowing for private sector overheads and profit (currently about 30 percent) and depending on the exchange rates used and import duties, the total price of the windmill and pump will be S£35,000 to S£80,000. Note that the labor component of the selling price of the wind pump is well under 20 percent regardless of how the materials' costs are calculated.

Installation costs can be reasonably estimated from the installation of the CWD 5000s in late 1986 and early 1987. During the original installation a crew of 11 was used and installation took longer than a week per site. This level of effort was the result of the training aspect of the exercise. Pumping team members estimate that a reasonably trained crew of five could erect a windmill in three to four days, not including ten person-days for fabricating the foundation. This does not include building the tank or any additional piping or fittings on the tank discharge. The estimated cost for windmill installation is S£13,000 to S£15,000.

6.4.2 Windmill and Pump Maintenance

There are ten CWD 5000 windmills currently installed in and around Khartoum. Of these systems, two have been out of service for a long time because of well problems. By the end of 1989, the total operating experience with the wind pumps was 34 months. Over this period the pumping team completed four scheduled maintenance trips per year per machine. Several trips were required to address additional maintenance requirements, retrofitting parts, and making repairs. After initial problems requiring the installation of redesigned pumps and adjustment of the furling mechanism to new specifications, roughly 1.2 trips per year per site were required, in addition to the preventative maintenance trips. Assuming that only one day trips are required on average (for wind pumps located near urban centers) and that three technicians and mechanics participate in each trip, the labor cost annually for each wind pump is in the range of S£800. Transportation cost is dependent on what vehicle is used and the distance that must be travelled. The sites in and around Khartoum are not typical in this regard, being close to the repair center. Assuming the use of a light vehicle and a 100 km round trip, annual transportation costs will be in the range of S£650. Note that both installation and transportation costs will be less for farmers due to the use of local labor (often the farmer himself) and more efficient use of transportation.

In most cases, the materials' cost for each repair trip has been minimal. However, the major repairs needed at several sites required new bearings, and repairs to the head frame. Given that several of the sites have suffered major breakdowns of the connection between the rod and crank and the headframe assembly, there is considerable concern about the long-term reliability of these windmills. The recent discovery at Soba that the bearings were deteriorating adds concern about what other weaknesses may emerge over the next months or years. The use of the windmills in and around Khartoum to test their longer term reliability is a worthwhile activity in order to gain information for design modifications. However, in its current design, the wind pump is clearly not ready for commercial production.

6.5 Solar Pumps

As with wind pumps, experience with the operation and maintenance of solar pumps in Sudan is fairly limited. However, the ERC participated in the installation of the two oldest operating solar pumps in Sudan which were installed in 1983 at the University of Gezira and at the Hodieba Agricultural Research Station. Complete records of the required operation and maintenance for these sites have been kept by ERC. In addition, personnel at these two sites have been interviewed. ERC has worked in collaboration with the Swedish Sudanese Friendship Association which installed the two solar pumps tested north of Bara. The more recent installation at Shambat is completely the work of the ERC. The summary experiences with these installations provide the basis for a discussion of the operation and maintenance requirements of these systems.

The current capital costs for solar pumps are readily available from the European and American manufacturers. Shipping, customs duties, taxes, port clearance, and handling charges must also be included in price estimates. The installation cost requirements were estimated based on the recent installation of a Grundfos pump at the Soba site by the GTZ-funded SEP project.

6.5.1 Procurement and Installation

Several early solar pumping systems were provided to the government of Sudan by the pump manufacturer. These systems are the two that are currently installed at the University of Gezira and the Hodieba Research Station. All other solar pumping systems have been provided by donor governments or projects funded through donors. Procurement of these systems has taken place offshore with the donor paying the hard currency costs directly to the pump supplier and then arranging for delivery to the Sudan. The Grundfos agent in Khartoum (United Engineering Ltd.) has at least one technician trained in PV pump repair and maintenance of the unit. This agent has not made a direct sale to date, and does not stock solar pump spare parts as the cost of maintaining this slow moving inventory is high.

Late 1989 price quotes for the complete Grundfos pumping systems used a solar module cost of US$5.00 per peak watt ($W_p$), not including shipping and handling costs. Estimated delivered in-country module cost is US$5.50/$W_p$. The Grundfos pump costs roughly US$5,000 with an estimated US$250 added for shipping and handling, customs clearance, and other charges. The KSB unit cost totals US$2,000 including all of these charges. Additional costs for array structures, wiring, and related hardware adds an additional ten percent of the total array cost. Additional installation materials including cement and aggregate for the foundation and rising pipes, and fittings for the pump and piping systems cost about S£50,000. All other costs depend on the specific application, water storage and distribution needs.

The installation of solar pumps is quite easy and straightforward. A typical example, the installation of the solar pump at the new site at Sheraim El Karamsha, is shown in Figure 6.4. A foundation must be built to hold the array and array structure; the components are then bolted together. For borehole pumps, the submersible pumpset is screwed onto the drop pipe and lowered into the borehole along with the power cable. One person skilled in this process can direct a team of four and install a pump in three to four days. In the case at Soba, an ERC team of four installed the pump in three days. The labor cost of this process when performed by the NCRWRD will cost closer to S£2000. For village applications, this does not include the cost of installing any other wateryard components such as tanks, distribution lines, and taps which will increase costs to near diesel installation levels. The transportation requirement for installation will include a medium truck to carry the cement and aggregate as well as the pump and solar array. An installation requiring two round trips to a site 50 km from the service center would cost about S£1,500. As for wind pumps, solar pump installation will cost more when performed by the NCRWRD.

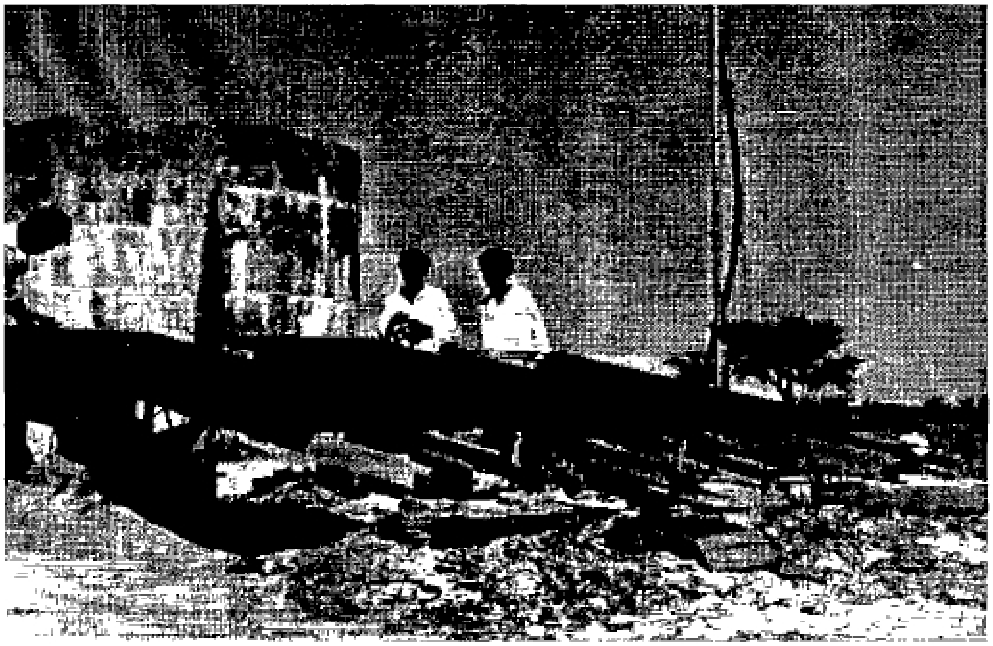


Figure 6.4. Newly installed solar pump at Sharaim El Karamsha with ARCO M-75 modules and Grundfos pump.

6.5.2 Operation and Maintenance

One of the primary arguments made in favor of solar pumps has been that they are nearly or completely maintenance free. The argument stems from the lack of moving components in the solar array and the possibility for a high degree of reliability in solid state electronic control circuitry. Without question, the solar modules themselves provide trouble-free operation. However, for maximum performance, the array must be cleaned periodically. This is particularly true in the dusty environment of most of Sudan. The other major array maintenance problem is the damage of modules by vandalism. In some places this has been a major problem. However, in Sudan, over the period of installation of the five solar pumps under test (358 months of module exposure) only two modules have been broken. This means that one module per array must be replaced every seven years or so, at a present value cost of roughly S£825 (at the regulated commercial exchange rate) annually.

Historically, the weakest component of most solar pumps has been the pump controller and any power conditioning required. The experience with these components for the test pumps was exceptional. For the Grundfos systems, one US$80 switch was replaced over 17 years of pump operation for the 4 units. An estimated spare parts' cost of S£500 per year has been assumed. The lifetime of the pump component of the solar pump systems is not likely to exceed the normal lifetime of a submersible pump. These lifetimes are estimated to be in the range of five to ten years, dependent on such factors as the quality of the water.

Two of the test sites are already within this age range and continue to operate without difficulties. It appears that there is some deterioration of pump performance over this time, but the reasons for this may not be the result of pump wear but other factors such as increased pipe friction as a result of the age of the rising pipes. For the purposes of the present analysis, a ten-year pump life is assumed.

6.6 Summary and Conclusions

The total installed cost for a typical village system is more than 40 times that of a comparably-sized small irrigation system. Much of this difference is additional wateryard equipment including storage tanks, water distribution facilities, fencing, pump house, and related items. These are not needed for small irrigation systems, and farmers seldom build them. However, there is also a significant difference in the cost of the pumping equipment used. Villages need a reliable system capable of long hours of operation pumping from boreholes as contrasted to a farmer's need to pump water on a less regular basis from shallow wells or a river. These differences dictate different engines and pumps.

Current economic constraints for pumping equipment, fuel, and spare parts cause both individual and government water systems to be less than reliable. Very little, if any, preventative maintenance is performed on either government or private sector pumps or engines. Much of the equipment is old and ready for replacement, but conditions dictate that the equipment must continue to be patched and used. This results in high maintenance and repair costs and more frequent breakdowns.

The maintenance and repair mechanisms, particularly for village systems, are largely reactive and adaptable to prevailing conditions. As long as the maintenance and repair needs are moderate, they can be addressed; in many cases minor problems and short outages are not even considered breakdowns. As soon as the problems become technically complex or expensive, the situation becomes overwhelming. When these conditions arise in a village setting, the villagers are likely to petition the NCRWRD for more active involvement.

Although much has been made of the chronic shortages of fuel, all indications are that fuel is usually located. However, this may require considerable cost and effort on the part of the villagers.

Solar pumps offer the promise of respite from fuel requirements. The Grundfos solar pumping systems, operating at the moderate pumping heads measured at the field test sites, have proven to be very reliable. This finding is in line with the results of other testing programs.

Some module breakage and the need to organize the regular cleaning of the array are the most pressing maintenance and repair issues. However, for a village water system the off-shore costs of these solar pumps are more than twice the cost of a diesel pump designed to match the pumps' output.

The KSB floating pump tested performed reasonably when operating, but had several very expensive breakdowns. Limited experience with the newer design (with the on-off switch) restricts conclusive statements. However, the design appears to be unsuitable for village water supply use and must compete with the inexpensive Indian Lister pumpsets. This is likely to be difficult within a group of users who are sensitive to initial cost.

Experience with the CWD 5000 windmill is sufficient to draw several conclusions. The repairs required to keep these windpumps operating are beyond what should be expected of a commercially viable machine. The design clearly needs reworking and refinement before it is suitable for Sudanese conditions. Currently there is no active program to build the machine in Sudan as originally planned, so the advantages of local manufacture and local skills' development cannot be realized. There is little question that the eventual sale price of a redesigned and commercially available wind pump will be considerably higher than the cost of the Indian Lister against which it must compete for a share of the market.

There are three Kijito wind pumps now installed near Shendi and in the early phases of evaluation. This design, proven in applications in other countries, is worth a closer look in Sudan. However, the sale price of the 20-foot diameter Kijito is likely to be in the range of US$12,000 or over S£140,000 (at the 12.2 exchange rate). Even if manufactured in Sudan, it will be more expensive than the S£50,000 estimated for the CWD 5000 as a result of increased material in the machine.

The following chapter examines the financial and economic implications of diesel, wind and solar pumping systems in detail.

7.0 Financial and Economic Analysis

In this chapter, the results of the testing program and the three surveys on pumping practices and costs are analyzed from both economic and financial perspectives. As mentioned in previous chapters, there are clear technical limits to the use of solar and wind pumps. Above certain head and water demand levels (discussed in the previous chapter), neither wind nor solar pumps are able to meet the pumping requirements, and diesel is the only option for rural village water supply or small-scale irrigation sites. There is little point in analyzing those high-demand or high-head cases further. Rather, the following sections look carefully at those limited situations where wind and solar pumps can meet water demand, demand which is currently being met using diesel pumps almost exclusively. In the low-moderate head and demand situations where all three systems are technically feasible, costs become the primary (but not the only) selection criteria. The methodology for calculating comparative costs is described in Section 7.1. Data sources are described in Section 7.2.

To do the comparative analysis, "base cases" or representative sites are defined for each of two type of systems - one village water supply and one small-scale irrigation system. Major characteristics of each base case system (primarily pump performance and energy resource characteristics) are described in Section 7.3 below. Detailed capital and recurrent cost breakdowns for the base cases are given in Appendix H. The results of the financial and economic analysis are described in Section 7.4 (for village water supply) and 7.5 (for small-scale irrigation). Sensitivity analysis is done to identify critical variables in the analysis, and to determine the effect of changes in those variables as assumptions about pump performance and costs vary.

7.1 Methodology

The financial and economic evaluations of pumping systems are based on present value analysis as outlined in *The Handbook for the Comparative Economic and Technical Performance of Water Pumping Systems* (Reference 19). The objective of this analysis is to provide comparative life cycle costs (LCC) for diesel, solar and wind pumps in various applications. These costs can then be used to help choose an appropriate pumping system, and to develop relevant system support programs. This discussion does not include a complete cost benefit and internal rate of return analysis, but such calculations are important for broader programmatic and policy decisions involving other sectors of the economy. Determination of the benefits stream for rural water supply and small-scale irrigated agriculture is beyond the scope of the present work.

In present value analysis, all costs unique to each technology are determined. In addition, expenses (such as well or borehole cost) incurred regardless of the technology choice are included for a complete site-specific cost picture. Life cycle cost analysis separates initial capital costs (i.e., the complete cost of purchasing and installing system) from recurrent costs. Initial capital costs are divided into four categories: materials (including equipment), labor (skilled and unskilled), transportation, and well development costs. Recurrent costs are divided into annual recurrent costs (such as spare parts, skilled and unskilled labor, transportation, and fuel) and non-annual costs (such as periodic engine overhauls or pump replacement). The stream of recurrent costs is discounted to its present value. The total life cycle cost is then the sum of the initial installed capital cost plus the present value of all recurrent costs. A 20-year term of analysis is used, with various system components requiring replacement from time to time. The water delivered by each system is also discounted, in accordance with Reference 19. This makes no significant difference in the analysis, since were it not discounted, the relative order of system costs would still remain the same.

To be properly compared, different pumping systems must operate under similar conditions, which means they must pump roughly the same quantity of water through the same pumping head. This allows the computation of a normalized "unit cost" of water (cost per cubic meter of water pumped at a given head, in S£/m^3) for each technology.

Financial analysis deals with actual payments made by pump users over the lifetime of their system. It incorporates various distortions in the overall economy, such as overvalued foreign exchange rates and fuel subsidies. Economic analysis recognizes factors which are of interest to the national economy, but which may not be reflected in the financial cost. These factors include a premium on imported goods (as they cost the economy in terms of foreign currency) and unskilled labor (often under-utilized and priced in accord with the economic cost to society). Taxes, duties and other internal monetary transfers included in the financial analysis are excluded from the economic analysis. Although they are appropriate to the financial analysis since they are paid by system purchasers, they are not a cost to the country's economy. A spreadsheet model was developed to facilitate the financial and economic analysis. The model permits sensitivity analysis of changes in technical, financial or economic factors.

The analysis focuses separately on village water supply and small-scale irrigation. From an economic perspective, the two must be treated separately because village water supply is normally a public sector activity, whereas small-scale irrigation occurs in the private sector. Differences between financial and economic analysis are reflected in differing assumptions about discount and exchange rates. Based on information from the surveys and field tests, the base cases for water supply and irrigation also make different assumptions about pumping head, water demand, pumping rate, types of engines and pumps used, and different ways in which pumping equipment is purchased, operated, and maintained. There are also variations in cost and O&M practices in different regions of the country, as well as varying distances to equipment repair centers and fuel depots. Values of these variables will be addressed further in the sensitivity analysis in Sections 7.4 and 7.5.

7.2 Information Sources

Several methods were used to obtain reliable information on capital and recurrent costs, and economic parameters. These included a series of surveys (described in Chapter Six), a literature search, interviews with government officials, private sector businessmen and donor agency representatives, and the commissioning of several local consultancies.

The series of surveys provided information on pumping practices and capital and recurrent costs for diesel systems. Two surveys, one on village water supply and one on small farm irrigation, focused on current operation/maintenance practices and recurrent costs. The village water survey was assisted by NCRWRD personnel, and included 28 villages in the Khartoum Commissionerate and 23 villages in Central Region. The Ministry of Agriculture Extension Service assisted with the small farmer surveys. They surveyed 50 farmers in the Khartoum area, 25 near Wad Medani and 25 near Kosti. In addition, the NCRWRD officers in Northern and Central Regions, and in the area around Kordofan were asked a series of questions to establish costs for diesel systems and the potential for renewable energy applications in their regions. Sample survey questionnaires (in English) are included in Appendix G. The equipment dealers survey identified current costs for various kinds of engine and pump makes and models available in Khartoum and elsewhere in the country.

Over the last several years, there have been a number of donor supported water projects in Sudan. Some of these have issued reports with estimates of installed capital costs and recurrent costs. Foremost among them are a series of papers presented at the Conference on Sustainable Operation and Maintenance of Rural Water Supplies held in Khartoum in May, 1989. Reports provided by the WADS project and the Western Savannah Development project also provided valuable information. When more specific questions arose or there were inconsistencies among figures provided by different sources, specific individuals were consulted, including NCRWRD and other public officials, donor project managers, and repair shop personnel. The interviewees offered information on pumping practices and often could explain why costs were as they were. They also confirmed the range of capital and recurrent costs reported by other sources.

In several cases, specific consultancies were commissioned to assist in defining important parameters. Already noted is the assistance provided by the Ministry of Agriculture Extension Service. Consultancies were also used to research relevant discount rates, shadow pricing factors, and the tax structure as it relates to importing pumping equipment.

7.3 Base Case System Descriptions

It is important to select base case assumptions that represent actual pumping conditions in Sudan, and at the same time are focused on those situations where the potential exists for using solar and wind pumps to displace standard diesels. The most important technical parameters defining the base case are:

- average daily water demand (in m^3/day);
- total pumping head (in meters);
- specific equipment used;
- energy resource levels, including average design month solar radiation levels (for solar pumps, in kWh/m^2/day) and design month site wind speed (for wind pumps, in m/s);

- location (as an indicator of transportation distance for installation and servicing, in km); and
- O&M requirements and their associated costs, as determined by the field testing and survey programs.

In order to compare systems of equal design quality, operating efficiencies were chosen to represent well-designed and maintained systems. Although this is certainly not the common state of affairs with many diesel systems, it was noted elsewhere in this report that the most cost-effective action which could be taken to reduce pumping costs in Sudan is to pay more attention to the proper design of existing diesel systems. It also makes little sense to skew the analysis by comparing new, properly designed wind and solar pumps to diesels in very poor condition.

In addition to the technical parameters defining the base cases, important financial and economic parameters included:

- discount rates (which varied depending on whether the purchaser or user was in the private or public sector);
- foreign exchange rates (multi-tiered in Sudan); and
- equipment and material (including fuel) costs, taxes, and dealer markups, which were based on the costs of existing systems, as well as on current supplier quotes and user interviews.

Loan interest rates were not as important, since most private sector purchases of diesels are typically made with cash, or through concessionary loans made available through the ABS. Loan interest charges are typically low (compared to inflation rates), and of even greater benefit to ABS equipment buyers is that imported equipment is priced at the very overvalued official exchange rate of S£ 4.5 to the US dollar. The impact of these loans is examined further in the sensitivity analysis.

Since the village water supply case and the small-scale farmer case are so different, the two base case situations are described separately in the following two sections.

7.3.1 Rural Village Water Supply

There are about 3,600 diesel wateryards in Sudan. According to the NCRWRD, average demand at these wateryards is about 50 m^3/day. Water head ranges from a low of 20-40 meters in many villages along the Nile (and at a few other locations) to a high of 80-100 meters in many locations in Western Sudan. From the results reported in Chapter 5, commercial solar and wind pumps clearly cannot meet these water requirements. However, there are a number of smaller villages, particularly in areas near the Nile, where the head is 35 meters or less and the water demand of about 20 m^3/day can be met by a solar or wind pump. To give some estimate of the size of the potential market here, extrapolating from the results of the NCRWRD surveys shows that there are an estimated 100-150 villages (3-4 percent of the total) which meet the two criteria of head 35 meters or less, and demand 20 m^3/day or less.

The base case systems used in the analysis all pump 22 m^3/day at a 35 meter head. A demand of 22 m^3/day rather than 20 m^3/day was chosen because the base case 1484 W_p solar system will pump that much during the low-radiation December design month. Using the World Health Organization's recommended minimum daily water consumption of 30 liters person per day, this is enough water for over 700 people. Of course, the number of people served by these systems would increase in inverse proportion to decreasing head (e.g., at only 15 meters head, the systems would serve over 1700 people). The three base case systems can be briefly described as follows (detailed system and component costs are given in Appendix H):

- diesel: Lister PHW-1 engine with a Grundfos vertical turbine pump, pumphouse, 50 m^3 elevated storage tank, system efficiency of 15 percent;
- wind: CWD 5000 wind pump (5 m rotor diameter), 100 m^3 elevated storage tank, system efficiency of 12.5 percent, design month wind speed of 4.1 m/s;
- solar: Grundfos solar submersible pumpset, DC-AC inverter/controller, 1484 W_p array, 50 m^3 elevated storage tank, subsystem (pump/motor/controller) efficiency of 34 percent, design month solar radiation level of 5.9 kWh/m^2/day on the array tilt.

In order to do a realistic comparison of diesel, wind and solar pumping costs, all necessary wateryard equipment, including drilled and cased well, storage tanks, and local area distribution system is included in the cost analysis.

A few comments will help to explain some of the points in the base case system descriptions. Although many diesel wateryards (particularly in Kordofan and Darfur) are equipped with Lister-Edeco or equivalent pumpsets, in their new system designs NCRWRD now uses vertical turbine pumps in locations with 35 meter pumping heads . For solar pumps, although other makes are available, the Grundfos is the only appropriate solar pump tested in the present study (the low-head KSB solar pump is not designed to pump through 35 meter heads). Since the CWD 5000 was the only wind pump tested, its performance and cost is used in this analysis. However, an important caveat is that this machine is not yet a commercially viable design. It is assumed that suitable design modifications will be made to adequately deal with the significant performance defects mentioned in Chapter Five. Also, the local manufactured cost (as opposed to imported cost) as estimated by CWD is used as its capital cost. Since these machines have not been produced in Sudan on a commercial basis, this estimated cost is somewhat speculative. An alternative windmill such as the well-tested (in other countries) Kijito is also a suitable choice, but it is both substantially more expensive, and was not tested during this program.

The solar radiation level assumed here is typical of much of the country apart from the South. The average annual solar radiation at the four reporting stations along the Nile is 6.4 kWh/m^2/day on the horizontal surface. The month with the lowest solar radiation level (known as the design month) is December, when the average daily levels are 5.4 kWh/m^2/day on the horizontal. By suitably tilting the array, the usable December radiation can be increased to about 5.9 kWh/m^2/day.

As discussed in Chapter Four, average wind speeds are not well defined for most locations in Sudan. At some stations, the average annual wind speed could be as high as 5 m/s, particularly along the Nile north of Khartoum. The average wind speed under design conditions (i.e., the lowest average wind speed month) is estimated to be about 4.5 m/s. So, the 4.1 m/s wind speed assumed in the base case analysis is a conservative estimate of available wind energy resources. The CWD 5000 at 4.1 m/s will just meet the 22 m^3/day pumping demand.

Other costs such as civil works, skilled and unskilled labor, local parts and materials, and transportation needs reflect data collected during the program. Apart from parts and fuel, a substantial component of recurrent O&M costs is transportation of fuel, parts and service personnel. Cost depends on distance travelled. A transportation distance of 50 km (one way) from the site to the service/fuel center was used, since areas where solar and wind pumps are technically attractive (low head) are primarily along the Nile, with installation and servicing facilities relatively nearby.

In recent years the discount rate used by the Sudanese Government to evaluate projects has ranged from 10-15 percent. Recent analysis uses a 15 percent discount rate (Reference 50). Sudan has a multi-tiered exchange rate. Official donor assistance is priced at S£ 4.5 = US$ 1, and the regulated commercial exchange rate is US$ 1 = S£ 12.2. The regulated commercial exchange rate was used for the (public sector) village water supply base case, and the somewhat variable free market exchange rate of S£ 18 = US$ 1 was used for the (private sector) small farmer irrigation base case. Given Sudan's high inflation rates over the last few years, its currency is severely overvalued. The net effect of the overvalued exchange rate is that it makes imported goods artificially cheap in terms of their true resource cost, which is the amount of goods and services which Sudan needs to export to fully cover the cost of these imports (Reference 27). In general, overvalued exchange rates favor more capital intensive imported systems such as wind and solar pumps.

7.3.2 Small-Scale Irrigation

The local consultant report on small irrigated perimeters (Reference 17) suggests that by far the largest number of areas in Sudan where renewable energy technologies are technically attractive are along the Nile, where the bulk of the low head, small irrigated perimeters exists. Installation and servicing facilities for diesels are usually found within 50 km (one way) from farms.

Average pumping heads for small-scale farmers lifting water from the Nile are much less than for rural villages, often less than 5 meters. Slightly higher heads are found in areas away from the Nile, where large diameter (2-5 m) dug wells are used as water sources. At the 5 m head used in the small-scale irrigation base case, a typical solar pump (again, a Grundfos is used) will pump about 150 m^3/day, so this is used as the base case demand. The system descriptions are then:

- diesel: the considerably less expensive Indian-made Lister copy (US$ 600 CIF) with a Cypriot or Indian surface-mounted centrifugal pump (US$ 100 CIF), no storage tank, system efficiency of 5 percent.

- wind: CWD 5000 wind pump (5 meter rotor diameter), 150 m^3 (one full day demand) ground storage tank;
- solar: Grundfos solar submersible pumpset (the smaller KSB pump is not adequate for meeting this size demand), DC-AC inverter/controller, 1484 W_p array, no storage tank.

For irrigation, by far the most common diesel system uses the much less expensive Indian-made versions of the Lister 8/1, and so that engine (and its considerably lower efficiency) is used in the analysis. Wind speed, solar radiation and system efficiencies for the wind and solar pumps are identical to the village water supply base case. No tanks are needed for diesel and solar pumps because of their relatively high flow rates, which are adequate for ditch or flood irrigation. Because of the much less uniform daily wind speed, the wind system necessarily includes one day of water storage. Other equipment and materials costs are minor (other than a pipe into the river and one or two discharge pipes or hoses, water is conveyed by dug channel).

The prevailing private sector discount rate is considerably higher than for the government. For the purchase of pumpsets, the Agricultural Bank of Sudan offers short-term loans at an interest rate of 19 percent. The discount rate applied by commercial investors to project analysis in the private sector is 25 percent. The base case rate used in this analysis is 25 percent, although the implicit discount rate applied by individual farmers to investment purchases may be much higher. However, since farmers normally purchase equipment on the open market, taxes of 30 percent and agent fees of 30 percent are included, and loan rates do not have a significant impact on this analysis. The tax rate reflects current taxes and duties imposed on imported items. The agent fee (markup) used is based on research and survey results. In most cases, the price of equipment purchased privately is based on the free market exchange rate for the Sudanese pound. The Government estimate of the true free market exchange rate for the Sudanese pound is S£ 18 = US$ 1, and so this rate was used for the financial analysis of the private sector irrigation system.

7.4 Results for Rural Village Water Supplies

The cost analysis for each of the base cases are presented separately in this and the following section. The results of the analysis clearly show that these situations are indeed quite different, and lead to very different sets of recommendations.

The main criterion for comparison is the economic unit water cost, in Sudanese pounds per cubic meter (S£/m^3) of water pumped at the specified head. Other secondary criteria (e.g., capital intensity) which will have an impact on system choice are also discussed.

7.4.1 Base Case Results

The base case village water supply system pumps at least 22 m^3/day through a 35 meter head during the design month, the average delivery for a 1484 W_p solar pump. Water delivered in excess of 22 m^3/day during other periods of the year (such as high solar radiation months) is not valued (by convention, see Reference 19). For the wind pump to be comparable to the diesel and solar pumps under these conditions, the site average wind speed during the design (calmest) month must be 4.1 m/s. Above this speed, a wind pump will meet the demand. A diesel system can easily meet demand running less than two hours per day.

Table 7.1 below gives both the financial and economic unit water costs for diesel, solar, and wind pumping systems. Since village water supplies operate primarily in the public sector, the economic results are of most interest.

Table 7.1: Unit Water Cost[1] (S£/m^3)

	Financial Terms	Economic Terms
Diesel Pump	10.1	13.9
Solar Pump	10.2	14.1
Wind Pump	10.4	14.2

[1] Conditions: 35 meters head, 22 cubic meters per day

The most important conclusion from the results shown in Table 7.1 is that for all systems, unit water costs calculated from the field tests and surveys are essentially identical for the base case. Differences are insignificant, and are well within the margin of error of the available data and calculations. The unit costs shown include all costs for NCRWRD installations, including pump, engine and associated equipment, well development, pump house, fencing, water storage tank (50 m^3), distribution piping and valves in the wateryard, and all recurrent costs. In the case of solar pumps, one storage tank (the same as the diesel system) is likely to be sufficient to ensure an adequate water supply during normally brief overcast periods. All systems include pump operators, as this is the NCRWRD convention (this has negligible impact on the overall analysis).

The present value of the major cost components of each of the water systems (materials and equipment, spare parts, labor, transportation, fuel, and well development) are summarized by installed system cost and recurrent costs in Table 7.2, and shown graphically in more detail in Figure 7.1. First, the most important conclusion here is the life cycle costs (LCC, in both economic and financial terms) for all three systems are very nearly the same. The slight (percent) difference in LCC between the various systems is not significant, since it is well within the measurement error of the analysis. Second, the table shows that the installed system cost is by far the dominant cost factor for all systems tested, representing 79 percent of the diesel LCC, and 94 percent of both the solar and wind LCC.

Third, the initial cost of buying and installing a diesel pump is considerably cheaper than either of the RET pumps. The economic installed cost for the solar and wind pumps (including well development costs) are roughly 20 percent greater (about S£ 116,000) than the diesel pump. The main reasons for this are the higher costs for the PV array and pumpset, and the cost of the additional storage tank (which costs about S£ 100,000) for the wind pump. Also, the diesel and solar pumps do not require as extensive civil works (the tower foundation) as the wind pump.

Table 7.2: Life Cycle Cost of Systems (S£)

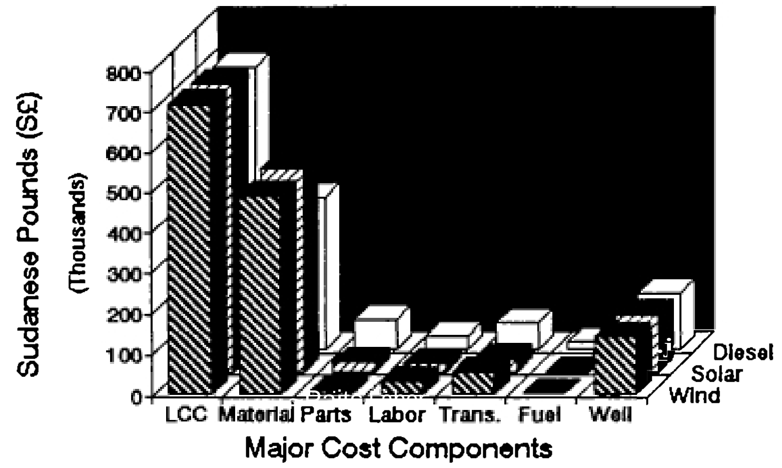
	Diesel	Solar	Wind
Economic Cost			
Installed System Cost[1]	552,792	668,968	669,560
Present Value of Recurrent Costs	145,706	41,179	41,544
Total Life Cycle Cost	698,498	710,147	711,104
Financial Cost			
Installed System Cost[1]	403,757	477,208	490,269
Present Value of Recurrent Costs	102,652	30,165	31,410
Total Life Cycle Cost	506,409	507,373	521,679

[1] including well development costs

The fourth conclusion is that the present value of all recurrent costs for both the solar and wind pumps is only 30 percent of that of the diesel pump. This has always been the factor which has generated the greatest interest in using RET pumps. Lower recurrent costs generally increase system sustainability, since users are often responsible for covering recurrent but not installed costs. The higher recurrent cost for the diesel is the result of not only fuel, lubricant and spare parts costs, but also the greater number of trips and labor required for maintenance and repair. In contrast, major recurrent cost items for the solar pump are module replacements (one every 7 years as a result of breakage) and periodic pumpset replacement (once every 10 years). Wind pump recurrent costs mainly involve occasional checkups, minor repairs such as replacement of the piston leathers (every year), and replacement of the piston itself (every five years). The figures used for the wind pump analysis reflect reason-

Figure 7.1 Present Value of System Costs

Economic Analysis-Village Water Supply



able maintenance costs for a market-ready windmill design. Current operation/maintenance costs for the CWD 5000 are higher than the levels assumed for the analysis.

Figure 7.1 breaks out the cost components in a somewhat different way than Table 7.2. The major cost component categories (life cycle cost, material and equipment, spare parts, skilled and unskilled labor, transportation, fuel, and well development) include all costs within each of those categories, whether those costs are part of system installation, or operation, maintenance, and repair. Note that fuel is a very small component of the diesel's life cycle cost, reflecting the relatively low capacity factor for the diesel system (it is only run abut 2 hours per day). This figure shows that while the recurrent costs of operating a diesel engine are considerably greater than those of operating a RET pump, recurrent costs (at least, for the base case considered here) are not nearly as significant as upfront costs in comparing relative system costs.

To better understand the effects of certain assumptions on the results of the analysis, it is useful to determine which cost or performance assumptions have the greatest impact upon costs, and to perform sensitivity analysis on those assumptions. A wide range of sensitivity analyses were performed, a summary of which is given in Table 7.3. The two major categories of parameters varied are physical (affecting pump performance) and economic (including financial parameters, which directly affect cost).

7.4.2 Sensitivity Analysis of Changes in Physical Parameters

The unit water cost for pumping with diesel, solar and wind pumps will vary as important physical parameters (e.g., head, water demand, equipment operating efficiencies) change. For example, unit costs are inversely proportional to the volume of water pumped. For diesel pumps, the initial capital and operating costs vary only slightly for moderate increases in water output. For moderate water demand variations, the only cost changes will be to parameters dependent on engine operating hours (e.g., fuel, periodic maintenance). Changes in pumping rate and engine loading are secondary effects which help reduce operating costs as pumping rate increases. On the other hand, the cost of solar (larger arrays) and wind pumps (larger rotors) can increase greatly as water demand increases. Any increase in water demand beyond that specified in the base case will exceed the technical capacity of commercial solar pumps (since solar radiation levels do not vary appreciably). Wind pumps could handle larger demand if site wind speed were greater. Table 7.3 shows various possible changes in physical and economic parameters, and their subsequent effect on economic unit cost. Next to the calculated unit costs are given the positive (+) or negative (-) percentage changes from the base case unit cost.

Reduced demand will increase unit water cost. For diesel, wind and solar, economic unit costs will roughly double when demand is cut in half. The greatest percentage increase in unit water cost will be for the diesel system, since it cannot be easily downsized like the solar pump. At the lower demand, the windmill will require less storage (reduced tank cost) to meet daily demand, and so it's unit cost will increase the least. Alternatively, with the base case two tanks, the windmill could be used in areas with wind speeds as low as 3.2 m/s.

Table 7.3: Results of Sensitivity Analysis
Unit Water Cost in Economic Terms (S£/m^3)

	Diesel	**Solar**	**Wind**
Village Water Supply Base Case	13.9	14.1	14.2
A. Changes in Physical Parameters			
22–>11 m^3/day Water Demand	27.4*(+97%)*	24.9*(+77%)*	22.9*(+61%)*
35–>70 meter Pumping Head[1]	17.0*(+22%)*	—	—
15–>8% Diesel Pumpset Efficiency	14.2*(+2%)*	same	same
Transport Distances 50–>100 km	15.2*(+9%)*	14.8*(+5%)*	15.3*(+8%)*
B. Changes in Economic Parameters			
Local Purchase of All Equipment	14.5*(+4%)*	15.6*(+11%)*	14.7*(+4%)*
20% Cost Reduction of Imported Solar Wind, and Diesel Components	13.4*(-4%)*	13.2*(-6%)*	13.9*(-2%)*
Diesel Fuel from S£ 15–>50/gallon	14.7*(+6%)*	same	same
PV Module Cost Reduction from:			
US$ 5.50–>5.00/W_p	same	13.9*(-1%)*	same
US$ 5.50–>4.00/W_p	same	13.3*(-6%)*	same
US$ 5.50–>3.00/W_p	same	12.8*(-9%)*	same
Exchange Rate Changes from:[2]			
S£12.2–>4.5 per US$	9.4*(-32%)*	8.2*(-42%)*	8.8*(-38%)*
S£12.2–>18 per US$	18.2*(+28%)*	17.3*(+24%)*	18.7*(+33%)*
Discount Rate from 15 –> 20%	17.0*(+22%)*	18.0*(+28%)*	18.0*(+27%)*

[1] At 70 meters head, neither the solar nor the wind pump could meet the base case demand of 22 m3/day, unless site wind speed is greater.

[2] No corresponding change in shadow price of foreign exchange.

Doubling the head makes the specified demand beyond the capacity of the solar and wind systems, unless the site wind speed is as much as 5.2 m/s (in which case the unit cost is only S£ 16.6). Reducing the diesel pump efficiency from 15 percent to 8 percent increases unit cost only slightly, since fuel cost is a relatively small component of diesel life cycle cost. However, keep in mind that even small savings in diesel operation can mean large savings for Sudan because of the very large number of systems installed. Also, running a diesel at higher efficiency not only reduces specific fuel consumption (fuel consumed per unit of water pumped), but also reduces periodic maintenance requirements and the frequency of major overhauls, since the engine runs warmer and has subsequently less carbon buildup.

Doubling the transportation distance from 50 to 100 km each way increases unit costs 4-9 percent, with the largest impact on the diesel because of its higher maintenance and fuel transportation requirements. An interesting example of such a case is a typical wateryard in

Kordofan or Darfur. There, total pumping head is about 100 meters and the water demand is about 50 m^3/day. Increasing transportation distances to 100 km to reflect the greater distances to service centers, and including the cost and performance of the Lister-Edeco pumps used in these areas (rather than the base case vertical turbine pump), the unit water cost for diesel is S£ 9.5/m^3. This is lower than the base case diesel unit cost because more water is pumped. Since neither solar or wind (except at much higher wind speed) pumps could meet that demand (e.g., a 9,000 W_p solar array would be required, much larger than common commercially available sizes), comparative analysis for such cases is meaningless.

7.4.3 Sensitivity Analysis of Changes in Economic Parameters

Sensitivity analysis was used to calculate changes in unit costs due to modified assumptions about:

- who pays for system components, which affects payment of taxes and dealer markups;
- base costs of various equipment components;
- fuel cost variations, which are partly dependent upon government policy and partly upon variable scarcity;
- the impact of the multi-tiered exchange rate system; and
- discount rates.

This base case assumes that major system components (except storage tanks) are purchased by donors and imported for donor-supported projects. There is no markup on materials procured directly by donors. Locally-procured items include tanks, pipes, fittings, and general construction materials. When NCRWRD wants to expand its procurement beyond what donors provide, it may purchase some equipment locally through a tender process. In that case, equipment becomes more expensive, since a 25-30 percent markup for handling and profit is charged by local dealers. Import duties are waived, because the equipment is supplied to the government. In such a case, economic unit costs will increase by 4 percent, 11 percent and 4 percent respectively for diesel, solar and wind pumps. The greater increase for solar is because it is a more capital intensive system (i.e., the equipment costs are a higher percentage of LCC than for the other two systems).

By buying in larger lots, it is possible to get more competitive bids for equipment. If, for example, NCRWRD were able to bid large enough tenders to reduce imported equipment and materials (except for the well) costs by as much as 20 percent, a consequent reduction in the economic unit water cost for diesel, solar and wind would be 4 percent, 6 percent and 2 percent respectively. For the solar pumps, such a price reduction may also come from higher volume production and increased product competition as international markets for these systems continue to expand. This is unlikely to apply to locally manufactured wind pumps.

Depending upon the application, fuel cost can be a major recurrent cost component for diesel systems. However, for the base case system (as seen in Figure 26), fuel consumption is not a major cost component. For this case, the average fuel price would need to reach S£ 25 per gallon over the long term before the economic cost of solar pumping would be less than diesel for the base case. This price does not include expected increases in transportation costs which will also result.

A question frequently asked with respect to solar pumps is what must the cost of modules be (in US$ per peak Watt, or US$/$W_p$) in order for solar to be competitive with diesel. For the base case, the answer is US$ 5.00/W_p. only slightly less than the current price. Table 7.3 also shows unit costs calculated on the basis of US$ 4.00 and US$ 3.00/W_p modules.

Economic variables such as foreign exchange rates, discount rates, and the term of analysis can have major impact on unit cost calculations. The term of analysis here was chosen to be the estimated lifetime of the longest lived component of any of the systems, in this case the 20 year lifetime of the windmill and the solar modules. All other system parts were replaced on an as-needed basis over the system lifetimes, so changes in the term of analysis will have no effect on the results.

Foreign exchange rates are another important issue. The base case analysis was done assuming an exchange rate equal to the regulated commercial rate of S£ 12.2 per U.S. dollar. The Ministry of Finance and Economic Planning (MFEP) argues that analysis of public sector projects should reflect the official exchange rate of S£ 4.5 per U.S. dollar. Table 7.3 shows the results of that calculation. Not unexpectedly, the solar system has the lowest unit cost, since the true worth of the capital intensive solar system is undervalued when using such an overvalued exchange rate. The wind system, which is more capital intensive than diesel but less so than solar, also has a lower unit cost than diesel. Changing the foreign exchange rate to the free market rate of S£ 18 to the U.S. dollar reflects a truer picture of relative system cost, with diesel cheapest, then wind, then solar, although again the differences are not significant.

Raising the discount rate from 15 percent to 20 percent will increase the LCC of all systems. However, it will favor the least capital intensive system (the diesel), since its higher recurrent costs will be devalued more than those of the relatively capital intensive RET systems. If the discount rate declines, the opposite is true, and RET systems will be favored. This is unlikely to happen however, since over the past several years (1987-88) inflation has been running at 50 percent or more, and inflation rates for 1989/90 are expected to be even higher.

In summary, LCC for all three systems are nearly the same, but the RET systems, especially the solar pump, are very capital intensive. High initial costs may well have a greater impact on system choice than life cycle cost (see Chapter Eight). Reduced pumping requirements favor solar and wind systems. Larger demand or higher head favors diesel, and beyond fairly modest increases, solar and wind systems simply cannot meet demand. Solar and wind systems are cost-competitive in certain low-head, low-demand situations. However, the number of villages with such pumping requirements is not likely to be large (perhaps 150 villages—less than five percent of the total number) in Sudan. A discussion of other factors which should be considered when making pumping decisions will be found in Chapter 8.

7.5 Results for Small Farm Irrigation

The base case pumping conditions assumed for the small irrigated farm is an average 150 m^3/day through a 5 meter head. This corresponds with the pump output from a Grundfos solar pump at a typical head for small farm irrigation. Depending on the crop and other farm variables, this should be enough water to irrigate 2 to 5 acres. For purposes of analysis, it is assumed that an average of 150 cubic meters is delivered each day, even if the farmer's irrigation rotation does not require it. It is assumed that the farmer will appropriately manage cropping patterns, operate his own pump, and maximize his use of the water available. Unlike the village water supply situation, no operator cost is assumed. For the wind pump to have output comparable to the diesel and solar pumps, the average site wind speed during the design month must be at least 4.1 m/s. Solar radiation levels are the same as the village water supply case.

7.5.1 Base Case Results

For small private sector farmers, financial unit costs are more relevant than economic unit costs. Although economic costs are an important factor in setting policy, farmers' decisions are based on the finances of pumping choices. Table 7.4 gives both the financial and economic unit costs (S£/m^3) for diesel, solar, and wind pumping systems for this base case.

These values include all site costs for installations completed by the small private sector farmer. Dug well costs are included, as well as limited piping costs to deliver water to earth irrigation channels. Since the wind pump's flow rate is not normally sufficient nor constant enough to allow easy channel irrigation, a tank is required to store water for periodic release into the main ditch. A 150 m^3 ground tank storage is assumed in order to allow water release each day to a different part of the farmer's irrigated fields. In the diesel and solar pumping cases, no tank is required since the water flow rate is sufficient to ensure adequate channel flow.

Table 7.4: Unit Water Cost[1] (S£/m^3)

	Financial Terms	**Economic Terms**
Diesel Pump	0.25	0.21
Solar Pump	2.03	1.57
Wind Pump	1.04	0.85

[1] 5 meters head, 150 m3/day

The most important conclusion from the results shown in Table 7.4 is that the unit cost of diesel pumps is far lower than either of the two alternatives. The financial unit cost of the diesel system is only 12 percent that of the solar system, and about 25 percent that of the wind system. Notice that economic unit costs are less than financial unit costs. This is a result of the inclusion of taxes, duties, and customs charges which are simple transfers and are not in-

Table 7.5: Life Cycle Cost of Systems (S£)

	Diesel	Solar	Wind
Financial Costs			
Installed System Cost[1]	34,846	421,561	224,282
Present Value of Recurrent Costs	20,134	28,397	6,815
Total Life Cycle Cost (LCC)	54,980	449,958	231,096

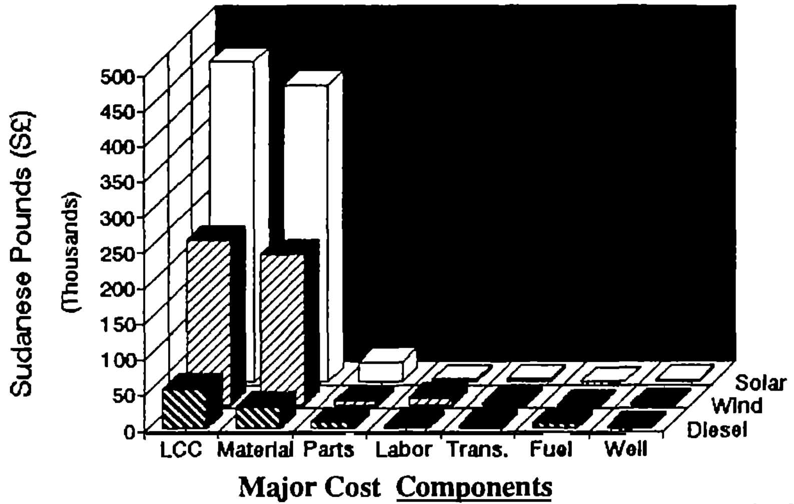
[1] Including well development costs

cluded in the economic analysis, and which outweigh the effect of the shadow foreign exchange rate. These unit costs are significantly less than those for the rural water supply case, mainly because of significantly decreased material and equipment costs (cheaper pumpsets and simpler physical installations). Also, the LCC is amortized out over a much larger quantity of water pumped (150 versus 22 m^3/day).

The present values of the major cost components for the three irrigation systems (materials and equipment, spare parts, labor, transportation, fuel, and well development) are summarized by installed system cost and recurrent cost in Table 7.5, and shown graphically in more detail in Figure 7.2. The clearly dominant cost factor is the installed system cost. A small-scale farmer can purchase and install an Indian version of the Lister pumpset for roughly S£ 35,000 including pump, piping, and installation. The installed cost for a solar pumping system to meet the same requirements is about S£ 422,000. The wind pump installed capital cost is about S£ 224,000. The solar system is so much more expensive than the wind system because of the greater effect of taxes, duties, and agent mark-ups on the mostly imported, considerably more capital intensive system.

Figure 7.2 Present Value of System Costs

Financial Analysis: Small Irrigation



The diesel engine and pump not only have very low capital cost, but the diesel system's recurrent cost is also lower than that of the solar pump, and only about three times that of the locally-manufactured wind pump. Recurrent costs for the diesel largely represent parts, labor, and fuel and lubricant costs. Repair costs for the Indian-made engine are considerably less than for a the Western-made equipment used in the village water supply system. Lower efficiencies (and consequently higher fuel costs) are more than compensated for by much cheaper spare parts costs. The reduced system reliability of the cheaper equipment (and subsequently more frequent outages) is not quantified in this analysis, but it is clearly acceptable to farmers because of the distinct cost advantage.

The major recurrent costs for the solar pump are replacements for expected broken modules (roughly one every seven years, based on experience thus far) and for the pumpset and controller (at 10-year intervals). Taxes, duties, and agent fees on pumpset replacements increase the present value of the recurrent cost for solar pumping significantly. For a 20-year solar pump life, and no module breakage, the present value of the recurrent costs drops to only about S£ 3,558.

The major wind pump recurrent costs are for labor and parts for occasional maintenance and repair. As in the village water supply case, the figures used for the CWD 5000 wind pump performance analysis reflect current field experience, and assume that major design flaws have been worked out before any further attempts at commercialization. If that is the case, most simple repairs could be done by the farmer himself.

7.5.2 Sensitivity Analysis of Changes in Physical Parameters

A tabular summary for sensitivity analyses of changes in both physical and economic parameters for the small-scale irrigation analysis base case is given in Table 7.6. Numbers in parentheses indicate the percentage change from the base case unit cost.

As in the village water supply case, reduction in water demand increases unit water cost across the board, but at different rates for each system. When demand is reduced by half, the unit costs for diesel, wind and solar pumps increases considerably, especially for diesel. The unit cost for wind pumping approaches that of diesel, but unit cost for solar pumping is still more than twice that of diesel.

Although not shown in Table 7.6, another solar alternative is the KSB floating pump, also tested by the project. The KSB (with a less expensive array and pump than the Grundfos) will pump just under 50 m^3/day through a 5 meter head in a solar regime of 5.9 kWh/m^2/day. To match these requirements, a small diesel pump will need to operate for only 2 hours a day pumping 25 m^3/hour. The financial unit water costs for this situation for diesel, solar, and wind pumping are 0.69, 2.53, and 3.21 respectively. Even if diesel fuel costs increase to S£ 25 per gallon, the diesel unit cost only rises to 0.77, which is still very competitive with respect to the alternatives.

When head is halved to 2.5 meters, the solar pumping rate can be maintained with a smaller array. The unit cost decreases by 4 percent for diesel and 28 percent for solar. The large change in solar cost is attributable to the reduction in solar array costs, the major expense of

Table 7.6: Results of Sensitivity Analysis
Unit Water Cost in Financial Terms (S£/m^3)

	Diesel	Solar	Wind
Small-Scale Irrigation Base Case	0.25	2.03	1.04
A. Changes in Physical Parameters			
150–>75 m^3/day Water Demand	0.47*(+88%)*	2.95*(+45%)*	1.34*(+29%)*
5–>2.5 meter Pumping Head	0.24*(-4%)*	1.47*(-28%)*	1.07*(+3%)*
Transport Distances 50–>200 km	0.31*(+24%)*	2.07*(+2%)*	1.09*(+5%)*
If Wind System did not Require Storage Tank as Specified	same	same	0.70*(-33%)*
B. Changes in Economic Parameters			
ABS Supply of All Pumpsets	0.14*(-44%)*	0.50*(-75%)*	0.39*(-62%)*
50% Cost Reduction of Imported Solar and Wind Pump Components	same	1.08*(-47%)*	0.54*(-48%)*
Diesel Fuel Cost Increase			
S£ 5–>50 per gallon	0.56*(+224%)*	same	same
S£ 5–>120 per gallon	1.04*(+416%)*	same	same
PV Module Cost Reduction from:			
US$ 5.50–>5.00/W_p	same	1.93*(-5%)*	same
US$ 5.50–>4.00/W_p	same	1.72*(-15%)*	same
US$ 5.50–>3.00/W_p	same	1.51*(-26%)*	same
Exchange Rate S£ 18–>12.2 per US$	0.21*(-16%)*	1.39*(-32%)*	0.77*(-26%)*
Discount Rate Increased 25–>35%	0.31*(+24%)*	2.76*(+36%)*	1.43*(+38%)*
Eliminate Import Tax on Imported Pumping Equipment (Rate 30–>0%)	0.22*(-12%)*	1.57*(-33%)*	0.85*(-18%)*

the system. For this low-head condition the windmill cost essentially stays the same, and it becomes an option to use in areas with a design month wind speed of only 3.2 m/s. However, diesel is still by far the least cost pumping option.

Since O&M requirements are greater with diesels, increasing the distance to service centers favors the use of solar and wind pumps. When installation and servicing distances are increased from 50 km to 200 km, unit water costs increase by 24 percent, 2 percent, and 5 percent for diesel, solar, and wind respectively. However, financial unit costs for wind and solar are still three to six times greater than for diesel systems.

7.5.3 Sensitivity Analysis on Changes in Economic Costs

The base case analysis has assumed that the major pumping components are purchased through the local private sector (except tanks which, when necessary, are built on-site). Taxes and customs duties are included in equipment costs, and agents take a markup on all items. However, an increasing percentage of pumps are now being supplied through the Agricultural Development Bank of Sudan (ABS), since recent government policies (especially those regarding foreign currency transactions and import license restrictions) have caused a reduction in equipment available through private sector sources. As described earlier, the ABS arranges for the purchase of equipment with hard currency supplied by donors, and then makes the equipment available to farmers at prices which reflect the official foreign exchange rate of S£ 4.5 to the U.S. dollar. Loans are made to farmers at the equivalent of 18 percent interest annually, if the farmer can provide a 30 percent down payment on the equipment. Under these conditions, financial unit costs drop by 44 percent, 75 percent, and 62 percent for diesel, solar, and wind respectively. More than 80 percent of this reduction in unit cost is the result of exchange rate assumptions. Even though unit costs are decreased significantly, diesel pumping remains the cheapest. Note however, that the ABS currently does not make loans for solar or wind pumping systems.

Since equipment and material cost is the major component in the life cycle costs, a substantial reduction in these expenses will reduce the economic unit water cost. Assuming for purposes of argument an almost impossible reduction of 50 percent in the installed capital costs for solar and wind pumps (except for the well costs), the unit water cost for solar and wind is reduced by only 47 percent and 49 percent to 1.08 and 0.54, respectively. This is still not a sufficient reduction to favor solar or wind pumps; the financial unit costs are still more than twice the cost of diesel pumping.

Fuel cost is often a major consideration in operating diesel irrigation pumps. However, diesel fuel costs would have to reach S£ 120 per liter before wind pumps were attractive from a financial point of view. This does not include changes in transportation cost which will result from increased fuel cost.

Again, since PV module cost has always been such an important indicator of solar pump cost, three different module costs are used to calculate unit costs. Even down to US$ 3.00/W_p, the solar pump is not even close to being competitive with the cheap diesel. Similarly, even if it is possible to successfully irrigate with a windmill without using a water storage tank, the wind pump is still not competitive with the cheap diesel.

The base case analysis assumed an exchange rate equal to a free market exchange rate of S£ 18 to the U.S. dollar. However, if currency were available to agents to import pumping equipment at the regulated commercial rate of S£ 12.2 to the U.S. dollar, the financial costs for all technologies would decrease. When this analysis is done, the economic unit costs will not change; the free market currency costs are not affected by the financial exchange rate used. However, the financial costs for all systems are significantly reduced to 0.21, 1.39, and 0.77 for diesel, solar, and wind, a reduction of 16 percent, 46 percent, and 35 percent respectively. Under these conditions diesel pumping remains the least cost alternative.

Revising the discount rate upward to 35 percent (from 25 percent) will tend to favor the technology with low capital cost and high recurrent cost (diesel) over those with low recurrent costs and high initial cost (diesel and wind). If the discount rate declines (as mentioned above, this is highly unlikely), the opposite is true. Increasing the discount rate from 25 to 35 percent increases financial unit water costs 29 percent (diesel), 29 percent (solar), and 38 percent (wind).

If the Government of Sudan were to eliminate tax on all imported water pumping equipment and materials, dropping the tax rate to zero reduces the unit costs of diesel, solar and wind by 14 percent, 29 percent, and 22 percent, but diesel is still the most cost-competitive.

The results of the irrigation base case analysis indicate that diesel pumps remain the most cost effective pumping system choice for all reasonable changes in performance and economic parameters. Changes in pumping conditions can alter the financial cost of the different technologies, but do not change the relative cost-effectiveness of diesel, wind, and solar pumps. Reduced pumping requirements, resulting in significant reductions in solar and wind pumping costs and limited reductions in diesel pumping costs, will favor solar and wind. However, these conditions are insufficient to make solar or wind pumping financially advantageous for small-scale irrigation.

Currently, there appears to be little opportunity for the cost-effective use of solar and wind pumps for small-scale irrigation. A discussion of other factors which should be considered when making pumping decisions will be found in Chapter 8.

7.6 Summary and Conclusions

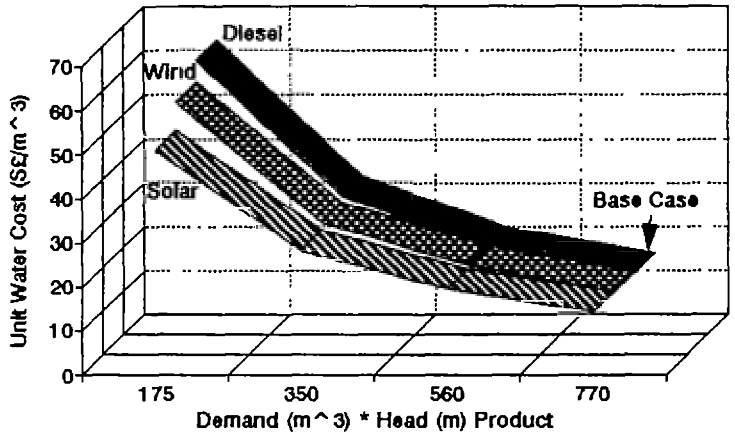
Given the differences in practices and costs between private sector small-scale irrigation and NCRWRD public sector wateryard construction and operation, these two situations must be analyzed as separate financial and economic cases.

Unit water costs for village water supplied by diesel pumpsets are much more expensive than small-scale irrigation from both the financial and economic perspective. The village wateryard has a distribution system which includes elevated water storage tanks, taps and troughs for animals and villagers, fencing, and pump-houses. None of these is required for small-

Figure 7.3

Unit Water Cost

Economic Analysis: Village Water Supply



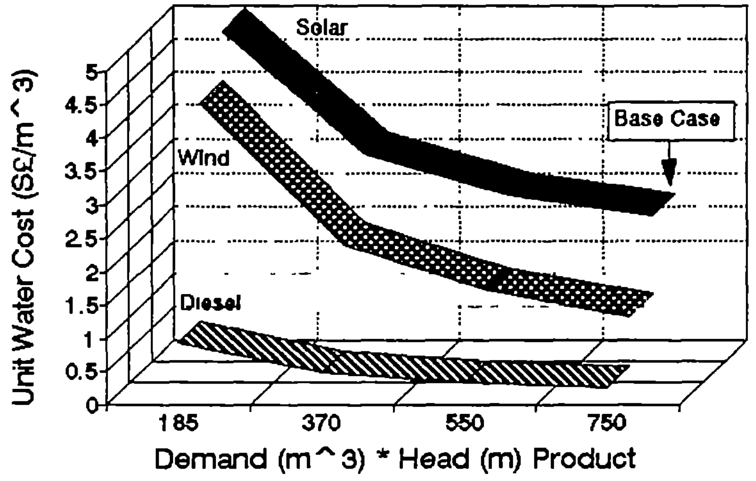
scale irrigation. Other significant differences include the use of much cheaper Indian diesel engines and lack of the need for a paid operator by private farmers.

Solar and wind pumps can be cost effective for village water supplies under certain circumstances. These cases are limited to small wateryards in areas where the total pumping head and the water demand are relatively low. Figure 7.3 indicates that the relative costs of diesel, wind, and solar pumping is a function of the product of the pumping head (meters) and the daily water delivery (cubic meters). This product is a measure of the energy required for pumping each day. Above the head*demand level (about 750 m^3*m) shown on the graph, diesel becomes the system of choice, except where wind speed is high enough (about 4.5 m/s) so that windmills can meet the required demand. Notice that for the base case, solar and wind pumping are both cost-effective over the range indicated. In Sudan, a realistic limit for solar pump applications is also about 750 m^3*m, equivalent to 22 m3/day pumped through a 35 meter head, or 50 m^3/day at a 15 meter head. For such sites, the choice between solar and wind is a matter of wind speed. If the site wind speed has been well documented to exceed 4.1 m/s in the design month, the wind pump will be more cost-effective. If not, the solar pump will be. Solar and wind pumping become more attractive as the daily demand and head decrease. In practice, these cases are fairly limited, because there are few wateryards which correspond to these conditions. The most likely areas exist are along the Nile to the north of Khartoum, and certain areas in Kordofan (such as Bara) and other provinces where water tables are near the surface.

For villages which have larger water demand or are pumping from greater heads, the opportunities for cost-effective use of either solar or wind are very limited under the present financial and economic conditions in Sudan. Current economic policies which favor diesel driven pumping include heavily subsidized diesel fuel, regulated (and overvalued) foreign exchange rates, lack of access to foreign capital, and heavy inflationary pressures. However, even allowing for these distortions in the local economy, diesel pumping will remain the dominant technology for providing village water for some time to come.

Figure 7.4 Unit Water Cost

Financial Analysis: Small Irrigation



Within the private sector where small-scale farmers are major users of diesel pumps, there are few opportunities for the cost-effective use of solar or wind. In this sector, the extremely low capital costs for common diesel pumping equipment make it difficult to compete with diesel pumpsets on the basis of either capital cost or life cycle cost. Farmers, who traditionally make investment decisions based on capital cost considerations, are unlikely to invest in a more expensive technology, even if it is more cost-effective in the long run.

As with the village water supply case, current economic policies favor diesel driven pumps. However, even allowing for distortions in the local economy, diesel pumping will remain the dominant technology for small-scale irrigation. Figure 7.4 (previous page) shows that the cost for solar or wind pumping for irrigation remains higher than for diesel for all low head, low demand situations. This continues to be the case above the base case head/demand range. However, there are important non-technical strategic and practical factors which affect pumping technology choice. Consideration of these factors in the following chapter shows that there is a small segment of both the irrigated sub-sector and the public water supply sector where solar and wind pumping are reasonable options.

8.0 Constraints and Incentives

There are technical and non-technical issues which favor the use of one water pumping technology over another. These issues may, in fact, be deciding factors in pumpset decisions and may over-ride financial and economic considerations. A number of factors which play a role in pumping choices in Sudan are outlined in this chapter.

8.1 Pumping Characteristics

Diesel pumpsets are flexible and powerful. Diesel engines are available in a wide variety of makes and models. Larger water demands and total pumping heads can be accommodated with only a moderate increase in capital cost. In many cases, increases in water requirement can be addressed quite easily by an increase in total pumping hours.

In low head, limited demand pumping conditions, diesel pumpsets are less appropriate. In Sudan, the smallest commonly used diesel engine has a de-rated output in the range of 3 kW. Several makes of smaller engines are available, a couple with outputs of 2 kW. In most small-scale pumping applications, the engines typically in use are considerably oversized. This causes them to be under-loaded and inefficient, which in turn increases maintenance and repair costs and reduces useful engine life.

Reliably tested commercial solar pumps are currently available in configurations of up to 1.5 kW peak output. Larger, specially configured solar pumping units can be specified to meet larger energy requirements. However, as has been shown, the financial and economic viability of larger systems is significantly compromised by the greater investment required for the solar array.

The solar radiation regime is a factor which often limits solar pumping. However, solar radiation levels are high in Sudan. Radiation levels are higher as one moves north. Average solar radiation levels in these places are both very high and very consistent. In southern regions and along the Red Sea coast, variations in solar radiation as a result of cloud cover and the rainy season make the daily water delivery from a solar pump more variable and, on average, not as high as in other areas.

The average performance of a solar pumping system is fixed by the array size and other technical parameters. The output of the pump cannot be increased to meet temporary demands, such as the needs of the nomadic population. Increasing average daily water delivery (as may be required by an increased village population) by adding more modules is expensive.

Prediction of solar pump performance (see Figure 8.1) is subject to the statistical variation in solar radiation levels on a daily, seasonal, and yearly basis. Solar radiation variations, as well as growth in water demand, require that excess capacity be built into the system design. Unfortunately excess capacity requires a greater investment in solar modules and increases total system cost.

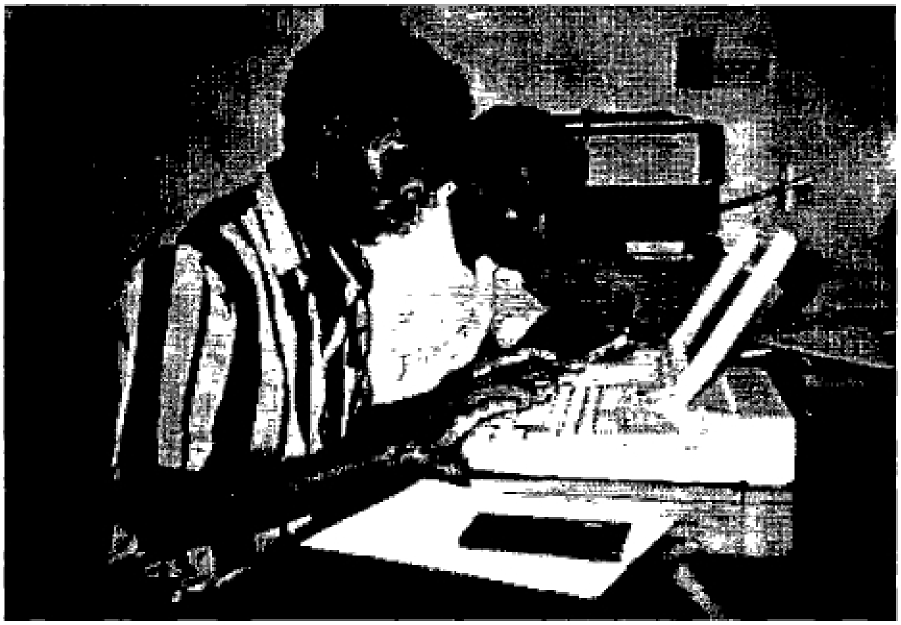


Figure 8.1. SREP pumping team members working on pump performance data analysis.

Commercially available wind pumps limit potential applications for wind energy since the pump output is a function of wind speed and rotor area. The largest diameter wind pump available is the 7.6 meter (25 feet) Southern Cross. The Kenyan Kijito (several have been imported into Sudan) is available in sizes up to a diameter of 7.3 meters (24 feet). The CWD 5000 is a 5-meter diameter machine.

A given wind pump's performance at a particular location is fixed and dependent on site wind speeds and pumping head. This means the wind pump output cannot be increased to meet increases in water demand. A careful assessment of present and future water requirements must be made before committing to this pumping technology.

The wind energy resource in Sudan is relatively favorable since the average annual wind speed in much of the country appears to be higher than 3 m/s. However, accurate wind pump performance predictions are difficult to make. This is an unfortunate corollary to the lack of accurate information on Sudanese wind regimes. This difficulty is magnified by the fact that wind pump performance is particularly sensitive to small differences in wind speed. Overly conservative estimates of pump performance must be used to ensure that the wind pump model and size are adequate to meet pumping needs.

Water storage is an important factor when considering wind pump use. Day to day variations in wind speed mean that daily water delivery will vary considerably. Water storage is usually necessary to offset periods of low wind speed and calm. When wind pumps are to be used for irrigation, a water storage tank is required to ensure that the water flow rate in the irrigation channels is sufficient for effective use of the water.

8.2 Fuel and Spare Parts Availability

The availability of the means to operate and maintain pumping systems is a major consideration in Sudan. At this time, fuel and lubricants are in particularly short supply, while the availability of spare parts is and has been a perennial problem. Diesel pumping relies on fuel and lubricants not only for operation but also for transport of fuel, spares, and maintenance teams to the pump site. During the past several years, there has been increasing concern about the availability and cost of petroleum products in Sudan. These concerns have always existed for the more remote areas. In some areas roads are often impassable. Recently fuel and lubricant shortages have threatened water pumping and other oil intensive activities even in more accessible areas. Diesel fuel, gasoline, and engine oil are now hard to obtain anywhere in the country and long queues are seen on a daily basis everywhere. Water delivery is considered an essential service, and it appears that fuel for water pumping is usually available even during the current period of shortage. However, the time and energy spent to ensure fuel availability for water pumping and the cash price for it, often purchased on the black market, is a major disincentive for continued use of petroleum based technologies.

Spare parts for many makes and models of diesel engine are in short supply or are simply unavailable. With an average of three to four diesel pump breakdowns annually, there is a constant need for spare parts. The NCRWRD is using more than five makes of engines. Several of these were supplied by donors with no arrangements for procurement of spare parts over the long-term. This has caused the stripping of some engines for spares in order to keep others operating. Many of these engines have very short useful lives because spare parts are unavailable. Lack of spares can interrupt water supplies for long periods. The availability of spare parts for the Indian Lister models has been greater in that merchants are willing to stock fast moving parts. However, complaints about their cost are common.

Solar pumps are free of fuel and lubricant needs for normal operation. Although there may be a secondary fuel requirement to cover transportation, even this requirement is less than for diesel pumping systems.

To date, the need for spare parts has been minimal. The tested solar pumps have suffered few major breakdowns so even maintenance requirements have not been significant (see Figure 8.2). However, if spare parts do become necessary, they are unlikely to be available in Sudan. Grundfos has an agent in Khartoum and KSB is represented, so at least there are avenues that can be explored when and if it becomes necessary. Any solar pump breakdown is likely to cause a prolonged outage, and repair is likely to be expensive. Procurement of specific items from overseas manufacturers will be a costly and time consuming process under existing currency and import restrictions. However, since the oldest installed solar systems in Sudan have been in place for more than six years and have had few major maintenance requirements, current concerns about spares are minimal.

The wind pumps tested in Sudan do not require fuel for their normal operation. None require oil changes since none utilize a gearing system in an oil bath. However, some makes such as Southern Cross or Fiasa do require an annual oil change. As with solar pumps, there may be a secondary need for fuel and lubricants to meet the transportation needs of supporting wind pump maintenance and repair.

The spare parts requirement should be minimal for a well-engineered and properly installed wind pump. Except for pump cup leathers, there should be no need for so-called fast moving spares. Some sizes of cup leathers are readily available in Sudan since leathers are required for the Edeco and other jack pumps. Larger sizes, likely to be needed for low head pumping situations, can be made locally. However, one must remember that lack of spares was a factor in the abandonment of Gezira windmills. Local wind pump manufacture as planned for the CWD 5000 and suggested for the Kijito, will help ensure the availability of spares.

Figure 8.2. Grundfos solar pump with Arco modules which has run for seven years.

8.3 Market Size and Availability

Market size and equipment availability are factors in determining the potential for the longer term success of wind and solar pumping. Several "orphan" systems are not likely to be successful in the long run. Larger markets and the existence of suppliers willing to provide technical support to these technologies increase the likelihood for sustainability.

Diesel engines and various types of pumps have been available through donor programs and the private sector. There are at least 10 active engine and pump agents in Sudan handling a similar number of engine and pump makes. At present, most of these agents are not able to import new equipment as a result of the current import restrictions. However, donors continue to provide equipment and funds to help supply both the pubic and private sectors.

There is a large market for diesel pumpsets. There are about 3,600 wateryards in Sudan. If each has only one pumpset which has a ten-year useful life, then the replacement requirements are 360 units. This is dwarfed by the private sector market. Ministry of Agriculture and private engine suppliers estimate that there are about 60,000 small diesel pumpsets in use in Sudan. If these have a 12-year useful life, the replacement requirements are 5,000 units annually, which is consistent with recent sales figures. These calculations do not include the large number of larger pumpsets used in the big cooperative and government irrigation schemes.

Distributors for solar pumping equipment exist in Khartoum. To date, solar pumps have been supplied through donor initiative and funds. Distributors for BP Solar and Grundfos exist; they are interested and to some degree active in supplying modules and complete solar systems, not only for water pumping but for refrigeration and lighting.

The current technical and economic prognosis is that the short-term market for solar pumps is very limited. There are less than 25 solar pumps now installed in Sudan. More are planned for installation under several donor supported projects. However, there have been no direct, full price sales of solar pumps to government agencies or private farmers. It is estimated that there are less than 100 sites where solar pumping is currently technically and economically feasible. A number of other sites may be appropriate for solar pumping for non-economic reasons.

The only agent for a windmill manufacturer (Southern Cross is represented by United Engineering) is currently inactive in the windmill market. Several engineering fabrication firms have shown interest in wind pump fabrication. Several firms have held talks with German and Dutch donors concerning support for local fabrication of the Kijito and CWD 5000 wind pumps respectively. These initiatives have produced little action in the last 2 years as a result of the currency restrictions and concerns about the market readiness of the CWD 5000 design.

Given current economic conditions, the scope for cost-effective use of wind pumps is limited. There are now ten CWD 5000 and three Kijito wind pumps installed in Sudan. None of these appears to be operating at maximum capability. A few traditional American farm type wind pumps may be in use in scattered locations. There may be possible application for wind pumps in regions along the Nile north of Khartoum, but the potential market cannot be considered large.

8.4 Infrastructure and Training

The existence of a reasonably developed infrastructure capable of being responsive to design, installation, and servicing needs is an important consideration for the use of any technology. Adequate training in these aspects of technology utilization is an essential part of the long-term planning for diesel as well as for solar and wind pumps.

A well-developed (albeit very inefficient) infrastructure already exists to support diesel pumping technology. Diesel pumps have been in constant use in Sudan for more than 50 years. During this time, both the NCRWRD and the private sector (both formal and informal) have learned how to keep these pumps operating. The NCRWRD argues, with some justification, that the introduction of new pumping technology, including Mono pumps and deep-well vertical turbine pumps, places additional burdens on the servicing capability of the organization.

Private farmers understand how their pumpsets work and know whom to turn to when repairs are necessary.

Although there are formal diesel mechanic training programs, many mechanics have received little formal instruction in diesel maintenance and repair. Diesel Engine Mechanics is part of higher diploma and certificate programs in mechanical engineering at the polytechnic, industrial and professional training schools. Training is also available to NCRWRD mechanics at the Wad Maboul Training Center. However, many mechanics receive little formal training. Although they may be able to get a pumpset running, this is often at the expense of the long-term well being of the engine and pump.

There is no broad infrastructure for the support of photovoltaics although mechanisms exist to support a small number of solar pumps. Solar pumps are essentially electrical and electronic devices. Most have separate controllers, or control circuits built into the pumps. Skills for the troubleshooting and repair of these components require training beyond that found in rural areas. NCRWRD technicians are generally unfamiliar with solar pump technology. However, agents for the equipment, some University students, and technicians and engineers at the ERC are capable of fault finding and component replacement.

There are only limited photovoltaic training opportunities at present. However, local skills exist to initiate such courses. Engineering courses at the University of Khartoum and technical training courses at the Polytechnic introduce photovoltaic principles. Periodic specialized seminars in photovoltaic applications such as refrigeration and communications take place. SREP and ARD staff have conducted courses on pump selection for rural water supplies, including discussion of diesel, solar and wind pumps for NCRWRD and PVO personnel. There are no broad certificate programs to train a cadre of technicians to install and service photovoltaic equipment. If wider use of photovoltaics in general and solar pumps in particular develops, a more focused and comprehensive training program could be developed by Sudanese experts.

Wind pumps in principle should be repairable at a local level with little need for major infrastructural support. Unlike solar pumps which require knowledge of electrical principles, wind pumps are largely mechanical devices. Competent mechanics should be able to diagnose and solve most problems. However, when specific spare parts are required or major breakdowns occur, assistance from more skilled mechanics with access to the needed equipment may be necessary. Local wind pump manufacture, if this develops in the future, should assure the availability of spare parts.

For the CWD design, a well trained maintenance crew capable of major as well as minor servicing and repair works with the ERC. The Dutch-funded Wind Energy Program recognized the need for trained wind pump technicians and included technical training from the outset of their program. The trained crew has been working with the CWD design for three years; they are capable of undertaking all necessary repairs to this design. The crew do not currently have the capacity to support and maintain many more than the 11 wind pumps already installed and logistical constraints limit the work they could perform in more remote areas.

8.5 Transportation Requirements

In Sudan, the largest country in Africa, transportation complications are often a major obstacle to smooth operation of technical equipment. These difficulties arise in both urban and rural settings. Current fuel shortages magnify these problems. Poor roads and large distances are also factors in making transportation a problem.

Diesel pumpsets are particularly vulnerable to transportation limitations. The constant maintenance and repair make transportation a critical constraint to the successful operation of diesel pumpsets. In rural areas, this means that when breakdowns occur they cannot be repaired promptly. Spare parts will be more expensive since transportation charges must be included, and any shortages are likely to cause additional price increases. The need to be continually transporting fuel is a major burden on the transportation network, particularly as one moves away from the rail and pipeline.

With few breakdowns so far and no fuel requirements, solar pumps do not depend heavily on the transportation network (see Figure 8.3). However, when breakdowns do occur, a trip or trips to Khartoum are likely to be required. In many parts of the country, this means that repairs cannot be made promptly.

Figure 8.3. ERC pumping team technician travelling to pump monitoring site with instrumentation.

Wind pumps operate relatively free of transportation requirements. Wind pump servicing and many wind pump repairs can be performed by local mechanics and technicians. Except for occasional procurement of spare parts and materials, difficulties requiring transportation are not likely to occur. This was not the case during the ERC testing program because the CWD 5000 wind pump is not yet a reliable design. However, other reliable designs do exist and the CWD could be improved to increase its reliability.

8.6 Financing Arrangements

Financing for capital and recurrent costs, and recovery of capital investment costs through fees or in kind payment are issues which may have a bearing on the choice of technology. As has been shown, for both rural village water supply and private sector farmers, the unit water cost will be affected by the financing arrangements. Donor agency contributions of equipment and material comprise a large part of the capital cost of a rural wateryard. Government contributions can also be significant when donors do not come forward to assist. Recurrent costs are borne by villagers and government agencies. Concern that local resources are not adequate to meet the recurrent cost of operation and maintenance has been one factor in the growing interest in solar and wind. Donors have shown some willingness to explore the potential for solar pumping, in spite of the high capital cost, if the associated recurrent costs show promise of being low enough to ensure more reliable water delivery systems over the long-term.

Agricultural Bank of Sudan loan programs for small diesel pumping systems are a major benefit to farmers. Not only do these programs reduce the immediate capital investment that a farmer must make, but they also make inexpensive pumping systems available as a result of the ABS policy of converting the value of the engine from the official S£4.5 to the U.S. dollar rate. This program is made possible by multi-lateral and bilateral donor assistance to the ABS. Similar programs are not available for the purchase of solar or wind pumping equipment.

The NCRWRD charges fees for water in some regions and not in others. These fees ostensibly pay for the services of the NCRWRD. The current tariff structure should, if managed properly, cover all operation and maintenance costs. However, in villages where the NCRWRD does collect fees, this does not appear to be the case and additional funds must be collected by the villagers in order to keep their water system operating. The NCRWRD does provide replacement engines and pumps occasionally, depending on equipment availability and the effectiveness of village petitioning. However, long delays are common. Innovative financing for replacement is often necessary. Sometimes a wealthy villager or merchant will provide equipment and wait for long periods for reimbursement from government agencies. Perhaps more often, replacements are not made and villagers must struggle.

Cost recovery for water used in irrigation is in many ways more straightforward than for rural village water supplies. Farmers own and repair their pumping equipment. They must harvest sufficient crops to pay the operating costs of the farm (including water pumping). Gross incomes in the range of S£10,000 per feddan, limit the pumping options of a small farmer. The lower capital cost of the Indian Lister diesel pumpset as compared to wind or solar pumps is likely to dictate system choice.

8.7 Environmental Considerations

Environmental concerns have been a factor in the water sector in Sudan in the past. These issues arise periodically in both the donor community and among concerned Sudanese. Large, high capacity wateryards have led to localized overgrazing around water points, particularly in Kordofan and Darfur Regions. These problems can be mitigated if more but smaller capacity systems were used. Wind and solar systems, with their limited pumping capacity, cannot provide enough water for large animal herds and are therefore more environmentally benign. However, this very factor, limited pumping capacity, is seen as a major limitation to villagers with small stock to water and nomads with herds of camels. This limits user willingness to accept these technologies.

In areas with limited water resources and low recharge, a potential exists to exhaust the aquifer by over-pumping and depleting the water resource. In the large areas of Sudan underlain by the Nubian and Uum Rwaaba aquifers, this is not likely to be a problem. However, diesel pumps, due to the relatively high pumping rate at which they are most efficient, are not well suited to water lifting in smaller, limited recharge aquifers such as are sometimes found in other areas of the country. Solar and wind pumps, with their limited pumping rates, can be more suitable technologies. The pumping rate or total pumping hours of these technologies cannot be changed; therefore they do not abuse a limited water resource.

Diesel engines pollute. Their emissions pollute the air, their operation contributes to noise pollution, spillage of fuel and disposal of lubricants pollute the soil and quite often the water as well. Solar and wind pumps do not pollute in any of these ways and their use is environmentally benign. Although these issues are of less importance to Sudan, they do concern the donors who are often concerned about the effects of pollution at home, and therefore retain that concern when planning projects overseas.

Recent concern about the deterioration of the ozone layer has again focused international attention on global warming and the greenhouse effect. Diesel water pumping in Sudan contributes a negligible percentage to this problem. In fact, within Sudan, water pumping plays much less of a role than the transportation sector.

Noise pollution, an aggravation to some, is likely to be a minor concern when water availability is at stake. In fact, in many areas the sound of the diesel pump operating is a reassuring rather than an unpleasant sound.

Other than the very real possibility that spilled fuel and oil may contaminate the water source, these sources of pollution are unlikely to be considered as major problems at the village level. Indeed, given the shortage and cost of both fuel and lubricants, particular care will be taken to minimize these losses.

Although these environmental aspects may be considered minor concerns by many, wind and solar pumping represent steps in a positive direction that should not be discounted.

9.0 Conclusions

The objective of the SREP pump testing and evaluation program was to determine the potential role of renewable energy pumping systems, specifically wind and solar pumps, in village water supply and small-scale irrigation applications in Sudan. To do this, it was first necessary to develop a broad understanding of the performance, cost, and socio-institutional characteristics of diesel pumping systems. As the program progressed, it became clear that considerable opportunity exists to improve upon the design and operation of the existing stock of diesel pumps, and much of that information is contained in the relevant sections of this report. It also became clear that while there are opportunities to displace some diesel pumps with wind or solar pumps, the range of these opportunities is fairly limited. This is due in part to the high head and moderate to high volume water demands often encountered in much of the country, and in part to very low cost diesel engines and pumps commonly used for small-scale irrigation. This chapter summarizes the conclusions reached during the program regarding the improvement of diesel pump operations in Sudan, as well as the technical and economic feasibility of displacing diesels with wind and solar pumps. Chapter Ten gives specific recommendations on how to achieve these goals.

9.1 General Conclusions

The Sudan is a large and varied country with a broad range of water pumping requirements. During the SREP pump testing and evaluation period from mid-1989 to early 1990, difficulties ranging from floods to severe shortages of fuel made a comprehensive country-wide assessment impossible. Politically and economically, Sudan is in flux. Consequently, it is difficult to make definitive statements about all possible applications or detailed assessments of market potential for wind and solar pumps. However, technical performance results obtained during this program will remain valid for use in future feasibility studies using then-current cost and economic variables. The analytical approach used here can be easily modified to reflect changing economic and policy circumstances. The conclusions presented here arise from conditions as they existed in early 1990.

Given the cost and logistics of operating and maintaining diesel pumping systems in Sudan, it is not surprising that there is interest in renewable energy technologies. Further away from the major urban centers, where fuel and spare parts are more available and transportation problems are easier to resolve, the myriad difficulties of using diesel pumps become more obvious. There, the relatively low operation and maintenance needs of wind and solar pumps become that much more appealing to both donors and system users. However, their high initial costs, coupled with a current lack of a suitable support infrastructure for proper system design, installation, maintenance and repair, are major obstacles in their widespread dissemination.

Supporters of renewable energy technologies emphasize the need to compare the life cycle costs of diesel, wind and solar pumps. In Sudan, this is not a trivial task. The economy is in crisis due to due to a variety of natural, political and fiscal phenomena. There are significant economic distortions which make the comparative analysis of pumping systems difficult, such as diesel fuel price subsidies, multi-tiered exchange rates, subsidized ABS loan programs for certain types of pumps but not others, and inadequate cost recovery mechanisms for village water systems. These distortions have been engendered in part by high level policy decisions which have implications in areas far more wide-ranging than simple decisions about pump applications.

At the academic research level, diesel, wind, and solar pumping are now fairly well understood. The ERC has the capability to analyze technical, economic, social and institutional issues related to different pumping applications. At this point however, long term field experience with wind and solar pumps in Sudan is limited. Research efforts funded locally and by donor agencies have focused mainly on RET pumps, but the applications and acceptance of these technologies in village and small farm settings have not been fully analyzed, since few RET systems have yet been installed and regularly monitored over the long term. While many skilled technicians exist in Sudan, especially in towns and urban centers, few have yet received the additional specialized training needed to support wind and solar pumping systems. Aside from the cost and performance issues summarized below, the development of a suitable local infrastructure (e.g., trained technicians, equipment and spare parts distribution networks) to support these systems will be a critical (and costly) component of any widespread dissemination program for RET pumps.

9.2 Technical Conclusions

The program's technical conclusions are summarized in separate sections below for diesel, solar and wind pumps. Conclusions regarding comparative system costs are given in Section 9.3.

9.2.1 Diesel Pumps

Diesel pump operating efficiencies and the condition of systems varied widely. Well-designed and properly maintained systems will have an efficiency of 15 percent or better. The village water supply systems monitored during the project had efficiencies ranging between 2-17 percent. In general, the higher the efficiency, the lower the specific fuel consumption (per unit of water pumped), the better the system operates, and the lower the maintenance and repair needs. Diesel systems (using jack or Mono pumps) recently installed by the NCRWRD for rural village water supplies in Western Sudan are reasonably well-designed, with initial system efficiencies of 12-15 percent in many cases monitored by this program. However, the continued lack of proper maintenance and repair procedures can and do significantly reduce this efficiency over time (to as little as 2 percent in one site tested). At another site, fuel consumption increased by 12 percent as a result of the poor condition of the wateryard equipment. The situation is somewhat different in areas where vertical turbine pumps are used. The design of these systems is more sensitive to head, pumping rate, and the specific model of pump chosen. Efficiencies of well under 10 percent at nearly half of the test sites and the NCRWRD design method used indicate that much can be done to improve design procedures, system efficiency, and fuel consumption rates.

Test results vary considerably across different types of diesel pumps. Edeco (jack-type) pumps are best suited for high head applications. When used on low head boreholes, operating efficiencies are poor. The Edeco systems tested had a wide range of operating efficiencies, from good to very poor. Pump leathers have to be replaced fairly frequently. If they are not, volumetric efficiencies drop as wear accelerates. Since they are purchased by special order only, they are also quite expensive. Many observed at other sites are in poor condition, operating without proper spares. Shaft-driven vertical turbine pumps can operate at high efficiency, but their operating efficiency depends heavily upon picking the right model for the desired head and pumping rate. NCRWRD's limited access to different models has resulted in systems which are often poorly matched to the water resource. Both vertical turbine sites monitored by this project had poor operating efficiencies because they were poorly matched to their boreholes. Mono pumps are designed to operate most efficiently at heads greater than 30 meters. Above that lower limit, their operating efficiencies are typically quite good, and independent of head so that design considerations are not so crucial. They have a higher capacity range than that of the Edeco models commonly used (whose output is constrained by the size of pump cylinder which can fit in the borehole casing). The Mono sites tested had uniformly acceptable operating efficiencies, and Monos generally have the reputation of being low-maintenance, reliable pumps.

For small-scale irrigation applications, the efficiencies of all privately owned pumpsets tested were very low (around 5 percent). This is partly the result of the poor power output and fuel consumption characteristics of the very inexpensive Indian-made versions of the Lister engine, usually coupled with cheap, low efficiency pumps. The head and flow rate characteristics for these systems are low for these 6 and 8 horsepower (nominal) engines. These engines are generally much larger than necessary for the work they perform (i.e., low-loaded, hence inefficient). Technically, it should be possible to double the efficiency of these configurations (hence roughly halving the specific fuel consumption). In practice, this could be done by using either larger pumps or smaller engines for a given pumping situation.

The increasing scarcity of spare parts and diesel fuel has been exacerbated by events over the last year (1989-90). Current import restrictions (on nearly all equipment, not just that for water supply) and shortages of fuel make the operation of diesel pumpsets increasingly expensive and problematic. Poorly maintained vehicles and uncertain access to fuel make proper maintenance and repair of diesel systems much more difficult. Skilled workers, so necessary to maintain the support infrastructure, continue to seek employment elsewhere. Stocks of spare parts continue to dwindle, bringing into question their future availability, and virtually insuring increases in cost over the near to medium term.

9.2.2 Solar

Solar pump performance depends directly on available solar radiation at the site. Solar radiation levels in Sudan are both high and seasonally fairly uniform, particularly in the north. Ten of the 16 meteorological stations recording solar radiation levels report annual averages of at least 6.0 kWh/m^2/day on the horizontal surface; analysis of data from other sources suggests that this average is accurate. The availability of solar radiation is less in southern Sudan because of the rainy season during the summer.

Some types of solar pumps have proven very dependable; the Grundfos pumps located at the University of Gezira and at the Hodieba Research Center are examples. Installed in 1983, at these two sites neither system has experienced any failures after seven years' operation. More recent Grundfos installations in villages have also proven reliable thus far. On the other hand, the KSB Aquasol floating pump at Shambat has been replaced in each of the last 2 years. While a single site sample is not necessarily an indicator of long-term performance, this certainly does not bode well. Recently, a modified version of this pump was installed at the site, and performance testing will continue.

In general, the performance of the solar pumps does not meet manufacturers' advertised specifications. Grundfos provides an easy-to-use sizing guide for estimating water output for its pumps. However, thorough pump testing during this program indicates that this guide consistently overestimates pump performance in Sudan by about 15-25 percent. There are several possible explanations for this observation. For older installations, inverter and pump performance may have decreased somewhat after 6 years' operation. Also, solar pump performance is a function of module temperature (the cooler the temperature, the higher the electrical output) and ambient solar radiation levels (the higher the radiation, the higher the pump output). Grundfos provides performance estimates based on a ambient temperature of 30^0C (equivalent to about 45°C cell operating temperature). Even after adjusting for a more realistic cell operating temperature of 60°C, the Grundfos performance charts overestimate both instantaneous and daily pump output by a considerable margin. The performance graphs provided by KSB account for temperature variations, but are more difficult to use; they also overestimate daily performance by roughly 10 percent.

Installation and maintenance of solar pumps is not always done properly. Reductions in power output may occur for the following reasons: the optimum array tilt is not used, arrays are partly shaded, improper wiring and loose connections unnecessarily dissipate useful energy, and modules are not kept clean. Sudan spans latitudes from 4^0 North to 22^0 North. Optimum tilt angles vary considerably across this area. In areas from Wad Medani and north, optimum angles are from 10° to 25° depending on the exact site location. For most of the current installations, the angle used is greater than it should be for maximum performance of the pump. At both Shambat and Hodieba, trees shade the arrays early in the morning during certain times of the year. In at least one notable case (Shambat), small power cable diameter and long length caused otherwise avoidable energy losses. Pump users typically do not regularly clean array surfaces to remove dust which blocks incoming solar radiation. All of these factors reduce solar pump performance, and may partly explain less than optimal test results. However, they do reflect fairly typical operational circumstances, a factor which system designers should bear well in mind. In order get maximum value from a solar pump (i.e., to minimize its unit water cost), it should be operated whenever the solar radiation is sufficient to drive the pump. At Shambat, the farmer chose to turn the pump off rather than expand his limited cultivated area. At Sheraim El Karamsha, when water is available from the local wateryard, the solar pump is not always used (for political rather than technical reasons). At Foja, the pump is turned off occasionally when the storage tanks are full, rather than finding alternative uses for the extra water. With time, and increased familiarity with and confidence in the technology, users will learn to more fully utilize the potential of solar pumps.

There are technically suitable applications for solar pumps, mainly for low to moderate head (up to about 50 meters) and low water demand (up to about 50 m^3/day) situations. A rule of thumb for estimating the capacity limit for commercially available solar pumps is that the product of the water demand (in cubic meters per day) and the total pumping head (in meters) should not exceed 750 m^4 for areas with good solar radiation levels (6.0 kWh/m^2/day) in the design month. Sites which meet these criteria in Sudan are mainly located in the Northern Region near the Nile and its tributaries, where water can be found close to the surface and the water demand is often moderate. Throughout Sudan there are other areas near seasonal streams and wadis, or where groundwater tables are fairly high (e.g., Umm Rawaba, Bara) which would be suitable solar pump sites.

9.2.3 Wind

Windmills are most appropriate at sites with good wind regimes (average design month windspeeds of more than 4 m/s) and low to moderate heads (no more than about 50 meters). In Sudan, windmills are most appropriate for use in the relatively windy areas along the Red Sea coast, and at sites north of Khartoum near the Nile. Unfortunately, a good estimate of wind energy potential is impossible given the generally poor quality and limited scope of existing wind data. Records for a number of years are available, but the continued use of Dines pressure plate anemometers (which are both very sensitive to correct calibration, and do not provide good wind speed resolution) limit the usefulness of this data. However, several recent wind speed data collection efforts suggest that wind resources may be better than anticipated at sites along the Nile north of Khartoum. Windmill output is very dependent on the daily average wind speed and distribution. Local wind speeds vary as a result of site-specific features and local topography. This makes an accurate estimate of wind speeds at a particular site difficult to predict. In Sudan, it is more difficult to predict windmill output than solar pump output because of greater local variation in the wind energy resource. In addition, the greater daily variability of wind pump output implies greater water storage requirements to maintain supply during anticipated and unanticipated calm periods.

Making general conclusions about windmill use in Sudan are limited by having only tested one type of machine, the CWD 5000. Other machines were either too distant (e.g., the Southern Cross at Wadi Halfa), or not yet installed before the major part of the testing program had been concluded (e.g., Kenyan-made Kijitos provided by the SEP program, or those installed with ODA assistance at Kelli). It has been just over three years since the first CWD 5000 machine was installed, and, due in part to extensive design problems which caused frequent machine failures, longer term field experience with these machines is still fairly limited. The CWD 5000 has not proved to be a reliable, commercially suitable design. After early problems with the furling mechanism and the pump itself were overcome, a series of more serious difficulties arose which called into question the long-term suitability of the current CWD 5000 design. Failures of the head frame assembly and the crank arm on more than one machine indicate that design weaknesses certainly need to be rectified before further dissemination is considered. In addition, the designer's performance predictions for the CWD 5000 considerably overestimate output when compared to tested performance, falling short of predicted values by 30-45 percent between daily average wind speeds of 3-5 m/s. At lower wind speeds, the predictions are even poorer. Performance is not as good as expected, due in part to poor volumetric efficiencies and higher-than-expected start-up wind speeds. Higher wind speed performance is impaired by rapid wear of cup leathers which reduce system operating efficiency. What can be done to remedy this is not yet clear, but further testing continues. However, even taking these factors into account, computer simulations based on field test results show that the performance predicted by CWD designers is overly optimistic.

Nonetheless, there are technically appropriate applications in Sudan for well-designed, reliable windmills. Windmill output decreases with increasing head and decreasing wind speed. The CWD 5000 is designed for low head (20 meters or less) applications. Other designs such as the Kijito are suitable for pumping heads up to 50 meters, and so would have a broader range of applications in Sudan. The Kijito has been field-tested in Kenya and Botswana, and found to be a well-designed and reliable (albeit fairly expensive) machine. Given the monitored performance of the CWD design, a rule of thumb for suitable sites for this windmill is that the product of the water demand (in cubic meters per day) and the total pumping head (in meters) should not exceed 750 m^4 for areas with average wind speeds of 4.1 m/s. This could be increased to 850 m^4 by selection of windmills with larger rotors, such as the 6-meter Kijito, or by improvements to the current CWD 5000 design. Suitable windmill sites in Sudan are mainly in the Northern Region near the Nile and its tributaries, and in Eastern Region coastal areas. Sites in these areas are appropriate wherever the water is close to the surface and the water demand is low to moderate. There are other scattered locations near seasonal streams and wadis where the water is close to the surface and wind pumps could be used. There will be considerable overlap with potential solar pump sites, since both technologies are most applicable where the energy needed to pump water is low to moderate. The technical decision will then be based on the particular site's wind and solar energy resources.

9.3 Economic Conclusions

The financial and economic profiles are so different for pumping systems for the rural water supply and the small-scale irrigated sectors that the two cases were analyzed separately. In general, the financial and economic unit water costs are much higher for rural village water supplies than for small-scale irrigation. Most of this difference is due to the use of more expensive wateryard components (elevated tanks, meters, valves, fencing, distribution pipes, and taps), which are not necessary for small-scale irrigation applications. In addition, farmers typically use much less expensive (and less reliable) brands of pumps and engines than are normally used for village water supplies. The current economic situation in Sudan forces the NCRWRD and the rural villages to be heavily dependent on donor support for the construction and rehabilitation of their water supplies. When donors are willing to provide equipment, the recurrent costs become important.

On the other hand, small farm cash flow constraints dictate that farmers must consider capital costs to be much more important than life cycle cost when it comes to making investment decisions about pumping equipment. Because of this, low cost diesel systems (with engines and pumps from India, China, or Cyprus) are and will likely remain the system of choice for small-scale irrigation pumping. Only where wind speeds are much higher than average, and where an alternative to diesel is being considered for other than cost reasons, might a windmill be an alternative to diesel for irrigation. Even if system life cycle costs were equivalent (and they are not even close to being so), the high initial costs of capital intensive solar and wind pumps are simply beyond the means of most small farmers, who would be unable to service that level of debt even if they had access to sufficient credit to buy the systems. It is unlikely that solar or wind pumps will attain any significant market share in irrigation applications in the near future.

Even given all of their well-documented problems, diesel pumpsets are cost-competitive with solar and wind in many of the village water supply applications for which solar and wind are technically suited, except in fairly low head, low demand situations. For applications where demand exceeds the limited capacity of commercially available solar and wind pumps, diesel is the only reasonable option (unless grid-connected electric pumps could be used).

Wind and solar systems become more cost-competitive with diesel as demand and head decrease, and as fuel prices and transport distances increase. The base case financial and economic analyses show that using wind or solar pumps for village water supply is cost-effective in instances where the demand*head product (meters of head times cubic meters of demand) is less than 750 m^4/day. This represents less than 5 percent of the village sites in the country. In these situations, windmills are the preferred choice at sites where design month windspeeds exceed 4.5 m/s. However, the lack of accurate wind speed data with which to make system design decisions, and the technical problems with the particular wind pumps tested in this program, must be weighed against the potential long-term economic benefits. Particularly in rural villages where water supply reliability is particularly important, serious consideration of wind pumps should be postponed until more dependable windmills have (such as the Kijito) been evaluated for use in Sudan.

9.4 Summary

Although fuel and spare parts availability and cost as well as transportation difficulties will continue to be major concerns in Sudan, in the current economic situation, capital cost is the most important consideration in choosing pumping equipment. While life cycle cost analysis and subsequent identification of potential long term savings from using RET pumps may have meaningful long-term policy implications, all indications are that this is not how equipment buying decisions are currently being made at the field level.

For rural village water supply, the size of the water demand and pumping head severely limits the use of wind and solar pumps. Nonetheless, there are still opportunities for solar pumping which are not based simply on cost-competitiveness with diesel pumps, but rather on other considerations such as independence from fuel cost and supply variations, minimization of maintenance needs, and long term reliable operation. These attributes are important to system sustainability, and should be considered in water system design decisions. Where site wind speeds are adequate, windmills also have a role to play, assuming that reliable, field-proven models are both available and locally supportable, and site wind speed data has been shown to be reliable.

For small farm irrigation, the Indian-made Lister-type engine will remain the system of choice in spite of its numerous shortcomings. Should the small-scale farmer want an alternative to diesel, windmills are a more likely choice over solar pumps, assuming their capacity is adequate to meet demand. However, without a reliable wind pump commercially available in Sudan, farmers will continue to use diesel pumps exclusively. Experience with a wider variety of wind pumps and a better understanding of Sudan's wind regime are necessary before accurately determining the market potential of wind pumps in Sudan.

Finally, the most cost-effective short term strategy for improving systems, reducing pumping costs, and increasing reliability of both village water supply and pumped irrigation in Sudan is to pay more attention to proper diesel pump design and maintenance. Better matching of pumps and engines to both the water resource and the demand profile will result in better engine loading, higher operating efficiency, lower specific fuel consumption, reduced engine wear, less frequent overhauls, and consequently lower operation and maintenance costs over the lifetime of the system.

10. Recommendations

There are several categories of recommendations given in this concluding chapter: broad energy and water policy recommendations for diesel, wind, and solar pumping in Sudan; recommendations for future ERC activities in pump testing and evaluation; and recommendations for the other governmental and non-governmental agencies in the sector.

10.1 Energy and Water Pumping Policy

Energy and fiscal policy in Sudan currently favors diesel fuel as an energy source. Given the potential benefits of expanded use of renewable energy and more efficient use of diesel fuel in Sudan, a series of actions is recommended which will promote the use of renewable energy in general and the use of renewable energy for pumping in particular. These actions include:

- Setting a more realistic price for diesel fuel. Reducing the government subsidy for diesel will foster a greater awareness of the economic benefits of using renewable energy technologies for a variety of end uses, including pumping.
- Setting water tariffs at the full life cycle cost recovery rate, so they truly reflect the cost of developing, operating, maintaining and repairing rural water supplies.
- Expanding long-term credit programs for water pumping investment to cover renewable energy pumping technologies, while at the same time pricing equipment on the basis of unregulated foreign exchange rates.
- Developing a viable institutional plan for commercialization of technically reliable wind and solar systems. This plan would include a program for financing the development of the necessary infrastructure to support these technologies over the long term.
- Reducing general inflationary pressures. This will encourage longer term resource allocation decisions in place of the capital cost-driven decisions of today. It will also promote more capital intensive technologies which in the long-term may be more cost-effective.

These actions will promote a more balanced evaluation of water pumping technologies by potential users, and increase interest in and use of solar and wind pump technologies where they are technically viable options.

Current diesel systems need upgrading; careful design and better maintenance of diesel systems will reduce fuel consumption and O&M costs. The NCRWRD should develop and follow design procedures to ensure that engines and pumps are better matched to the water resource and site demand profile. Donors should also be responsive to the design procedures when providing equipment for rural village water supplies. Equipment standardization should be encouraged whenever possible. Training programs in system design and equipment selection would also enhance NCRWRD's ability to upgrade current systems. The NCRWRD should also ensure that pumpsets are maintained properly. This may require that villagers take a larger role in operation and minor servicing of equipment, while the NCRWRD uses its resources to provide major service and repair. Involving villagers in system planning, design, construction and operation will greatly help to insure their sense of direct responsibility for properly supporting the system, and hence increase its sustainability long after external funding sources are exhausted.

An examination of wateryard construction costs should be undertaken. These costs appear to be higher than necessary. For example, water storage is expensive, especially for elevated storage. A careful evaluation of water storage needs, types and designs of tanks used, and a comparison of costs for importation and local fabrication of tanks could lead to significant reductions in wateryard costs. This evaluation might include smaller tanks, ground tanks, or tanks that can be built on site with materials such as concrete or ferro-cement. There also may be opportunities for savings in transportation costs. A study of transportation requirements and costs could lead to more effective patterns for utilization of vehicles, and subsequently reduced transportation costs.

Small farm diesel pumps are particularly inefficient. Information should be provided to the National Extension Administration to help their staff advise farmers on more effective use of diesel systems. The staff should explain the cost savings inherent in using larger pumps (to increase engine loading and reduce engine hours of operation). They also should emphasize the potential cost savings when engines and pumps are properly maintained.

There are a number of technically suitable applications where solar pumps are cost-competitive with diesels. These are low head and low water demand sites where the demand*head product is less than 750 m^4. These sites exist in northern Sudan where the solar radiation levels are high. The solar pumping alternative will become more attractive if solar equipment costs decrease, or diesel fuel costs increase, or fuel and spare parts for diesel engines become more expensive and harder to obtain. Broader long-term experience with solar pumps is needed to develop the necessary technical skills, more fully evaluate acceptance and performance, and enable promotion and dissemination of the technology. Additional sites suitable for the limited capacity of solar pumps should be sought, particularly in the Northern Region. Equipment for five to ten sites has already been procured by GTZ and other donors. Installation and performance monitoring should include villagers and the ERC as well as the NCRWRD. As NGO groups continue to install solar pumps around the country, the performance of these sites should be monitored as well. Continued monitoring of these and the current project monitoring sites will significantly broaden the data base of long-term performance and costs for solar pumping in Sudan, and thereby generate a better understanding of its long term recurrent cost structure.

There are also technically suitable applications for wind pumps. The product of the demand*head should not exceed about 750 m^4 (the high side for larger windmills) for sites with average design month wind speeds of 4.5 m/s. Areas and applications which meet these criteria are located in the Northern Region near the Nile and its tributaries and on the Eastern

Region coast; here there are areas where water can be found close to the surface, and water demand is typically moderate. Suitable locations near seasonal streams and wadis can be found in other areas of northern Sudan.

The current CWD 5000 design should not be considered for future dissemination. Further consideration of this design should occur only after a thorough review of the causes for the more serious failures of the past several years. There has been no evaluation of other windmills during this project, and this shortcoming should be corrected. Monitoring and evaluating the now-available Kijito wind pumps should be initiated. This machine has proved to be robust and reliable in field tests undertaken in other countries. Financial analysis does not favor the use of wind pumps by small-scale farmers unless they seek an alternative to diesel pumps. Local manufacture of wind pumps contributes little to economic viability because of the comparatively small labor component of their life cycle cost. A focused study of the market for wind pumps should be conducted before further dissemination of any design is seriously considered.

10.2 Short- and Medium-Term Activities for the ERC

The ERC/SREP water pumping program has been collecting data for nearly two years; pump monitoring has been taking place for less than one year. During the project, a series of unforeseen events and logistical difficulties limited the scope of activities. Program support and technical assistance provided by the SREP project ended prematurely in February 1990. However, the results of the evaluations conducted to date have raised additional questions. The ERC Pumping Team should continue evaluating small-scale pumping systems to build on the considerable work accomplished thus far (see Figure 10.1). The following section outlines ERC's short- and medium-term plans in this field.

Detailed pump monitoring will continue for several of the solar and wind pumps until a full year of data has been collected. Data collection will continue at the University of Gezira, Hodieba, Shambat, and Foja solar sites. Short-term data and at least several months' long-term data should be collected at the solar pump site at Sheraim El Karamsha, but since its design and pumping conditions are similar to those at Foja, resources can best be used monitoring other sites.

Wind pump monitoring will continue at Soba. If the wind pumps at other sites are not in use, monitoring should be stopped. Additional wind and solar sites should be monitored. Likely candidates include: the solar pump recently installed at Soba, the solar pumps to be installed by the WSDP near Nyala, pumps to be installed by SEP near Wadi Kutum, and KSB pumps to be installed by the SEP in areas near Khartoum. One or (preferably) two Kijito sites should be monitored.

Focused technical studies to broaden the data base of long term solar and wind pump field performance should be undertaken. Among these is a more detailed study of the performance of the solar pump at the University of Gezira, to determine if indeed its poor performance can be attributed to the age of the installation or other cause. Also a feasibility study for the Swedish-Sudanese Association should be completed, giving pump performance details for watering the shelterbelt and garden at Foja. Necessary repairs should be made to the wind pump at Soba, and tests conducted to determine if predicted pumping rates can be achieved. Further tests of the Indian-made Lister-type diesel pumpsets should be conducted, and a report prepared of the results.

The detailed Rural Village Survey reached only the Khartoum Commissionerate and the Central Region. The surveys should be continued to include the remaining regions of Sudan. This will provide information on regional variations in operation/maintenance practices and costs.

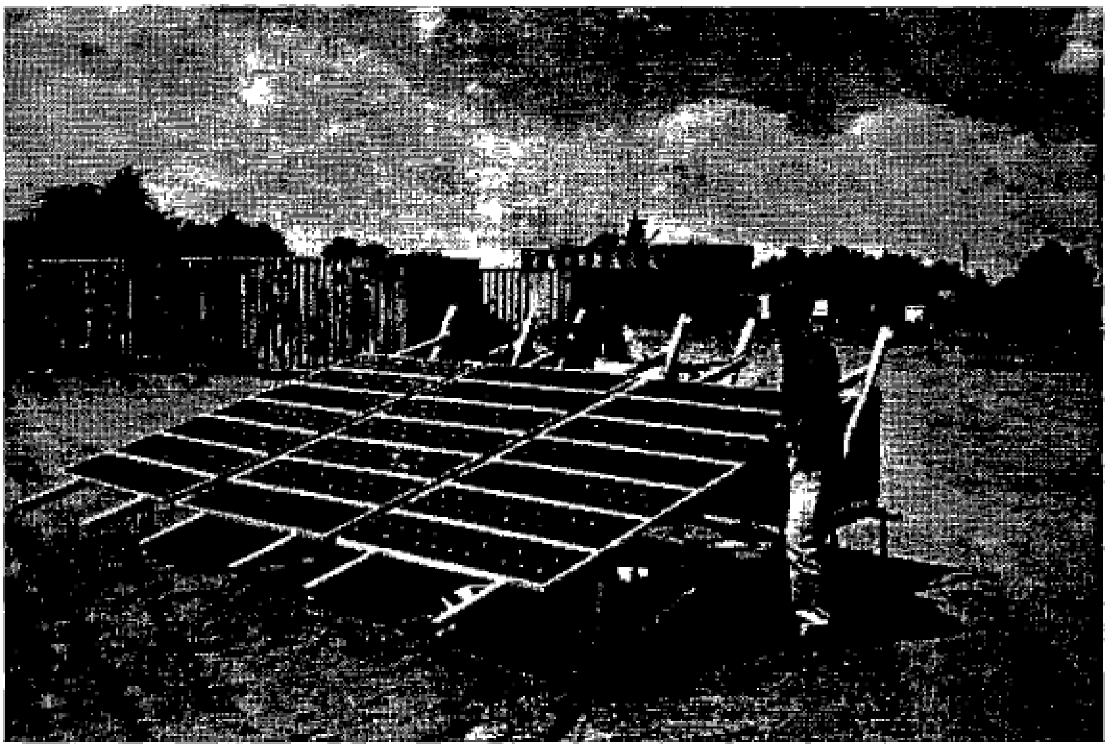


Figure 10.1. Newly installed Grundfos solar pump with ARCO M53 modules at Soba Research Station with pumping team technician.

The Small Farmers' Survey, begun with the assistance of the National Extension Administration, should be continued and include surveys of more remote small irrigated farms. Focus should be directed towards the Northern Region along the Nile and areas in the west with pumping heads of under 20 meters. The results should include a cost-benefit analysis of diesel as well as solar and wind pumping.

With the changing economic conditions in Sudan, it is important to update financial and economic costs. In periodic updates on the financial and economic feasibility of solar and wind pumping, the results of the completed surveys should be included.

It is important that the ERC Pumping Team continue to provide information and consulting services to interested government and non-governmental organizations. These services should include practical information on technical capacities; recommendations on pumping system designs; and cost estimates for solar, wind, and diesel pumps.

10.3 Other Organizations

There are several specific recommendations for other government, non-government, and donor organizations. The Sudan Meteorological Department should continue to collect solar radiation data at the 16 sites now in operation. Pyranometers (and other instrumentation) should be calibrated on a regular basis, and annual summaries made available to the ERC and other interested organizations. The Department should replace the Dines pressure plate anemometers with modern equipment which requires less maintenance and provides better wind speed resolution. New instruments should be located ten meters from the ground surface in unobstructed wind flows to give the most useful data for windmill design.

Technical training institutes, including the Sudan Technical University, technical training institutes, and professional mechanical training schools should introduce photovoltaics into the curriculum. Although photovoltaic principles are taught at the University of Khartoum and are being introduced at the Technical University, a more comprehensive curriculum should be developed to train technicians in practical aspects of photovoltaic installation, maintenance, and repair. Only with these initiatives will a trained cadre of technicians be available not only for solar pumping support, but also for other cost-effective photovoltaic applications such as vaccine refrigeration and telecommunications.

Donors and non-governmental organizations should continue to fund appropriate solar and wind pumping programs, with a clear understanding of the limitations and applications of both. Current conditions make solar pumping more favorable than wind for rural village applications, partly because of the lack of commercially available reliable windmills in Sudan, and partly because of the lack of reliable, site-specific wind data. Eventually, more widespread dissemination of these technologies, if it occurs, will depend on a broader understanding of the potential applications and limitations of these technologies. Although Sudan cannot now afford to purchase the equipment itself, the NCRWRD needs experience if these technologies are to be used in the future. Such a program should be committed both to training NCRWRD staff, and familiarizing the public with the technologies. It should also include the participation of local pump agents to ensure the long-term support necessary for these technologies. Such a program should be coordinated through the ERC, since it has the formal government mandate to research and promote renewable energy use in Sudan, and ERC staff also now have the capacity to assist with technical, economic, and related renewable energy analysis.

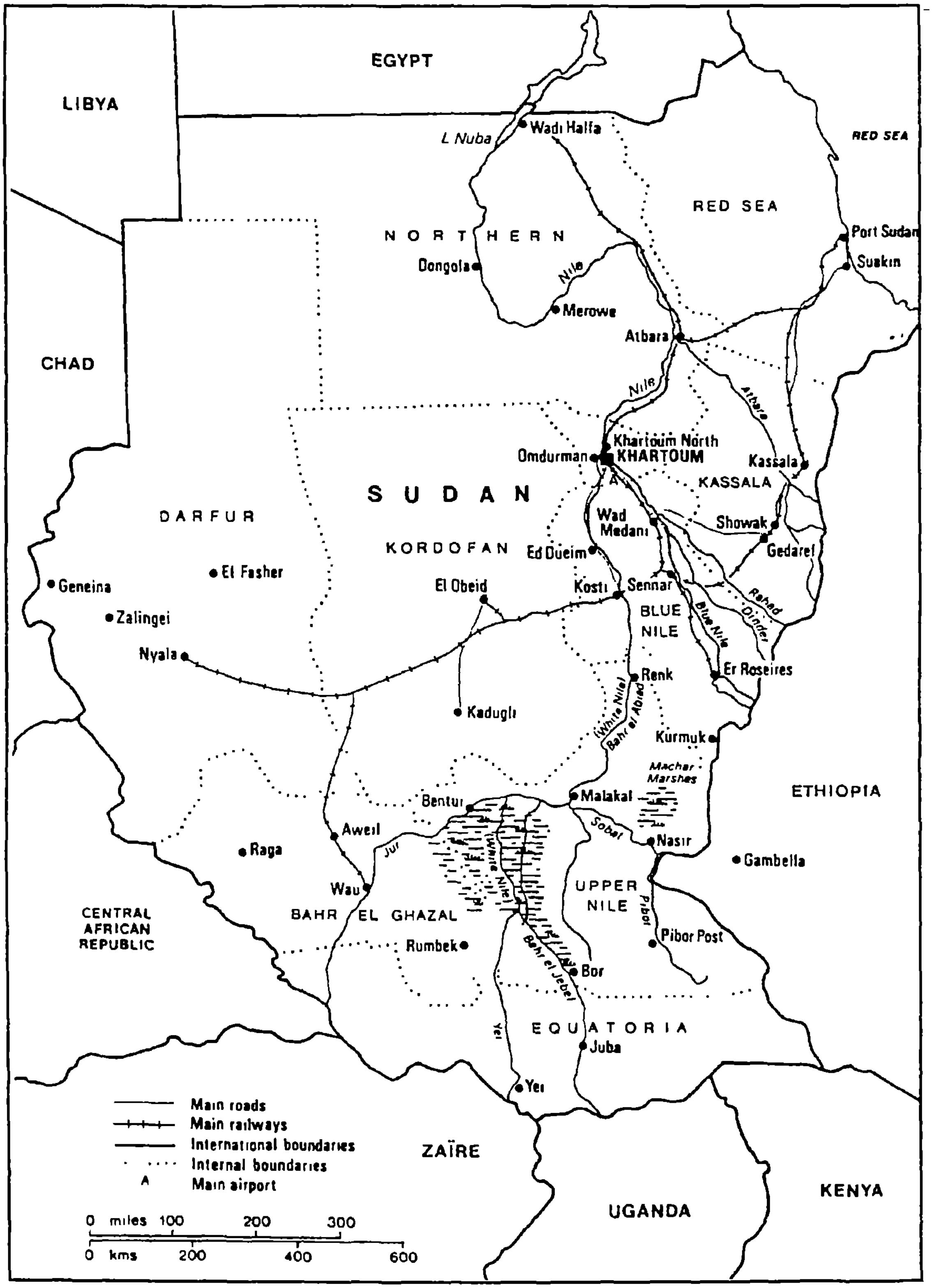
Appendix A. Test Sites

Test Sites Village	Region	Pump-set Configuration
Diesel Pumps		
Bara	Kordofan	Indian Lister
Wad Medani	Central	Indian Lister
Ed Damer	Northern	Indian Lister
Wad Sabeel	Kordofan	Lister-Edeco
Obeid Mahdi	Kordofan	Lister-Edeco
Malaga	Kordofan	Lister-Edeco
Abu Auwa	Kordofan	Lister-Edeco
Abu Hamra	Kordofan	Lister-Edeco
Um Kharain	Kordofan	Lister-Edeco
Sheraim El Karamsha	Kordofan	Lister-Edeco
El Mugdab	Khartoum	Yanmar-Kato
El Sundudab	Khartoum	Andoria-Grundfos
Sharafa	Darfur	Lister-Mono
Shangeltobai	Darfur	Lister-Mono
Musco	Darfur	Lister-Mono
Tabit	Darfur	Lister-Mono
Solar Pumps		
Gezira	Central	Arco Solar-Grundfos
Hodieba	Northern	Arco Solar-Grundfos
Foja	Kordofan	Arco Solar-Grundfos
Sheraim El Karamsha	Kordofan	Arco Solar-Grundfos
Shambat	Khartoum	BMC Solartechnic-KSB
Wind Pumps		
Soba	Khartoum	CWD 5000
Jebel Aulia	Khartoum	CWD 5000
Shambat	Khartoum	CWD 5000

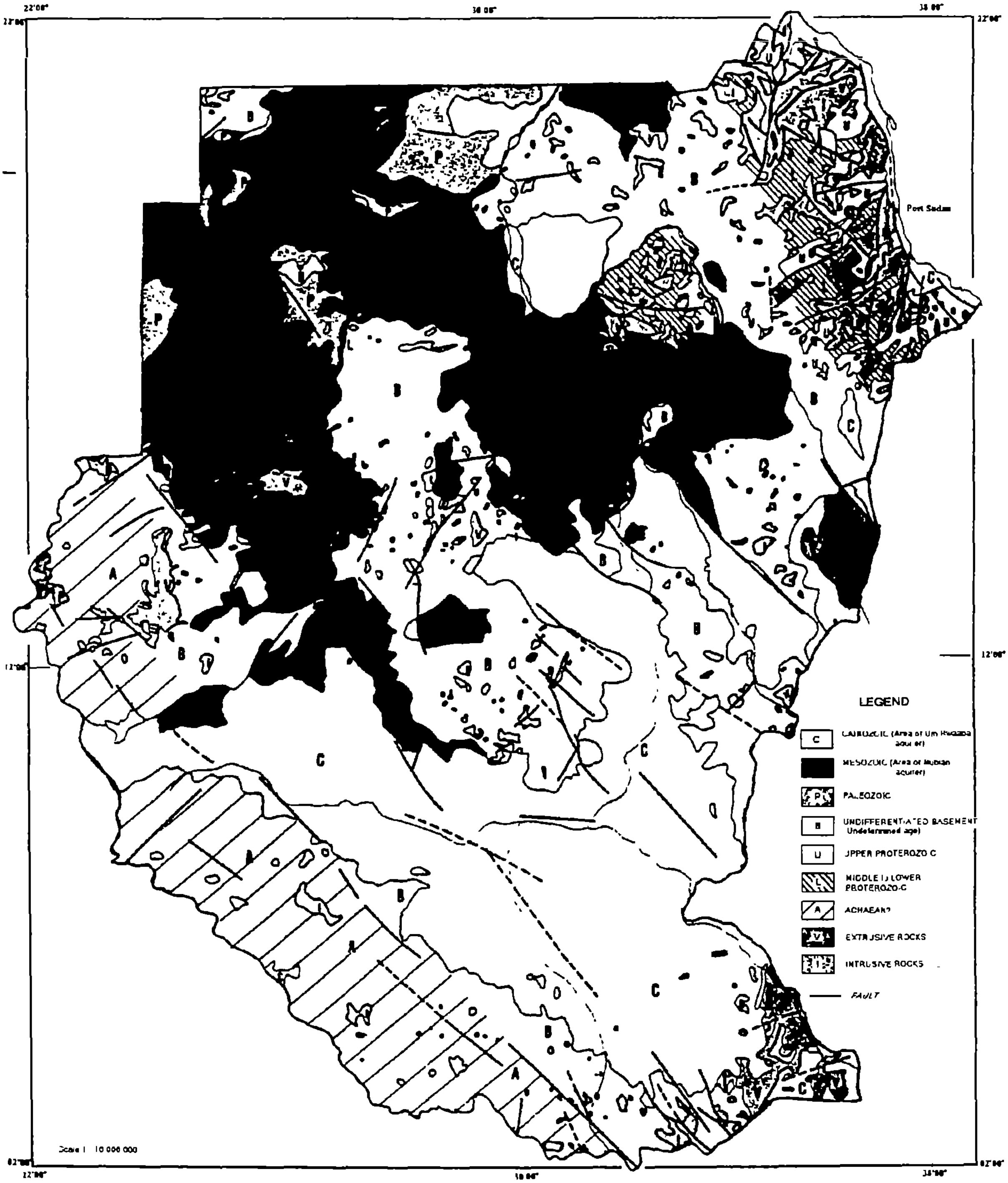
Appendix B. Maps

Geographical
Geological
Wind Speed Isovents
Distribution of Total and Diffuse Solar Radiation

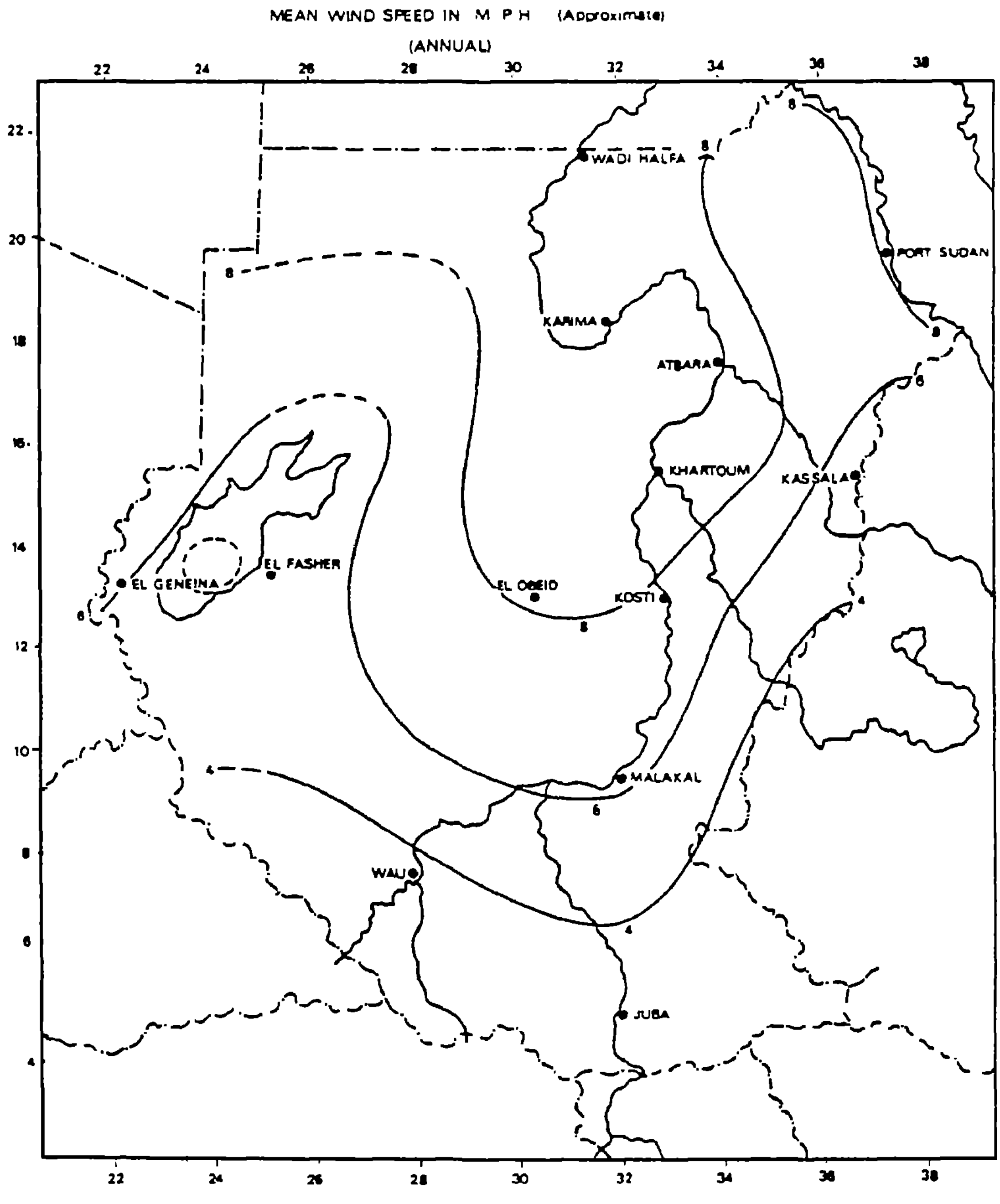
Geographical Map of Sudan



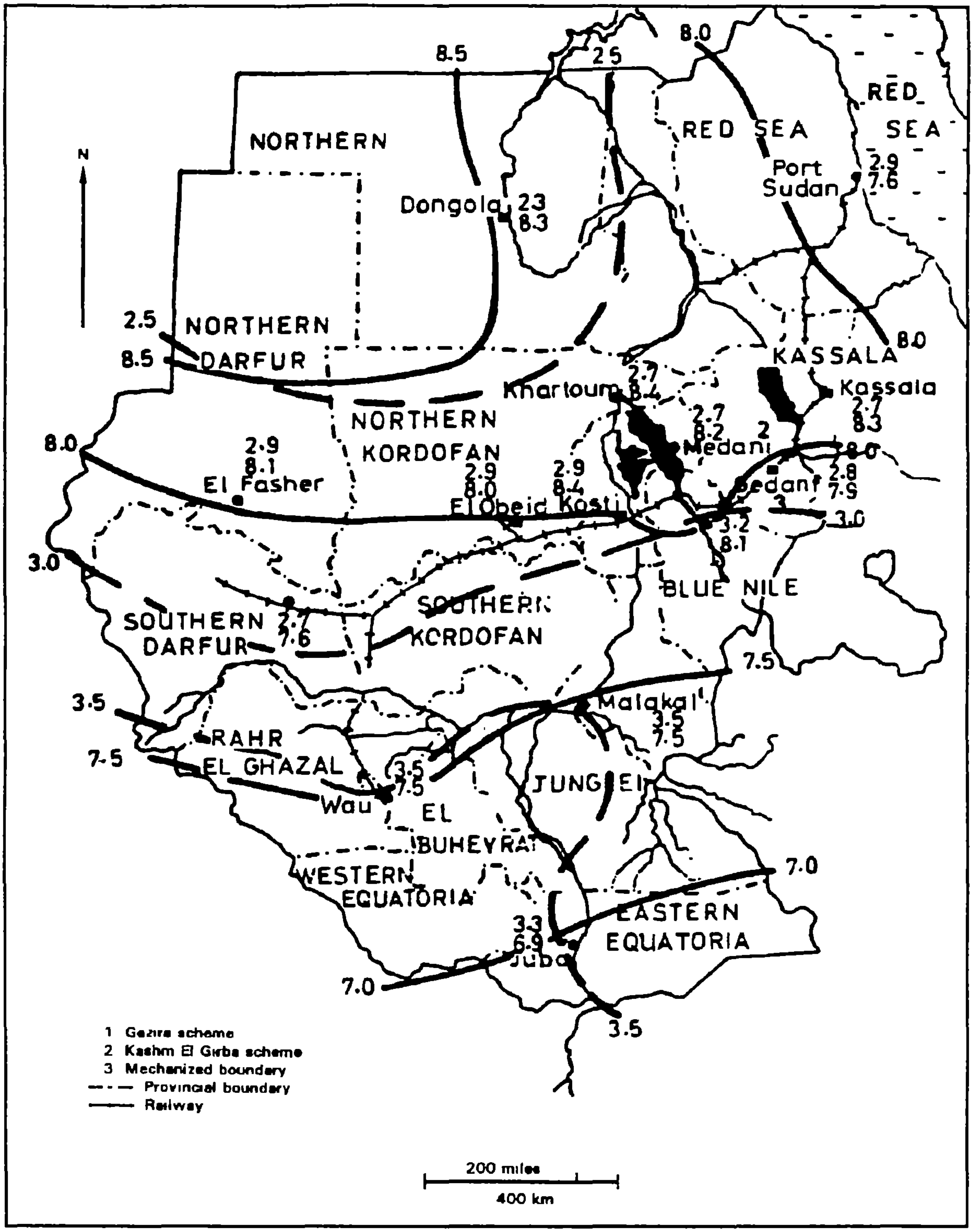
Geological Map of Sudan



Wind Speed Isovents — Sudan



Distribution of Total and Diffuse Solar Radiation—Sudan



Source: *Solar Radiation Climate of the Sudan.* Dr. M.O. Sid-Ahmad, RERI, 1985.

Appendix C. Test Procedures

Diesel Pump Test Procedure

Purpose

The performance of a diesel pumping system depends on proper equipment selection, quality of installation, quality of operation, and maintenance. Except to the extent that the water level varies during pumping and the long-term performance is degraded by maintenance practice and equipment age, the performance of a diesel pump is not variable over time. This means that short-term measures of water delivery as a function of fuel used are sufficient to characterize pump performance and predict water delivery rates. Therefore, diesel pump testing was limited to short-term tests. Other important information regarding system age, overhaul intervals, and maintenance practices were also collected but are not considered here as part of the test procedure.

Approach

The diesel tests consisted of a series of short consecutive tests of from 10 to 20 minutes' duration. During each period, the amount of water pumped is recorded, and at the end of each period, the pump and engine RPM are checked and the fuel required during the interval is recorded. To measure the fuel consumption accurately, the normal fuel tank was by-passed and a plastic container with a fill line was substituted. At the conclusion of each time interval, the fuel level was restored to the fill line from a graduated cylinder. The amount of fuel used during the interval was determined from the graduated cylinder readings.

Equipment Used

The equipment used to complete the diesel pump test included mechanics and pipe-fitters tools to modify the engine, pump and delivery system to allow measurements to take place and several more specialized tools and pieces of equipment. These included:

- Stop watch
- Powers electronic well sounder
- Photo-digital tachometer
- Pressure gage
- Three liter clear plastic container and tube to connect to the engines fuel line
- Graduated cylinder (250 ml)
- Water meter

Set-up and Test

The test required at least two people. The set-up procedure required several steps. The first was to disconnect the fuel tank, substitute the three liter plastic container, and fill it with diesel fuel. The end of the battery-operated well sounder was dropped in the borehole next to the rising main in order to measure the water level. In several cases this was not possible because the well head was sealed. The pressure gage and water meter were installed in line in the water delivery pipe. The engine was then started and allowed to warm up and establish a constant pumping rate. The warm-up period was typically 10-15 minutes. At this time, the pump and engine RPM, the well sounder reading, and the pressure gage measurement were recorded as the fuel level was returned to a predetermined level marked on the plastic tank. Simultaneously the stopwatch was started. The test interval was determined as the test progresses. The interval was selected so that less than 250 ml of fuel is consumed during the interval. Once the interval was selected, the graduated cylinder was filled to the 250 ml level and fuel poured into the three liter fuel tank, almost to the marked fill line in preparation for the end of the test interval.

At the end of the time interval, diesel fuel was added to bring the level just to the fill line marked on the plastic fuel tank. The water meter was read simultaneously by a second person. Then the engine RPM, the water level, and the water pressure in the delivery pipe were measured and recorded. Speed and accuracy were important at this time, particularly when filling the fuel tank and noting the water meter reading.

The fuel consumption during the interval could then be determined. The level of remaining fuel in the graduated cylinder was subtracted from the original 250 ml to give the fuel consumed during the test interval. Fuel was then added to the cylinder to restore the 250 ml in preparation for the end if the next test interval.

Data Analysis

At the end of each interval calculations were made of the fuel consumption per hour, fuel consumption per cubic meter of water pumped, the pumping rate and the overall efficiency of the system from diesel delivered water (assuming 38,000 MJ/liter as the energy content of the diesel). The results of these tests are presented in Chapter 5.

Solar Pump Test Procedure

Purpose

The purpose of solar pump testing is to characterize the performance of the pump as a function of solar radiation. This is accomplished by conducting both short and long-term tests. Short-term tests were completed to characterize the performance of the pump over the course of a day. These results were used to determine the efficiency of the solar system at various solar radiation levels and the solar radiation required to start the system pumping in the morning. In addition, these short-term results were used to ascertain that the pump was operating properly.

Long-term tests were conducted to measure the daily output of the pump as a function of total daily solar radiation. These results were compared to manufacturer's output projections for the pump. In addition, the long-term data were used to develop projections for the average monthly and annual performance for the system.

Approach

Unlike diesel pump performance, a solar pump's performance depends on the solar radiation level. This is variable over the day. Therefore data must be collected over an entire day to allow the development of a pump curve showing how water delivery varies with radiation level. In order to capture this information a datalogging system was employed. This system utilized a series of electronic sensors to measure important parameters, a datalogger to sample and pre-process the data collected, and Erasable Programmable Read Only Memory (EPROM) data storage packs (DSPs) to store the data on site. The data stored on the DSPs were downloaded to a computer when brought from the field to the office. This method was used to collect data at ten minute and hourly intervals. The data collected at hourly intervals were used to calculate daily averages of all pertinent variables.

Equipment Used

The equipment used falls into several categories: sensors, datalogging equipment, hand tools used in the field to calibrate sensors and set up the data loggers, data transfer equipment, and data analysis hardware and software. The sensors used for solar pump testing included:

- Drucks water level sensor PDCR 830 (pressure type)
- Drucks water pressure sensor PDCR 810
- Li-Cor voltage output pyranometer
- Omnidata voltage divider
- Omnidata current shunt
- Western water meter flow transducer with pulse output
- Omnidata ES-060 temperature probe

The data loggers used were Omnidata EZ loggers. These could be programmed to sample data at one minute intervals and then average and record these sampled data at intervals ranging from one minute to one day. 32 kilobyte EPROM data storage packs were used. These enabled data collection and storage for several months when data were collected at hourly intervals.

A variety of hand tools were used to install and check the calibration of the sensors. Important tools used in calibration included:

- Kipp Zonen Pyranometer CM-11 (calibrated standard)
- Powers electric well sounder
- Wika dial pressure gage
- 4.5 digit Fluke Multi-meter (model 8060A)
- Clamp-on ammeter
- Thermometer

Data were transferred by bringing the EPROM packs to the office and downloading the data using an Omnidata data reader. The data were downloaded to a Zenith portable computer and analyzed using Lotus 123.

Set-up and Test

Equipment installation followed a preliminary site visit. The initial site visit tasks included a site description and a detailed plan for locating the dataloggers and test sensors, including any special equipment and materials which may be needed. Equipment installation usually took place over a several day period. The installation phases included locating and mounting of the data logger and sensors, connection of sensors, programming the data logger for short tests, and calibration of sensors using hand held instruments. During the first test period, lasting for at least one full day, data were recorded at ten minute intervals. The data thus recorded consisted of the average of samples taken every minute over the ten minute period. At the end of this initial test, the data storage pack (EPROM) was replaced with another one so that the initial day's data could be brought to the office for analysis. At this time the long-term testing with the collection of hourly averages of one minute samples being recorded on the DSP.

At intervals, depending on the pump location and transportation constraints, each site was visited. During these visits, the pump was checked to be sure that it was operating properly and each of the sensors were checked for correct calibration. In addition, the datalogger was re-programmed to collect an additional day of short-term data (ten minute averages of one minute samples). After this day of short-term tests, the datalogger was again set to collect long-term data.

Data Transfer and Analysis

Data were brought in from the field on EPROM data storage packs. These were downloaded to a computer in the office using available software (Crosstalk). This resulted in an ASCII text file which was then imported into Lotus 123. Initial analysis included calculating averages, maximums, and minimums for each parameter measured and identifying any values which fall out of the expected ranges (i.e., no water being pumped when the solar radiation is high, temperatures in access of 130°, etc.). Times when the pump or datalogging equipment were not operating properly were recorded in a site log file. The data were then converted and processed to generate water flow rates, average power output, overall solar radiation levels, efficiencies and daily average values in appropriate units of measurement. These results were then plotted and examined.

Wind Pump Test Procedure

Purpose

The purpose of wind pump testing was to characterize the performance of the pump as a function of the prevailing wind speed. As with solar pumps, this is accomplished by conducting both short- and long-term tests. Short-term tests were completed to characterize the pump curve as a function of wind speed. This allows the measured short-term energy efficiencies of the system to be compared to predicted values, helping to determine if the wind pump is operating properly. Long-term tests were conducted to measure the daily output of the pump as a function of the daily average wind speed. This information was used, along with Meteorological Department data, to develop projections of the monthly and annual water delivery of the windmill.

Approach

A wind pump's performance is variable over the day. However, unlike solar pump output, wind pump output can increase or decrease at any time of the day or night, depending only on increases and decreases in wind velocity. Therefore short-term data must be collected over period long enough to allow the development of a pump curve showing how water delivery varies within the range of wind speeds anticipated at the site. As with solar pump testing, a datalogging system was employed. This system was the same as that used to collect data for the solar pump tests except that different sensors were used. The datalogger was used to collect data at ten minute and hourly intervals. The data collected at hourly intervals were used to calculate daily averages of all pertinent variables.

Equipment Used

As with solar pump testing, the equipment used falls into several categories: sensors, datalogging equipment, hand tools used in the field to calibrate sensors and set up the data loggers, data transfer equipment, and data analysis hardware and software. The datalogging equipment, data transfer and analysis hardware and software, several of the sensors, and many of the hand tools were the same as used for the solar pump tests. The sensors used in wind pump testing included:

- Drucks water level sensor PDCR 830 (pressure type)
- Drucks water pressure sensor PDCR 810
- Met-One anemometer
- Western water meter flow transducer with pulse output

A variety of hand tools were used to install and check the calibration of the sensors. Important tools used in calibration included:

- NRG calibrated wind speed standard
- Powers electric well sounder
- Wika dial pressure gage

As with solar pump testing, data were transferred by bringing the EPROM packs to the office and downloading the data using an Omnidata data reader. The data were downloaded to a Zenith portable computer and analyzed using Lotus 123.

Set-up and Test

Equipment set-up and test procedures followed a similar pattern as described for solar pump testing. However, since all of the wind test sites were within several hours drive of

ERC/RERI offices, visits could be made more frequently. Equipment installation usually took place over several days. Once the initial installation and sensor calibration was complete, short-term testing began. During this test period, usually lasting for several days, data were recorded at ten minute intervals. If, after several days, it was believed that the wind speed had varied from calm to seven meters per second, short-term tests were suspended and long-term testing began. Once the data were downloaded and analyzed, the minimum and maximum wind speeds observed during the test period could be determined. Additional short-term testing could be scheduled if there were not sufficient data. As with solar pump testing, long-term testing meant sampling each sensor at one minute intervals and recording averages each hour. These one hour averages were then processed to yield one day averages of wind velocity and wind pump output. The wind pump test sites were visited more often than most of the solar pump sites. During each of these visits, checks were made to determine if the wind pump and datalogging system were operating properly.

Data Transfer and Analysis

As with solar pump testing, data were brought in from the field on EPROM data storage packs. These were downloaded to a computer in the office using available software (Crosstalk). This resulted in an ASCII text file which was then imported into Lotus 123. Initial analysis included calculating averages, maximums, and minimums for each parameter measured and identifying any values which fall out of the expected ranges (i.e., no water being pumped when the wind speed was above four meters/second, etc.). Times when the pump or datalogging equipment was not operating properly were recorded in a site log file. The data were then converted and processed to generate water flow rates, average wind speed, overall efficiencies, and daily average values in appropriate units of measurement. These results were then plotted and examined.

Appendix D. Site Descriptions

DIESEL PUMP TEST SITES

Surface Centrifugal Pumps

Wad Medani

This small farm of 8 feddans is located about 20 kilometers east of Wad Medani on the Rahad river. The river is only seasonal at this location. Water is pumped from the river when possible and pumped from a drilled well when there is no water in the river. The pump-set consists of an Indian Lister driving a 3" centrifugal pump; both are mounted together on a skid. The pump-set is moved as necessary, and the pumping head changes from season to season. The farmer grows vegetables year-round for sale in Wad Medani markets. There is no water storage at the site. Water is pumped directly into earth channels for distribution throughout the farm.

Bara

The Bara police farm is located in the town of Bara, northeast of El Obeid in North Kordofan Province. The pumping set-up includes an Indian Lister located at the ground surface with a centrifugal pump located at the bottom of a shallow hand dug well. The engine is located near the top of the well. A series of flat belts transmits power from the engine to the pump. The water distribution system consists of 20 meters of 2" pipe for distribution of water for human and animal consumption just outside the police farm. A series of pipes, in poor condition, with many leaks, supplies water to the farm's irrigated area. At the time of the test, the land was not under cultivation. The total irrigated area is less than 2 feddans. Vegetable crops are grown largely for consumption at the police post and occasionally for sale in the local market.

Ed Damer

This farm is about 4 km from the village of El Musiyab, near Hodieba in the Northern Region. The total farm area is about 10 feddans with an irrigated area of 5 feddans. The well has been dug to 8 meters and then drilled an additional 6 meters. The engine and belt-driven 3" centrifugal pump are located at the bottom of the dug well. The pump intake descends into the drilled portion of the well. At the time of testing, the total pumping head was 9 meters. The farmer is growing some vegetables and watering date trees scattered on the farm. He is planning to plant and water mesquite trees as a perimeter fence.

Edeco Jack Pumps

Wad-Sabeel Wateryard

Wad-Sabeel is about 16 miles northeast of Um-Ruwaba. The water level in the drilled well is 290 feet. The total population including nearby villagers using water from this wateryard is about 7,000. The wateryard at this site was rehabilitated in March 1989. The engine is a Lister 6/1 water cooled model overhauled by SCF. The pump is of the Edeco-MK IIIM type which was provided by SCF. The pump stroke is 18 inches with 3.75-inch working cylinder. The pump was set at 322 feet below ground level. Four-inch main drop-pipes are used. Water is pumped 26 feet to a British made elevated tank (10,000 Imp. gallon) through a 2-inch diameter steel pipe 127 feet long.

Obied-Mahadi Wateryard

Obied-Mahadi is about 31 miles southeast of Um-Ruwaba. Water level at the site is 280 feet. The population is about 2,850. The wateryard was last rehabilitated in December 1988 by SCF. The new engine is a Lister (series number 3700260 8/1 001) water cooled model. The pump is an Edeco-MK IIIM type driven by using 5 V type belts and clutch pulley transmission system. The pump-set is 334 feet below the ground level. Water is pumped through 66 feet of 2-inch diameter steel pipe to a 10,000 gallons water tank (elevated 26 feet).

Abu-Auwa wateryard

Abu-Auwa is about 38 miles northeast of Um-Ruwaba. It has a population of about 5,000. The water level is 290 feet. Equipment at this wateryard was installed in January 1989 by SCF. The engine is a Lister (S/N 3700250 8/1 001) water cooled model. It was repaired in July 1989 (the piston was replaced). The pump is an Edeco MK-IIIM driven by 5V belts with a clutch pulley transmission system. The pump was set 322 feet below the ground level with a 4-inch drop-pipe. The pump piston leathers were replaced in October 1989. Water is pumped to an elevated (26 feet) 10,000 gallon water tank through about 716 feet of 2-inch diameter steel pipe.

Malaga Wateryard

Malaga is about 13 miles southeast of Um-Ruwaba. The total population is around 3,400. The water level is 250 feet. A Lister engine (S/N 3700210 8/1 001) water cooled model and an Edeco MK IIIM unit have been installed at this site by SCF. The working cylinder is 3.75 inches in diameter. A clutch pulley transmission system with 5V belts was used to connect the pump and engines. The pump was set at 324 feet below the ground level and 4-inch drop-pipes were used. Water is pumped through 66 feet of 2-inch diameter steel pipe to a 6,000 gallon elevated (20 feet) tank. The wateryard operates 12 hours during the summer season, 8 hours during the winter season, and about 2 hours during the rainy season.

Abu-Hamra Wateryard

Abu-Hamra is about 15 miles southeast of Um-Ruwaba. The population is about 2,000. Water level is 220 feet below ground level. The engine at this wateryard is a Lister 6/1 type which has been overhauled by SCF. The pump installed by SCF is an Edeco MK III type c with an 18-inch stroke and 3.75-inch working cylinder diameter. The pump is set at 322 feet below the ground level by using 4-inch drop-pipes. The water is pumped through 450 feet of 2-inch diameter steel pipe to an elevated (20 feet) British 10,000-gallon water tank.

Um-Kharain Wateryard

There is no SCF equipment installed at this site. The site is about 8 miles east of Um-Ruwaba. The population of this village is about 1,500. The water level is at 253 feet. The engine is a Lister 6/1 water cooled type, last overhauled 2 years ago. An Edeco-MK III type c pump in bad condition is operating at this site. Only one V-belt is used for the transmission system. Pump stroke is set to 18 inches and according to wateryard records the working cylinder is 4.25 inches in diameter. The pump was set 336 feet below the ground level and a 3-inch drop-pipe is used. Water is pumped through 33 feet of 2-inch diameter steel pipe to an Indian made 11,851 gallon water tank at 26 feet elevation.

Sheraim El Karamsha Wateryard

Shearim El Karamsha is about 15 kilometers northeast of Bara in North Kordofan Province. The borehole is equipped with a Lister 8/1 engine driving an Edeco pump. The wateryard was built in 1982 and the engine was last overhauled in January 1987 at NCRWRD workshops. Water is pumped through a total dynamic head of 17 meters. The engine operates 5 to 8 hours per day depending on the season, with longer pumping hours in the summer. Water is pumped to a 45 m3 tank and distributed to 3 working taps within the wateryard compound. The wateryard was out of service 3 times in the last year with breakdowns lasting 2 to 3 days. In addition to the fees collected by the wateryard clerk, the village committee collects S£2.50 per month in additional tariff.

Vertical Turbine Pumps

El Mugdab

This village, south of Khartoum near the Jebal Aulia dam, is on the west side of the White Nile. The population is about 1,000. A number of people and animals from surrounding areas utilize the water from this wateryard. The pumping equipment consists of an 11.5 HP Yanmar engine driving a Kato vertical turbine pump installed in 1986. The engine operates about 7 hours per day. The most recent engine overhaul took place in July 1988. The engine was out of service on 2 occasions during the last year with repairs taking 2 to 3 days on each occasion. The equipment is now in reasonable condition with the cooling system modified to a flow-through instead of a recirculating system. Water is pumped to a 45 m3 elevated tank and reaches households through a distribution system. There is an overhead tap at the wateryard for filling donkey carts (S£0.75 per 44 Imp. gal. drum). The wateryard is managed by a village committee. The operator is a committee member. Fees are assessed per household on a monthly basis depending on whether the house has a private tap. The committee contributes for fuel, luricants, maintenance, and repair, but does not appear to fund the full cost.

El Sundudab

This village is near El Mugdab on the west side of the White Nile. The estimated village population is 1,000. The village is more dispersed than at El Mugdab. Water is pumped with an Andoria engine (13.3 HP) driving a Grundfos pump with belts. An elevated 25 m3 tank feeds to distribution system into the village. As at El Mugdab, there is an overhead tap for filling donkey carts. There is also a public tap for filling jerricans. The wateryard is managed in the same fashion as at El Mugdab.

Mono Pumps

Sharafa (1) Wateryard

The Sharafa (1) wateryard has just recently been completed. It is about 25 km west of El Fasher. Measured water level at this site is 70 meters below ground level. A 30 m3 elevated water tank was constructed, and there are 3 water troughs for animal drinking and several taps. Population does not exceed 500; most of them come from nearby villages. The original cooling system (radiator) was replaced by a 44 gallon barrel. A village water committee has been formed to manage the operation/maintenance of the wateryards in cooperation with the NCRWRD. It is too early to tell how well this arrangement will function.

Tabit Wateryard

Tabit is about 60 km from the city of El Fasher on the El Fasher-Nyala road. It is slightly bigger than Sharafa, with a population of around 800 including those from nearby villages. The water level at this site as measured during testing is 46 meters below ground level. This was an old NCRWRD wateryard which was being rehabilitated by WUSC. The old Lister-Edeco system was replaced by a new Petter/Lister-Mono pump unit. A new imported 30 m3 elevated water tank is installed beside the old NCRWRD elevated tank. A village water committee has been formed to share in managing wateryard operation/maintenance.

Shangel Tobai Wateryard

Shangel Tobai is one of biggest villages between El Fasher and Nyala. It is about 75 km from El Fasher. The population is around 1,000, including nearby villagers. An old NCRWRD-equipped wateryard is still operating. The new borehole drilled by WUSC is about 225 meters away from the old one. The new 30 m3 elevated tank is erected beside the old one. Water is pumped 218 meters to the new water tank, and then to the distribution system. There are trough facilities for animal watering, and taps which villagers use to fill their girbas and jerrikans The measured water level is 57 meters below the surface. A village water committee has formed here as well.

Musco Wateryard

Musco is about 20 km from Shanel Tobai. The wateryard was constructed by WUSC and a village water committee formed. The wateryard is in an isolated area like Sharafa; people come from nearby villages for water. The measured water level is 53 meters. The tests for this system were done by the WUSC team (Engineer Abdul Ali, Engineer Abdul Elazaim Ahmed, and their crew). After assisting with the testing of the first 3 systems at the other sites, the WUSC crew had enough experience to conduct field tests on their own. This will help them determine the typical operating performance of the new systems they are going to install in the Tabit area.

SOLAR PUMP TEST SITES

Grundfos Pumps

University of Gezira

In early 1983, a Grundfos SP4-8 utilizing 28 Arco Solar M-51 modules was installed on the University of Gezira research farm. The site is at the southwest edge of the campus about one kilometer west of the Blue Nile north of Wad Medani. The pump is installed in a cased borehole with a static water level of 19 meters and a total pumping head of 21 meters. The well experiences very little drawdown (less than one meter during the pumping day). Pump production is used to water a small research plot of roughly one feddan. Garlic is presently being grown there. There is no storage tank at the site so the water is being delivered directly into irrigation channels at a peak rate of about 1.5 liters per second.

This pump was the focus of an evaluation performed by the students of the Physics faculty at the university in 1985. Unfortunately adequate testing equipment was unavailable to measure the solar radiation levels, so the performance of the pump could not be measured as a function of radiation levels. The pump monitoring instrumentation (including sensors to measure water delivery, solar radiation levels, water delivery pressure, ambient temperature, and array voltage) was installed in April 1989. The pump has been continuously monitored since that time with hourly values of all technical parameters measured. Short- term tests have also been conducted on several occasions. The pump is currently operating and continues to be monitored by the ERC, although no effort is made to keep the array clean to maximize performance.

Hodieba Research Center

A Grundfos SP4-8 utilizing 21 Arco Solar M-51 modules was installed at the Hodieba Agricultural Research Station Farm south of Ed Damer in 1983. The site is just east of the rail line about 2 kilometers east of the Nile. The pump is installed in a cased borehole with a static water level of 9.5 meters and a total pumping head of just over 10 meters. As at other sites, the well experiences very little drawdown (well under one meter during the pumping day). Pump production is used to water a small tree nursery; unfortunately the trees shade the array during the first hour of sunshine during winter months. Several families who live nearby regularly get water from the pump. At the site there is a small splash box where the water enters the irrigation channels but no storage tank. Water is delivered directly into irrigation channels at a peak rate of about 1.5 liters per second. The pump monitoring instrumentation (including sensors to measure water delivery, solar radiation levels, water delivery pressure, ambient temperature, and array voltage) was installed in June 1989. The pump was monitored from that time until November when operator error damaged the data-logging unit. Transportation limitations have prevented replacement of the unit. Hourly values of all technical parameters measured were taken during the 5-month monitoring period. Short-term tests have also been conducted on 2 occasions. The pump is currently operating, although as at other sites, there does not seem to be any effort to keep the array clean to maximize performance. The pump will continue to be monitored by the ERC.

Foja

In early 1988, the Swedish-Sudanese Friendship Association (a small non-governmental organization) installed a Grundfos SP4-8 solar pump utilizing 21 Arco Solar M-53 modules in the village of Foja, northeast of Bara in North Kordofan Province. The pump is within the village, installed in a 4-meter diameter open well. The static water level remains at 20.5 meters. The well experiences very little drawdown (well under one meter during the pumping day). The pump production is used to water a community garden and a shelterbelt. There are two 20 cubic meter storage tanks at different locations and a valve system to direct the water to the 2 tanks. These are situated at the well head (pumping head 24 meters) and some distance away in the shelterbelt (pumping head of 38 meters). Water is provided individually to the trees using donkeys.

The pump monitoring instrumentation (including sensors to measure water delivery, solar radiation levels, water delivery pressure, ambient temperature, and array voltage) was installed in August 1989. The water meters for the 2 Kordofan sites were both installed here (necessitating the delay in full instrumentation at the Sheraim El Karamsha site discussed below). As was eventually done at the other site, one water meter was installed to measure the total water delivery and one to measure water delivery to the shelterbelt. The pump has been continuously collecting hourly data since early August. A first series of short-term tests was conducted at the time of the initial installation and again in mid-November. The pump is currently operating and being cared for by villagers involved with the project. The array appears to be cared for and cleaned. Monitoring is continuing at the site.

Sheraim el Karamsha

In 1987, the Swedish-Sudanese Friendship Association installed the first solar pump in the village of Sheraim El Karamsha, east of Bara in North Kordofan Province. The system consisted of 21 Arco Solar M53 modules operating a Grundfos SP4-8 pump. The original site was within the village at a tree nursery where the water was used not only for the nursery, but also for watering a shelterbelt. At this time the pump was installed in a cased borehole (along with a Mono gear driven handpump) with a static water level of 20 meters. However, in early 1989, the pump was moved to a new site and installed in a 4-meter diameter open well. It is at this site that monitoring began in August 1989. The static water level remains at 20 meters. There is very little drawdown during pumping. When the pump is in use, the water is delivered to a community garden and the shelterbelt as before. There are two 20 cubic meter storage tanks at different locations and a valve system to direct the water to the different tanks. One tank is just at the well head giving a total pumping head of 22 meters, and the other is not yet in use. As at Foja, water is provided individually to the trees using donkeys.

The pump monitoring instrumentation (including sensors to measure solar radiation levels, water delivery pressure, ambient temperature, and array voltage) was installed in August

1989. However, water meters were not installed at this site until September when 2 meters were installed, one to measure the total water delivery and one to measure water delivery to the shelterbelt. The pump has been monitored since that time with hourly values of all technical parameters measured. A first series of short-term tests was conducted in September.

Unfortunately the villagers do not use the pump continuously and the pump has been switched off for long periods of time. The reason for this is not known, but there is a diesel pump in the village (see Edeco test results) and the villagers may see little need to use the solar pump. Also the trees were planted before the trees at Foja; they have grown and the watering interval has been increased. The pump is currently operating and being cared for by villagers involved with the project. The array appears cleaned and cared for although recently the glass surface of the array was slightly scratched during the cleaning process. Since the site characteristics are similar to Foja, it is likely that intensive testing will be discontinued. The site will continue to be visited when trips are made to Foja.

KSB Pump

Shambat

The GTZ-funded Special Energy Program (SEP) in collaboration with the ERC, purchased a number of KSB model 50M floating pumps to demonstrate their technical capacity for low head irrigation of small farm plots. One of these pumps was installed at a small farm at Shambat in Khartoum North in early 1988. The installation utilizes twelve 30 wp BMC Solartechnik modules connected to the pump which floats in the Nile by a long (30- meter) power cable. Water is delivered to the garden through a 2-inch flexible hose. The pump is floating in the Nile and held in place by a cable to the bank. The pumping head changes with fluctuations in the water level of the river. The water level during the test period was between 4.5 and 5.5 meters. The total pumping head is 7 to 8 meters, depending on where the farmer directs the water. Pump production has been used to water a vegetable garden. There was very little farming activity at the site during the spring and summer so the pump was not used extensively. There is no storage tank at the site. The water is delivered directly to shallow plots by moving the flexible hose from one location to another. The peak water delivery rate is about 1.4 liters per second.

The pump monitoring instrumentation (including sensors to measure water delivery, solar radiation levels, water delivery pressure, ambient temperature, and array voltage) was installed in June 1989. The pump has been continuously monitored since that time with hourly values of all technical parameters measured.

Unfortunately, the inactivity of the farmer has limited the collection of useful performance data. Short-term tests have been conducted on several occasions.

WIND PUMP TEST SITES

CWD 5000

Soba

A CWD 5000 wind pump with a 108-D pump (4.25-inch cylinder) was installed at the ERC research station at Soba, just south of Khartoum in July 1986. The wind pump is installed over a cased borehole. The static water level in the borehole is 19 meters with an additional meter of head required to reach the 60 cubic meter water storage tank. The well experiences very little drawdown (well under one meter even during windy periods of heavy pumping). The pump production is being used to water a small demonstration farm of about 4 feddans at the Soba site. CWD, the Dutch contractors, has designed an optimum cropping rotation for the demonstration farm and is monitoring vegetable and crop production as part of the project. The wind speed at this site has been monitored for several years using wind run totalizers. However, CWD had no firm plans to install instrumentation to measure actual pump performance.

Shambat

There are 3 CWD wind pumps installed at Shambat. The machine chosen for the monitoring program (#6) was installed in December 1986 at the farm of Mr. Abdel Aziz Bedran. He is retired from the postal service and has a farm of nearly 8 feddans in Shambat (Khartoum North), just east of the rail line about 3 kilometers from the Nile. The windmill is installed over a borehole with a static water level of 18 meters. There is a water storage tank of roughly 20 cubic meters next to the windmill. While pumping at higher wind speeds, the well experiences very little drawdown.

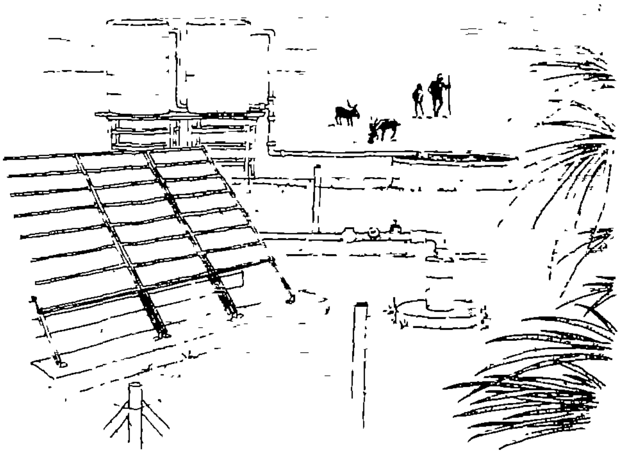
The pump cylinder is the same 108-D as that at the Soba test site. The farm has been planted in fodder crops and beans during past seasons. Now the windmill owner is offering the farm for sharecropping but at this time there is no farmer working at the site. The windmill stands furled a good portion of the time since the water is not being used. This has limited the operating experience and the amount of useful data collected on the potential performance of the windmill. The site was chosen because the windmill had been in use during the year prior to the beginning of the test program. The windmill operates under very similar conditions to the machine at Soba.

Jebel Aulia

As was the case for the windmills at Soba and Shambat, the windmill at Jebel Aulia is one of the imported CWD 5000 machines used for demonstration by the Dutch project mentioned above. This machine was also installed in November 1986 at the 50-feddan farm of Mr. Mohammed Nageeb, a dealer in agro-chemicals in Khartoum. His farm, south of Khartoum on the east bank of the White Nile, was cultivated for the last 3 years using a diesel pump. There has never been any intention of trying to irrigate the entire area, nor of trying to recover the windmill investment through its water production. In fact, the water is used for drinking and to water a small shelterbelt. Plans have also been made to use some of the water for a small tree nursery. At the time of installation, the water reservoir had not been completed. As of early 1990 shortages of materials and other factors continued to prevent the completion of the reservoir. The windmill is installed over a borehole with a static water level of 16.5 meters. The total head including delivery head is 17 meters. As with the others, very little draw-down is experienced at this test site during pumping. A 108-D pump is installed.

Appendix E. Solar Pump Technical Information

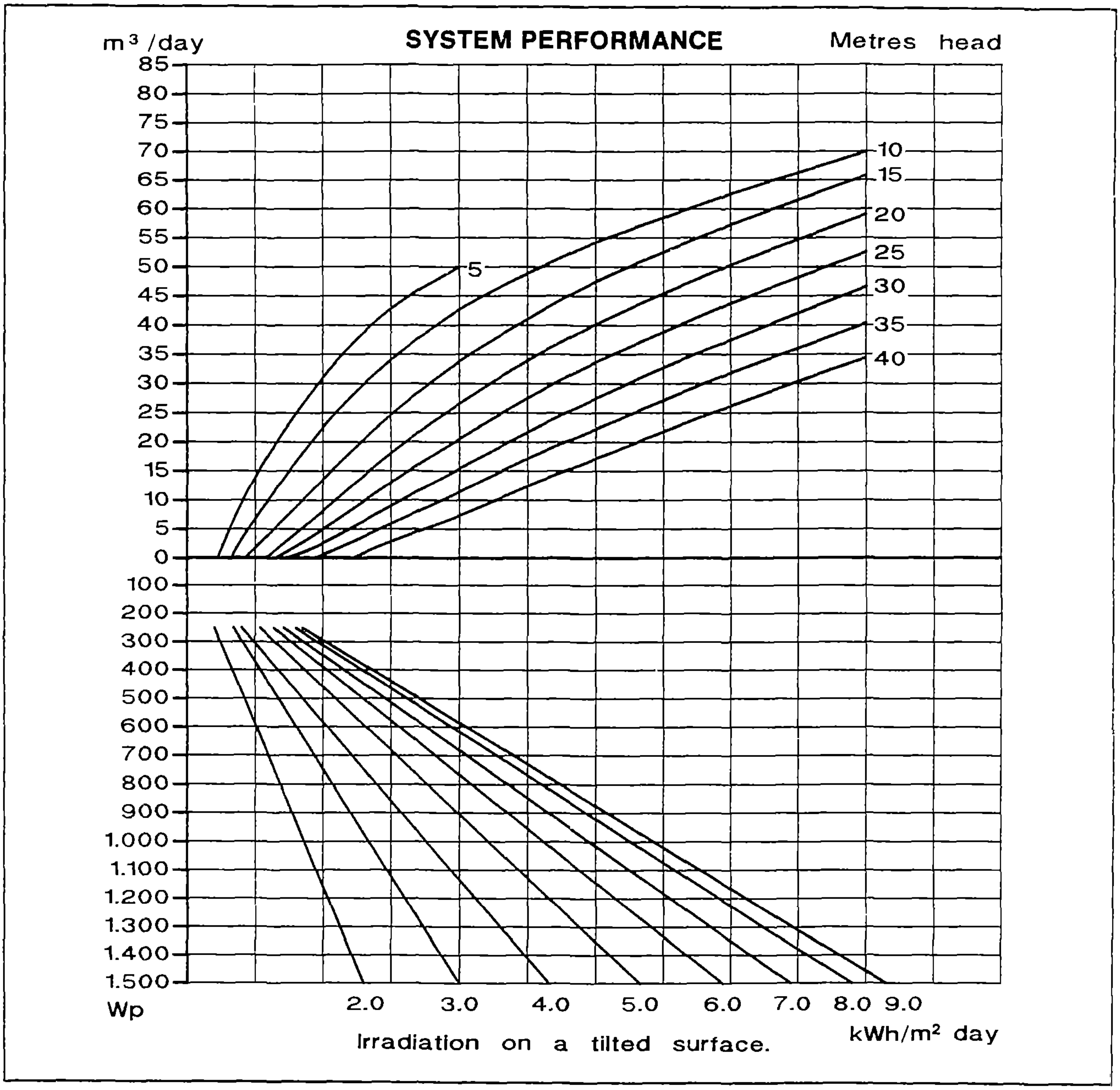
Grundfos Solar Pumps
KSB Solar Pumps
Arco Solar M51 Solar Modules
Arco Solar M53 Solar Modules



Solar Pumping System Type SP 4-8

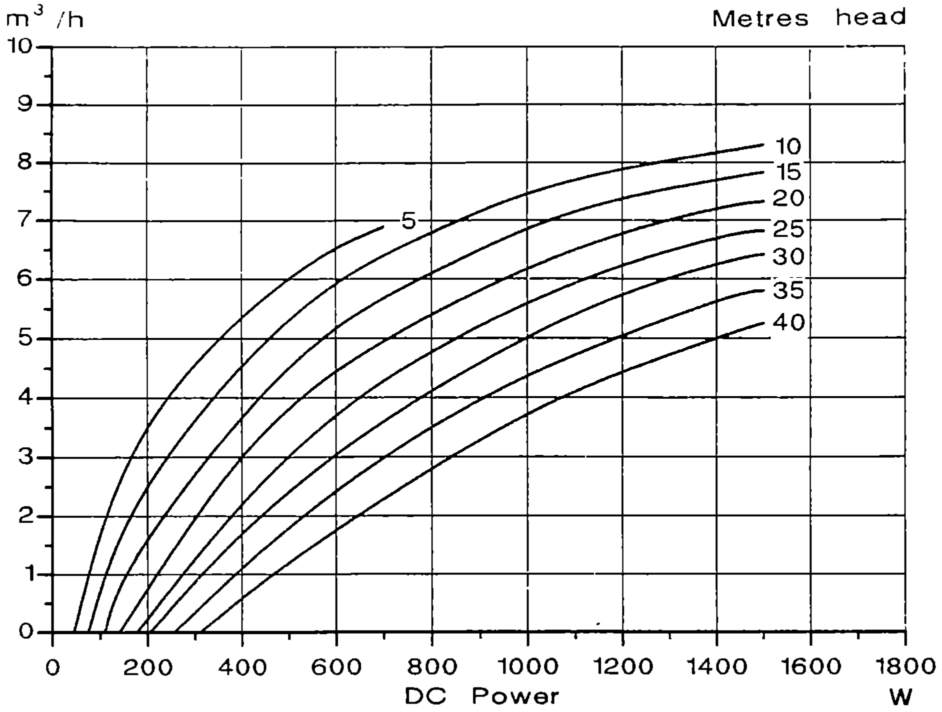
The system performance curves are based on

- An 11 hour standard solar day.
- An average ambient temperature of 30°C

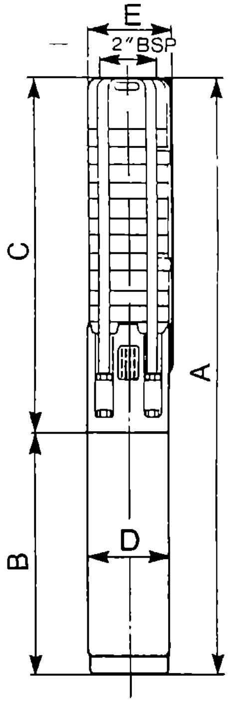


GRUNDFOS

Instantaneous Output



Dimensional Sketch



Pump Type	Dimensions [mm]						Minimum Internal Diameter of Borehole
	A	B	C	D	E	BSP	
SP 4-8	627	258	369	95	95	2"	4" (104 mm)

System Performance

An irradiation value and the required head in metres are given for a certain solar pumping system.

Note: Use the irradiation value on a tilted surface from the tilt factor curves

By connecting the point for the power output in Wp of a given solar array with the irradiation value and the required head, the quantity of water in m³/day delivered by the solar pumping system can be found from the curves

By connecting the point for the required quantity of water in m³/day with the required head and the irradiation value, the necessary power output in Wp of the solar array can be found.

Instantaneous Output

From the above curves, the maximum quantity of water in m³/h for a given array size in Wp and head in metres can be found.
Start on the DC power axis. Maximum DC power = 0.8 x Wp under normal conditions

Pump

The pump is a multistage centrifugal pump with radial impellers direct coupled with a GRUNDFOS submersible motor The pump part is made entirely of stainless steel and has water lubricated rubber bearings The discharge chamber is internally threaded and is designed with a non-return valve.

Motor

The GRUNDFOS submersible motor, type MS 401, is a 2-pole asynchronous squirrel cage motor of the canned type with slide bearings.

The motor is made entirely of stainless steel to AISI 304.

The thrust bearing is hydrodynamically and gyroscopically suspended The radial bearings are made of ceramic/tungsten carbide. The shaft is made of stainless steel to AISI 431

The stator is hermetically sealed in stainless steel to AISI 304 or AISI 904L and encapsulated in synthetic resin

The anti-freeze and anti-corrosive motor liquid lubricates the bearings and carries the heat away

The motor is frost-protected down to −20°C

Electrical Data

MS 401. 3 x 60 V, 50 Hz
Nominal Power: 550 W, 0.75 HP.
Nominal Current. 8 8 A
Cos φ: 0 87
Winding Resistance: 0 8 Ω.

Subject to alterations

GRUNDFOS

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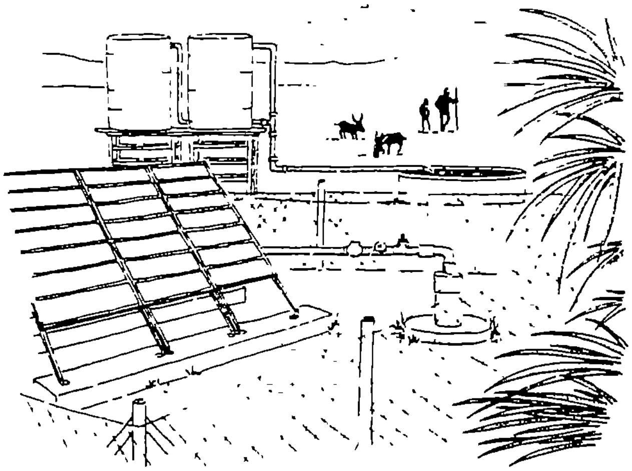


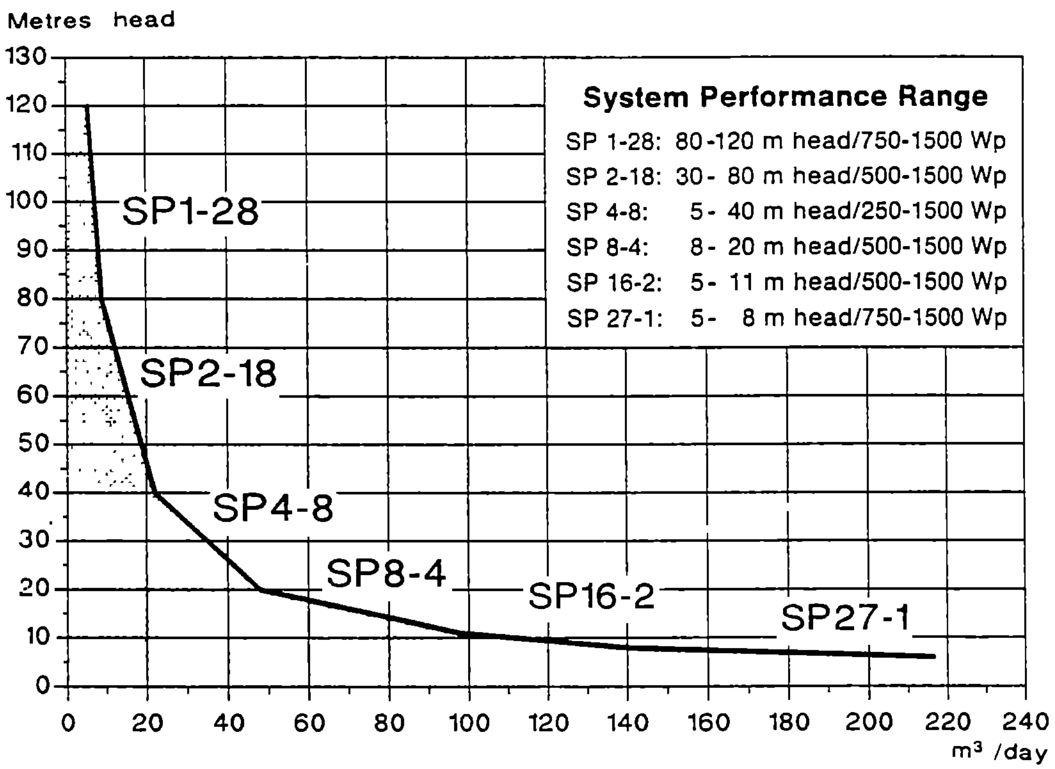
Solar Pumping Systems

General Data and Survey Capacity Diagram

The curve shows the capacity of a 1500 Wp system The shaded area applies to lower Wp values.

The curve is based on.

- Irradiation on a tilted surface H_T = 6 kWh/m² day
- Irradiation on a horizontal surface H_H = 5.5 kWh/m² day (473 cal/cm² day)
- An average ambient temperature of 30°C
- 20° northern latitude
- A tilt angle of 20°



System Performance Range

SP 1-28:	80-120 m head/750-1500 Wp
SP 2-18:	30- 80 m head/500-1500 Wp
SP 4-8:	5- 40 m head/250-1500 Wp
SP 8-4:	8- 20 m head/500-1500 Wp
SP 16-2:	5- 11 m head/500-1500 Wp
SP 27-1:	5- 8 m head/750-1500 Wp

Applications

GRUNDFOS solar pumping systems are specially designed for water supply and irrigation in remote areas where no reliable electricity supply is available. Features like extremely long life and minimum maintenance are key factors with these pumping systems.

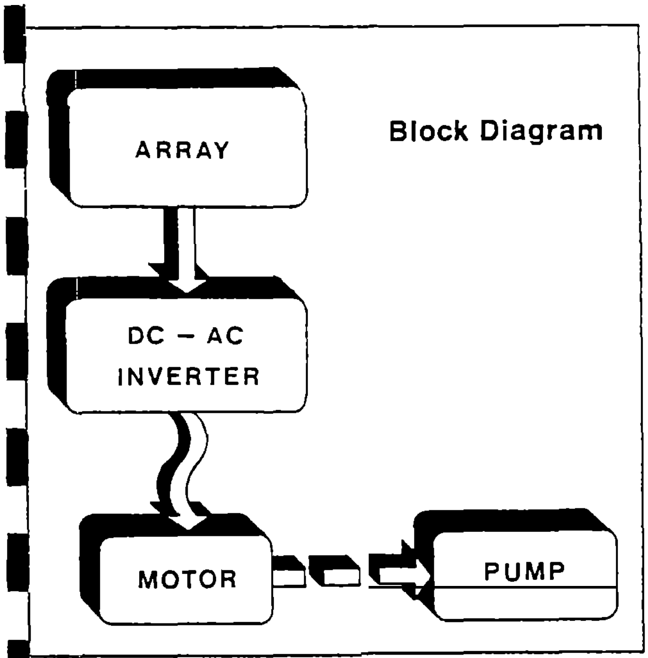
The only moving part of the system is GRUNDFOS' well-known submersible pump/motor unit made entirely of stainless steel. There are several unique advantages of using photovoltaic power in connection with water pumping.

Primarily, there is a natural relation between the availability of solar power and the water requirement The water requirement grows during periods of hot weather when the sun shines most brightly and the output of the solar array is at a maximum Conversely, the water requirement will decrease when the weather is cool and the sunlight is less intense.

The water can be pumped during the day and stored. Water is then available at night and during cloudy periods

The possibility of storing the pumped water eliminates the need for batteries in the system

GRUNDFOS®



Description of System

Quality, high efficiency, reliability, and minimum operating costs are typical characteristics when describing GRUNDFOS products.

These characteristics have also been the key factors in the development of GRUNDFOS solar-powered irrigation and water supply systems or simply GRUNDFOS solar pumping systems. The system consists of a few simple units only, which are connected to form a complete system.

The Elements:

- Solar Array with a variable number of solar modules built together to form a self-containing DC power generating system
- DC-AC Inverter
- Submersible Pump/Motor Unit
- Batteries

Solar Array:

The highly efficient solar modules are connected in series and in parallel to form a complete solar array with a nominal output voltage of approx. 105 VDC The output current varies with the irradiation on the array.

The DC output from the array is transmitted to the inverter through a main switch in the inverter.

DC-AC Inverter:

The GRUNDFOS inverter converts the DC power from the solar array into three-phase AC power which is transmitted to the submersible motor.

The AC output voltage and frequency vary continuously as a function of the irradiation.

The construction and mode of operation of the GRUNDFOS inverter are unique, i e the system utilizes the power output of the solar DC generating system to an absolute maximum.

Submersible Pump/Motor Unit:

The submersible motor is direct coupled underneath the pump so that the motor and the pump form a complete unit All vital parts of both motor and pump are manufactured from stainless steel

The motor is a high-efficiency GRUNDFOS MS 401 motor, and the same motor is used for all systems

As the AC power input to the motor changes according to the irradiation on the solar array, the water output will vary with the irradiation as well

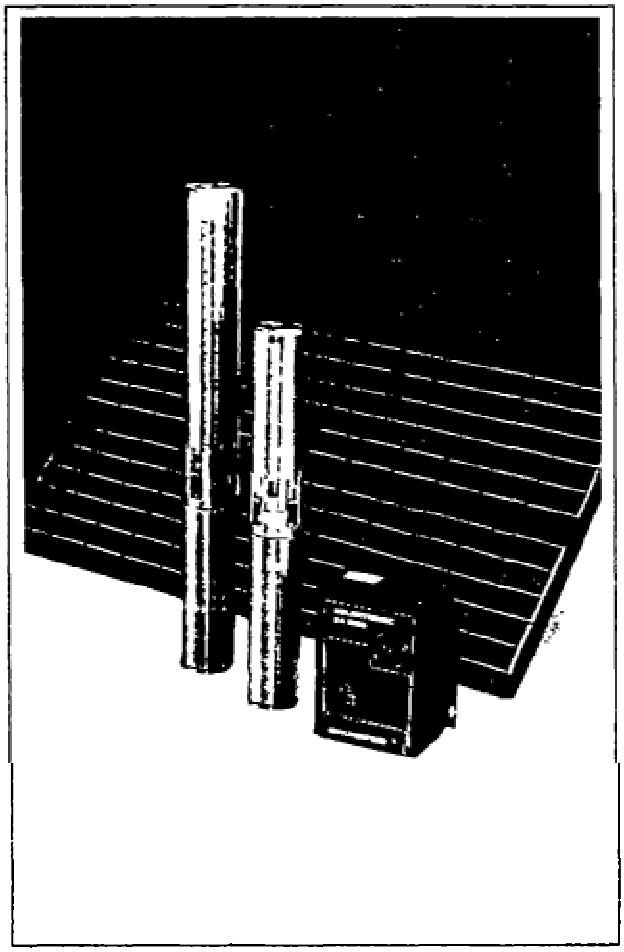
The submersible pump unit is installed in the bore hole, connected to the riser main and after electrical connection to the main switch box and connection of the solar array, the pump will deliver water through the riser pipe

Batteries:

Batteries for storage of the electrical energy from the array are very expensive and have a relatively short life.

Instead of storing the energy in batteries it is much cheaper and more reliable to store the energy by storing the water in a water storage tank or reservoir.

GRUNDFOS solar pumping systems require no batteries, but the inverter can operate with batteries, in connection with a charge regulator.



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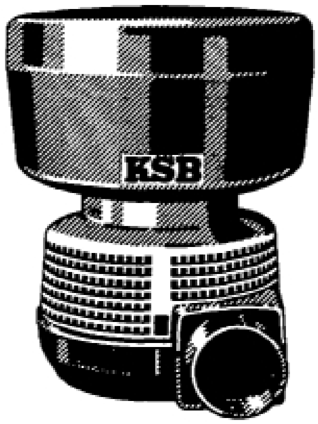
GRUNDFOS

Pump catalogue booklet

Aquasol

Buoyant Solar Energy Pumps



Fields of Application

Aquasol pumps are used in regions with an abundance of solar energy to pump water from wells, lakes, rivers and reservoirs, for clarification of sludge liquor in settling tanks, irrigation of cultivated areas, water supply for road construction and housebuilding, to keep the groundwater level low, for drainage, soil desalinization, delivery of salt/seawater, to circulate the water in fish farms, to handle the water required at archaeological sites, for flushing water for soil examinations and to fill water towers and towers for fire-fighting purposes.

Operating Data

depending on the daily irradiation value

	Aquasol 50 M	**Aquasol 100 L**
Q	up to 5 l/s 18 m³/h	up to 12 l/s 43.2 m³/h
H	up to 11.5 m	up to 5 m
t	up to 35 °C	up to 35 °C
P	450 W	450 W

Design

Buoyant, close-coupled submersible motor pump, floodable, with brushless DC motor, 10 m connecting cable and CEE plug for the connection of the solar generators.

Shaft

Impeller side.	mechanical seal
Motor side:	radial shaft seal ring, with sealing liquid chamber.

Materials

Pump casing	Polypropylene talcum stabilised
Shaft	Chrome nickel steel
Impeller	Polyphenylene oxide
Mechanical seal	Carbon / ceramics
Float	Polyethylene
Cable	NSS Höu-03 x 2.5

Driver

Special brushless DC motor with built-in temperature and dry running protection, IP 68.
Max. perm. voltage: 100 V during no-load operation
68 V during operation

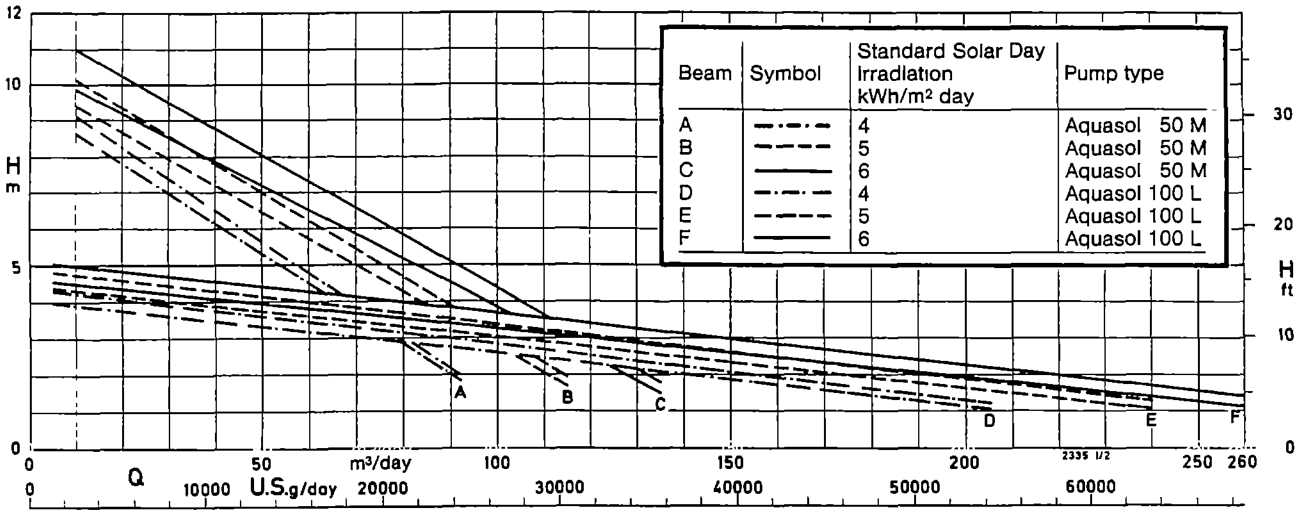
Max. perm. peak current: 8.4 A (= max. short circuit current of solar generator).

Bearings

Deep groove ball bearings with return stop and lifetime grease lubrication.

Pumps
Valves
KSB

Examples



Beam	Symbol	Standard Solar Day irradiation kWh/m² day	Pump type
A	—·—·—	4	Aquasol 50 M
B	— — —	5	Aquasol 50 M
C	———	6	Aquasol 50 M
D	—·—·—	4	Aquasol 100 L
E	— — —	5	Aquasol 100 L
F	———	6	Aquasol 100 L

Fig. 3 **Note:** The beams represent a PV-arry with output P = 530 Wp (Peakwatt) – approx 350 W motor input at an ambient temperature of 40 °C. The upper and lower boundaries of each beam correspond to ambient temperatures of 25 and 40 °C respectively Intermediate temperatures are to be interpolated.

The following example will give a rough estimate for the layout of pump and equipment

Example

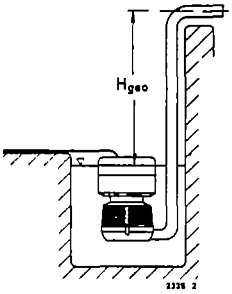
Data required from customer

Site location Central India 13 °N →

Layout

From the Standard Solar Day irradiation curves we have
in January 6 kWh/m² day (fig. 1)
in July 5 kWh/m² day (fig. 2)

Static head $H_{geo} = 4$ m → Total head $H = H_{geo} + H_{loss}$
(add a flow loss of 0 5 m in 10 m long discharge hose pipe $H_{total} = 4 + 0.5 = 4.5$ m)



Quantity Q. comprising of → Water requirement

200 inhabitants	6.0 m³/day	
20 oxen	0.8 m³/day	
20 buffaloes	0.8 m³/day	see table fig. 4
100 goats	0.5 m³/day	
0 8 ha rice field	80 0 m³/day	
water requirement approx	88.1 m³/day	

Ambient air temperature in January: 25 °C → Pumping capacity = 98 m³/day (Fig. 3, beam C, upper boundary)

Average temperature beginning
2 h after sunrise, right through midday
and up to 2 h before sunset

Ambient air temperature in July 40 °C → Pumping capacity = 77 m³/day (Fig 3, beam B, lower boundary)

Aquasol 50 M connected to a PV-array with 350 Wp output The limiting values of solar irradiation in the months of January and July are sufficient for the determination of min and max pumping capacities

A precise calculation will be worked out for you at our computer centre in Frankenthal

Per head	Quantity in m³/day
Human beings (adult)	0 03
Cattle/Horses	0.04
Camel/Donkey	0 02
Sheep/Goat	0 005

Per hectare of cultivated area	Quantity in m³/day
Rice crops	100
Sugar cane	66
Cotton	55
Vegetables	50
Corn/Wheat/Grain crops	45

Fig 4 Table of water requirements

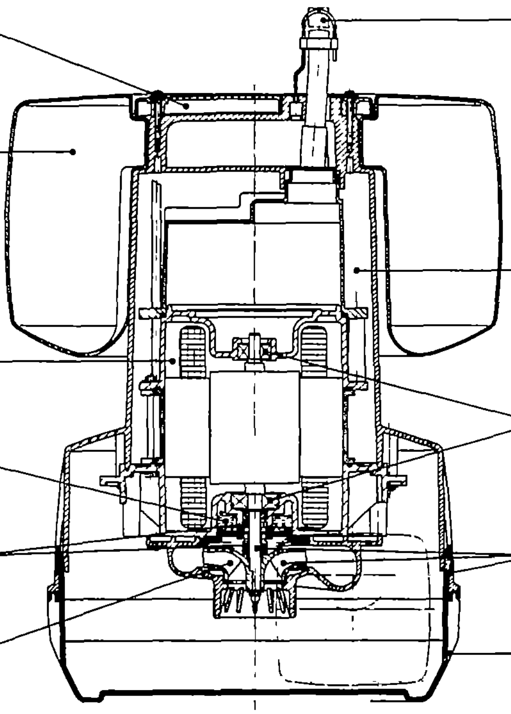
Pumpset

Pump sizes	Aquasol 50 M	Aquasol 100 L
Ident no.	29 117 822	29 117 823
Weight approx. kg	16	16
Dimensions in mm Discharge nozzle Diameter Height	 50 360 455	 100 360 455

Accessories

Item	Part designation	Ident no	Wight approx. kg
P 1	Discharge hose, PVC DN 50 spiral-reinforced, 10 m long DN 100 incl. hose clamp	00 100 825 00 114 550	9,0 23,0
E 1	Cable extension, 30 m with plug in connection	18 040 032	7,6

Not harmful to the environment
starts up automatically at sunrise
no operating personnel
no fuel and electricity bills
no switchboard or measuring instruments
maintenance-free
robust design



With solid **handle**, easy to carry around

Float makes sure the pump does not take in mud

DC motor with built-in temperature and dry-running protection

Sealing liquid lubricates the contact surfaces in case of water shortage

Double **shaft seal** reliably separates motor and water

High pump efficiency, therefore only small solar generators are required

10 m **connecting cable** and CEE plug for direct connection of solar generators

Double **jacked cooling** allows continuously operation, even when pump is not immerged

Solid **motor bearings,** maintenance-free during the whole service life

Corrosion-resistant materials, also suitable for salt water and seawater

Flexible **pump foot,** can be easily dismounted for cleaning purposes

Subject to technical modifications

A.N. 40819

2335.178/3-10 / 1989

M51
40 Watt Solar Module
High Efficiency Cells

ARCO Solar, Inc.

The M51 is a 35 cell photovoltaic solar module producing a nominal 40 watts at 17 3 volts of peak power ideal for a variety of applications, large and small

Module efficiency is more than 10 percent and significant power is delivered in light conditions as low as 5 percent of full sun

Each of the 35 series connected cells generates more than 2 amps at 0 5 volts These 4 inch diameter cells are made from single-crystal silicon grown by the Czochralski method. Twin redundant connections are provided on both front and back of each cell

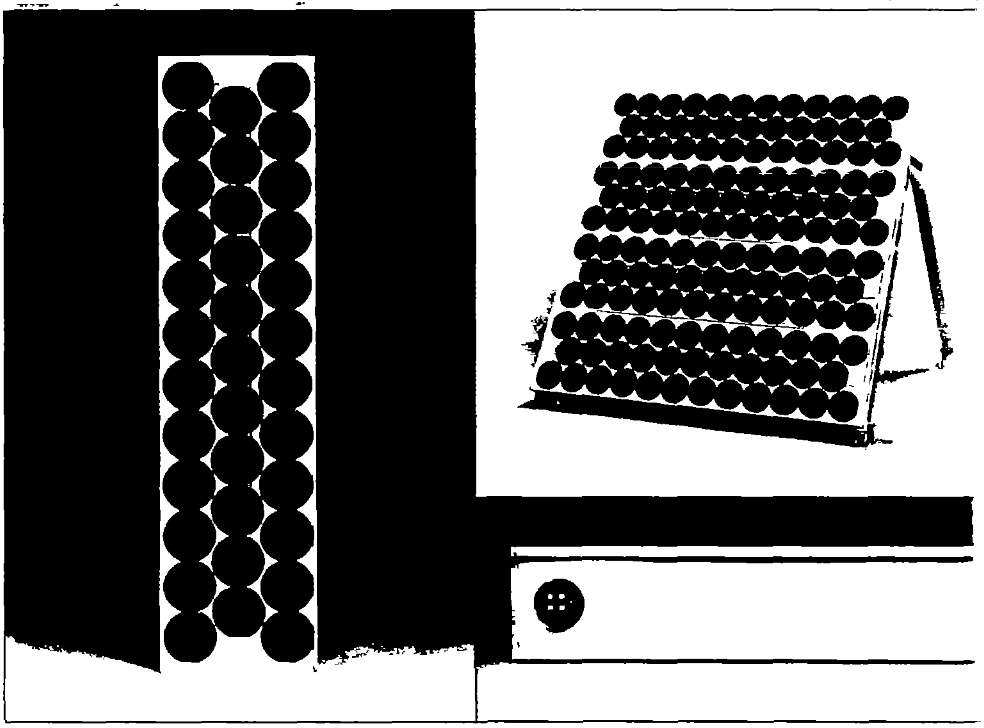
To protect the cells from moisture and impact, the M51 employs a weather-proof glass laminate construction with cells sandwiched between tempered glass and metal The front glass is tempered to withstand hail, rain, snow and blowing sand. The back surface consists of a tough plastic coated metal foil that blocks out moisture A special laminating process assures a strong bond between the glass, cells and back surface by fusing them together with layers of polymeric encapsulant

The M51's lightweight, aluminum frame interlocks at all four corners for outstanding mechanical support and easy installation Frames are sealed by a rubber compound that prevents moisture penetration A grounding terminal is provided on the frame for improved safety in high voltage applications Total module weight is only 12 5 lbs

Power output terminals are solder-plated brass posts with captive screws Two output terminals are provided per polarity, located inside a weatherproof junction box

Module Characteristics (typical)

- 100 percent electrically matched solar cells mean the module is not effected by sustained operation at the I_{sc} or V_{oc} points
- All modules have leakage current of less than $50\mu A$ at 3000 V, even above 60°C
- Ground continuity of less than 1 Ohm for all metallic surfaces (including metal back plane which has quadruple redundant connections to the integral frame)
- Module capacitance of 0 0022 micro farads



Cell Characteristics (typical)

- Area of 81 29 square cm
- Voltage coefficient of −0 00225 volts $°C^{-1}$
- Current coefficient of +0,0002977 amps $°C^{-1}$
- Shunt conductance of 0 035 MHO
- Series resistance of 0 014 OHM
- J_{01} of 2 36 x 10^{-12}
- J_{02} of 7 60 x 10^{-7}
- N of 2 47

Physical Characteristics

- Interchangeable standard dimensions Length 48" (121 9cm) Width 12" (30 5cm) Depth 1 5" (3 8cm)
- Weight of 12 5 pounds (5 7Kg)
- Forty-four total contacts on each cell for enhanced reliability
- Metal foil back plane for hermeticity
- Standard cell operating temperature (SOCT) of 36°C
- Operating conditions of −40°C to +90°C, 0 to 100 percent humidity
- Self-cleaning tempered water-white glass front.
- Desiccated polymeric encapsulation
- High emissivity back side
- Specular reflection by inside of front glass
- Efficient conversion of both direct and diffuse light
- Five layer coating behind cells
- Fault tolerant cells and interconnects
- Single crystal silicon cells

Power Specifications

	100mW/cm², AM 1 5 spectrum and 25° (± 0 5° C) cell temperature
Open Circuit Voltage	21 0 volts
Short Circuit Current	2 6 amps
Voltage, Test	17 3 volts
Current, Test (±10%)	2 31 amps
Module Efficiency	10 76%
Power (Watts @ Test)	40 0 watts

Testing

The ARCO Solar M51 meets the demanding requirements of the U.S Department of Energy as proven by the Jet Propulsion Laboratory Block IV Test Requirements Additionally the modules must pass numerous tougher tests including a 5 day exposure to 95 percent humidity at 95°C The ARCO Solar test sequence is shown below

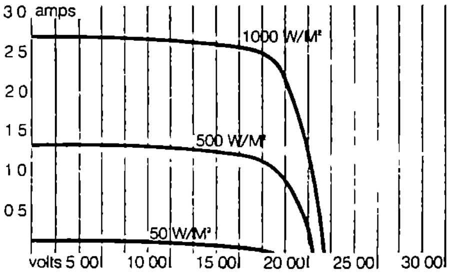
- Thermal Soak
- Thermal Cycling
- Thermal/Freezing and High Humidity-Cycling
- Mechanical Wind, and Twist Loading
- Hail Impact
- Salt Fog
- Hot Spot
- Thermal/Humidity Soak
- Field Exposure

ARCO Solar, Inc.

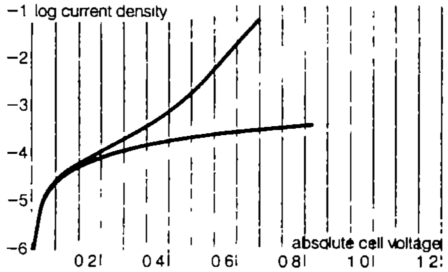
Performance Characteristics

The power response profiles at the right give an indication of the amount of power that can be expected when an M51 module is used in various types of environments—from hot sunny deserts of Saudi Arabia in summer to a nearly sunless Norway in the middle of winter

The I-V curve (current vs voltage) below demonstrates typical M51 power response to various light levels at 25°C cell temperature



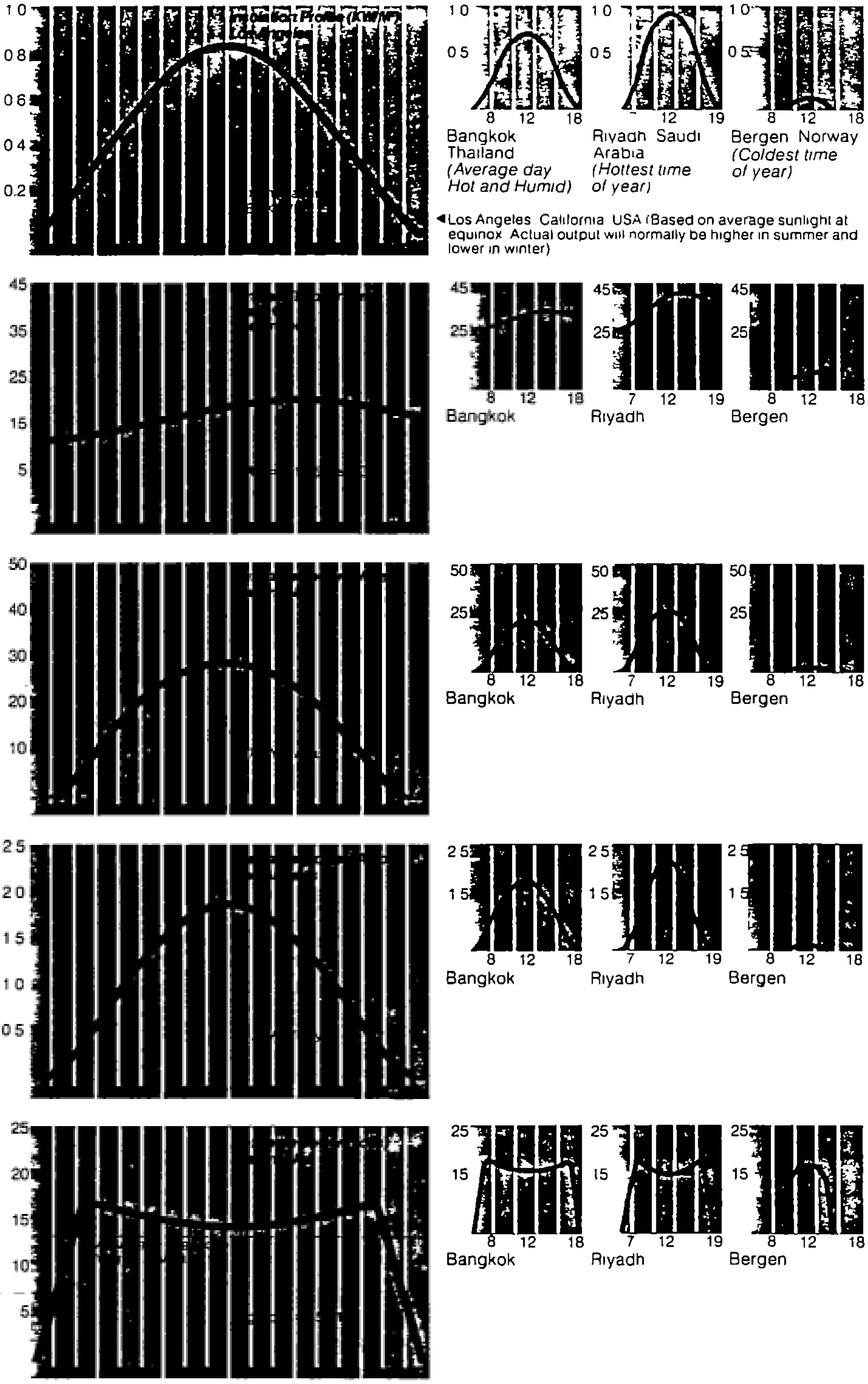
The exceptional low light level performance of the M51 can be predicted from this Dark I-V curve for a cell



Warranty

The power output on ARCO Solar M51 modules is warranted for a period of five years During that time, ARCO Solar will repair or replace modules to make up for any power loss greater than 10 percent of the originally specified minimum power output at the time of installation if the loss is due to defective materials or workmanship

Because of differing regulations worldwide, there may be differences between warranties in various countries Each ARCO Solar affiliate will be glad to provide a specific warranty statement for the country of installation



◄Los Angeles California USA (Based on average sunlight at equinox Actual output will normally be higher in summer and lower in winter)

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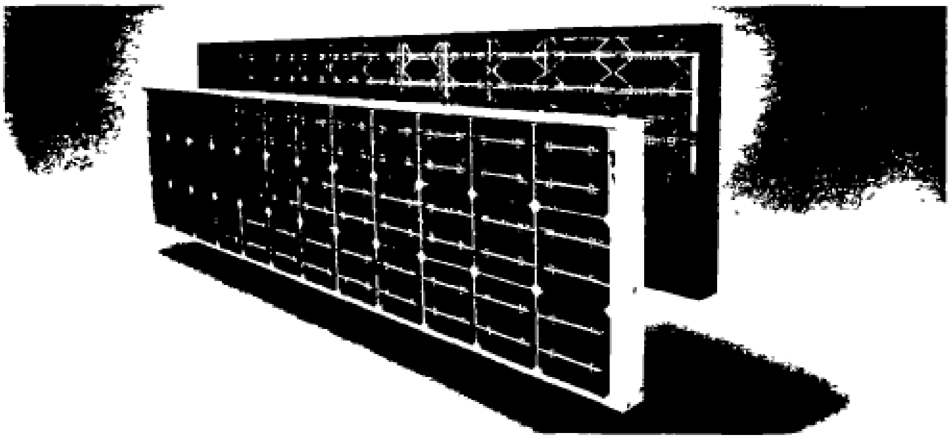
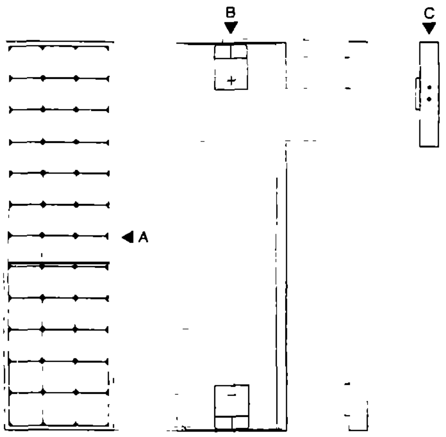
Woodland Hills CA 91365
Tel (213) 700 7393
Telex 674838
TWX 910-494-2791

ARCO Solar®

M53 Photovoltaic Module



A Length 48 in/121.9 cm
B Width 12 in/30.5 cm
C. Depth 1.5 in/3.8 cm
2.4 in/6.1 cm including Junction Box



New High Efficiency Square Cells

The ARCO Solar M53 is a nominal 43 watt photovoltaic (solar electric) module, it is the first ARCO Solar module to utilize our high efficiency single-crystal silicon square cells. The M53 continues to maintain the quality and features that have established ARCO Solar modules as an industry standard, and also incorporates mar new features. These innovations make it an even more efficient, reliable and durabl solar module, well suited for a wide variety of applications—large and small. The M53 is available either with regular aluminum frame and white backing, or with black anodized aluminum frame and black backing. The M53 is physically and electrically compatible with existing ARCO Solar systems.

Each of the M53's 36 series-connected solar cells produces over 2.4 amps* Overall module efficiency is greater than 11.5% due to the denser packing allowed by the square cells. Multiple redundant connections on the front and back of each cell help assure module circuit reliability, and by using single-crystal silicon cells, the module can produce power in as little as 5% of noon sun. Two by-pass diodes are wired into each module to reduce potential power loss from partial shading of a single module within an array.

Specialized Construction

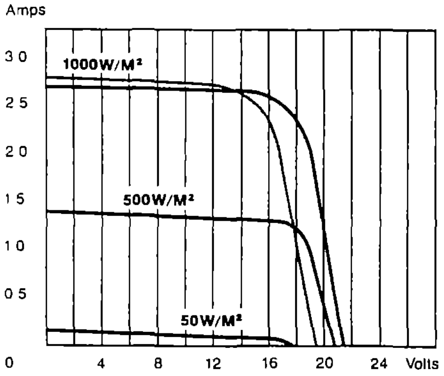
The M53 utilizes our highest standard of glass laminate construction. This enables it to withstand some of the harshest environments and continue to perform efficiently. This same standard of construction has allowed other ARCO Solar modules to meet the design, performance and durability requirements of the U.S. Department of Energy and pass additional, more stringent, ARCO Solar tests. Solar cells are permanently laminated between special anti-reflective tempered glass and EVA, backed by multiple layers of polymeric protection. This weatherproof package is then sealed by a neoprene edge-gasket and supported by a rugged lightweight aluminum frame.

There are two environmentally sealed junction boxes on each module, one for positive and one for negative termination. Each junction box contains dual terminations, a wired-in by-pass diode and two additional non-active termination posts. Designed for easy wiring access, the junction boxes accept standard ¾" flexible conduit or our Standard Interconnect Wire (SIW) and grommets. Junction boxes are securely attached to the module frame with screws and to the module backing with adhesive.

* Performance Characteristics

The IV curve (current vs. voltage) below demonstrates typical M53 power response to various light levels at 25°C cell temperature and at the NOCT (Nominal Cell Operating Temperature) 47°C.

1000 w/m² @ 25°C	■
1000 w/m² @ 47°C	■



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ARCO Solar®

Power Specifications	1000 w/m^2 AM 1.5 spectrum and 25°C (±0.5°C) cell temperature
Open Circuit Voltage/Typical	21.7 Volts
Short Circuit Current/Typical	2.7 Amps
Voltage/Typical at Load	17.3 Volts
Current/Typical at Load	2.49 Amps
Module Efficiency/Typical	11.5%
Average Power/Typical Watts @ Test, ±10%	43 Watts/P. Max.

Module Characteristics

- *Electrically matched single-crystal silicon solar cells.*
- *Fault tolerant, multiple redundant contacts on each cell for circuit reliability.*
- *Nominal operating cell temperature (NOCT) 47°C/50°C (black version).*
- *Service Temperature conditions of −40°C to +90°C, 0 to 100 percent humidity.*
- *Computer designed cell grid pattern for high conductivity.*
- *Cells chemically textured for anti-reflection enhancement.*
- *Two by-pass diodes. Each by-passes 24 cells, with 12 cell overlap.*
- *Tempered anti-reflective glass front.*
- *Specular reflection by inside of front glass.*
- *Efficient conversion of both direct and diffuse light.*
- *Polymeric encapsulant.*
- *Multiple-layer protective coating behind cells.*
- *Interlocking aluminum side rails–(black anodized optional).*
- *External grounding screw.*
- *Module surface promotes self-cleaning by natural processes (rain, wind, etc.)*
- *Junction boxes designed for easy wiring access.*
- *Module leakage current of less than 50μA at 3000 VDC.*
- *Ground continuity of less than 1 ohm for all metallic surfaces.*

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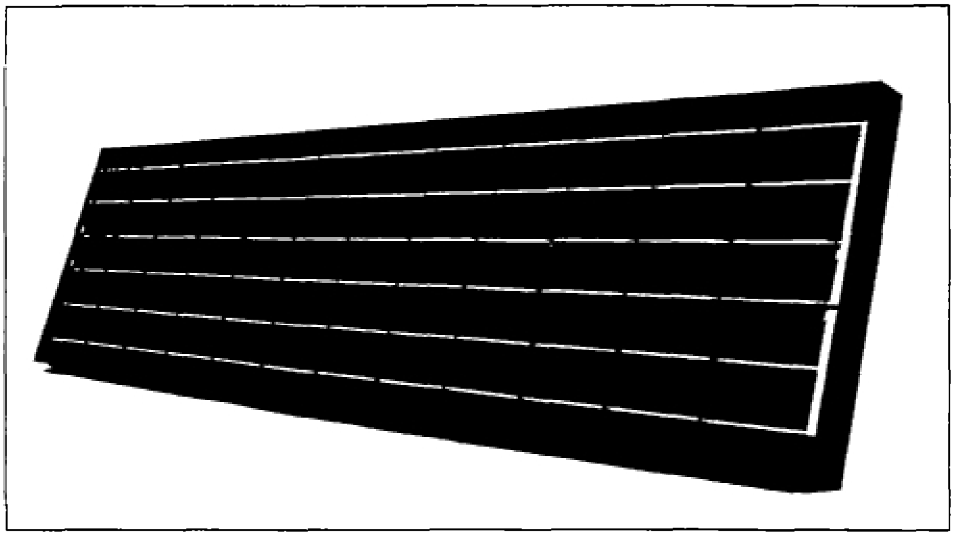
Consult your dealer for full and complete details regarding the installation and use of ARCO Solar M53 photovoltaic modules

Specifications subject to change without notic
09

ARCO Solar®

Model M55
Photovoltaic Module

M55
High Efficiency Solar Electric Module



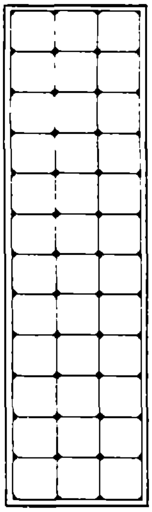
53 Watts* UL Listed **10 Yr.** **Limited Warranty* on Power Output**

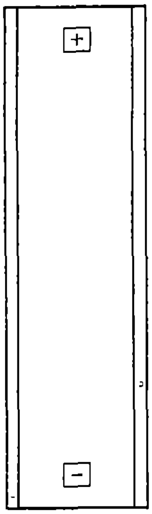
The M55 is ARCO Solar's most powerful standard module Efficiency and quality construction are combined in a highly dependable solar electric generator

Utilizing 36 specially processed single-crystal solar cells, the M55 is capable of producing 53 watts at over 3 amps Charging voltage is achieved in as little as 5% of full sunlight resulting in power being produced from early to late in the day

Employing ARCO Solar's highest standard of glass front, metal side rail construction, the M55 is able to withstand the harshest environments and continue to perform efficiently. Cells are protected from dirt, moisture and impact by a special low-iron, anti-reflective tempered glass front The solar circuit is laminated between the glass front and a durable, multi-layered polymer backsheet using EVA for superior moisture resistance. Dual junction covers, one for positive and one for negative termination each contain a built-in bypass diode. These reduce the potential power loss from module shading within an array

The M55 carries a 10-year limited warranty on power output and is Listed by Underwriters Laboratories (UL), an independent, not for profit organization testing for public safety





Power Specifications*

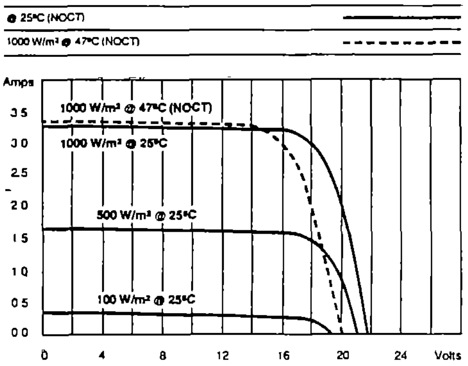
Model	M55
Power (typical ± 10%)	**53.0 Watts**
Current (typical at load)	3.05 Amps
Voltage (typical at load)	17 4 Volts
Short Circuit Current (typical)	3.27 Amps
Open Circuit Voltage (typical)	21 8 Volts

Physical Characteristics

Length	50 9 in/1293 mm
Width	13 in/330 mm
Depth	1 4 in/36 mm
Weight	12 6 lb/5 7 kg

*Power specifications are at standard test conditions of 1000 W/M², 25°C cell temperature and spectrum of 1 5 air mass.

Performance Characteristics



The IV curve (current vs voltage) above demonstrates typical power response to various light levels at 25°C cell temperature, and at the NOCT (Normal Cell Operating Temperature), 47°C

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P O Box 2105, Chatsworth, CA 91313

Available From:

* These charts are for estimating purposes only specifications are subject to change without notice

Complete warranty and installation information is included in module package or is available from ARCO Solar or your dealer prior to purchase

Modules marked with an (X) on the back will have different power ratings

ARCO Solar®

Model M55
Photovoltaic Modules

ARCO Solar single crystal modules represent the optimum in solar electric generators. They combine the time proven reliability of modules from the world's leading manufacturer with innovations and advances that continue the ARCO Solar tradition of industry leadership.

Through the use of larger solar cells and special processing, ARCO Solar Modules now feature higher current (amperage) ouputs and increased area efficiencies. This means more useable power every day. Improved junction covers with self locking lids provide for easy array wiring and environmental protection.

ARCO Solar tests modules to meet or exceed government standards, as well as even more rigorus ARCO Solar quality and performance requirements. The module's test performance and our years of experience providing dependable power in locations throughout the world assure you that ARCO Solar modules can meet your solar power needs today.

Module Characteristics:

- Electrically-matched single-crystal silicon solar cells for efficient conversion of both direct and diffuse light
- Cells chemically textured and coated for anti-reflection enhancment
- Fault tolerant, multiple redundant contacts on each cell for greater circuit reliability
- Circuit laminated between layers of ethylene vinyl acetate (EVA) for moisture resistance UV stability, and electrical isolation
- Tough, multi-layered polymer backsheet for resistance to abrasion, tears and punctures
- Interlocking, rugged, lightweight black metal frame
- Two junction covers with self-locking lids for safety and environmental protection
- Junction covers are designed for easy field wiring. Wired-in bypass diodes reduce potential loss of power from partial array shading
- Module leakage current of less than 40 µA at 3000 VDC electrical voltage isolation
- External grounding screw for electrical safety
- Normal operating cell temperature (NOCT) 47 °C
- Laboratory tested for wide range of operating conditions (−40 °C to + 90 °C, 0 to 100% humidity
- Ground continuity of less than 1 ohm for all metallic surfaces
- Ten-year limited warranty on power output
- UL Listed

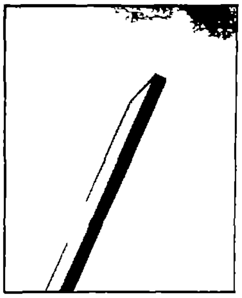
Module Features:

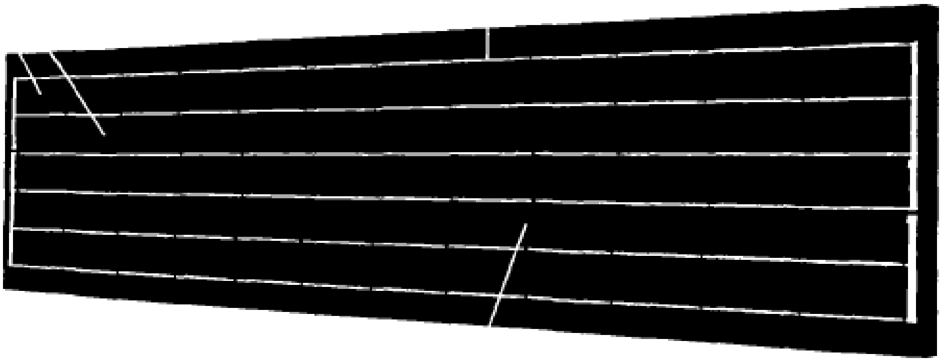
High efficiency single crystal solar cells. Each specially processed cell is anti-reflective coated. All cells within a module are electrically matched.

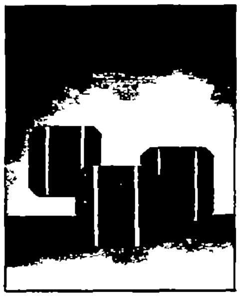
Tempered glass front provides strength and superior light transmission through an anti-reflective coating.

Multiple redundant contacts on the front & back of each cell provide a high degree of fault tolerance and circuit reliability.

Rugged side rails are designed for exceptional structural strength. The lightweight, black rails have multiple mounting holes strategically located for easy module installation.



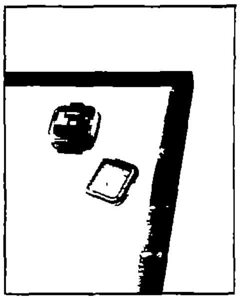




ARCO Solar modules may be combined in series and/or parallel to meet nearly any power requirement.

Multi-layered polymeric backing is used for environmental protection and enhanced heat dissipating properties.

Large area single crystal silicon cells provide the highest light to energy conversion efficiency available from ARCO Solar.

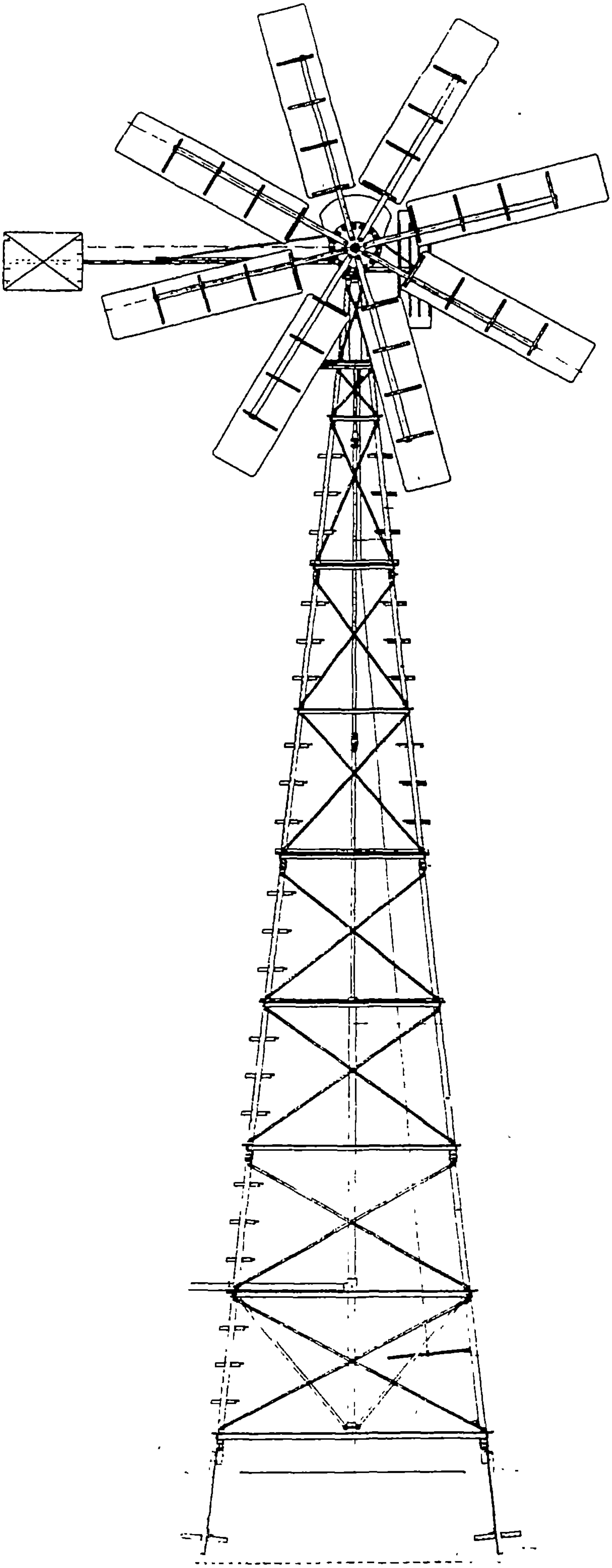


Circuit is laminated between layers of ethylene vinyl acetate (EVA) for moisture resistance, UV stability and electrical isolation.

Junction covers with self-locking lids are engineered for easy wiring access.

Appendix F. Wind Pump Technical Information

CWD 5000
Kijito



CWD 5000 LW

PURPOSE : water lifting; designed for use in low and moderate wind regimes (yearly averages below 6 m/s)

ROTOR : horizontal axis; upwind position by means of a tail vane; rotor diameter 5 m, 8 blades of galvanized steel sheet; fixed pitch

TRANSMISSION. direct drive crank mechanism with adjustable stroke and overhead swing arm; strokes: 80-200 mm

CONTROL SYSTEMS : over speed control by yawing, activated by side vane and hinged tail vane system; with manually activated furling device

PUMP SYSTEM : single acting piston pump with pressure air chamber and starting nozzle; galvanized steel pump; nominal pump diameter of 150 mm.

TOWER : lattice steel tower; height 12 m (alternative 9 m)

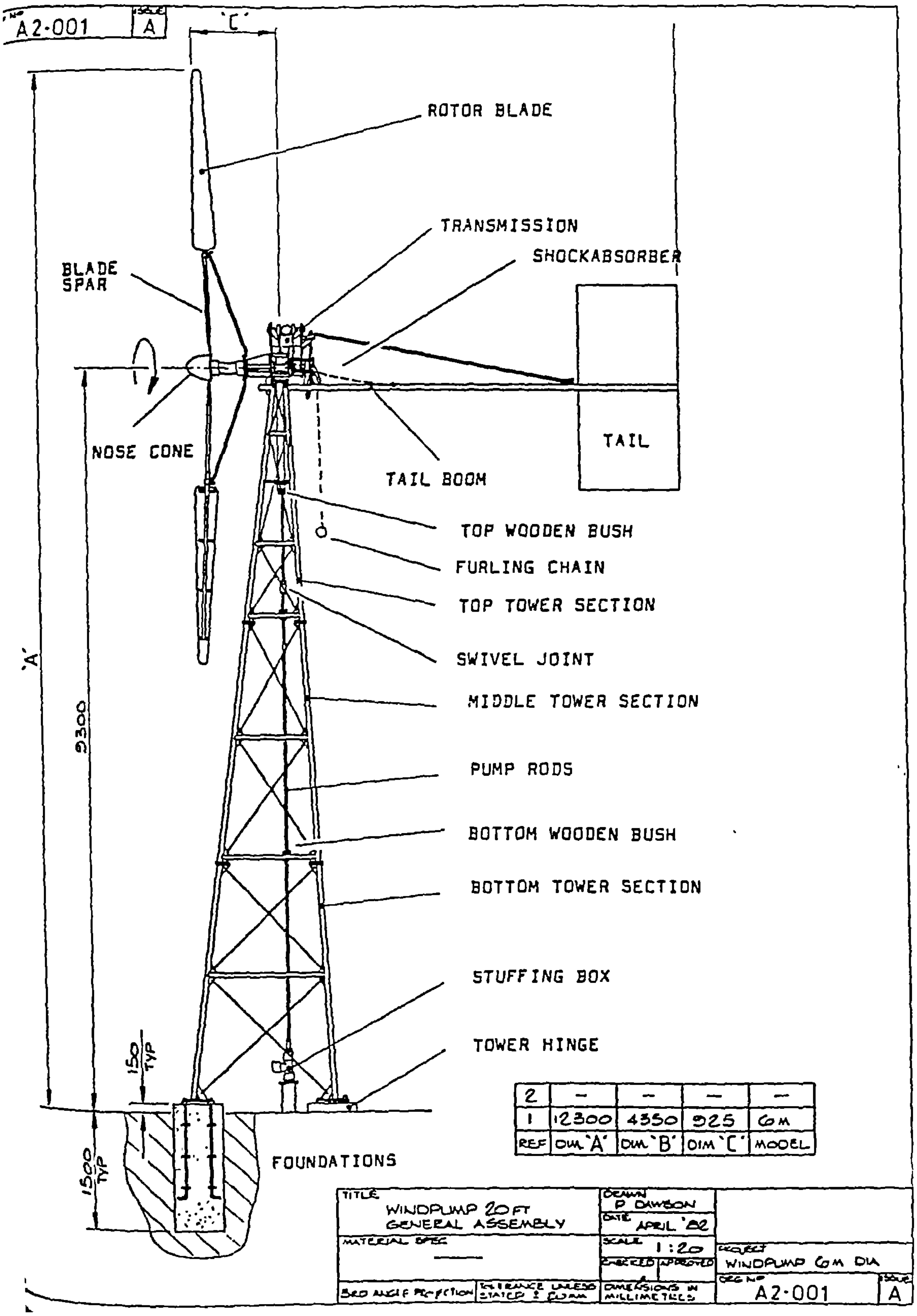
FOUNDATION : requires about 1 m^3 reinforced concrete per leg.

CAPACITY : 50 m^3/day at 20 m static head and 4.5 m/s wind speed.

OPERATING WIND SPEEDS : -cut-in : 4 m/s
-rated : 9 m/s
-cut-out : 12 m/s (automatic furling between 8 and 12 m/s)
-survival: 50 m/s

AERODYNAMIC PROPERTIES : -λ (design): 2
-Cp (max): 0.35
-solidity: 0.34
-typical design wind speed: 4.5 m/s

WEIGHTS : -rotor, head and transmission: ± 350 kg;
-tower: 450 kg (9 m) resp. 650 kg (12 m)
-pump including 25 m piping below ground level 280 kg



REF	DIM 'A'	DIM 'B'	DIM 'C'	MODEL
2	–	–	–	–
1	12300	4350	925	6M

TITLE WINDPUMP 20FT GENERAL ASSEMBLY
DRAWN P DAWSON
DATE APRIL '82
MATERIAL SPEC ——
SCALE 1:20
CHECKED
APPROVED
PROJECT WINDPUMP 6M DIA
3RD ANGLE PROJECTION
TOLERANCE UNLESS STATED ± [illegible]
DIMENSIONS IN MILLIMETRES
DRG NO A2-001
ISSUE A

Appendix G. Example Surveys

NRC Questionnaire
Rural Village Questionnaire
Private Farmer Questionnaire

Note: These surveys were translated to Arabic for use by the survey teams.

VILLAGE QUESTIONNAIRE

A) Wateryard Inspection Date: ___________

Village: ________________

Province: __________________

Rural Council: _________________

Wateryard name or designation: _________________________

No of equipped boreholes: ____

	A	B	C
For each:			
Engine Make:	___________	___________	___________
Engine model:	___________	___________	___________
Pump make:	___________	___________	___________
Pump model:	___________	___________	___________

Tank size: ___________
Elevated (Y/N) _____

Number of taps total ________

Number of taps working _________

B) NRWC Clerk/Operator

Name of clerk: ________________________

Name of operator: ___________________________

(Note engines and pumps are to be designated A,B, and C as above)

In Summer:

How many hours per day do you operate the engines

A __________ B __________ C __________

How much fuel does each engine use

A __________ B __________ C __________

How much water does each engine pump

A __________ B __________ C __________

How much water is pumped in total for the village each day ______

In Winter:

How many hours per day do you operate the engines

A __________ B __________ C __________

How much fuel does each engine use

A __________ B __________ C __________

How much water does each engine pump

A __________ B __________ C __________

How much water is pumped in total for the village each day ______

Have any of the boreholes been out of service for more than one year? If yes what is the problem?

the engine ____
the pump ____
the borehole ____

For each engine:
(answer each question for each engine and breakdown)

1. When did each engine break down last year? __________

How long did it stay without repair? __________

What was the problem? __________

Who performed the repair? __________

What was the cost for spare parts? __________

What was the cost for labor? __________

What was the cost for transportation? __________

The reasons for each trip and the destination? __________

2. When did each engine break down last year? __________

How long did it stay without repair? __________

What was the problem? __________

Who performed the repair? __________

What was the cost for spare parts? __________

What was the cost for labor? __________

What was the cost for transportation? __________

The reasons for each trip and the destination? __________

When did each engine break down last year? __________

How long did it stay without repair? __________

What was the problem? __________

Who performed the repair? __________

What was the cost for spare parts? __________

What was the cost for labor? __________

What was the cost for transportation? __________

The reasons for each trip and the destination? __________

3. When did each engine break down last year? __________

How long did it stay without repair? __________

What was the problem? __________

Who performed the repair? __________

What was the cost for spare parts? __________

What was the cost for labor? __________

What was the cost for transportation? __________

The reasons for each trip and the destination? __________

4. When did each engine break down last year? __________

How long did it stay without repair? __________

What was the problem? __________

Who performed the repair? __________

What was the cost for spare parts? __________

What was the cost for labor? __________

What was the cost for transportation? __________

The reasons for each trip and the destination? __________

5. When did each engine break down last year? __________

How long did it stay without repair? __________

What was the problem? __________

Who performed the repair? __________

What was the cost for spare parts? __________

What was the cost for labor? __________

What was the cost for transportation? __________

The reasons for each trip and the destination? __________

For each engine:

When was it first installed

A __________ B __________ C __________

When was it last replaced

A __________ B __________ C __________

When was it last overhauled

A __________ B __________ C __________

Was overhaul in the workshop or at the wateryard

A __________ B __________ C __________

What was the cost of the overhaul

A __________ B __________ C __________

C) Village elder or member of the village committee on water

Village: ________________________

Person interviewed: ________________________

Position in the village: ________________________

Does the Village have a water committee or self-help group for water? ____________

If so when was it established: ______________________

Why was the group formed: __________________________________

Does the group keep records relating to water matters _________

What are the activities of the committee: ____________________

____

How are these activities financed?

water fees _______

local tax ________

sale of commodities _______

collection when funds are needed _______

What are the fees for water?

per jerikan ______

per goat _______

per camel ______

How many times was the village without water from the wateryard last year _______

For each time how long was the village without water ____________

Does the village contribute to maintenance and repair of the wateryard (Y/N) _____

For fuel and lubricants ____ how much last year _____

For repairs ____ how much last year _____

Where do people go to get water when the wateryard is not operating ___________ How far away is this source _________ what kind of source (dug well, another wateryard, canal, etc) _________

Do you agree with the information provided by the clerk or operator (Y/N) ______

If not, what errors do you see _______________________________

NRWC Questionnaire

Location: ______________________ Date: ______________

Name of the Regional Director General: ______________________

Number of Wateryards in the Region: __________

Total number of equipped boreholes: ____________

Total number of single cylinder engines installed: ____________

Total number of equipped boreholes out of service: _________
(based on monthly reports from regional councils)

Total number of wateryards where no NRWC boreholes are operating: _________
(based on monthly reports from regional councils)

Reasons for out of service boreholes (not wateryards) and number falling in each category:

Borehole dry: __________
Engine out of service __________
Pump out of service __________
Other (explain)m __________

Total number of dug wells supported by NRWC in the region: _______

Rural councils with a high number of NRWC supported dug wells

____
____
____
____

Location of workshops in the Region:

____
____
____
____
____
____
____

Total number of operating vehicles in the Region

Trucks:_______

Land cruiser type:_________

Other (specify):__________

Range in amount of water pumped per wateryard:

_____ gal/day (low) to _____ gal per day (high)

Name of villages with low volume (less than 5,000 gal/day)

____

____

____

____

Name of village with high volume of water pumped (more than 50,000 gal/day)

____

____

____

____

Typical wateryard layout in the Region (include two if two are common):

Engine (make and model):	_____________	____________
Pump type:	_____________	____________
Tank size:	_____________	____________
Is tank elevated (Y/N)	_____________	____________

Wateryard construction costs for above configurations:

Engine : ____________ ____________

Pump: ____________ ____________

Tank: ____________ ____________

Piping(incl. valves etc) ____________ ____________

Fencing: ____________ ____________

Civil works(concrete, shed) ____________ ____________

Installation Labor (typical)

Erecting engine and pump ______ days for a crew of ______ persons

Erecting tank and pipes ______ days for a crew of ______ persons

Persons in a typical installation crew for erecting the engine :

Title	Base Salary	Allowances[1]	Const. allowance	perdiem	overtime

---

[1] include full time, living, transportation, and any other additions to base salary

Vehicle trips required:

Heavy trucks (7-10ton): _____ trips per installation

Light trucks: (3-5 ton) _____ trips per installation

Land Cruiser type: _____ trips per installation

Private farmer's questionnaire (only diesel irrigated schemes)

Name:________________________

Village:_____________________

Location:____________________

Farm size: ________________ Feddans

Irrigated areas:___________ Feddans

crops grown	season	area
----------	---------	--------
---------	---------	--------

Water source : well___________ (x as appropriate)

river________

borehole_____

others ______

Is the water from the source available all the time (Y\N)-------

If answer is (NO) determine the part of the year of low water capacity--

Part of the year when the source completely dry out--------------

When river is a limitted capacity source determine the distance the engine moved to get close to the water--------------(meters)

Engine owner: ____

" brand name: ________________________________

" model and kW rating): ______________________________

Where purchased: ______________________________________

When purchased_________

Cost new _____________ including pump and piping

How mush was paid for installation:___________

How was the purchase financed:

cash_______

terms of purchase

ADB_______ ___________________

sheil______ ___________________

Do you sell the water or share the engine:_________

Under what conditions:
When neighboring farmers need it:______

On a regular basis: _______

How are you paid for use of your engine:______

User pays fuel ____
User pays per hour of use, if so how much ______
User pays per irrigation application, if so how much ______

Pump type : surface centrifugal_______ brand_________

jet _______ _________

submersible _______ _________

other _______ _________

Size 2"_______3"______4"______ other_______

Estimate (or measure if possible) total head________

Water storage tank size (if applicable)______________
(if not please note there is no tank)

IRRIGATION PRACTICE:

Who much area irrigated each day__________________

How many days of working per week_________________

Working hours per day__________________________

Water conveyance system

Earth canal___________

Lined canal___________

Pipe lines____________

Other ________________

Irrigation frequency ____________(days per week)

Operation: How many hrs/day do you operate your engine __________

How much fuel do you use ______day________week_______________

How often do you change oil ________________________

How much (in gallons) is your fuel allocation _________

What is the cost per gallon of your allocation _________

If your allocation is available, is it sufficient (Y\N)_______

If no what is current price for additional fuel______________

Is your allocation always available (Y/N) _________

How many times last year was the allocation not available ______

What times of the year was fuel unavailable, and can you give a reason why it was not available: __________________________

Do you employ operator or a guard for your engine___________

How much is he paid ___________

What duties does have (including operating the engine)

___________________________________ __________________________

Maintenance:

How many breakdowns of your engine and pump last year__________

How long pumpset out of service last year because of breakdowns

____

Did crops fail as a result, if so what crops ____________________

Who maintains your engine and pump

Who makes repairs when it is broken

__________self
__________local mechanic
__________other

If not self, how much is he paid __________(per job, day, or hour)

How is he contacted when you need him ______________________

If travel is required how does he get to your pump _______________

How much did you spent on engine service and repairs last year

____

How much for spare parts__________________

" " labour _____________________

" " transportation _____________

What are your most common problems

(1) _____________________________ what does this cost______________

(2)_______________________________" " " "_________________

When was the last time the engine was overhauled________________

How much did this cost___________________________________

Did it include new piston______piston rings_________crankshaft____

Was the work done at the farm__________________

in the workshop__________________

When do you expect to have new engine________________________

Appendix H. Base Case Assumptions

Base condition cost assumptions are divided into the two broad catagories of analysis: village water supply and private sector small-scale irrigation. The assumptions made for capital cost, installation, and operation and maintenance are different for each of the pumping technologies considered. The following paragraphs outline cost assumptions for these six cases. Costs are given Sudanese Pounds as of late 1989 unless otherwise indicated.

Cost item	Cost (Financial)	Source or Justification
Rural Village Water Supply		
DIESEL		
Capital Costs		
Engine	US$2,200	Equipment survey (including port fees, handling & transport)
Pump	US$3,000	Same as above
Other offsore costs	US$500	Estimate for pulleys, belts, etc.
Pipes and fittings	35,000	NCRWRD estimate
Construction Materials	40,000	NCRWRD survey average
Water storage tank	100,000	NCRWRD estimate for a locally built tank (20% is labor)
Other Misc. items	20,000	NCRWRD survey average (major component is fencing)
Skilled Labor	7,000	NCRWRD survey average
Unskilled Labor	4,000	NCRWRD survey average
Transportation	20,000	NCRWRD survey average to establish trips, commercial vehicle cost per km used
O&M Costs (annually)		
Operator	2,000	Assumes an operator and guard
Fuel	—	Calculated based on efficiency and hours of operation, 20% added for oil and lubrication
Spare parts	5,100	NCRWRD estimate divided by 3 to account for low operating hours, "field overhauls" incl.
Skilled Labor	1,000	Estimate based on 3 breakdowns annually
Unskilled Labor	600	Same as above
Transportation	3,600	Estimate based on village survey

Cost item	Cost	Source or Justification
SOLAR		
Capital Costs		
Solar Array	US$8,162	Quote (Siemens) SEP project (US$5.5/$W_p$
Pump/Motor/Controller	US$5,000	Quote (Siemens) SEP project
Other array costs	US$742	Quote (Siemens) SEP project (includes wiring & connections)
Pipes and fittings	30,000	Assume similar costs as diesel
Construction materials	20,000	Assume 1/2 of diesel since no engine frame, foundation or pumphouse
Water storage tank	100,000	Assume that for a small village storage equal to diesel system is adequate
Other Miscellaneous items	20,000	Assume similar to diesel
Skilled Labor	6,000	Assume costs slightly less than diesel due to easy installation
Unskilled Labor	3,000	As above, less concrete required
Transportation	15,000	Assume less than diesel, less to haul
O&M Costs (annually)		
Operator	1,000	One person (assumed guard & operator combined)
Fuel	0	No fuel required
Spare parts	500	Estimate based on experience
Module replacement	—*	Cost based on breakage rate in Sudan, dollar cost, discount rate, and exchange rate
Skilled Labor	300	Estimate based on inspection and occasional maintenence
Unskilled Labor	120	As above
Transportation	900	As above

*Approximately one module replaced every seven years based on experience thus far

Cost item	Cost	Source or Justification
WINDMILL		
Capital Costs		
Windmill	US$2,750	Estimate of current material cost, quantities from CWD
Windmill tower	US$1,100	As above
Pump	US$ 200	As above
Other Offshore costs	US$ 500	Estimate rods, couplings, etc.
Fabrication Labor	6,000	CWD time estimate, current labor rates
Pipes and fittings	30,000	Similar requirements as solar
Construction materials	40,000	Assume 1/2 of diesel since no engine frame, foundation, or pumphouse
Water storage tank	200,000	Twice diesel and solar to allow sufficient storage during calm periods
Skilled Labor	7,000	Same as Diesel
Unskilled Labor	4,000	Same as Diesel
Transportation	20,000	Same as Diesel
O&M Costs (annual)		
Operator	1,000	Similar to solar
Fuel	0	No fuel required
Spare parts	500	Best estimate of a redesigned CWD, given field experience to date
Skilled Labor	500	As above
Unskilled Labor	280	As above
Transportation	2,400	As above, more than solar due to equipment needs, primarily leather replacement

Cost item	Cost	Source or Justification
Small-Scale Irrigation		
DIESEL		
Capital Costs		
Engine	US 600	Equipment survey (including port fees, handling & transport)
Pump	US 100	Same as above
Pipes and fittings	7,300	Small farmer survey
Construction material	0	Included in above
Water storage tank	0	None required
Other local costs	1,000	Estimate - pulleys, belts, frame
Skilled Labor	2,000	Small farmer survey
Unskilled Labor	0	Farmer provides unskilled labor
Transportation	1,500	Small farmer survey
O&M Costs (annually)		
Operator	0	Farmer operates engine
Fuel	—	Calculated based on efficiency and hours of operation, 20% added for oil and lubrication
Spare parts	1,500	Farmer survey
Skilled Labor	400	Estimate based on 4 breakdowns annually
Unskilled Labor	150	Farmer provides labor, occaisional extra labor
Transportation	600	Farmers survey weighted for base case distance
SOLAR		
Capital Costs		
Solar Array	US$8,162	Quote (Siemens) SEP project
Pump	US$5,000	Quote (Siemens) SEP project
Other array costs	US$240	Siemens quote, less array frame (includes wiring & connections)
Pipes and fittings	7,300	Assume similar costs as diesel
Construction materials	1,000	Includes cement for array base and array frame
Water storage tank	0	Assume flow rate is sufficient to irrigate directly
Skilled Labor	2,000	Assume costs the same as diesel, less complex but fewer capable technicians
Unskilled Labor	100	Help with concrete work
Transportation	1,200	Same as diesel

Cost item	Cost	Source or Justification
O&M Costs (annually)		
Operator	0	Farmer operates system
Fuel	0	No fuel required
Spare parts	500	Same as village base case
Module replacement*	—	Cost based on breakage rate in Sudan, US$ cost, discount and exchange rate, taxes and fees
Skilled Labor	100	Estimate based on inspection and occasional maintenence
Unskilled Labor	0	As above
Transportation	300	As above

*One module replaced every seven years

Windmill

Capital Costs

Cost item	Cost	Source or Justification
Windmill	US$2,750	Estimate of current material cost, quantities from CWD
Windmill tower	US$1,100	As above
Pump	US$200	As above
Other Offshore costs	0	Rods and couplings–local purchase, included with pipes and fittings
Fabrication Labor	6,000	CWD time estimate, current labor rates
Pipes and fittings	7,300	Similar requirements as solar and diesel
Construction materials	6,000	Large foundation required
Water storage tank*	75,000	Storage required to ensure flow rates needed for channel irrigation
Skilled Labor	2,500	Estimate based on ERC experience
Unskilled Labor	120	As above
Transportation	2,000	As above, estimate greater than diesel/solar due to materials requirements

O&M Costs

Cost item	Cost	Source or Justification
Operator	0	Farmer operates system
Fuel	0	No fuel required
Spare parts	500	Best estimate of a redesigned CWD given field experience to date
Skilled Labor	200	As above, farmer performs some maintenance
Unskilled Labor	0	As above
Transportation	300	As above

*Brick and masonry tank built on-site at ground level

Appendix I.
Base Case Financial and Economic Analysis

Village Water Supply
Small-scale Irrigation

TECHNICAL AND COST ANALYSIS SPREADSHEET FOR PUMP TESTING AND EVALUATION PROGRAM

Sudan Diesel, Solar, and Wind Pump Comparisons

150	Demand (cubic meters/day)
5	Total Head (meters)

Demand (m^3)*Head (m) Product 750

Diesel Pump ----------------

25	Pumping Rate (m3/hour)
5%	Overall System Efficiency
6.0	Hours per day operation

Solar Pump -----------------

5.9	Solar Radiation (on array tilt, kWh/m2/day)
34%	Subsystem Efficiency (Pump/Motor/Controller)
1453	Array Design Size (Wp)
1484	Actual Array Size (based on voltage req'd)

Wind Pump -----------------

4.1	Average Site Wind Speed (m/s)
5	Rotor Diameter (meters)
12.5%	Overall System Efficiency

PUMP OUTPUT (m3/day)	
150.0	Diesel
153.2	Solar
153.5	Windmill

Small Farm Irrigation

150	Cubic Meters/Day Demand
5	Meters Total Head

	Diesel	Solar	Wind
FINANCIAL UNIT COST (S£/m3, incl. well)			
Unit Cost	0.25	2.03	1.04
Installed Cost	34,845	421,560	224,282
PV of Recur.Costs	20,134	28,397	6,815
Life Cycle Cost	54,978	449,957	231,096
ECONOMIC UNIT COST (S£/m3, incl. well)			
Unit Cost	0.21	1.57	0.85
Installed Cost	27,900	325,516	181,840
PV of Recur.Costs	17,690	21,935	5,425
Life Cycle Cost	45,590	347,451	187,265

MAJOR ASSUMPTIONS

Engine operates 365 days at head and output
20 year term of analysis
No salvage value for any components
Solar array will last 20 years
PV calculated on delivery for each pump
Installed costs include taxes, if any
Water is discounted at the rate given below

0.25	Discount Rate
1	Shadow Price--unskilled labor
1	Shadow Foreign Exchange
30%	Taxes On Equipment
18	Exchange rate (S£ = 1US$)
5.00	Fuel Price (S£/Imperial Gallon)
$5.50	Solar Modules Price ($/Peak Watt)
0	Loan Rate (%)

3	Year Term
30%	Agents markup
2158	Annual Module Replacement Cost (S£)
30%	Down Payment

Secondary Technical Assumptions

10	Life of Engine in years
10	Life of Engine Pump in yrs
10	Life of Solar Pump (only)in yrs
20	Life of Windmill in yrs
5	Life of Windmill Pump in yrs
60	Cell temp. (deg C)
1.03	kg/m3 air density
7	Depth of Well (meters)
250	Well Cost (S£/meter)

LOAN INFORMATION

(financial only)

DIESEL	
0	Loan amount
0%	Loan int. rate
3	Term of loan
SOLAR	
0	Loan amount
0%	Loan int. rate
3	Term of loan
WIND	
0	Loan amount
0%	Loan int. rate
3	Term of loan

Diesel System (Financial)

Capital Costs	(US $)	(S£)
engine	$600	18252
pump	$100	3042
fittings etc	$240	7301
constr materials	$0	0
storage tank	$0	0
local component		0
other local costs		1000
installation		
skilled labor		2000
unskilled labor		0
transport		1500
Total Installed Cost		33095
(not incl. loan, if any)		

Recurrent Costs	(S£)
Annual	
operator(s)	0
fuel	1864
parts/materials	1500
skilled labor	400
unskilled labor	150
transportation	600
SUM=	4514
Non-annual	
replace engine	18252
replace pump	3042

Diesel System (Economic)

Capital Costs	(S£)
engine	14040
pump	2340
pipes and fittings	5616
constr. materials	0
storage tank	0
local component	0
other local costs	1000
installation	
sk. labor	2000
unsk. labor	0
transport	1154
Total Installed Cost	26150

Recurrent Costs	(S£)
Annual	
operator(s)	0
fuel	1864
parts/materials	1154
skilled labor	400
unskilled labor	150
transportation	462
SUM=	4029
Non-annual	
engine replacement	14040
pump replacement	2340

TECHNICAL AND COST ANALYSIS SPREADSHEET FOR PUMP TESTING AND EVALUATION PROGRAM

Small Farm Irrigation

Solar System (Financial)

Capital Costs		(S£)	Recurrent Costs	(S£)
solar array	$8,162	248288	Annual	
pump	$5,000	152100	operator	0
other array costs	$240	7301	fuel	0
fittings etc		7300	parts/materials	500
constr. materials	$50	1521	module repl.(l.cost)	2158
local component			skilled labor	100
storage tank	$0	0	unskilled labor	0
local component		0	transportation	300
installation			SUM=	3058
skilled labor		2000		
unskilled labor		100		
transport		1200	Non-annual	
Total Installed Cost		419810	replace pump only	152100
(not incl. loan, if any)			(not array)	

Solar System (Economic)

Capital Costs	(S£)	Recurrent Costs	(S£)
solar array	190991	Annual	
pump	117000	operator	0
other array costs	5616	fuel	0
pipes and fittings	5615	parts/materials	385
constr. materials	1521	module replacement	1660
local component	0	skilled labor	100
storage tank	0	unskilled labor	0
local component	0	transportation	231
installation		SUM=	2375
sk. labor	2000		
unsk. labor	100		
transport	923	Non-annual	
Total Installed Cost	323766	pump replacement	117000

Wind System (Financial)

Capital Costs		(S£)	Recurrent Costs	(S£)
windmill	$2,750	83655	Annual	
tower	$1,100	33462	operator	0
pump	$200	6084	fuel	0
other offshore		0	parts/materials	500
fabrication labor		6000	skilled labor	200
fittings etc	$230	6997	unskilled labor	0
constr. materials	$200	6084	transportation	300
local component		0	SUM=	1000
storage tank	$1,500	45630		
local component		30000		
installation				
skilled labor		2500		
unskilled labor		120		
transport		2000	Non-annual	
Total Installed Cost		222532	replace windmill	88455
(not incl. loan, if any)			replace pump	6084

Wind System (Economic)

Capital Costs	(S£)	Recurrent Costs	(S£)
windmill	64350	Annual	
tower	25740	operator	0
pump	4680	fuel	0
other offshore	0	parts/materials	385
fabrication labor	6000	skilled labor	200
fittings etc	5382	unskilled labor	0
constr. materials	4680	transportation	231
local component	0	SUM=	815
storage tank	35100		
local component	30000		
installation			
sk. labor	2500		
unsk. labor	120		
transport	1538	Non-annual	
Total Installed Cost	180090	mill replacement	68042
		pump replacement	4680

DIESEL - SMALL FARM IRRIGATION

Diesel Financial Analysis

Recurrent Costs		year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10	year 11	year 12	year 13	year 14	year 15	year 16	year 17	year 18	year 19	year 20
fuel	1864	1864	1864	1864	1864	1864	1864	1864	1864	1864	1864	1864	1864	1864	1864	1864	1864	1864	1864	1864	1864
operator(s)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
parts/materials	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500
engine replacement	18252	0	0	0	0	0	0	0	0	0	18252	0	0	0	0	0	0	0	0	0	0
pump replacement	3042	0	0	0	0	0	0	0	0	0	3042	0	0	0	0	0	0	0	0	0	0
skilled labor	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400
unskilled labor	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150
transportation	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600
loan repayment	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SUM		4514	4514	4514	4514	4514	4514	4514	4514	4514	25808	4514	4514	4514	4514	4514	4514	4514	4514	4514	4514
	parts	1500	1500	1500	1500	1500	1500	1500	1500	1500	22794	1500	1500	1500	1500	1500	1500	1500	1500	1500	1500
	labor	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550	550

Economic Analysis

Recurrent Costs		year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10	year 11	year 12	year 13	year 14	year 15	year 16	year 17	year 18	year 19	year 20
fuel	1864	1864	1864	1864	1864	1864	1864	1864	1864	1864	1864	1864	1864	1864	1864	1864	1864	1864	1864	1864	1864
operator(s)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
parts/material	1154	1154	1154	1154	1154	1154	1154	1154	1154	1154	1154	1154	1154	1154	1154	1154	1154	1154	1154	1154	1154
engine replacement	14040	0	0	0	0	0	0	0	0	0	14040	0	0	0	0	0	0	0	0	0	0
pump replacement	2340	0	0	0	0	0	0	0	0	0	2340	0	0	0	0	0	0	0	0	0	0
skilled labor	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400
unskilled labor	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150	150
transportation	462	462	462	462	462	462	462	462	462	462	462	462	462	462	462	462	462	462	462	462	462
SUM		4029	4029	4029	4029	4029	4029	4029	4029	4029	20409	4029	4029	4029	4029	4029	4029	4029	4029	4029	4029

* * *

SOLAR - SMALL FARM IRRIGATION

Solar Financial Analysis

Recurrent Costs		year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10	year 11	year 12	year 13	year 14	year 15	year 16	year 17	year 18	year 19	year 20
fuel	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
operator(s)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
parts/materials	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500
module replacement	2158	2158	2158	2158	2158	2158	2158	2158	2158	2158	2158	2158	2158	2158	2158	2158	2158	2158	2158	2158	0
pump replacement	152100	0	0	0	0	0	0	0	0	0	152100	0	0	0	0	0	0	0	0	0	0
skilled labor	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
unskilled labor	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transportation	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300
loan repayment	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SUM		3058	3058	3058	3058	3058	3058	3058	3058	3058	155158	3058	3058	3058	3058	3058	3058	3058	3058	3058	900
	parts	2658	2658	2658	2658	2658	2658	2658	2658	2658	154758	2658	2658	2658	2658	2658	2658	2658	2658	2658	500
	labor	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Economic Analysis

Recurrent Costs		year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10	year 11	year 12	year 13	year 14	year 15	year 16	year 17	year 18	year 19	year 20
fuel	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
operator(s)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
parts/material	385	385	385	385	385	385	385	385	385	385	385	385	385	385	385	385	385	385	385	385	385
module replacement	1660	1660	1660	1660	1660	1660	1660	1660	1660	1660	1660	1660	1660	1660	1660	1660	1660	1660	1660	1660	0
pump replacement	117000	0	0	0	0	0	0	0	0	0	117000	0	0	0	0	0	0	0	0	0	0
skilled labor	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
unskilled labor	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transportation	231	231	231	231	231	231	231	231	231	231	231	231	231	231	231	231	231	231	231	231	231
SUM		2375	2375	2375	2375	2375	2375	2375	2375	2375	119375	2375	2375	2375	2375	2375	2375	2375	2375	2375	715

WIND - SMALL FARM IRRIGATION

Wind Financial Analysis

Recurrent Costs		year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10	year 11	year 12	year 13	year 14	year 15	year 16	year 17	year 18	year 19	year 20
fuel	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
operator(s)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
parts/materials	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500
windmill replacement	88455	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
pump replacement	6084	0	0	0	0	6084	0	0	0	0	6084	0	0	0	0	6084	0	0	0	0	0
skilled labor	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
unskilled labor	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transportation	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300
loan repayment	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SUM		1000	1000	1000	1000	7084	1000	1000	1000	1000	7084	1000	1000	1000	1000	7084	1000	1000	1000	1000	1000
	parts	500	500	500	500	6584	500	500	500	500	6584	500	500	500	500	6584	500	500	500	500	500
Economic Analysis	labor	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200

Recurrent Costs		year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10	year 11	year 12	year 13	year 14	year 15	year 16	year 17	year 18	year 19	year 20
fuel	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
operator(s)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
parts/material	385	385	385	385	385	385	385	385	385	385	385	385	385	385	385	385	385	385	385	385	385
windmill replacement	68042	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
pump replacement	4680	0	0	0	0	4680	0	0	0	0	4680	0	0	0	0	4680	0	0	0	0	0
skilled labor	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
unskilled labor	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
transportation	231	231	231	231	231	231	231	231	231	231	231	231	231	231	231	231	231	231	231	231	231
SUM		815	815	815	815	5495	815	815	815	815	5495	815	815	815	815	5495	815	815	815	815	815

YEAR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Diesels	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	2
Eng.repl.	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
Diesels	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	2
Pump repl	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Solar	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	2
Pump repl	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Windmill	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Mill rep	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Windmill	0	0	0	0	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3	4
Pump rep	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0

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Sudan - Diesel, Solar, Wind                                        Rural Village Water Supply
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     22  Cubic Meters/day water delivery                              *     22  Cubic Meters/Day Demand                    *
     35  meters total delivery head          770  demand (m3)*head(m) *     35  Meters Total Head                          *
Diesel Pump                                                           *  Type of System·      DIESEL    SOLAR     WIND    *
     10  Pumping rate (M3/Hr)                                         *                       ======    =====     ====    *
    15%  Overall efficiency                                           *  FINANCIAL UNIT COST (incl. well)                 *
              2.2  Hrs per day operation                              *   per m3                10.1      10.1      10.4   *
Solar Pump                                                            *   per jerrican          0.18      0.18      0.19   *
    5 9  kW/m2/day solar radiation on array tilt                      *                                                   *
   0.34  Daily subsystem efficiency (pump/motor/controller)           *   Installed Cost     403,757   474,158   490,269   *
  Wp =       1492  Design                                             *   PV of Recur.Cost   102,652    30,165    31,410   *
   1484  = Wp Actual                                                  *   Life Cycle Cost    506,409   504,323   521,679   *
Wind Pump                            m3/day OUTPUT                    *  ======= =======  ======= =======  =======         *
    4.1  m/s Average wind speed             22.0  Diesel              *  ECONOMIC UNIT COST (incl. well)                  *
      5  Rotor diameter in meters           21.9  Solar               *   per m3                13.9      14.1      14.2   *
  12 5%  Overall efficiency                 21.9  Windmill            *                                                   *
         (average daily)                                              *   Installed Cost     552,792   664,393   669,560   *
                                                                      *   PV of Recur.Cost   145,706    41,179    41,544   *
                                                                      *   Life Cycle Cost    698,498   705,572   711,104   *
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Assumptions                                              Secondary Technical Assumptions         LOAN INFORMATION
 Engine operates 365 days at head and output               10  Life of Engine in years           (financial only)
 20 year term of analysis                                  10  Life of Engine Pump in yrs         DIESEL
 No salvage value for any components                       10  Life of Solar Pump (only)in yrs         0  Loan amount
 Solar array will last 20 years                            20  Life of Windmill in yrs                0%  Loan int. rate
 PV calculated on delivery for each pump                    5  Life of Windmill Pump in yrs            3  Term of loan
 Installed costs should include taxes, if any              60  Cell temp. (deg C)                 SOLAR
 Water is discounted at the rate given below             1.03  kg/m3 air density                       0  Loan amount
                                                           44  Depth of Well (meters)                 0%  Loan int. rate
   0.15  Discount Rate                                   2500  Borehole Cost in S£/m                   3  Term of loan

      1  Shadow Price--unskilled labor                    50%  of well cost is imported material  WIND

    1.5  Shadow Foreign Exchange Rate                                                                  0  Loan amount
     0%  Taxes On Equipment                 30%  agents fee (incl. handling and ship)                 0%  Loan int. rate
   12.2  Exchange rate (SL = 1USD)                                                                     3  Term of loan
  15 00  SL fuel cost/Imp gallon          3,422  Module Cost (51 Wp)
  $5.50  per Peak Watt for solar modules    823  annual rpl cost
      0  Loan Inters.Rate        3 Year Term    30%  Down Payment
======= ======= ======= ======= ======= ======= == ======= ======= = ======= ======= ======= ======= ======= =======
Diesel System  (Financial) - incl. agent fees, no tax            *  Diesel System  (Economic) - incl. shadow prices, removes tax
  Capital Costs       (US $)    (S£)    Recurrent Costs    (S£)  *   Capital Costs                     Recurrent Costs
------- ------- ------- ------- ------- ------- ------- ------- ------- ------- ------- ------- ------- ------- ------- -- -
engine               $2,200           | Annual                   *  engine          USD    $3,300  |  Annual
pump                 $3,000           | operator(s)        2000  *  pump            USD    $4,500  | operator(s)            2000
other offshore         $500           | fuel/lubricants    1914  *  other offshore ore USD   $750  | fuel                   2870
ittings etc          $2,200   34892   | parts/materials    5100  *  pipes and fittings      52338  | parts/materials        7650
const  materials     $1,250   19825   | skilled labor      1000  *  constr. materials       29738  | skilled labor          1000
 local component              20000   | unskilled labor     600  *   local component        20000  | unskilled labor         600
storage tank         $5,000   79300   | transportation     3600  *  storage tank           118950  | transportation         5400
 local component              20000   |          SUM      14214  *   local component        20000  |
other                $1,250   19825   |                          *  other                   29738  |
installation                          |                          *  installation                   |
        skilled labor          7000   |                          *          sk. labor        7000  |
        unskilled labor        4000   | Non-annual               *          unsk. labor      4000  |  Non-annual
        transport             20000   | replace engine    26840  *          transport       30000  | engine replacement    40260
Tot Inst.Cost (w/o well)     294382   | replace pump      36600  *  Total Installed Cost   416073  | pump replacement      54900
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Rural Village Water Supply

Solar System (Financial)

Capital Costs	(US $)	(S£)	Recurrent Costs	(S£)
solar array	$8,162		Annual	
pump	$5,000		operator	1000
other offshore	$742		fuel	0
fittings etc	$1,900	30134	parts/materials	500
const materials	$750	11895	module repl.(l.cost)	823
local component		10000	skilled labor	300
storage tank	$5,000	79300	unskilled labor	120
local component		20000	transportation	900
other	$1,250	19825	SUM	3643
installation				
skilled labor		6000		
unskilled labor		3000	Non-annual	
transport		15000	replace pump only	30000
Tot.Inst.Cost (w/o well)		364783	(not array)	

Solar System (Economic)

Capital Costs			Recurrent Costs	(S£)
solar array	USD	$12,243	Annual	
pump	USD	$7,500	operator	1000
other offshore ore	USD	$1,113	fuel	0
pipes and fittings		45201	parts/materials	750
constr. materials		17843	module replacement	1234
local component		10000	skilled labor	300
storage tank		118950	unskilled labor	180
local component		20000	transportation	1350
other		29738	SUM	4814
installation				
sk. labor		6000		
unsk. labor		3000	Non-annual	
transport		22500	pump replacement	45000
Total Installed Cost		527674		

Wind System (Financial)

Capital Costs	(US $)	(S£)	Recurrent Costs	(S£)
windmill	$2,750		Annual	
tower	$1,100		operator	1000
pump	$200		fuel	0
other offshore	$500		parts/materials	500
fabrication labor		6000	skilled labor	500
fittings etc	$1,900	30134	unskilled labor	280
const. materials	$1,250	19825	transportation	2400
local component		20000	SUM	4680
storage tank	$10,000	158600		
local component		40000		
other	$1,250	19825		
installation				
skilled labor		7000		
unskilled labor		4000	Non-annual	
transport		20000	replace windmill	33550
Tot Inst.Cost (w/o well)		380894	replace pump	2440

Wind System (Economic)

Capital Costs			Recurrent Costs	(S£)
windmill	USD	4125	Annual	
tower	USD	1650	operator	1000
pump	USD	300	fuel	0
other offshore ore	USD	750	parts/materials	750
fabrication labor		6000	skilled labor	500
fittings etc		45201	unskilled labor	280
const. materials		29738	transportation	3600
local component		20000	SUM	6130
storage tank		237900		
local component		40000		
other		29738		
installation				
sk. labor		7000		
unsk. labor		4000	Non-annual	
transport		30000	mill replacement	50325
Total Installed Cost		532841	pump replacement	3660

DIESEL - Village Water Supply

Diesel Financial Analysis

Recurrent Costs		year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10	year 11	year 12	year 13	year 14	year 15	year 16	year 17	year 18	year 19	year 20
fuel	1,595	1,595	1,595	1,595	1,595	1,595	1,595	1,595	1,595	1,595	1,595	1,595	1,595	1,595	1,595	1,595	1,595	1,595	1,595	1,595	1,595
operator(s)	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000
parts/materials	5,100	5,100	5,100	5,100	5,100	5,100	5,100	5,100	5,100	5,100	5,100	5,100	5,100	5,100	5,100	5,100	5,100	5,100	5,100	5,100	5,100
engine replace	26,840	0	0	0	0	0	0	0	0	0	26,840	0	0	0	0	0	0	0	0	0	0
pump replacement	36,600	0	0	0	0	0	0	0	0	0	36,600	0	0	0	0	0	0	0	0	0	0
skilled labor	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
unskilled labor	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600
transportation	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600
loan repayment	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SUM		13,895	13,895	13,895	13,895	13,895	13,895	13,895	13,895	13,895	77,335	13,895	13,895	13,895	13,895	13,895	13,895	13,895	13,895	13,895	13,895
		5,100	5,100	5,100	5,100	5,100	5,100	5,100	5,100	5,100	68,540	5,100	5,100	5,100	5,100	5,100	5,100	5,100	5,100	5,100	5,100
		3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600

Economic Analysis

DIESEL

Recurrent Costs		year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10	year 11	year 12	year 13	year 14	year 15	year 16	year 17	year 18	year 19	year 20
fuel	2,870	2,870	2,870	2,870	2,870	2,870	2,870	2,870	2,870	2,870	2,870	2,870	2,870	2,870	2,870	2,870	2,870	2,870	2,870	2,870	2,870
operator(s)	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000
parts/material	7,650	7,650	7,650	7,650	7,650	7,650	7,650	7,650	7,650	7,650	7,650	7,650	7,650	7,650	7,650	7,650	7,650	7,650	7,650	7,650	7,650
engine replace	40,260	0	0	0	0	0	0	0	0	0	40,260	0	0	0	0	0	0	0	0	0	0
pump replacement	54,900	0	0	0	0	0	0	0	0	0	54,900	0	0	0	0	0	0	0	0	0	0
skilled labor	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
unskilled labor	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600	600
transportation	5,400	5,400	5,400	5,400	5,400	5,400	5,400	5,400	5,400	5,400	5,400	5,400	5,400	5,400	5,400	5,400	5,400	5,400	5,400	5,400	5,400
SUM		19,520	19,520	19,520	19,520	19,520	19,520	19,520	19,520	19,520	114,680	19,520	19,520	19,520	19,520	19,520	19,520	19,520	19,520	19,520	19,520
	parts	7,650	7,650	7,650	7,650	7,650	7,650	7,650	7,650	7,650	102,810	7,650	7,650	7,650	7,650	7,650	7,650	7,650	7,650	7,650	7,650
	labor	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600

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SOLAR - Village Water Supply

Solar Financial Analysis

Recurrent Costs		year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10	year 11	year 12	year 13	year 14	year 15	year 16	year 17	year 18	year 19	year 20
fuel	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
operator(s)	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
parts/materials	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500
module replace	823	823	823	823	823	823	823	823	823	823	823	823	823	823	823	823	823	823	823	823	0
pump replacement	30,000	0	0	0	0	0	0	0	0	0	30,000	0	0	0	0	0	0	0	0	0	0
skilled labor	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300
unskilled labor	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120	120
transportation	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900
loan repayment	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SUM		3,643	3,643	3,643	3,643	3,643	3,643	3,643	3,643	3,643	33,643	3,643	3,643	3,643	3,643	3,643	3,643	3,643	3,643	3,643	2,820
	parts	1,323	1,323	1,323	1,323	1,323	1,323	1,323	1,323	1,323	31,323	1,323	1,323	1,323	1,323	1,323	1,323	1,323	1,323	1,323	500
	labor	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420

Economic Analysis

SOLAR

Recurrent Costs		year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10	year 11	year 12	year 13	year 14	year 15	year 16	year 17	year 18	year 19	year 20
fuel	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
operator(s)	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
parts/material	750	750	750	750	750	750	750	750	750	750	750	750	750	750	750	750	750	750	750	750	750
module replace	1,234	1,234	1,234	1,234	1,234	1,234	1,234	1,234	1,234	1,234	1,234	1,234	1,234	1,234	1,234	1,234	1,234	1,234	1,234	1,234	0
pump replacement	45,000	0	0	0	0	0	0	0	0	0	45,000	0	0	0	0	0	0	0	0	0	0
skilled labor	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300
unskilled labor	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180
transportation	1,350	1,350	1,350	1,350	1,350	1,350	1,350	1,350	1,350	1,350	1,350	1,350	1,350	1,350	1,350	1,350	1,350	1,350	1,350	1,350	1,350
SUM		4,814	4,814	4,814	4,814	4,814	4,814	4,814	4,814	4,814	49,814	4,814	4,814	4,814	4,814	4,814	4,814	4,814	4,814	4,814	3,580
	parts	1,984	1,984	1,984	1,984	1,984	1,984	1,984	1,984	1,984	46,984	1,984	1,984	1,984	1,984	1,984	1,984	1,984	1,984	1,984	750
	labor	1,480	1,480	1,480	1,480	1,480	1,480	1,480	1,480	1,480	1,480	1,480	1,480	1,480	1,480	1,480	1,480	1,480	1,480	1,480	1,480

WIND - Village Water Supply

Wind Financial Analysis

Recurrent Costs		year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10	year 11	year 12	year 13	year 14	year 15	year 16	year 17	year 18	year 19	year 20
fuel	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
operator(s)	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
parts/materials	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500
windmill replace	33,550	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
pump replacement	2,440	0	0	0	0	2,440	0	0	0	0	2,440	0	0	0	0	2,440	0	0	0	0	0
skilled labor	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500
unskilled labor	280	280	280	280	280	280	280	280	280	280	280	280	280	280	280	280	280	280	280	280	280
transportation	2,400	2,400	2,400	2,400	2,400	2,400	2,400	2,400	2,400	2,400	2,400	2,400	2,400	2,400	2,400	2,400	2,400	2,400	2,400	2,400	2,400
loan repayment	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SUM		4,680	4,680	4,680	4,680	7,120	4,680	4,680	4,680	4,680	7,120	4,680	4,680	4,680	4,680	7,120	4,680	4,680	4,680	4,680	4,680
		500	500	500	500	2,940	500	500	500	500	2,940	500	500	500	500	2,940	500	500	500	500	500
Economic Analysis		1,780	1,780	1,780	1,780	1,780	1,780	1,780	1,780	1,780	1,780	1,780	1,780	1,780	1,780	1,780	1,780	1,780	1,780	1,780	1,780

WIND

Recurrent Costs		year 1	year 2	year 3	year 4	year 5	year 6	year 7	year 8	year 9	year 10	year 11	year 12	year 13	year 14	year 15	year 16	year 17	year 18	year 19	year 20
fuel	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
operator(s)	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
parts/material	750	750	750	750	750	750	750	750	750	750	750	750	750	750	750	750	750	750	750	750	750
windmill replace	50,325	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
pump replacement	3,660	0	0	0	0	3,660	0	0	0	0	3,660	0	0	0	0	3,660	0	0	0	0	0
skilled labor	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500	500
unskilled labor	280	280	280	280	280	280	280	280	280	280	280	280	280	280	280	280	280	280	280	280	280
transportation	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600	3,600
SUM		6,130	6,130	6,130	6,130	9,790	6,130	6,130	6,130	6,130	9,790	6,130	6,130	6,130	6,130	9,790	6,130	6,130	6,130	6,130	6,130
	parts	750	750	750	750	4410	750	750	750	750	4410	750	750	750	750	4410	750	750	750	750	750
	labor	1780	1780	1780	1780	1780	1780	1780	1780	1780	1780	1780	1780	1780	1780	1780	1780	1780	1780	1780	1780

YEAR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Diesels	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	2
Eng repl.	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
Diesels	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	2
Pump repl	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Solar	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	2
Pump repl	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Windmill	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Mill rep	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Windmill	0	0	0	0	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3	4
Pump rep	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0

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