ia S. Veenstra.

UNDP Project GLO/80/003

Executed by
The World Bank

SMALL-SCALE SOLAR-POWERED PUMPING SYSTEMS: THE TECHNOLOGY, ITS ECONOMICS AND ADVANCEMENT

MAIN REPORT

Sir William Halcrow and Partners
in association with
Intermediate Technology Power Ltd.

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London, Swindon, and Reading, UK.

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PROJECT DOCUMENTATION

Main Report

The Main Report describes the work which the Consultants undertook for the World Bank in the period April 1981 to March 1983 as part of UNDP Project GLO/80/003 to test and demonstrate renewable energy technologies, in particular small-scale solar-powered pumping systems.

As will be evident from the Contents list, the Report is written in four main parts as follows:

Part A :	Scope and Purpose of Project
Part B .	The Technology
Part C :	Economic Evaluation of Solar Water Pumping
Part D :	Advancement of Application

A summary of each part of the Report is given in Section 3.2 to assist the reader identify sections of particular interest.

Consistent with its limited compass, this Main Report explains the origin of the Project, what was done, the assumptions and input data, the principal results and the conclusions from each of the activities.

Support Record Documents

For management purposes the Project was divided into eight activities each of which generated considerable written material. The Report cannot include all the detail which those with a specialised interest in particular aspects of the work might find useful and so the Consultants have prepared supporting record documentation on the main activities as follows:

1 Performance Tests on Improved PV Pumping Systems
2 Economic Evaluation of Solar Water Pumps
3 Potential for Improvement of PV Pumping Systems
4 Review of Solar Thermodynamic Pumping Systems
5 Manufacture of Solar Water Pumps in the Less Developed Countries
6 Potential for Field Programmes in Selected Countries
7 Proposal for Phase II
8 Program Users' Guides

This material is prepared in annotated report form and is available for reference by those with specialist interest from either the World Bank or the Consultants. In the text these documents are referred to as *Supporting Documents. A brief description of the scope of each Supporting Document is given in Appendix 5.

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Costs

All costs in this Report are expressed in US dollars at the levels current in mid-1982. Future costs are also based on this datum, although money values in future years will of course be different, depending on the general level of inflation.

Conversion Factors

It may be useful to have the following conversion factors for reference when reading the Report:

Area 1 ha = 2.471 acres

Energy 1J = 9.485 x 10^{-4} BTU
1kWh = 3.6 MJ
= 8.60 x 10^2 kcal
= 3.4 x 10^3 BTU

Flowrate 1 l/s = 13.20 Imp. gallon per minute
1 l/s = 15.85 US gallon per minute
0.35 l/s for 8 hours yields 10m^3

Irradiance 1 W/m^2 = 0.317 BTU/ft^2 hr (= 0.00143 cal/cm^2)
= 0.086 Langleys/hr

Irradiation 1 MJ/m^2 = 88.1 BTU/ft^2 (= 23.88 cal/cm^2)
1 kWh/m^2 = 3.6 MJ/m^2
= 317 BTU/ft^2
= 86.0 Langleys

Standard Solar day of 5kWh/m^2
Peak irradiance (Horiz) = 708 W/m^2
Average irradiance (Horiz) = 456 W/m^2

Power 1 watt = 3.41 BTU/hr
= 1.34 x 10^{-3}hp

Rainfall 1mm depth = 10m^3/hectare

Notation

Symbols are defined in the text when first used. For convenience a complete list of symbols is given below.

Symbol	Description	S.I. Unit
a,b,c	constants	-
B	motor brush loss	volts
C	total capital cost	\$
C_f	operating costs	\$ p.a.(or 1000 hr)
C_o	fixed cost	\$
C_d C_1	size related cost	\$
g	gravitational acceleration day	9.81 m s^{-2}
G	solar irradiance	W m^{-2}
H	static head	m
i	real discount rate	%
i_c	capital cost differential inflation rate	%
i_f	fuel cost differential inflation rate	%
i_m	maintenance cost differential inflation rate	%
I	array or motor current	amps
I_{sc}	short circuit array current	amps
L_c	local cost factor for operating costs	-
L_{c_o}	local cost factor for fixed capital cost	-
L_{c_1}	local cost factor for size related capital cost	-
L_m	local cost factor for maintenance cost	-
M	maintenance cost	\$ p.a (or 1000 hr)
n	period of analysis	years
N	motor speed	Hz or rpm
NOCT	nominal operating cell temperature	^oC
P	hydraulic power	watts
Q	flow rate	l/s
S	Size (e.g. power, area) of component	as appropriate
SCC	specific capital cost	\$/kJ.d.
T	motor torque	Nm
T_a	ambient air temperature	^oC
T_c	cell temperature	^oC
V	array or motor voltage	volts
V_{oc}	array open circuit voltage	volts
$\mathcal{V}$	volume of water pumped	m^3
W_p	array peak power output	watts
ρ	density of water	kg m^{-3}
1234	suffixes	-

SUMMARY

SUMMARY

1. SCOPE AND PURPOSE OF PROJECT

1.1 Introduction

One of the primary energy requirements throughout the developing world results from the need for power for pumping water, both for irrigation and, even more universally, for human and live-stock water supplies. Of the alternative decentralised energy resources available and suitable for use in the rural areas of developing countries, direct solar energy is of particular interest for pumping water. The pumping needs of the majority of countries which lie in the sunny tropics or subtropics usually match the availability of solar energy closely, and this resource, although diffuse, is widely available, can be tapped near the point of application and is reasonably predictable. The technology has been steadily advancing in recent years in response to a general recognition that, potentially, solar irradiation is a technically appropriate and economically viable source of energy for small water pumps and is now at the point where it should be considered seriously as a possible component of rural development schemes.

Within the context of the Project, the term "small-scale" refers to pumping systems designed either to supply typically $60m^3$ of water per day through static heads of 2m to 10m suitable to meet the irrigation water requirements of the many land holdings in the developing countries with areas up to 2 hectares, or to supply typically $20m^3$ per day through static heads of 10m to 30m suitable for meeting the water supply needs of the many small villages having populations of up to 1500 people. The hydraulic power output requirement of the systems considered lies in the range 100W to 800W. Although it is technically feasible to produce larger power outputs, an approach which concentrates on pumping systems suitable for the irrigation needs of small farms and the water supply needs of small villages has a number of real advantages. Not only is the solar pumping system at its most cost-effective in these circumstances, but the costs of the individual pumping units are lower and hence more affordable, responsibility for the efficient use of the pump and water is placed squarely on the farmer or villagers, and distribution and management of the use of water is greatly simplified. Further, a technology intended for these situations helps to focus attention on the rural poor in the developing world, a group whose lack of well-being and prosperity are major factors hindering the proper economic development of these countries. Major improvements to health, output and economic position can be brought about by increasing the productivity of agricultural land and by providing a reliable, safe and conveniently sited water supply.

1.2 UNDP/World Bank Projects

Phase I of the Project which was financed by UNDP as Project GLO/78/004 was undertaken for the World Bank by Sir William Halcrow & Partners acting in association with the Intermediate Technology Development Group Ltd. in the period July 1979 to around July 1981. Its overall objective was to advise the UNDP and World Bank on whether solar pumping technology was in such a position that it would be worth promoting its development to make it appropriate for pumping water under the conditions that prevail on small farms in the developing world and, if so, what steps should be taken.

The overall conclusion to emerge from Phase I was that there was potential in the technology, but that further technical development was required to make the systems more robust, reliable and efficient (and hence more cost-effective) and that, with anticipated reductions in the real costs of the systems, there was a definite prospect that they could be used economically within a few years for irrigating areas of around 0.5 to 1.0 hectares pumping through heads of less than about 5m.

Preliminary views on a possible Phase II Project were discussed with the UNDP and World Bank towards the end of Phase I and it was agreed that certain preparatory work should be undertaken for Phase II in the period between April 1981 and January 1983 as UNDP Project GLO/80/003. This work constituted 'Phase II Preparation', the results and conclusions of which form the basis of this Report. There was naturally some overlap between the ending of Phase I and the starting of Phase II Preparation.

The World Bank placed a contract for these preparatory studies with Sir William Halcrow & Partners now acting in association with Intermediate Technology Power Ltd., an associated company within the Intermediate Technology Development Group.

1.3 Objectives of Phase II Preparation

It was agreed with the UNDP and World Bank that, working from the position reached on Phase I, the overall objectives of Phase II Preparation should be to investigate and advise on the following aspects:

- the technical and economic factors which need to be satisfied if solar pumps are to be used effectively for agricultural and water supply purposes in developing countries;
- the types of pumping system which will best satisfy these technical and economic requirements, and the possibility of procuring photovoltaic (PV) pumping systems which meet performance specifications of the type proposed in Phase I;
- the way in which local assembly and/or manufacture might be encouraged;
- the countries which should be involved in Phase II;
- the purpose of Phase II and the programme to be followed.

These objectives were formulated on the assumption that the ultimate objective of Phase II would be to develop small-scale pumping systems to the stage where they would be suitable for general use and pilot manufacture or assembly in developing countries.

It will be noted that the scope of Phase I was extended from irrigation to include the important water supply application as well.

1.4 Reports

Phase I has been reported extensively, but the two principal documents were the Project Report and the Technical and Economic Review published by the World Bank in July 1981 and September 1981, respectively. The Main Report on Phase II Preparation has been written in four parts as follows:

- Part A - Scope and Purpose of Project
- Part B - The Technology
- Part C - Economic Evaluation of Solar Water Pumping
- Part D - Advancement of Application

The Report thus gives an overview of all the work undertaken in Phase II Preparation, the principal conclusions and recommendations arising from it and an outline of the work proposed for Phase II. Additional detailed data and other material covering the topics listed in Section 1.3 above are given in eight supporting documents lodged with the World Bank for reference purposes (see Appendix 5).

1.5 Principal Findings

The Executive Summary follows the order of the Main Report and the conclusions of each part of the work are given in the appropriate sections. For convenience the main points to emerge are outlined below.

- The pumps recently tested are technically considerably improved over those tested in Phase I and a number of pumping systems are now available that are good enough to warrant field demonstrations to verify performance and cost-effectiveness under typical operating conditions. The best systems tested were found to have daily efficiencies at design head in the range 3.4% to 3.8% compared with around 2.2% in Phase I and these do not alter greatly with variation of static lift from 75% to 150% of the design static head.

- A study of motors and pumps indicated that there was potential for improvement of the peak efficiency of motors to around 85% to 90%, and that pumps could reach around 65% to 70% (depending on the type of pump and operating conditions) to give subsystems with daily efficiencies in excess of 50%, compared with best values of 41% and 46% at present.

- Costs have declined appreciably and will probably continue to do so. At the cost levels which it is predicted will apply by 1987, the Specific Capital Cost* of systems designed to pump through static lifts of 7m and 20m are estimated to be in the band $0.9 to $1.5/kJ.d, compared with around $2.8/kJ.d for well designed systems at prices current in Phase I. As the price of photovoltaic arrays continue to fall and systems become more efficient and manufactured in greater volume, the Specific Capital Costs should fall to around $0.5/kJ.d by 1993.

- A major study of the comparative economics of solar, wind, diesel, kerosene, animal, and human powered pumping systems in the context of their use for small-scale irrigation and village water supply applications was carried out for "international" baseline cost and technical parameters and for conditions representative of Bangladesh, Kenya and Thailand. This identified the circumstances in which solar water pumps would be economically viable.

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* The Specific Capital Cost (SCC) is the capital cost of the system (operating under reference conditions) per unit of hydraulic energy output over a Standard Solar Day of 5 kWh/m^2.

- This study has shown that, even at 'present' photovoltaic array costs, solar pumps can lift water at a cost that is competitive with the primary alternatives. Photovoltaic systems are particularly suited to regions where diesel costs are high and wind speeds low, provided that conditions are suitable with a favourable solar irradiation regime, a steady demand for water all the year round and (for irrigation) low pumping heads (2m for baseline conditions). When costs fall to the levels expected in five years, solar systems will be cheaper than all other alternatives over the head range studied (2m to 20m) except for situations where diesel system costs are very low.

- For water supply applications solar pumps at present costs are comparable with high diesel system costs and within five years are expected to be cheaper than all other systems for heads up to at least 30m. Thus it is anticipated that solar water pumping will in general find economic applications in water supply before irrigation. These general conclusions regarding economics obviously depend on the detailed assumptions made in these studies and should be reviewed when considering specific locations.

- The way in which the technology of solar water pumping could be advanced in the best interests of the end user in developing countries was considered and it was concluded that one more phase involving field demonstration was needed. Progress would be made most satisfactorily if the work was supported by further funds from international sources (eg. UNDP).

- Three levels of field programme were proposed and it is recommended that Bangladesh, Brazil, Egypt, Kenya, Mexico, Pakistan and Thailand should participate in these programmes at levels appropriate to their respective interests, needs and resources. The importance of having the facilities available locally to repair and maintain the systems is stressed. The ways in which local manufacture could be encouraged would be examined in detail.

2. THE TECHNOLOGY

2.1 Testing of Improved Photovoltaic Pumping Systems

2.1.1 Objectives

One of the most important of the Consultants' activities in Phase II Preparation was the procurement and testing of improved commercially available PV pumping systems tendered by manufacturers to meet performance specifications specially prepared by the Consultants to match the requirements of small-scale water supply and irrigation applications in the developing world. The specifications represented improved performance and were developed on the basis of expereince gained in Phase I. The main objectives of the test programme were:

- To evaluate the performance under controlled conditions of solar pumps selected from those which had been tendered to meet the Consultants' specifications.

- To assess the present and potential future cost-effectiveness of quantity produced examples of the present generation of commercially available solar pumps.

The information on pump performance gained from these tests will provide a firm basis for the selection of equipment for the Phase II field demonstration programmes.

2.1.2 Selection of pumping systems for test

It was decided that three broad bands of hydraulic duty should be defined to represent categories of pumping system which were believed to have significant market potential. The following were adopted:

Category A :	to pump $60m^3$/day output through a static design head of 2m, intended mainly for irrigation applications
Category B :	to pump $60m^3$/day output through a static design head of 7m, intended for water supply and/or irrigation applications
Category C :	to pump 20 m^3/day output through a static design head of 20m, intended mainly for water supply applications.

The environmental conditions for which the pumps were to provide these outputs were defined in the detailed performance specifications. One of the most important innovations was the introduction of a 'Standard Solar Day', the profile of which provided a daily irradiation of 5 kWh/m^2 on the horizontal plane. The specification also called for systems to have an efficiency not less than 75% of the daily efficiency at design head when operating under heads of 75% and 150% of the design head, and for them to provide not less than 70% of the daily volume (at an irradiation of $5kWh/m^2$) when operating under an irradiation of 4 kWh/m^2.

These specifications for the three categories of system were incorporated into tender documents sent early in 1982 to 62 suppliers who responded to an international call for tenders. A total of 64 systems were offered in the 26 completed tenders received.

A careful evaluation was made of each system tendered: this was based primarily on its overall compliance with the specification; an assessment of its performance; its design, including any operation and maintenance requirements; its potential for local manufacture; its likely future cost-effectiveness; and its delivery schedule for the testing programme. The experience and resources of the tenderer and the amount of supporting information provided were also taken into account.

The Projected Specific Capital Cost was used as the principal criterion of cost-effectiveness and this was calculated assuming quantity production of the system based upon a PV array price of US$5 per peak watt and the tenderer's estimated price of motors and pumps for orders of 100 units (or more).

It was agreed with the World Bank that two complete systems and two subsystems (system less array) for each category should be procured for testing. Orders were placed with selected suppliers in April 1982 for delivery by the end of August 1982. Details of the equipment supplied for testing including order and delivery dates are shown in Table I.

System			Array				Motor		Pump			
Supplier (Country)	Complete System Tender Price FOB (1982 $)	Claimed Output(1) m^3/day	Manufacturer (Country)	Type	No of Modules in Series (S) and in Parallel(P)	Nominal Power Wp (12)	Manufacturer (Country)	Model or Type and Spec	Manufacture (Country)	Model or Type and Spec	Date System Ordered Day/Mo/Yr	Date System delivered Day/Mo/Year
CATEGORY A												
Monegon (USA)	2860(2)	50	Solarex(2) (USA)	5300 SG	3S x 1P or 1S x 3P	105	Remond (USA)	PMDC(3)Type E25-2A 12V	Everest	helical gear	5 4 82	27 5 82
Solar Electric International (Malta)	6000	140	Solar Power (USA)	LG 12-250(11)	3S x 3P	351	AEG (FR Germany)	PM brushless 360W,2735 RPM	KSB (FR Germany)	Aquasol 100 L floating centrifugal	6 4 82	13 10.82
Solamat (USA)	8965(2)	75	Arco Solar(2) (USA)	ASI 16 2300	3S x 2P	222	Honeywell (USA)	PMDC type BA 3624-3349-56	Berkeley (USA)	B11/2MPKS self priming Surface pump	20 4 82	4 8 82
TPK (Canada)	4680	60	TPK		(5)	210	Boston Gear (Canada)	90U, 194W PMDC	TPK	all plastic PDRD(6)	5 4 82	2.9 82
CATEGORY B												
AEG(7) FR Germany)	10150	62	AEG	PQ 10/20/0(8)	8S x 4P	614	Engel (FR Germany)	GNM 7045 67V PMDC	Loewe (FR Germany)	submerged centrifugal pump on floating unit	6 4 82	13 9 82
Heliodinamica (Brazil)	14360(2)	67	Heliodinamica(2) Brazil	HFP19815	5S x 9P	882	Honeywell (Brazil)	modified type SR5316-2546 PMDC	Jacuzzi (Brazil)	plastic self priming surface mounted	19 4.82	28.9 82
KSB(9) (FR Germany)	8440	60	Arco Solar (USA)	ASI 16-2300	4S x3P	480	AEG (FR Germany)	PM brushless 360W, 3450 RPM	KSB (FR Germany)	Aquasol 50 M Floating centrifugal	5.4 82	16.9.82
Solar Force (France)	22240(2)	62	France Photon(2) (France)	G76	11S x 1P	836	Leroy-Somer (France)	M71 A 150 PMDC	Pompes Guinard (France)	Alta X F6-5-73 submerged centrifugal	5 4 82	10.11 82
CATEGORY C												
Grundfos (Denmark)	13360	20	Arco Solar (USA)	M51(11)	7S x 3P	840	Grundfos	MS 401 3 phase ac motor with inverter	Grundfos	Sp4-8 multistage centrifugal	5.4.82	19 8.82
Wm Lamb (USA)	14470	15	Arco Solar (USA)	ASI 16 2300(11)	5S x 3P	555	Honeywell (USA)	BA 3640-3412-56B 390W PMDC	Baker (USA)	reciprocating borehole	5 4.82	17 7 82
Sofretes (France)	21050(2)	20	Solar Power Corp(2) (USA)	LG 12 351	6S x 5P	990	CEM (France)	PMDC with magnetic coupling	Jelien & Mege (France)	A410Fe5 multistage centrifugal	5 4 82	3.9 82
Trisolar Corp (USA)	25500(2)	23	Solar Power Corp(2)	LG 12 351	9S x 2P	540	Honeywell (USA)	PV 5316-3597 56BC PMDC with MPPT(10)	Baker (USA)	reciprocating borehole	5 4 82	16 9 82

NOTES
(1) See Section 6 for measured performance
(2) Only subsystem ordered so array not tested
(3) PMDC = Permanent Magnet Direct Current
(4) Model 350L
(5) 3S x 2P low mode, 2S x 3P high mode
(6) PDRP = Positive Displacement Reciprocating Pump
(7) Model Swimpump 400
(8) Incorporating polycrystalline silicon cells
(9) Type "Aquasol" 50
(10) MPPT = Maximum Power Point Tracker
(11) Different from equipment tendered
(12) Powers quoted correspond to arrays delivered in case of complete systems or motor/pump suppliers recommendations in case of subsystems

Table I Equipment Selected for Testing

2.1.3 Test Programme and Results

All system and subsystem testing took place in the period September 1982 to January 1983 under controlled conditions at a facility which was purpose designed and built by the Consultants at the offices of Sir William Halcrow & Partners near Swindon, UK.

To obtain consistent and comparable results, each of the twelve subsystems was tested using a photovoltaic array output simulator which had been especially developed in collaboration with the Imperial College of Science and Technology, University of London. The simulator provides the current-voltage output (I-V characteristic) which would be produced by a given array under specified irradiance and ambient temperature conditions. Using the simulator, the daily pumped volume and overall efficiency of each system were measured under the conditions of static head and solar input specified.

Each of the complete systems was also tested in sunshine and the results used to validate those obtained from the simulator tests. In addition performance tests were carried out on the electric motors at Imperial College to evaluate the motor efficiency and hence to assess pump efficiency.

A detailed test report was completed for each of the systems and subsystems. The report included details of the results of the simulator tests, sunshine and motor tests where applicable, the performance specifications which were met (or not), and comments on the design features including ease of installation and operation, durability and reliability, maintenance requirements and suitability for local manufacture. The Projected SCC calculated during the tender assessment was updated taking into account the performance actually achieved by the system.

A summary of the main test results is presented in Table II and Fig. I and they are briefly discussed below. The validity of the results and conclusions is limited to the range of conditions under which the tests were carried out.

2.1.4 Conclusions

General

It is apparent that most system designers found meeting the various performance specifications quite challenging. The systems which passed and failed these requirements are indicated in Table III.

It is clear that, in general, the low head Category A systems are the most difficult to design to meet the three performance specifications and the Category C are the easiest. This is not surprising because the peak efficiencies are the most difficult to match within the small operational head range of Category A and the losses are proportionately higher.

Cat.	System Supplier	Project (5) Capital Cost $	Vol (2) del at design hd m³	Daily Efficiency (DE)% (1) at			Max Subsystem Effic at Design Hd m³	Projected Specific Capital Cost $/kld	Results @ 4 kWh/m²/d at Design Hd		Remarks
				low hd (3) (75% DH)	Design hd (DH)	high head(3) (150% DH)			Daily Efficiency (DE)	Vol (4) Del m³	
A	Monegon	2124					-		-	-	Failed to work needs further development.
	SEI	4415	90	2.5	2.3	0.6*	33	2.5	1.8	63	Good system concept but could have lower SCC with better matching. System best at 3.5m head
	Solamat	2150	48*	2.0	1.9	2.0	34	2.3	1.4	30*	Performance not as good as expected. Flap valve in self priming tank could be unreliable and causes energy losses.
	TPK	2231	16*	0.5	0.6	0.7	12	7.1	0.5	13	Interesting system but performance poor due to many losses. PV array deteriorated rapidly. Good scope for for local manufacture.
B	AEG	4614	73		2.8	1.9	57	0.9	2.5	55	Good concept and very efficient subsystem but several minor features need to be modified to improve reliability. Very low SCC. Performance generally met or exceeded specification.
	Heliodinamica	5276	62	1.3	1.5	1.4	33	1.2	1.3	44	Good surface mounted pumpset with self priming tank. Needs more efficient pump & motor to bring SCC down to $1.0 kl/day
	KSB	4822	48*	3.5	3.4	2.0*	53	1.5	2.2	27*	Very efficient subsystem but output below specification. More suited to 5m head than 7m. Good system concept
	Solarforce	9544	64	2.0	2.2	2.0	30	2.2	1.8	44*	Good system for permanent installation in borehole. Pump efficiency poor. Robust design, but complicated to install.
C	Grundfos	7812	33	3.4	3.8	3.3	44	1.2	3.2	24	Very good concept, easy to install and operate. Performance met or exceeded specification in all respects. Very good daily efficiency. Low SCC
	Wm Lamb	4445	16(6)	2.6	2.5	2.3	41	1.5	1.6	8*	Good system provided head remains constant and daily insolation is >5kWh/m² since high threshold irradiance
	Solartec	11239	23	1.6	1.8	1.6	30	2.4	1.3	15*	Good concept and performance met specification, but efficiency poor, hence high SCC
	Trisolar Corp	10770	19*	2.1	2.3	2.5	38	2.9	1.9	13	Performance just below specification. MPC ensures low threshold to start. Unsuitable for situations where head changes over day. Fine filter cannot be back-flushed if it becomes blocked.

NOTES

(1) Based on gross array area

(2) Spec required 60m³ for A & B and 20 m³ for C for 5kWh/m² day

(3) Spec. required DE at end of head ranges to be ≮75% of DE at DH

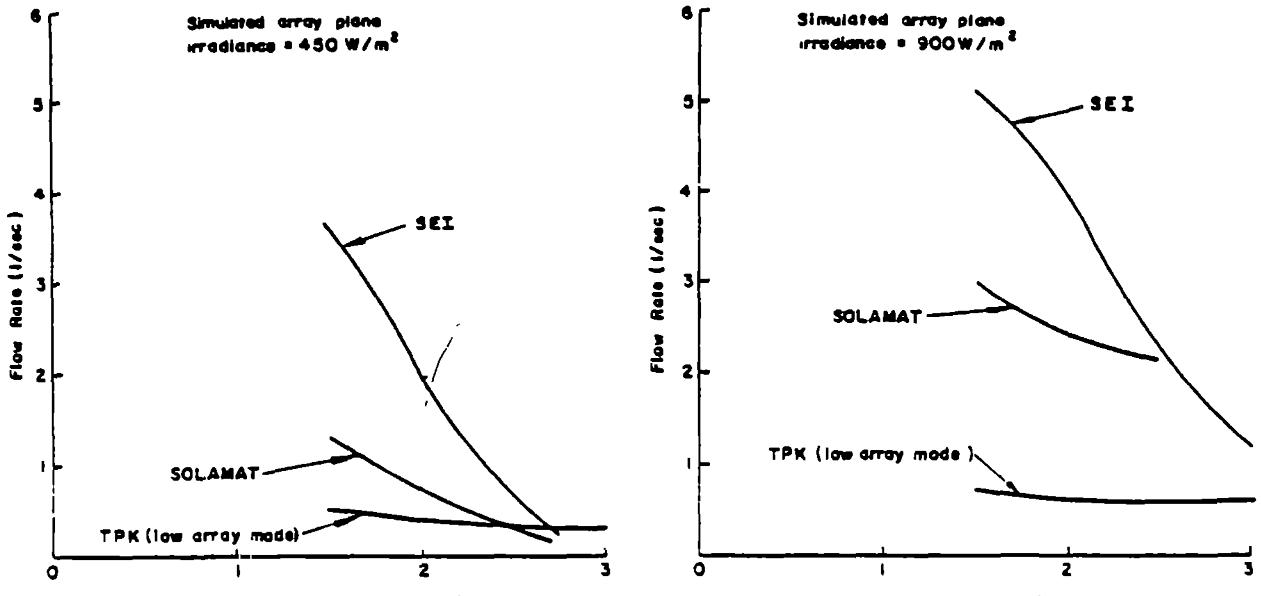
(4) Spec. required vol. under 4 kWh/m² d to be ≮ 70% of design volume under 5kWh/m² d

(5) Based on array $5/Wp plus estimate for system in quantity production. Equivalent to FOB costs, installation costs not included.

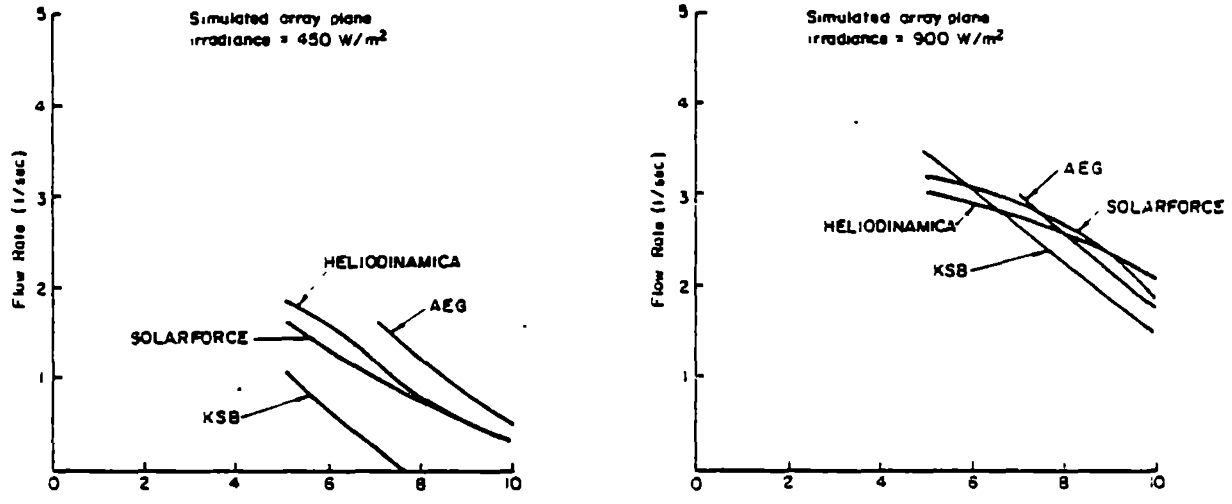
(6) System accepted on basis of 15m³/day output.

(7) * indicates below specified performance

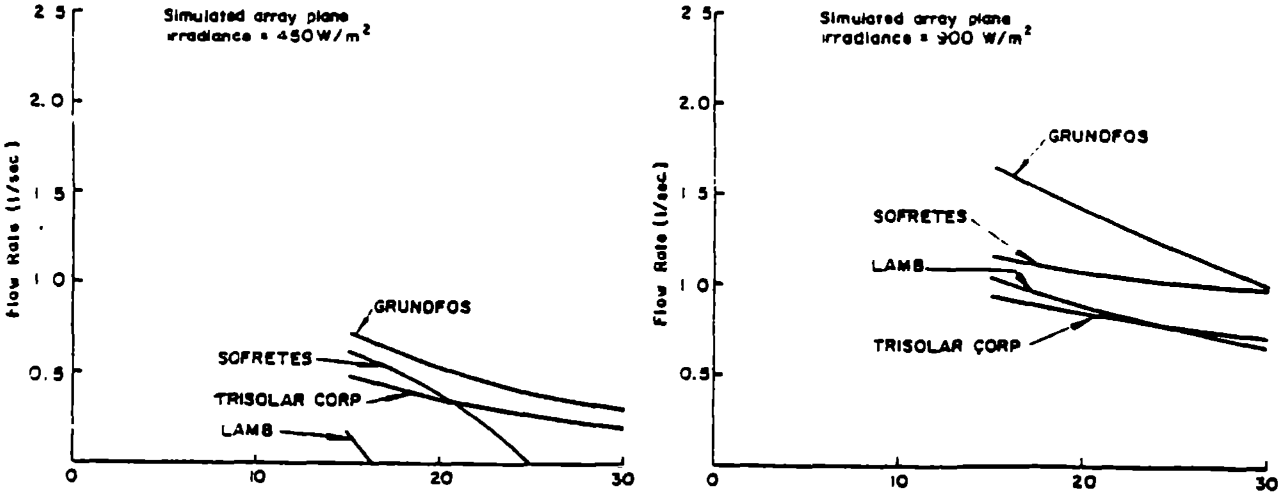
Table II Summary of Test Results on PV Pumping Systems



Category A Systems



Category B Systems



Category C Systems

Figure I Summary of Simulated Test Results (Flow v Static Head)
Categories A, B and C at irradiances of 450 and 900 W/m²

Pump Supplier	Daily Volume Specification		Daily Efficiency Specification	
	at 5 kWh/m^2	at 4kWh/m^2	at 75% DH	at 150% DH(1)
A Monegon	x	x	x	x
SEI	* (2)	*	*	x
Solamat	x (3)	x	*	*
TPK	x	*	*	*
B AEG	*	*	- (6)	x
Heliodinamica	*	*	*	*
KSB	x	x	*	x
Solarforce	*	x (5)	*	*
C Grundfos	*	*	*	*
Wm Lamb	* (4)	x	*	*
Sofretes	*	x	*	*
Trisolar Corp	x (5)	*	*	*

(1) DH = Design Head
(2) * Met specification
(3) x failed specification
(4) accepted on basis of lower volume specified
(5) only just failed
(6) no result

Table III Summary of systems meeting and failing performance specifications

(NB See Table IV for numerical values)

Provided relatively minor changes are made, two of the Category A and all of the Category B and C systems tested would be suitable for deployment in the Phase II field trials programme. The remaining two systems in Category A have significant shortcomings at the present stage of development.

The general standard of system design and overall efficiency has improved significantly compared with the systems tested in Phase I. The best daily efficiency has increased from 2.2% recorded for a Phase I system to 3.8% for a system tested in Phase II Preparation. Systems are now available where daily efficiency changes little with static lift over a range of 75% to 150% of design head and which can pump well under an irradiation of 4kWh/m^2. This last characteristic is largely dependent on low threshold irradiances for starting and stopping, and the best systems had threshold values in the range of 220 to 320 W/m^2. The best motors tested had maximum efficiencies in the range of 81 to 84%, around 2% less than the motors tested in Phase I but this small difference is not significant. Peak pump efficiencies have improved from 46% to 69% for the best single stage centrifugal pumps and from around 50% to over 60% for the best multi-stage centrifugal pumps. The best daily subsystem efficiencies (inferred from measured values of daily system efficiency and supported by measured values of subsystem efficiency) were in the range 41% to 46%. Efficiencies of over 50% were recorded for some of the reciprocating borehole pumps tested.

A summary of the findings of the tests on each system is given in Table IV.

CATEGORY A

Monegon

Unconventional concept based on rotary positive displacement (gear) pump, but prototype system did not work in configuration supplied Needs considerable development

SLJ (350)

A well engineered system based on a floating centrifugal pumpset, incorporating a brushless dc motor, and portable array Performance good but system more suited for 1 5m static head Projected SCC was quite high at $2 5/kJ d but probably better matching of PV array would improve cost-effectiveness It failed the daily efficiency specification at the high head limit

Solamat

System based on compact surface mounted centrifugal pumpset Performance was below specification, as a good motor was offset by a pump with relatively poor efficiency Non-return valve in self-priming chamber contributes to losses and may be an unreliable feature Projected SCC was quite high at $2 3/kJ d It also failed the daily volume specification at 4kWh/m^2

TPK

Prototype positive displacement system, well-suited to local manufacture, but inadequately developed in present form Performance very poor due to many losses in pump and supporting framework PV modules rapidly deteriorated around edges, due either to water ingress or chemical reaction with sealants

CATEGORY B

AEG-Telefunken (Swimpump 400)

Promising system based on compact and very efficient floating centrifugal pumpset, but prototype unit supplied sank during testing due to a leak at cable gland Array support structure unwieldy to assemble and wiring not considered sufficiently robust System performance good, with particularly low projected SCC of $0 9/kJ d It just failed the daily efficiency specification at high head limit

Heliodinamica

Well-engineered system incorporating compact surface-mounted centrifugal pumpset with large spherical self-priming chamber Plastic pump casing and impellor may have limited life if water heavily silt laden Performance good but would have been better if more efficient motor used Projected SCC low at $1 2/kJ d, with scope for further reduction

KSB (Aquasol 50M)

Well-engineered system based on floating centrifugal pumpset, incorporating a brushless dc motor, and portable array Performance below specification at 7m static head but system more suited for operation at 5m static head Projected SCC reasonably good at $1 5/kJ d It also failed the daily efficiency specification at the high head limit and the daily volume specification at 4 kWh/m^2

Solarforce (Alta X F6-5-T3)

Robust, well proven system with submerged centrifugal pump driven by shaft from motor on surface Best suited for permanent installation in borehole but needs skilled fitter to install Performance met specification but pump efficiency low Projected SCC fairly high at $2 2/kJ d, with scope for further reduction if efficiency can be improved It just failed the daily volume specification at 4 kWh/m^2

CATEGORY C

Grundfos

Well-engineered system based on standard mass produced submersible multi stage centrifugal pumpset incorporating water filled ac motor driven from variable frequency inverter Overall system daily efficiency particularly good at 3 8% and performance well within specification Projected SCC low at $1 2/kJ d Local manufacture not feasible in present form

Wm Lamb

Robust positive displacement (reciprocation piston) pumpset with array mounted on structure that can be manually rotated to face the sun This structure was not considered to be strong enough for long life and storm conditions Performance with fixed array met reduced output of 15m^3/day agreed when tender accepted, but counterbalance weights and pulleys need changing when head departs significantly from design level of 20m Projected SCC quite low at $1 5/kJ d It also failed the daily volume specification at 4 kWh/m^2

Sofretes

System incorporates a submersible multi-stage centrifugal pumpset with flexible delivery pipe The dc motor drives the pump through a magnetic coupling Pumpset easy to withdraw for changing brushes on motor Pump noise at high heads may indicate cavitation problem if pump not sufficiently submerged Performance met specification but efficiency poor Projected SCC quite high at $2 4/kJ d, with scope for improvement with more efficient pumpset It just failed the daily volume specification at 4 kWh/m^2

Tnsolar Corp

After modifications by the manufacturer, this positive displacement (reciprocating piston) system operated well, although the daily performance was about 10% below specification Maximum Power Controller ensures low threshold for start-up Pump plunger easy to withdraw for maintenance, but lifting equipment needed to install pump and pipework in borehole Projected SCC high at $2 9/kJ d

Table IV   Summary of Findings of Tests on Individual Systems

2.2 System Development

2.2.1 Objectives

The main objectives of the system development studies were:

- For photovoltaic systems, to examine the potential for improvement in performance of the main components and to assess the cost-effectiveness of these in system terms. The photovoltaic system development studies were based upon data obtained from the tenders and test programme on improved commercial systems and utilised a mathematical solar pumping system simulation model developed from the model constructed in Phase I.
- For thermodynamic systems, to review developments since the end of Phase I and to assess the cost-effectiveness of various system configurations. These studies were based upon information from and discussions with manufacturers and utilised a modified version of the thermal system mathematical model developed in Phase I.

These studies were limited to the pumping system itself and no account was taken of the characteristics or cost of the infrastructural works needed for irrigation or water supply applications: these were examined separately and are discussed in Section 3.

2.2.2 Photovoltaic Systems

General

The development of system components (ie. array, motor and pump) were studied, and power conditioning was reviewed. The effects of these developments on system cost-effectiveness were assessed in terms of the Specific Capital Cost. Some of these analyses require the costs and efficiencies of modules and subsystems to be assumed for different time horizons and the combination of values adopted for these studies are set out in Table V. Prospective cases are entitled 'Projected', 'Target' and 'Potential'.

PV arrays

Monocrystalline silicon cells incorporated into fixed flat plate modules were used in most of the improved commercial systems tendered, although one of the systems procured incorporated an array with poly- crystalline silicon cells. The reliability of modules with these types of cells is in general very good and costs are reducing due to increased scale of production and improvement in manufacturing techniques and performance. The Consultants consider that the present (mid-1982) cost of arrays of about \$10/Wp will reduce to about \$5/Wp over the next 5 years and this latter value has been used when calculating Projected and Target Specific Capital Costs (see Table V).

Further cost reductions to levels as low as \$0.50/Wp may be achieved in time with modules incorporating thin film solar cells. There are several promising developments in this field but the performance and reliability of thin-film cells has not yet been proved. For calculation of longer term Potential Specific Capital Costs, an array cost of \$2/Wp was used.

Case	Assumed Time Horizon	Module Cost $/Wp	Balance of System Costs		Daily subsystem efficiency			Remarks
			Basis of Motor/Pump Costs	Basis of other BOS Costs(7)	Basis	Value adopted in Project (2)		
						Economic (1) Studies	System Cost effectiveness Studies	
Tender	mid 1982	Costs and efficiences as for individual systems tendered in January 1982 (3)						Prices are for one off items and will not sustain general analysis
Present	mid 1982	10	Curve representative of average costs of units produced in quantity (4) C = 530 + 1.5P	Cat A B $3/Wp Cat C $4/Wp	Best measured	40%	N/A	Modules available commercially for most orders irrespective of size Motor/pump costs are estimated by manufacturers for quantity production in 1982
Projected	in period up to 1987	5	Cost estimated by each supplier for quantity production		Best measured	40%	Around 40%	Calculated for individual systems on basis stated Modules not likely to be available at price quoted on regular basis until 1987
Target	1987	5	0.5 C (5)	Cat A, B - $1.5/Wp Cat C $2/Wp	developed	50%	Cat A, B - 52% C - 50%	Module costs based on large scale production and available commercially Developed subsystem costs halved through quantity production (1000+) Improved subsystem efficiency achieved through developed components consistent with peak subsystem efficiencies of 63% for A & B, 55% for C
Potential	reached in period 1993 - 1998	2	0.5 C (6)	Cat A, B $1.5/Wp Cat C - $2/Wp	developed	50%	Cat A, B 52% C 50%	Module cost based on technological improvement and large scale production

NOTES

(1) See Table 8 4 for details of costs
(2) Cell efficiency assumed to be 11%
(3) See Table 5 3

(4) See Fig 8 3 Production runs 100+
P = Peak hydraulic power
(5) Production runs 1000+
(6) Production runs 1000+ but further reduction to (say) 0 25 C possible for production runs of 10000+
(7) Covers pipework, wiring, power conditioning (if any) and array support structure

Table V Basis of Costs and Efficiencies of PV Pumping Systems for Study of Cost-Effectiveness and Economics

Some of the improved commercial systems tendered incorporated concentrating and non-concentrating tracking arrays with the advantage that the area of photovoltaic cells and hence cost can be reduced. One disadvantage of the concentrating array is that it cannot make such efficient use of diffuse sunlight and another is that the tracking mechanism may pose reliability problems. These disadvantages, coupled with the likely fall in total fixed plane PV array costs make it unlikely that these approaches will be widely adopted.

Motors

Most low and medium head pumping systems incorporate permanent magnet dc electric motors, while for higher head borehole applications ac motors are also used. The design studies identified a number of improvements to motor performance to reduce maintenance requirements and/or to increase motor life, in particular improvements to bearing design, use of longer life brushes, and development of brushless motors.

It was concluded that the peak efficiency of future commercially available dc brushed motors could reach 85% to 90% compared with typical values in the range 81% to 86% recorded previously. In general the improvements in system performance obtained by using more efficient motors will be cost-effective.

Pumps

The performance of the pump is crucial for satisfactory system operation. Single stage centrifugal pumps have been used successfully for low and medium head applications: submerged pumps operating within a floating unit are a good example of this option and a peak subsystem efficiency of 57% inferring a high pump efficiency of around 65% was achieved under test. With improvements, future single stage centrifugal pumps can be expected to operate with peak efficiencies of around 70% to 72%: these are most likely to come from attention to improvements to flow distribution in volute and diffuser and improving the surface finish to internal flow surfaces.

For very low head applications (2m), the development of a simple axial flow propellar pump offers promise.

Multi-stage centrifugal pumps are suitable for medium and high head applications. The implied peak efficiency for this type of pump recorded under test in Phase II Preparation was just over 60%. With improvements to flow distribution, interstage leakage and final head recovery, a slight rise in peak efficiency to around 65% should be possible.

For high head (borehole) applications, positive displacement pumps (either reciprocating or progressing cavity) can be appropriate choices. Two Category C systems incorporated reciprocating pumps and tests indicated a peak efficiency of around 50% for heads in the 15-30m range. Higher efficiencies can be expected from pumps used for greater static lifts, along with further developments to reduce sliding friction and improve load levelling.

Progressing cavity positive displacement pumps have recently been incorporated into several high head solar pumping systems. Tests of one such installation in Egypt indicated a pump efficiency of over 70% at 49m head while still higher efficiencies have been reported by manufacturers but not independently verified. Provided the high breakaway torque inherent in this type of pump can be reduced without a significant fall in performance, they appear to be suitable for solar pumping applications. Unfortunately no solar powered progressing cavity pumps were available for test during the Project.

Although peak efficiency figures have been quoted for the pumps considered above, it is important to match the characteristics of the motor and pump to minimise the fall-off in subsystem efficiency as conditions vary from the design optimum.

Power Conditioning

Electronic power conditioners are used for impedance matching, dc to ac voltage conversion, battery charge regulation and component protection. For dc systems, a maximum power controller (MPC) can be used for the continuous adjustment of the array voltage to maximise the output from the motor and pump. The benefits of MPC's are in greatest evidence when used with systems with poorly matched components or for well matched systems operating away from their design head. Impedance matching is also important for systems with positive displacement pumps, for their load characteristics do not match the array characteristic, unlike centrifugal pumps which can be well matched without power conditioning over a wide range of operating conditions. However MPC's do increase system cost and may possibly introduce reliability problems. With the anticipated fall in array prices it is expected that the most cost-effective systems will incorporate improved component matching, eliminating the need for an MPC, although a simple switch to alter the series/parallel configuration and hence voltage/current characteristic of the array could be used for irrigation applications where a farmer is in attendance to operate the switch at the appropriate times.

With the development over the last few years of efficient (90-95%) medium cost (< $ 1000) dc to ac inverters in the 500-1500W power range, ac motor driven pumps have been incorporated into several well-designed systems for high head applications. Further development of ac systems is anticipated which will include improvements in the efficiency and cost of inverters. An advantage of this approach is that reliable mass produced motor/pump units developed for use with ac mains power or diesel generating sets are already in mass production in many parts of the world.

System cost-effectiveness

Improvements to components can result in four kinds of benefit: improvement in efficiency, reduction in capital costs, reduction in recurrent costs, and increase in system life. A simple sensitivity analysis on a Category B system using present costs showed that changes in system capital cost had the most significant effect on system cost-effectiveness, followed closely by changes in subsystem efficiency and then changes in lifetime and recurrent costs.

At present with array costs dominating system costs, higher efficiency (and higher cost) motors and pumps will normally be cost-effective due to the decrease in array costs. For Category B systems at array costs of \$10/Wp an increase in price of \$610 for a motor whose peak efficiency improves from 82% to 90% could be justified, while for a pump an increase in price of \$290 could be justified for a peak efficiency increase from 69% to 72%. (At an array cost of \$5/Wp these increases are halved). These price increases represented around 130% of the present price of motors and around 50% of the present price of pumps, so it is clear that the scope for development is greater in the case of motors.

The PV mathematical simulation model developed in Phase I was updated and then used to assess the potential cost-effectiveness of a Category B system incorporating some of the developed components discussed above. The analysis started with a system having a 77% peak efficiency motor and a 48% peak efficiency pump: 44.1 m^3 per day was delivered through 7m static lift under a global irradiation of $5kWh/m^2.d$ with a 570 Wp output array whose parallel/series connectors had been optimised. The SCC was \$1.8/kJ.d. Improving the motor performance to a peak efficiency of 90% and the pump performance to a peak efficiency of 72% resulted in an increase of water pumped to $71.8m^3$ (63% gain) and a drop in the SCC to \$1.1/kJ.d (39% improvement). These results took full account of the part load characteristics of motor and pump. The Category B specified output of $60m^3/day$ was produced with an array having a peak output of 430W and represented a capital cost saving of \$700 on the baseline case. (Note: the costs quoted included an allowance for installation).

As part of a separate exercise, predictions of capital cost and SCC values were made for well designed systems in each of Categories A, B and C for the prospective Projected, Target and Potential cases defined in Table V. As an illustration, the results for Category B (7m lift, $60m^3/day$) are summarised below:

	Projected (up to 1987)	Target (1987)	Potential (1993-1998)
Capital Cost (\$)	3780	3370	2010
SCC (\$/Kj.d)	0.90	0.80	0.48

(Note: these costs do not allow for shipping and installation)

The Target SCC's are respectively 27%, 26% and 20% of those procured for testing in Categories A, B and C; the slight reduction from the Projected to the Target case is caused by an assumed improvement to daily subsystem efficiency (40% to 50%) and a halving of subsystem costs, while the larger reduction to the Potential case is caused by an assumed reduction in PV array costs (from \$5/Wp to \$2/Wp).

These values may be compared with estimates of SCC made in Phase I. At the prices then ruling the best systems had SCC of around \$2.8/kJ.d (after allowing for the change in Standard Solar day) and this was expected to fall to around \$1.2/kJ.d when array costs fell to \$4/Wp.

It should be noted that it can be misleading to compare systems simply on the basis of $ per Wp: for a given hydraulic output, a less efficient system with a larger array can have a lower $/Wp value than a more efficient system with a smaller array. SCC is a more realistic guide to cost-effectiveness and for more detailed studies the costs should be assembled from the costs of the individual components expressed in terms of their own power outputs.

2.2.3 Thermodynamic Systems

Enquiries were made of 51 developers of solar thermodynamic pumping systems; 36 responded, but only eleven organisations stated they were continuing active development of small-scale (<10 kW shaft power) systems. Visits were made to several manufacturers/ organisations to assess the more interesting systems.

Design studies of a number of solar thermodynamic systems based on the limited amount of performance and cost data available showed that high temperature systems incorporating parabolic dish or central receiver two axis tracking collectors and Rankine or Stirling cycle engines were the options most likely in theory to be competitive with developed PV systems. However, these systems are furthest from development.

Systems with linear parabolic (trough) collectors requiring single axis tracking and organic Rankine cycle engines could be reasonably cost-effective compared with PV systems, and are further developed than high temperature systems. The main disadvantage is vulnerability to loss of working fluid. Although the concept of expansion engines is familiar throughout much of the developing world, the skills required to manufacture them are as high as for PV systems.

Field experience of successful small-scale thermodynamic solar pumps is still extremely limited, although several manufacturers are proposing to undertake field trials of newly developed systems in the near future. Independent evaluation of selected systems under laboratory and field conditions is required before their potential cost-effectiveness for use for small-scale pumping applications can be confirmed.

3. ECONOMIC EVALUATION OF SOLAR WATER PUMPING APPLICATIONS

3.1 Objectives and Applications

The main objectives of the system applications and economic studies were to identify the technical and economic circumstances under which solar water pumps become viable. This was achieved through a systematic and structured analysis of and comparison between the economics of solar pumps and alternative prime-movers with different conveyance, distribution and storage options selected to meet the following three requirements:

- irrigation applications, where water is raised through static lifts in the range 2m to 10m to suit land areas of 0.25 to 4 ha (these correspond to the performance envelope of Category A and B systems);

- village water supply applications, where water is raised through static lifts in the range 15m to 30m to serve populations of 375 to 1500 people (these correspond to the performance envelope of Category C systems).

- livestock water supply applications, where water is raised through static lifts in the range 15m to 30m for herds of 1000 to 4000 animals (these correspond to a hydraulic output 2 to 4 times the performance envelope of Category C systems).

For each case studied, the output water cost (in US cents/m^3) was calculated. This is the uniform annual sum equivalent to the Present Worth of all the life cycle costs (capital and recurrent) for a specified period of analysis and discount rate, divided by the total volume of water pumped in a year. The water costs quoted are for delivery to the crop (not the field).

3.2 Models, Analyses and Scenarios

Two computer based mathematical models were developed, one for the irrigation applications and the other for the water supply applications. A modular approach was adopted for both models utilising components for water source, power source, pump, water storage unit, conveyance or distribution method and field application method (the last only for the irrigation model). The models allow for the specification of the technical cost features of each component and their combination in appropriate order for each of a number of scenarios studied.

The six energy sources considered were solar, wind, diesel fuel, kerosene fuel, animal and human. Two cases were considered for the diesel and kerosene engines: a "low" recurrent cost case which represents the best which can be expected under good conditions in a developing country, and a "high" recurrent cost case representative of realistic performance under normal field conditions, where engines are usually run below optimum efficiency and with poor servicing, maintenance, and operating management. For irrigation applications, the time a person spent handpumping was given a value, whereas for village water supply it was assumed to be zero.

Three basic types of analysis were carried out:

- Baseline studies, chosen to represent typical conditions under which six pumping system options were compared in the context of their irrigation or water supply applications.

- Sensitivity analyses, in which some of the input parameters used in the baseline case were systematically changed to investigate their relative importance to the output water costs;

- country specific case studies in which parameters representative of three countries - Bangladesh, Kenya and Thailand - were used to assess the effects of local conditions on the relative competitiveness of the different pumping systems.

Data for the baseline studies were collected from international sources, while information on water use and practice and costs in Bangladesh, Kenya and Thailand was obtained through detailed questionnaires prepared especially for this study. Capital costs were expressed in a form which enabled the variation of cost with size or power output to be related, and recurrent costs were calculated in three parts ie. replacement of an item after the end of its operating life, maintenance and repair, and operation. International cost data were deemed to be free of taxes and subsidies. All economic comparisons were carried out on classical DCF principles, using a real discount rate of 10% and a period of analysis of 30 years.

For each scenario incorporating wind and solar pumps, the systems were sized as necessary to meet the mean daily volume of water required for an assumed demand in the critical month. For irrigation this is the month in which the ratio of the renewable energy available to the hydraulic energy required is a minimum. For animal pump and handpump scenarios, systems were sized to meet the maximum mean daily water demand, while the size of the diesel and kerosene engines were fixed at nominal rated 2.5 kW shaft power.

The studies also included comparisons with the costs of water delivered by solar pumping systems with the performance and cost characteristics defined for the Target and Potential cases (see Table V).

3.3 Irrigation Studies

The baseline models consisted of the six different prime movers coupled with appropriate selections from three methods of water conveyance (earth channel, concrete lined channel and pipes) and two methods of application to the crop (furrows or trickle pipes) on a 2 hectare plot. The solar and wind scenarios were considered with and without half day storage, and the model allowed for drawdown in the water source and head loss in the channels and pipes. The baseline models were run for static lifts of 2m and 7m. The model was used to compute the unit cost of water provided under each scenario to meet the net crop irrigation water requirement for a baseline cropping pattern (peak requirement 6mm/day). This involved the analyses of 60 scenarios.

As part of the baseline studies, the irrigation area was varied from 0.25 to 4 hectares and the input values for which the output water cost was a minimum were noted. An illustration of the type of result obtained from use of solar pumps with pipe and channel distribution, with and without storage is shown in Fig. II. It will be noted that the cost was a minimum for an area of about one hectare; up to 4 ha minima were also found for windpumps and kerosene engine pumps but not for diesel engine powered pumps, because the increased demand could still be met by an engine of the minimum size specified (2.5 kW).

In order to make a fair comparison between different pumping methods, a further analysis was undertaken to establish the cost of supplying a 2 hectare area using the appropriate number of each type of optimally sized system. Detailed results of this analysis are shown in Table VII for the 7m static lift case. It was apparent from the comparison that kerosene fuelled engines are less cost-effective than diesel fuelled engines and hence they were not considered further. A general comparison was made of the output water cost with a global target for the upper limit to the economic cost of water of 10 cents/m^3 (delivered to crop).

The sensitivity studies considered the combination of optimally sized systems required to supply a 2 hectare irrigation area. Four groups of parameters were considered (climate, agricultural and technical factors, costs and economic) and the percentage change from the

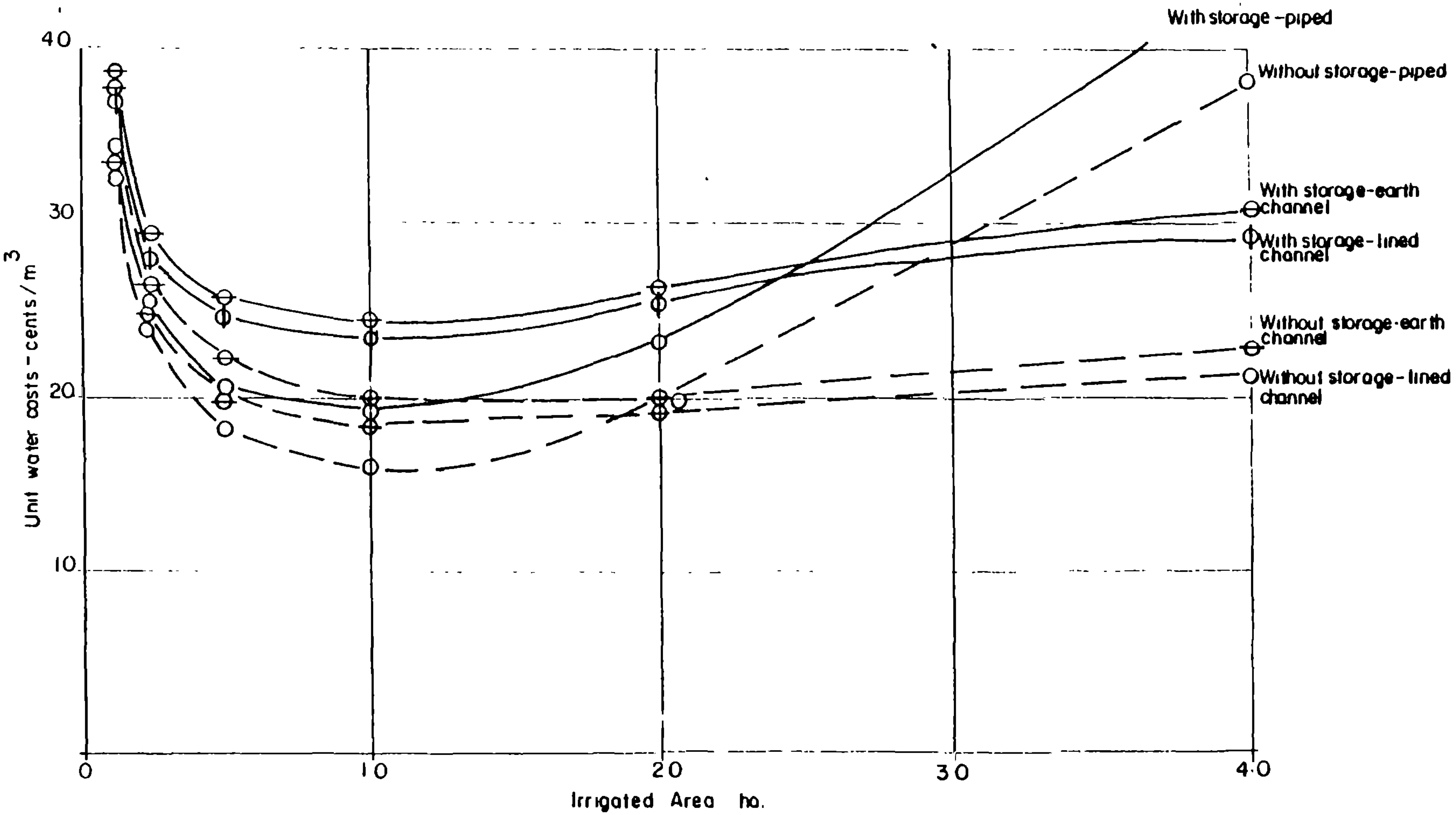


Figure II Cost of irrigation water for a solar pump - 7 metre static lift (Baseline scenario)

Pump	Optimum Supply Area	Optimum Distribution Method	Number of Pumps	Power Source Size per pump	Actual Lifetime Power Source	Actual Lifetime Pump	System Capital Cost	PW of replacements	Annual Running Costs	Annual Maint Costs	Life Cycle Costs (PW)	Unit Cost of water to crop
	hectares				yrs	yrs	$	$	$	$	$	cents per m^3
Solar	1	piped	2	636 Wp (2)	15	6.9(7)	33093	8707	0	175	43615	16.9
Solar Store	1	piped	2	802 Wp (2)	15	6.9(7)	39731	9336	0	175	50885	19.8
Wind	1	lined channel	2	46.2 m^2(3)	30	10	27892	1461	0	187	31295	12.2
Wind + Store	1	piped	2	31.2 m^2(3)	30	10	29830	6063	0	117	37107	14.4
Diesel - low	> 4	lined channel	1	2.5 kW(4)	5.5	10	3014	2561	748	241	15828	6.1
Diesel - high	> 4	lined channel	1	2.5 kW(4)	4.0	10	3014	3537	2243	441	34384	13.4
Kerosene - low	1	lined channel	2	1.1 kW(4)	1.9	10	2450	1986	1982	282	27192	10.8
Kerosene - high	1	lined channel	2	1.1 kW(4)	1.9	10	2450	1986	3969	482	50537	19.6
Animal	1	piped	3	350W/animal(5)	10	10	14110	6036	971	20	30425	11.8
Handpump	0.12(1)	piped	16	60W/person(6)	-	10	26681	9425	3176	800	77337	30.0

NOTES
(1) Not optimum but limited by pump output
(2) Array output
(3) Rotor area
(4) Shaft output
(5) Assumed output per animal
(6) Assumed input power maintained over 5 working hours
(7) Includes electric motor

Table VI Results for Optimum 2 hectare Irrigation Baseline Scenarios. 7m static lift (6mm per day peak, annual crop water requirement 24820 m^3, peak monthly demand factor = 1.76; critical solar month = 20.8 MJ/m^2, critical wind month = 2.5 m/s, ı = 10%, n = 30 years).

baseline unit water costs was calculated for variation of each individual major parameter in each of the groups by ±50% (except where this was physically impossible). Systems with storage were not examined as they were always more expensive than similar systems without storage. As expected, one of the most important parameters was static lift and the variation of output water cost with lift for each of the pumping systems studied is illustrated in Fig. III; this Figure also shows the output cost for the solar Target and Potential cases. It is anticipated that solar systems with Target characteristics - PV modules at $5/Wp, motor/pumps at half present day quantity prices, daily subsystem efficiencies of 50% - should be available by 1987 and that such systems will be competitive with all alternatives except low case diesel.

For the three country case studies, data on local costs, cropping patterns and meteorological conditions were abstracted from the detailed questionnaires completed for the Project by local organisations or individuals in the three selected countries. The unit cost of water delivered to the crop by each pumping system for the baseline and country case studies for a 2m and 7m static lift was calculated using the same general method adopted for the baseline sensitivity analyses although the input cost data include subsidies and taxes. The results obtained for the 7m lift are illustrated in Fig IV.

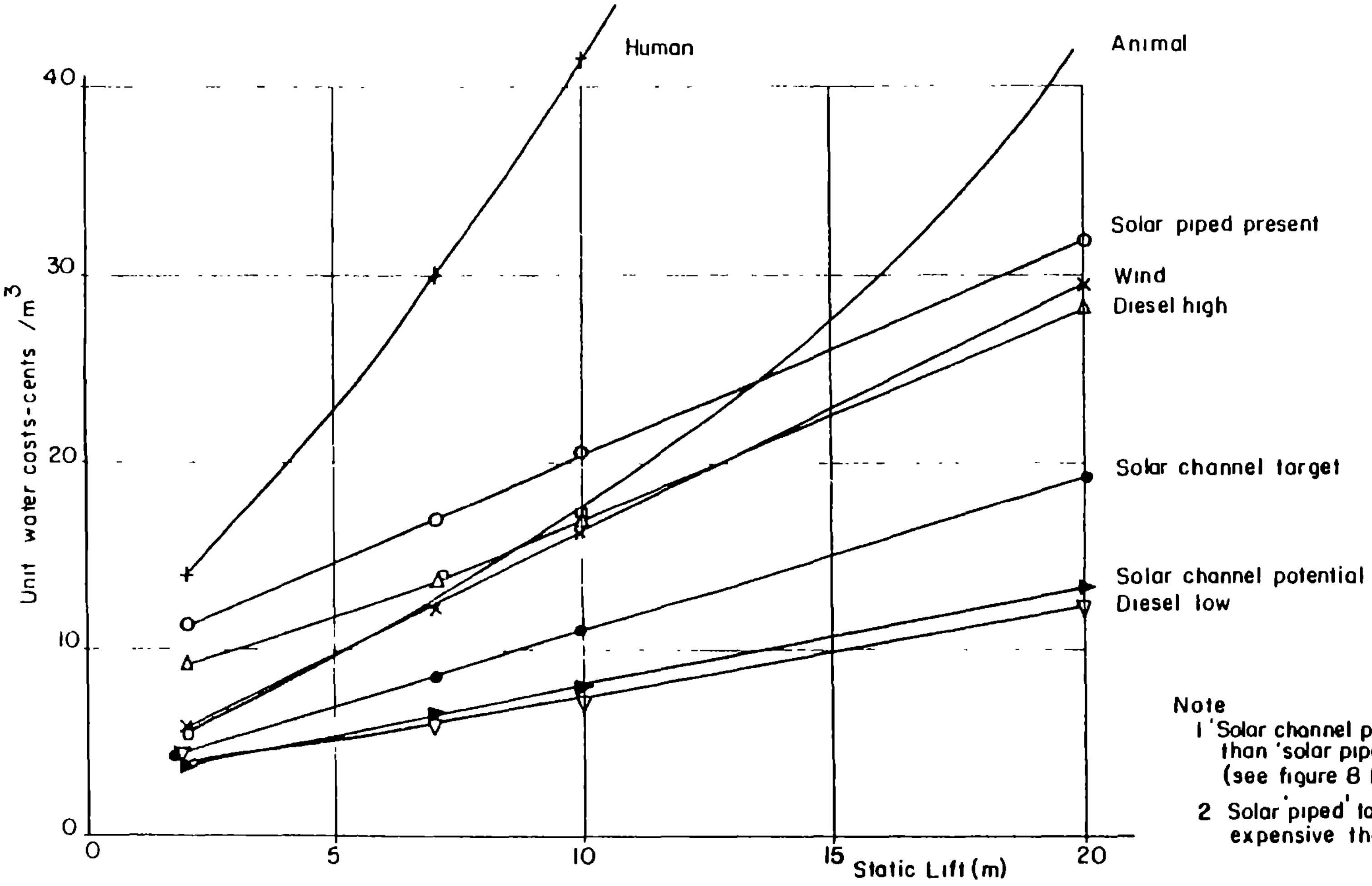
3.4 Rural Water Supply Studies

For the village water supply studies, the baseline models incorporated four different prime movers (solar, wind, human and high and low case diesel). The mechanised scenarios included central storage equivalent to one day's supply and systems with and without a piped distribution system were studied. The handpump scenario had neither storage nor distribution system. Thus a total of 9 baseline scenarios are analysed. Animals are rarely used for water supply pumping and thus were not investigated. The baseline village had a population of 750 people at 75 persons/hectare using 40 litres per capita per day throughout the year pumped through a static head of 20m. The maximum distance between a user and water point was fixed at 100m for the piped distribution case. The variation in output water cost was studied over a range of village population from 375 to 1500 people.

For livestock water supply studies, the baseline models incorporated three different prime movers (solar, wind and high and low case diesel) and storage equivalent to one days supply and no distribution system. This gave a total of 4 baseline scenarios. One water point with storage was assumed to serve 1000 to 4000 head of cattle, with a baseline herd of 2000 consuming 40 litres of water per head per day throughout the year, pumped through a static lift of 20m.

The technical and cost data and the procedures adopted for the initial baseline studies were the same as those used in the irrigation studies, except that no cost was allocated to the time spent operating handpumps.

There was an ill-defined minimum point in the curve of unit water cost against population for both the solar and wind systems when used for the pipe distribution case: for both systems this minimum occurred with a population of around 1000 people. The cost of diesel pumped water



Note
1 'Solar channel present' more expensive than 'solar piped present' and not shown (see figure 8 10)
2 Solar 'piped' target and potential more expensive than channel and not shown.

Figure III Effect of Reduced PV Solar Pumping System Capital Costs in Comparison with Alternatives as a Function of Static Lift (Baseline irrigation scenario - no storage)

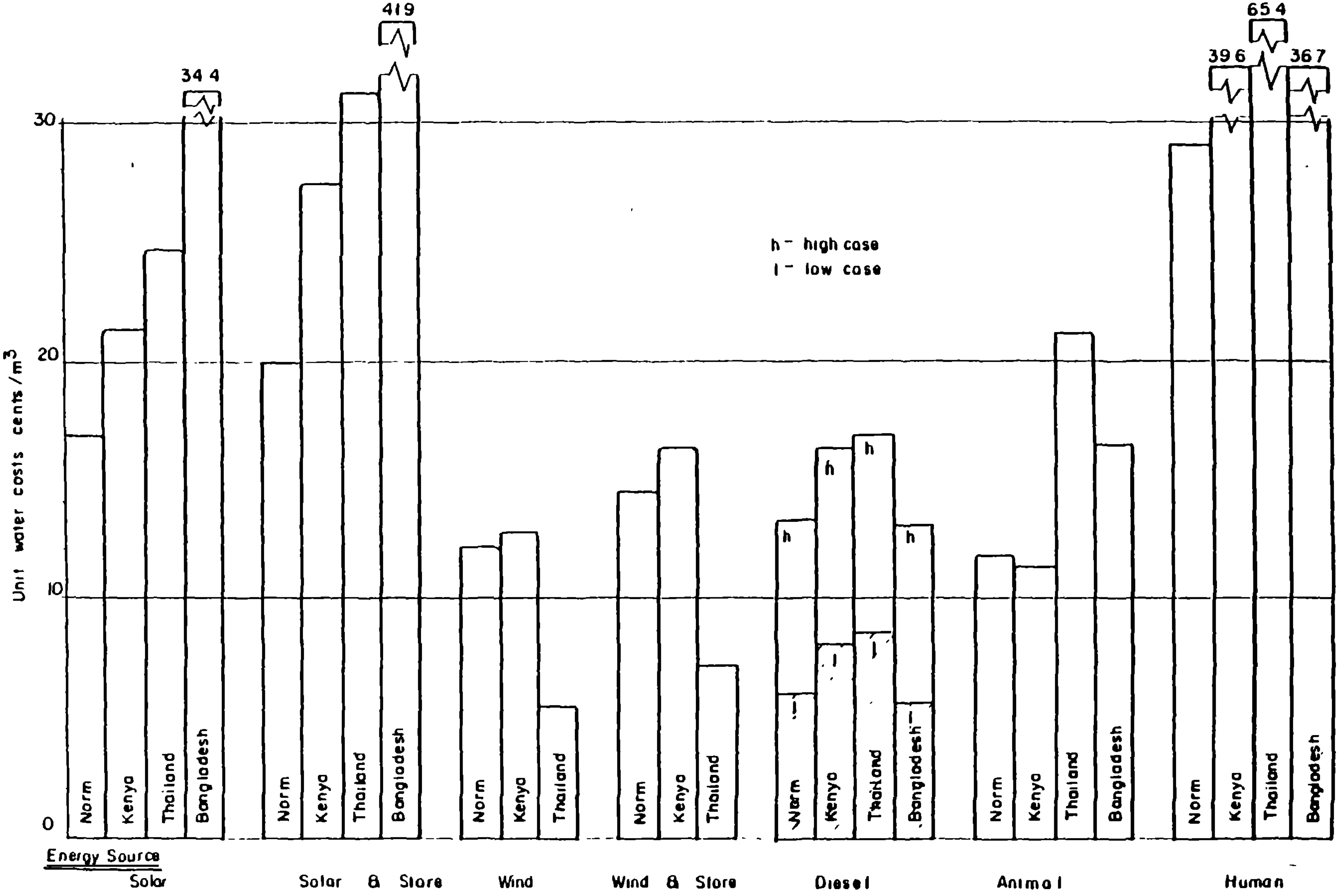


Figure IV Histogram showing optimum irrigation water costs for alternative pumping methods to supply 2 ha at a 7 metre lift with peak water requirements of 6 mm per day continued to decrease slightly up to the maximum population considered. The different pumping options were compared on the basis of the baseline scenarios. Details of the results of this comparison for the village scenario are given in Table VII.

The baseline scenarios for village water supply only were used in the sensitivity analyses. The effect on unit water costs of varying individual parameters in each of four main groups (climate, water supply factors, costs and economic) was evaluated using the same procedure adopted for the irrigation studies. The effect of variation in static lift on unit water costs is shown in Fig. V: this also includes curves of output cost for the solar Target and Potential cases.

Country case studies of the rural water supply applications were carried out using local technical and cost data for Bangladesh, Kenya and Thailand. A histogram summarising the results of this work for village water supply is shown in Fig VI.

3.5 Conclusions

3.5.1 Introduction

The results obtained from comprehensive analyses of the type reported here naturally depend on the performance and cost data assumptions incorporated into the baseline models or input for the purposes of the analyses. Very little work of this type has been reported previously and it is considered that the results obtained provide a very fair indication of the relative merits of the systems studied and give a good indication of the circumstances in which solar water pumping systems can be expected to become viable. Even so, this study should be regarded as being pioneering and indicative, rather than definitive and there is a continuing need for more detailed assessments to proceed in parallel with further technical development.

3.5.2 Irrigation Studies

A wealth of information was obtained from these economic analyses and the Main Report discusses the results and presents the conclusions at length. The principal points to emerge in connection with solar pumping systems are as follows:

o solar channel distribution systems presently provide water for less than 10 cents/m^3 at static lifts up to around 3m, but at heads above 4m piped distribution systems deliver water more cheaply.

o both Present* case solar pipe and solar channel systems are a few cents/m^3 more expensive than high case diesel, although the difference is probably not significant in view of the neglect of operator attendance costs in the diesel analysis. The solar system output costs are thus considerably higher than low case diesel.

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* See Table V for statement of costs and efficiencies associated with each case.

Pump	No. of Pumps	No of Water points	Population per water point	Power Source size per pump	Actual Lifetimes Power Source	Pump	System Capital Cost	P.W of Replacements	Annual Running Costs	Annual Maintenance Costs	Life Cycle Cost	Unit Water Cost
					yrs	yrs	$	$	$	$	$	cents per m^3
With piped distribution												
Solar	1	4	187	974 Wp(1)	15	5.3(5)	21169	3113	0	98	25301	22.3
Wind	1	4	187	40.7 m^2(2)	30	10	16038	823	0	59	17469	15.4
Diesel 'low'	1	4	187	2.5 kW(3)	9.9	10	6649	1549	414	206	14629	12.9
Diesel 'high'	1	4	187	2.5 kW(3)	7.3	10	6649	2063	1242	406	25806	22.7
Without distribution												
Solar	1	1	750	944 Wp(1)	15	5.3(5)	19849	1017	0	98	23273	20.5
Wind	1	1	750	39.4 m^2(2)	30	10	14500	522	0	59	15629	13.8
Diesel 'low'	1	1	750	2.5 kW(3)	10	10	5641	1164	402	206	12932	11.4
Diesel 'high'	1	1	750	2.5 kW(3)	7.5	10	5461	1641	1206	406	23832	21.0
Handpump	7	7	107	60W (4)	-	10	12796	1077	0	350	17497	15.4

NOTES

(1) Array output
(2) Rotor area
(3) Shaft output
(4) Assumed input power maintained over 5 hours
(5) Includes electric motor

Table VII Results of Analyses on Village Water Supply Pumping Systems (Population 750, consumption 40 litres per capita per day, static lift 20m, population density 75 per hectare, critical solar month = 19.3 MJ/m^2, critical wind speed = 2.5 m/s, i=10% n = 30 years).

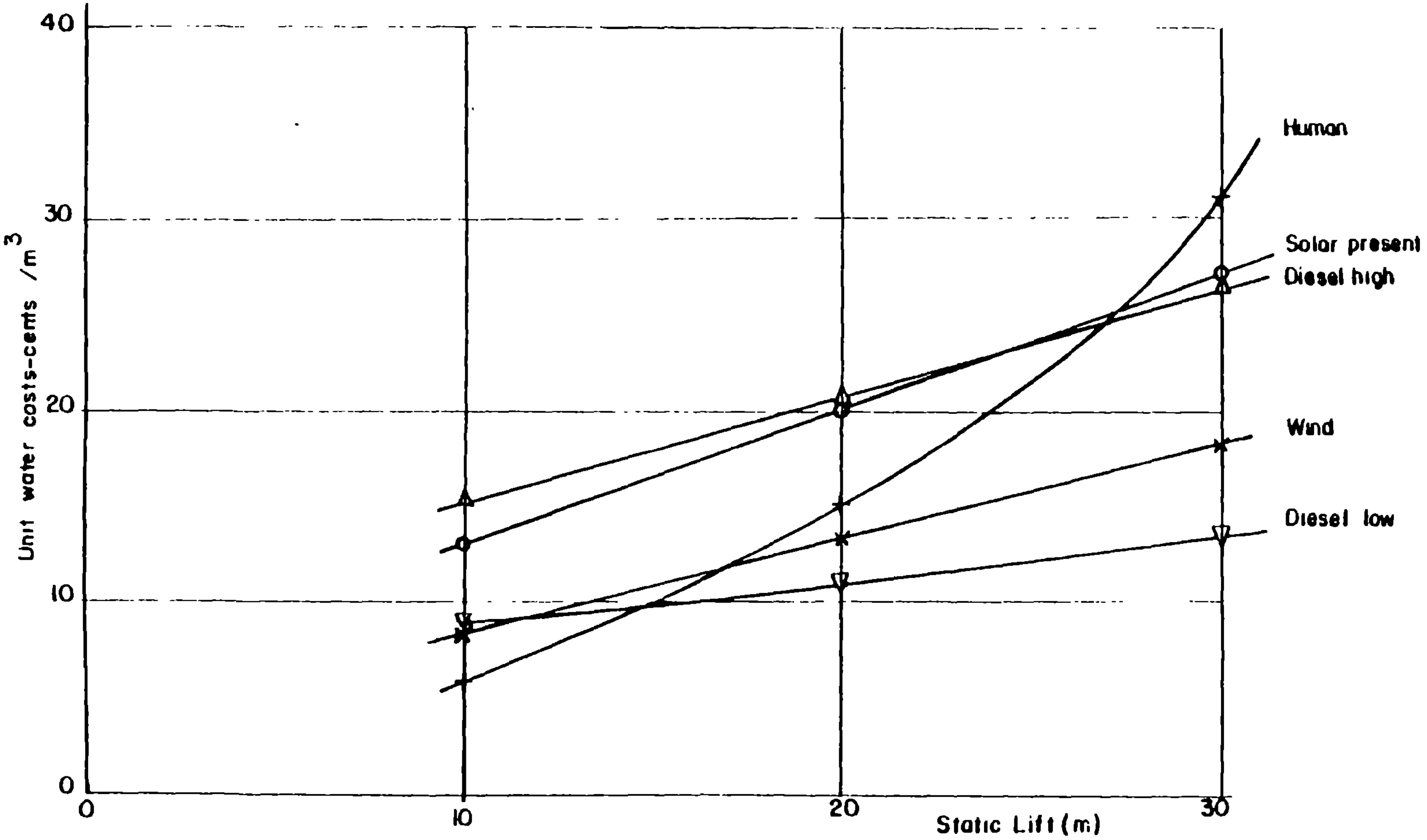


Figure V Effect on Static Lift on Cost of Water for Village Water Supplies
(Baseline scenario - population 750 - no distribution)

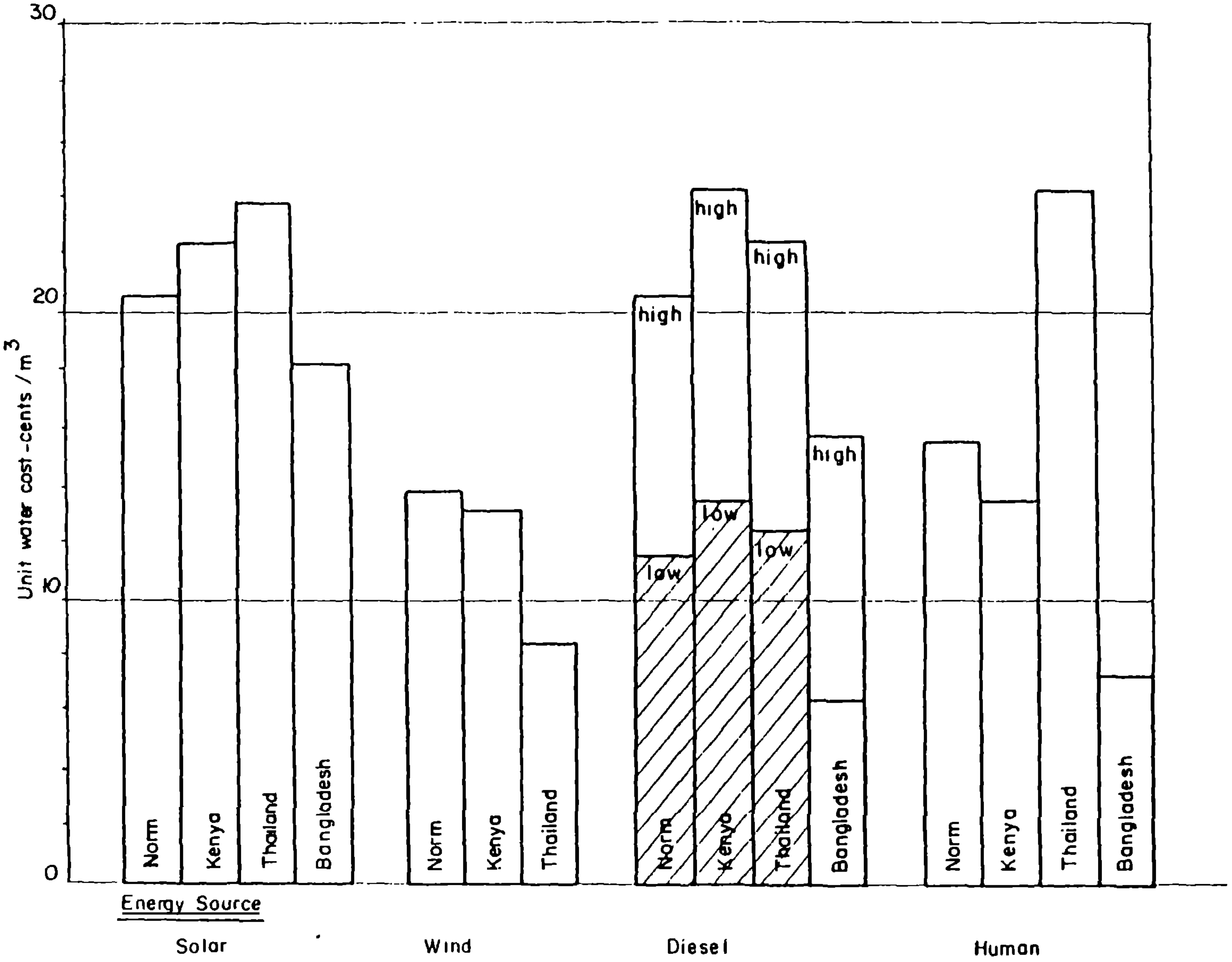


Figure VI Histogram showing village water costs for alternative pumping methods
Village population 750, per capita consumption 40 litres/day 20 metre lift

- the Target* case solar pumping system (with channel distribution) can deliver water for less than 10 cents/m^3 for lifts up to around 9m and is cheaper than all other systems (apart from low case diesel) over the whole range of lift studied (2 to 20m). It is anticipated that solar pumps with Target costs and efficiencies will be available by 1987.

- low case diesel is some 2 cents/m^3 cheaper at 2m lift and 7 cents/m^3 cheaper at 20m lift than Target case solar, but since the low case diesel is unlikely to be attained frequently, the Target case solar water pump should be generally competitive.

- the Potential* case solar system is competitive with low case diesel over the whole range of lifts studied. These solar systems are expected to be available in the period 1993 - 1998.

- storage adds some 3 to 7 cents/m^3 to output costs of solar pumps and so they will find their first applications where storage is not needed.

- the output water costs of solar pumping systems are particularly sensitive to area irrigated, peak monthly demand factor, solar energy available in critical month, subsystem efficiency, field application efficiency, static lift, capital cost and discount rate. Their competitiveness is dependent on the recurrent cost of diesel pumps, the wind regime and the value of time spent handpumping.

- for the conditions assumed, Kenya was most favourable to solar pumps and Bangladesh the worst because the solar regime in Kenya was better and the assumed irrigation water demand was more even.

Points relating to the other systems which are worthy of note include:

- windspeeds of around 2.5m/s for the critical month represent an approximate break even point between wind and solar. For locations with better wind regime, output costs will fall and they will be competitive with low case diesel.

- the output cost of handpumped water depends on the lift, the cost of boreholes and value assigned to time spent pumping. The costs of handpumped water do not become comparable with wind, low case diesel or animal systems at 2m lift until the daily wage rate has fallen from $1 to $0.10. Thus, on the basis of the assumptions adopted, the economic use of handpumps appears very questionable.

- animal powered pumps are competitive with high case diesel for lifts up to 10m. For low lifts of 2m there is little to choose between the wind and animal pumps and although they are about 2 cents/m^3 more expensive than low case diesel, the difference is so small and the chance of low case diesel attained so low that animal pumps would appear to be competitive with all alternative systems; this would suggest that for low lift pumping the declining use of animal power should be critically reassessed.

- the smallest diesel engine pump is still oversized for irrigated areas less than 4 hectares and changes in hydraulic output requirements simply affect fuel consumption.

3.5.3 Rural Water Supply Studies

The principal points to emerge from the economic analysis in connection with the solar pumping systems are as follows:

- for the baseline conditions, solar pumps without distribution can deliver water for around 21 cents/m^3. This cost is well under the prices at which many people have to buy water in the developing world.
- piped distribution increases all output costs by 2 to 3 cents/m^3, a relatively small price to pay compared with the extra convenience.
- the Present case solar pumping system delivers water for around the same cost as high case diesel over the full range of lifts studied (10m to 30m).
- Target case solar pumps are competitive with all other systems, except for handpumps at lifts below 12m. A market for solar pumps should develop as costs fall and efficiencies rise to Target case levels.
- Potential case solar pumps are cheaper than all other alternatives for lifts from 10m to 30m.
- the output costs of solar pumping systems are sensitive to populations of less than around 500, solar energy available in critical month, per capita consumption, subsystem efficiency, static lift, capital cost and discount rate. Their competitiveness is dependent on recurrent cost of diesel pumps, the wind regime, the value of time spent hand/pumping and the sustainable human power input to handpumps.
- the same general pattern of costs of solar relative to other techniques applies to conditions in Bangladesh, Kenya and Thailand and at present prices they are competitive with high case diesel. Three factors cause differences; the first is the high cost of boreholes in Thailand which makes handpumped water as expensive as high case diesel, the second is the low cost of diesels in Bangladesh which reduces the output cost relative to other systems and the third is the low cost of boreholes and handpumps in Bangladesh which makes them the cheapest option at lifts of 20m.

Points relating to other systems which are worthy of note include:-

- windspeeds greater than 2.5m/s in the critical month will make wind power competitive with all other systems.

- the cost of handpumped water is only competitive with Target case solar for lifts up to 12m and thereafter rises steeply with increase in head. If the cost of time spent pumping is included at US$ 0.25 per day, the output cost rises from 15 cents/m^3 to 23 cents/m^3 at a lift of 20m when it equals Present solar or high case diesel. However an increase in power input from 60W to 150W results in a drop in cost from 15 cents/m^3 to 7 cents/m^3.

- the smallest engined pump is oversized for villages smaller than around 1500 people. The inclusion of operator attendance costs will make the high case diesel the least competitive of all the options studied.

3.5.4 Summary

This study has confirmed the importance of studying small pumping systems comparatively in the context in which it is proposed to use them. The costs and efficiencies of the different infrastructural elements make a significant difference to the output water costs and it is very misleading to quote output costs based on a consideration of the pumping system alone.

This study has shown that, even at 'present' photovoltaic array costs, solar pumps can lift water at a cost that is competitive with the primary alternatives where diesel costs are high and wind speeds low - given suitable conditions such as a favourable solar irradiation regime, a steady demand for water all the year round and (for irrigation) low pumping heads (2m for baseline conditions).

The results of the analyses also show that, whereas for irrigation Potential case solar is competitive with low case diesel, for water supply Target use solar is competitive with low case diesel. In other words, solar water pumping should first find economic application for water supply.

It can reasonably be anticipated that, for the Target case, as designs mature, production levels increase and array costs fall, solar pumps will become more widely applicable than at present: notably it will be possible to use them cost-effectively at high pumping heads. Within five years, relative costs should have changed to the extent that solar water pumps should always be among the serious options to be evaluated for small-scale applications.

4. ADVANCEMENT OF APPLICATION

4.1 Strategy

The Consultants consider it is vital that, for the long term good of technology, for the good of the country in which solar water pumps have a genuine potential use and, above all else, for the good of the prospective farmer or villager purchaser, the most careful economic analysis should be made of prospective applications so that, as far as possible, pumps are only bought for and used in those situations where they have a genuinely useful and economic role to fulfil.

The whole question of fiscal policy and incentives can then be considered, however these two related (but distinct) matters must not be allowed to become confused; it is essential that a true economic picture first be obtained free from the distortions which the inclusion of subsidies (for example) would introduce.

The overall task remaining is to ensure that the market is developed in a responsible manner so that appropriate solar pumps reach the people who need them. This task is best achieved in a number of steps, the most important of which are: demonstration of suitable pumps and verification of cost-competitiveness; detailed economic study of particular applications; and market surveys. If economic prospects appear good, the next steps are consideration of the supply of pumps, derivation of market demand-price relations and preparation of business development plans; provision of finance for pump purchase and establishment of local repair facilities; and commencement of local operations. The satisfactory execution of these steps will depend on a blend of continuing international and local self help and private business infrastructure, and selective support from the local government.

It is considered that international aid is necessary for the satisfactory progression of the work through one more phase, for the following main reasons:

- it is the only way to obtain independent performance data;
- the field demonstration aspect would be difficult to organise without it;
- the knowledge gained can be made available to the international community;
- the governments of the developing countries have an important part to play and they need the assurance provided by an international project;
- training can be more readily provided;
- the interests of the final end user remain paramount.

4.2 Proposed International Project for Phase II

4.2.1 Objectives

The results and conclusions of the work to date, set in the context of the discussion in this Report, lead to the conclusion that one further international Phase of the Project should be undertaken, mainly devoted to a programme of field demonstrations, detailed economic analysis and the transfer of manufacturing technology. This conclusion was founded on the Consultant's view that firstly, there are circumstance in which solar pumps are already competitive with some alternative pumping techniques and will shortly be economic in their own right, and secondly, there are solar pumps good enough to warrant final evaluation in the field and demonstration of their capabilities to intending users.

The objectives of a Phase II of the Project to be funded from international sources can be summarised as follows:

- To confirm the technical, economic, financial and social conditions under which selected solar power pumping systems are able to provide a cost-effective, reliable and appropriate means of pumping water for agricultural and water supply purposes.
- To demonstrate by field trial and pilot use that selected solar powered pumping systems do provide a cost-effective, reliable and appropriate means of pumping water.
- To finalise the specifications of appropriate pumping systems taking account of the need for them to be suitable for operation, maintenance, repair, assembly and/or manufacture in the developing countries.
- To make background studies relating to the local assembly and/or manufacture on a pilot basis of suitable systems and for their distribution, manufacture and financing in appropriate developing countries.
- To prepare and issue technical and economic guidelines for purchasers and users in the selection, operation, monitoring and evaluation of solar water pumps.

It is intended that at the end of this second Phase, appropriate pumping systems will be at the stage where they are immediately suitable for pilot scale assembly/manufacture in selected developing countries. No further international support for the global project should be necessary after the end of Phase II. The market will then develop depending on normal commercial prospects, with possible aid inputs limited to assistance for specific projects, as for any other pumping technology.

Since the previous Phases have been financed by the UNDP, it is presumed that Phase II will be considered for similar funding and for convenience Phase II has been linked with UNDP.

The Consultants submitted a detailed proposal for Phase II to the World Bank in January 1983 which described a 30 month project to achieve these objectives. A vital feature of the work proposed was the active role which the local managing institutions were to play in partnership with the Consultants.

4.2.2 Field Programmes

Field testing and demonstration is a critical step in moving renewable energy technologies from the laboratory into the hands of users in developing countries and in the project proposed for Phase II the emphasis is once again on work in the field. There is a continuing need to build up experience and knowledge of technical performance and durability, reliability and life expectancy, and so to provide prospective purchasers of commercial products with reliable and independent data on performance and cost-effectiveness. However attention also needs to be paid to assessing economic, market and social viability.

Three different types of field programme are envisaged, depending on the country and available budget:

- A full field programme involving three distinct phases. Initially a technical evaluation of the systems would be completed involving performance monitoring by trained local staff, followed by central demonstrations of proven systems to selected end users and local agency staff. In the third stage, the local agency staff would complete an user orientated operational assessment of the systems following their installation in selected farms and villages.

- A limited field programme concentrating on the technical evaluation of solar pumping systems and, if appropriate, central demonstrations.

- A monitoring and evaluation programme of existing solar pumping trials incorporating aspects of technical evaluation and operational assessment. The appropriate comparative measurements could also be made of other pumping technologies used widely in the country concerned.

Particular attention would be paid to the choice of the local collaborating institutions. Technical evaluation will need to be carried out by an institution with a high level of engineering capability and resourcefulness while the operational assessments would best be carried out in association with agencies experienced in evaluating the introduction of new technology into rural areas and having a good extension service. If technical objectives are to be met, appropriate management procedures will have to be set up in each country.

4.2.3 Prospective Countries for Phase II

Joint World Bank/Consultant missions visited eight countries which were not involved in Phase I to investigate the prospects for their involvement in Phase II. The assessment was primarily based on the country's water pumping requirements and practices, its technical and economic conditions, competitive energy sources, the amount of data on key physical parameters, and the existence of suitable implementing agencies interested in participating in the Project. These visits resulted in the following recommendations:

- Brazil, and Thailand to participate in the full field programme;
- Bangladesh, Kenya and Mexico to participate in the limited field programme;
- Egypt and Pakistan to participate in the monitoring and evaluation programme.

In addition it was proposed that the Phase I host countries, Mali, Philippines and Sudan, should maintain close contact with the Consultants and participate in a modified field programme involving relocation of reliable systems to sites where they will be actively used for irrigation or water supply, or for education, training and demonstration and where some performance monitoring and operational assessment could be carried out. Some new PV systems may also need to be provided to replace Phase I systems which proved unsuccessful.

A further six countries - Botswana, China, India, Nigeria, Somalia and Zimbabwe-have been identified by the Consultants as appropriate for consideration if one of the short-listed countries does not participate.

4.3 Local Manufacture

4.3.1 Reason for and scope of study

If solar pumping systems are to realize their full potential for widespread use in developing countries, it is vital that suitable facilities are established for the repair and maintenance of solar pumps in the countries concerned. The overall aim of Phase II of the Project is to reach a stage where appropriate pumping systems could be assembled/ manufactured at pilot scale in selected developing countries and a brief study has been made of the technical, management and contractual aspects involved in setting up these repair and manufacturing facilities. The study relating to technical aspects of local manufacture concentrated on PV pumping systems, since these are further developed than thermal systems and a number of types are commercially available. General discussions were held with Project advisers and two European pump suppliers who also had experience of manufacture in developing countries on the design features, materials, manufacture and assembly processes and quality control associated with the transfer of technology to repair and make PV modules, motors, pumps and thermal systems.

Management aspects were also studied, with particular reference to the financial and contractual arrangements through which a capacity to manufacture solar pumps locally could be established. Attention was directed towards the phases in development of a local facility· how a developmental strategy could be adapted to the needs of different countries; the importance of innovation and information; and the contractual mechanisms available for technology transfer.

4.3.2 Conclusions

The study concluded that, given time, investment and training there was no intrinsic reason why high efficiency electric motors and pumps of the type appropriate for use with PV pumping systems should not be produced in developing countries with a reasonable manu- facturing base, although some special materials and components may need to be imported until demand justified a local capability.

The establishment of manufacturing facilities for photovoltaic cells would be an expensive operation. As there are a number of photovoltaic conversion processes currently under development in industrialised nations, investment decisions should be delayed for several years until the best option can be identified. In the meantime photovoltaic cells could be imported and modules assembled locally where the market is clear and cost savings will accrue.

Appropriate quality content standards must be established and enforced. Full advantage should be taken of the craft skills of local workers and manufacturing processes should be adapted to these to achieve an optimum mix of the cost of labour, plant and materials. Manufacturing technology transfer should follow a planned programme through the stages of repair, manufacture of a few frequently needed items, assembly of sub components and then components, leading eventually to complete local responsibility for the whole system.

One of the essential non-technical factors to be considered is the establishment of equitable financial and contractual arrangements which are attractive enough for a foreign manufacturer to commit himself fully to a planned programme of technology transfer while at the same time granting and maintaining rights to the recipient firm to utilise and exploit the knowledge and experience gained. The local firm should aim at acquiring a capability to appraise and select appropriate pumping systems and to develop innovative as well as productive skills. A type of Joint Venture arrangement is preferred which maintains the interest and commitment of both parties.

PART A

Scope and Purpose of Project

PART A - SCOPE AND PURPOSE OF PROJECT

1. BACKGROUND TO PROJECT

1.1 Introduction

Although the rise of oil prices has temporarily slackened, the prospect of the continuing depletion of petroleum, fuel wood and other energy sources poses horrendous problems for the developing countries. Their economic development, particularly in rural areas, inevitably calls for an increase in energy consumption. These increases are too low to be mitigated by measures which may be viable for industrialised countries (eg. conservation).

A primary and widespread energy requirement throughout the developing world results from the need for power for pumping water, both for irrigation and, even more universally, for human and livestock water supplies. The solar pumping project addressed these vital energy applications.

The traditional approach to the mechanisation and improvement of water lifting in developing countries has been through the use of petroleum fuelled internal combustion engines applied either as relatively small-scale autonomous units or, on a larger scale, through rural electrification networks. The increasing cost of petroleum fuels makes this approach increasingly unattractive, both on the micro-economic scale for the end user and on the macro-scale for the balance of payments of the economies of oil importing developing countries.

The rise in the price of petroleum based fuels is only a partial justification for giving increased attention to the use of decentralised renewable energy sources in the context of the development of the vitally important rural areas in developing countries. Other material factors which contribute to this emphasis on the utilisation of small alternative sources include, for example: encouragement of personal responsibility for use and maintenance; reduced dependence on central power facilities and long transmission lines; reduced effect of irregularity in supply of fuel; reduced dependence on third parties and improved agricultural productivity and rural health.

A number of alternative energy resources to petroleum have been demonstrated as being technically feasible in developing countries although, as a result of either the immaturity or neglect of the alternative technologies, it is only recently that a few have approached economic viability for lifting water on a small scale. More show promise of becoming viable in the future, through improvement in their efficiency and reliability, reduction in unit costs, and increases in petroleum prices.

Of the alternative energy resources available, the use of direct solar energy is of particular interest for pumping water in developing countries. Since the majority of these countries lie in the sunny tropics or sub-tropics, their pumping need often correlates closely with solar energy availability and the solar energy resource, although diffuse, is widely available and reasonably predictable.

1.2 Potential of Solar Water Pumping

The technology of solar water pumping for agricultural and water supply purposes in the developing world has been steadily advancing in recent years in response to a general recognition that, potentially, solar irradiation is a technically appropriate and economically viable source of energy for small pumps. It is normally available when the need for water is greatest, it is decentralised and can be tapped at or near its point of application.

To give the reader some feel for the range of flows, heads and powers involved in the agricultural and water supply applications, some typical values are presented in the paragraphs below.

The majority of farms in the developing world have areas in the range from 0.5 hectares to 2 hectares (Ref 1) and many villages have populations in the range from 500 to 1,500 people. The volume of irrigation water which has to be delivered to the field each day depends on a wide range of factors (including the efficiency of its use) but it is generally in the range from about 20 to 120 cubic metres per hectare per day. Corresponding peak flows are thus in the range from 1 to 6 litres per second per hectare, assuming pumping is carried out over an 8 hour period. With a static head of 5 metres the peak hydraulic output power required from the pump is typically in the range from 50 to 300 watts per hectare; these power figures will of course vary in direct proportion to the total head imposed on the system, including the energy losses associated with the water delivery system.

People living in situations where water has to be carried for a considerable distance typically consume 10 to 20 litres per capita per day, while those with water close to hand and at moderate depths may consume up to 50 litres per capita per day (Refs 2 and 3). For the design of rural water supply schemes volumes of 40 to 60 litres per capita per day have been adopted (Ref 4). At a figure of 40 litres per head, the daily volume which would have to be supplied to a village of 500 people could be around 20 cubic metres - the peak hydraulic power output of such a system, pumping through a static head of 20 metres, would be around 200 watts. A village of 1000 people where water is to be pumped through a head of 40 metres, would correspondingly need a peak power output of around 800 watts. These power outputs are well within the range provided by solar powered pumping systems.

Although it is technically feasible to produce larger power outputs, an approach which concentrates on pumping systems suitable for the irrigation needs of small farms and water supply needs of small villages has a number of real advantages. Not only is a solar pumping system usually at its most cost-effective in these circumstances (as will be shown later in the Report) but the costs of the individual pumping units are less and hence more affordable - an obvious point but one sometimes overlooked - responsibility for the efficient use of the pump and water is placed squarely on the farmer or villagers, and distribution and management of the use of the water is greatly simplified. Furthermore, a technology designed for these situations helps to focus attention on the rural poor in the developing world, a group whose lack of well-being and prosperity are major factors hindering the growth of these countries. The improvements to health, output and economic position brought about by increasing the productivity of agricultural land and by providing a reliable, safe and conveniently sited water supply are self-evident. The United Nations International Drinking Water Supply and Sanitation Decade owes its origins to a general acceptance by the international community of the fundamental importance of a reliable supply of clean water.

To be economically viable for agricultural uses, the cost of water delivered must be less than the value of the benefits obtained by use of the irrigation water, either through improved yields or by enabling a second (or even third) crop to be grown. A global norm for the economic cost ceiling for water to be delivered to the field was around US $0.06 per cubic metre in 1982, although clearly the actual figure in a particular situation will depend upon the crops grown, the field application efficiency and market prices. The best solar pumps can just meet these costs limits when pumping through very low (i.e. 2m) static heads.

Rather different conditions attach to the value of water for personal consumption and priority domestic use in villages in remote areas. For the relatively small quantities involved, people are prepared to pay exorbitant prices by world standards: whereas the typical cost of water supplied to a domestic household in the UK at a per capita consumption of around 250 litres per head per day might be US $0.40 per cubic metre, in developing countries it is by no means unusual to find people paying the equivalent of US $3 per cubic metre (or even more) for 10 to 30 litres per capita per day (see for example Refs 5 and 6). Although these prices are usually paid in remote areas, water sellers in urban areas where clean water is in short supply can also command high prices (Ref 7). This point is made, not to justify such prices, but to show that, for the small volumes required, people are prepared to pay a price many times that for irrigation water; at these figures, solar pumping systems including basic storage and distribution arrangements are already competitive by a considerable margin. There may, of course, be alternative methods which can deliver the water more cheaply than solar pumps.

Although the practical feasibility of the technology has been effectively demonstrated, not all the equipment commercially available in the past has been sufficiently simple or robust to be appropriate for use in the rigorous conditions of the developing world. The price of equipment have also been too high for it to be used on its own economic merits. However, as a result of an increasing general interest in this technology, plus the availability of independent information on performance and cost obtained through international projects, there has been a welcome improvement in the design and quality of solar water pumps and some reduction in their real costs. These trends continue and the day is now nearer when solar pumping systems and components will be available which are acceptably efficient, robust, reliable and economic and which can be repaired, maintained and assembled (or made) in developing countries.

1.3 Previous UNDP/World Bank Projects

1.3.1 General

In 1978 the UNDP and World Bank considered that the time was right to investigate the development of small-scale pumping systems for irrigation and water supply applications in developing countries which:

- are based on renewable energy sources;
- are decentralised;
- have costs low enough for small farmers;
- have minimal operational and maintenance requirements;
- have good prospects for local manufacture and/or assembly.

A project document was signed by the UNDP and World Bank in June 1978. It was decided that the work should first concentrate on the use of solar energy and its application to agriculture.

1.3.2 Phase I - UNDP Project GLO/78/004

Phase I of the Project was undertaken by the Consultants in the period July 1979 to July 1981 with the overall objective of advising the UNDP and World Bank on whether solar pumping technology was in such a position that it would be worth promoting its development to make it appropriate for pumping water under the conditions that prevail on small farms in the developing world and, if so, what steps should be taken. To that end, the Consultants undertook a State-of-Art Review (subsequently revised to form a Technical & Economic Review), organised field trials and performance measurements on solar powered pumping systems installed under typical field conditions in Mali, Sudan and the Philippines in close association with their national energy research institutions, made laboratory tests on the performance of components of the pumping systems and studied the performance of a number of feasible system options utilising mathematical modelling techniques. In all this work attention was concentrated on systems delivering flows in the range from 1 to 5 litres per second through static heads from 2 to 7 metres.

The work was reported extensively but the two principal documents issued through the UNDP and World Bank were:-

(a) Small-Scale Solar-Powered Irrigation Pumping Systems:
Phase I Project Report, July 1981.

(b) Small-Scale Solar-Powered Irrigation Pumping Systems:
Technical & Economic Review, September 1981.

A UNDP/World Bank/Ministry of Energy (Philippines) Workshop was held in Manila in June 1981 at which the results and conclusions of Phase I were presented to a group representative of the Phase I countries, additional developing countries with potential interests in solar pumping and a number of international funding agencies. (Ref 8).

The overall conclusion to emerge from Phase I was that there was indeed potential in the technology, that further technical development was required to make the systems more efficient, reliable and robust (and hence cost-effective) and that, with anticipated reductions in the real costs of the systems, there was a definite prospect that they could be used economically within a few years for irrigating areas of around 0.5 to 1.0 hectares pumping through heads of less than about 5m.

Preliminary views on a Phase II (set out in Chapter 12 of the Phase I Project Report) were discussed with the UNDP and World Bank towards the end of Phase I and it was agreed that certain preparatory work should be undertaken for Phase II in the period between April 1981 and March 1983 as UNDP Project GLO/80/003. This work constituted 'Phase II Preparation', the results and conclusions of which form the basis of this Report.

1.4 Possible Objectives of Phase II

Although one of the purposes of the Phase II Preparation Project was to consider the objectives of Phase II in the light of the work done to January 1983, it may be helpful at this stage in the Report to provide some perspective for the reader by outlining the likely basic objectives of Phase II.

It was thought that these objectives should include the following:

o to confirm the technical, economic, financial and social conditions under which selected solar powered pumping systems are able to provide a cost-effective and reliable means of pumping water for agricultural and water supply purposes;

o to demonstrate by field trial and pilot use that solar powered pumping systems do provide a cost-effective, reliable and appropriate means of pumping water,

o to finalise the specifications of appropriate pumping systems taking account of the need for them to be suitable for operation, maintenance, repair, assembly and/or manufacture in developing countries;

o to make background studies relating to the local assembly and/or manufacture on a pilot basis of suitable systems and for their distribution, manufacture and financing in suitable developing countries;

- to prepare and issue technical and economic guidelines for purchasers and views on the selection, operation, monitoring and evaluation of solar water pumps.

The scope for Phase II is considered in detail in Chapters 12, 13 and 14.

2. PHASE II PREPARATION (UNDP GLO/80/003)

2.1 General

It was envisaged that Phase II Preparation would provide a period in which to review the results and conclusions of Phase I of the Project, to study applications, economics and systems design in more detail, to confirm the objectives of Phase II and to make preparations for it.

It was agreed that the scope of Phase I had to be extended to include the water supply application as well as irrigation. It was also agreed that it was important to develop the economic study initiated in Phase I in order to provide a basis for appraising the circumstances in which solar water pumps would be likely to be economic in comparison with other lifting devices. Another important part of the preparatory work would lie in preparing performance specifications and in procuring and testing suitable systems so that they (or similar) would be available for final field tests in Phase II.

2.2 Objectives

It was agreed with the UNDP and World Bank that, working from the position reached on Phase I, the overall objectives of Phase II Preparation should be to investigate and advise on the following aspects:

- the technical and economic factors which need to be satisfied if solar pumps are to be used effectively for agricultural and water supply purposes in developing countries;
- the types of pumping system which will best satisfy these technical and economic requirements, and the possibility of procuring photovoltaic (PV) pumping systems which meet performance specifications of the type proposed in Phase I;
- the way in which local assembly and/or manufacture might be encouraged;
- the countries which should be involved in Phase II;
- the purpose of Phase II and the programme to be followed.

These objectives were formulated on the assumption that the ultimate objective of Phase II would be to develop small-scale pumping systems to the stage where they would be suitable for general use and pilot manufacture or assembly in developing countries.

2.3 Principal Activities

For management purposes the programme of work to achieve these objectives was divided into the following principal activities:

- Continuation wherever feasible of field trials initiated in Phase I and analysis of additional data.
- Study of the technical and economic factors which need to be satisfied if solar pumps are to be viable for agricultural and water supply purposes, both in general and in relation to specific countries.

- Assessment of prospective countries for participation in Phase II.
- Preparation of performance specifications and the procurement and testing of improved commercial PV pumping systems and subsystems.
- Study of further developments of components in PV systems.
- Evaluation of further developments of thermal pumping systems.
- Study of potential for assembly and / or manufacture of systems in selected developing countries.
- Report to World Bank, including recommendations for Phase II.

In contrast to Phase I in which there was major emphasis on the field trials in Mali, Sudan and the Philippines, most of the work in Phase II Preparation was completed by the Consultants in the UK. Visits to the Phase I field trial countries and the prospective countries for participation in Phase II were made as necessary.

2.4 Administration and Management

2.4.1 Contract

The World Bank, acting as executing agency for the UNDP, appointed Sir William Halcrow & Partners acting in association with the Intermediate Technology Development Group Ltd as Consultants for Phase I of the Project on 1 July 1979 under UNDP Project GLO/78/004. This original contract expired on 31 March 1981 and was subsequently extended to 31 December 1982 to cover the work to be executed under a new UNDP and World Bank Agreement GLO/80/003 entitled "Testing and Demonstration of Renewable Energy Technology: Solar Pumping - Phase II Preparation."

Throughout the period of the Contract, the Consultants worked very closely with Mr R S Dosik, New Energy Sources Adviser, World Bank and firstly with Dr E M Mitwally, UNDP Project Manager in the period up to November 1981 and subsequently with Dr M A S Malik, Renewable Energy Specialist, World Bank.

2.4.2 Consultants' organisation and management

Sir William Halcrow & Partners carried out Phase II Preparation of the Project working in association with Intermediate Technology Power Limited (an associated Company within the Intermediate Technology Development Group). The Consultants established a small executive Project Management Group responsible for all day to day matters, allocation of responsibilities, review of progress and approval of reports. Arrangements were made for specialist advice to be given by a number of leading UK experts in solar pumping technology and a Management Advisory Group was set up to provide a forum for a general review of progress and for an exchange of views and information. The names of the members of the Project Management, Management Advisory Groups and the Specialist Advisers are given in Appendix 1.

The Consultants placed contracts for the procurement of improved commercial PV pumping systems with suppliers approved by the World Bank. The Consultants established their own solar pump test facility at the offices of Sir William Halcrow and Partners located near Swindon.

Wiltshire and the majority of tests on complete systems and subsystems (motors and pumps) were carried out there. Tests on individual motors were carried out under contract by the Imperial College of Science & Technology, University of London. Some verification tests on individual PV cells were carried out at the Royal Aircraft Establishment, Farnborough. Useful informal contacts were maintained with University College, Cardiff and the University of Reading.

2.4.3 Contacts with developing countries

Contact was maintained with the energy research agencies in the countries in which the systems were installed for field trials in Phase I. These were:

o	Mali	-	Laboratoire de l'Energie Solaire (Solar Energy Laboratory - SEL) of the Direction de l'Hydraulique et de l'Energie.
o	Philippines	-	Energy Research and Development Centre of The Philippines National Oil Corporation (formerly the Centre for Non-Conventional Energy Development)
o	Sudan	-	Energy Research Institute of the National Council for Research.

As an extension to the Phase I field trials, arrangements were also made by the World Bank for the installation of monitoring instruments to measure the performance of an Arco Solar pump installed by others at the Desert Development Demonstration and Training Site of the American University in Cairo at Sadat City, Egypt.

Visits were made to each of the institutions in these four countries twice during the Project.

In addition, joint World Bank/Consultant Missions visited Bangladesh, Brazil, Egypt, Kenya, Mexico, Pakistan, Sri Lanka, and Thailand under the auspices of the UNDP to discuss their prospective participation in Phase II.

3. REPORTS

3.1 Purpose of Main Report

The work on the Project was carried out through the eight closely related activities listed in Section 2.3. This Report is based on the material prepared during each of these activities and in one unified document explains the origins of the Project, outlines what was done and why, states the assumptions which were made, presents and discusses the principal results, draws conclusions and makes recommendations, all at a length consistent with the limited compass of the Report.

The Report includes a summary of the Consultants' recommendations for the work to be done in Phase II: these were set out in full in a Proposal submitted separately to the World Bank.

3.2 Structure of Main Report

The Report gives an overview of the entire Project and is written in four parts·

Part A	Scope and Purpose of Project
Part B .	The Technology
Part C :	Economic Evaluation of Solar Water Pumps
Part D :	Advancement of Application.

A synopsis of the contents of each part is given below to assist the reader to identify those sections in the Report which are of particular interest.

Part A: Chapter 1 of this introductory part gives some background information on the scope for solar water pumps in rural development and the value of water used for irrigation and water supply and then shows how the objectives of Phase II Preparation grew from Phase I and link into Phase II. Chapter 2 traces the objectives and activities of Phase II Preparation and outlines management aspects, while Chapter 3 describes the way the Project has been reported.

Part B: Chapters 4, 5 and 6 concentrate on the technology aspects. Chapter 4 reviews the system aspects of both photovoltaic and thermodynamic pumping systems, explains the performance requirements which were established, and the criterion used to assess cost-effectiveness. Chapter 5 describes the way in which 12 photovoltaic pumping systems were procured by international tender, the test facilities and procedures used and reports on the results which were obtained. These results are then discussed and the prospects for further development of individual components are assessed. Chapter 6 reviews the present status of solar thermodynamic pumping systems and assesses the prospects for this type of pump.

Part C: Chapters 7, 8, 9 and 10 report on the economic studies. Chapter 7 sets the scene, describes the irrigation and water supply scenarios, and outlines the development of the mathematical models and the cost calculation procedures. Chapter 8 first describes the agricultural, technical and cost inputs to the irrigation studies: the results from baseline, sensitivity and country case studies are then presented and discussed. Chapter 9 deals with village and livestock water supply in a similar way. Chapter 10 presents the overall conclusions from the work, discusses them and recommends topics for additional study.

Part D: Chapters 11, 12, 13, 14 and 15 deal with a range of topics related to the advancement and responsible use of solar water pumping technology. Chapter 11 discusses strategy, the steps to be followed to advance the application and the role of international aid. The place and purpose of field programmes are discussed in Chapter 12 and proposals are made for three types of field work; institutional requirements are also noted. Chapter 13 outlines the benefits, objectives and activities of Phase II and explains the management requirements which it will impose.

Chapter 14 reviews the results of missions to eight countries to assess their suitability for participation in Phase II, while Chapter 15 looks at the technical, management and contractual questions which will need to be resolved if solar pumps are to be repaired and made in the developing countries.

Five Appendices are attached to the Report : these list the names of those involved in the study, gives typical test report on a PV pump, tabulates the cost factors used in the economic studies, give a glossary of terms and summarise the contents of the supporting documents.

3.3 Supporting Record Documents

As already explained, the Project was based on the work done in a number of related activities, each of which represented a coherent programme of work in its own right and which generated considerable written material. This material was submitted to the World Bank in preliminary draft form, but was modified as the draft of this Report was finalised. The Report cannot include all the detail which those with specialised interest in particular aspects of the work might find useful and so the written material on each activity has been prepared in an annotated report form suitable for reference by those with professional interest in the work.

The Supporting Documents are referred to by number in the text as follows:

1 Performance Tests on Improved PV Pumping Systems
2 Economic Evaluation of Solar Water Pumps
3 Potential for Improvement of PV Pumping Systems
4 Review of Solar Thermodynamic Pumping Systems
5 Manufacture of Solar Water Pumps in the Less Developed Countries
6 Potential for Field Programmes in Selected Countries
7 Proposal for Phase II
8 Program Users& Guides

A summary of the contents of each document is given in Appendix 5. They are available for reference from the World Bank.

PART B

The Technology

PART B - THE TECHNOLOGY

4. INTRODUCTION

4.1 Cost-Effective Design

Solar radiation may be converted into mechanical energy for pumping duties either by using photovoltaic cells to generate electricity to drive an electric motor or by means of thermal collectors supplying heat to a thermodynamic engine.

In either case, good design consists of matching the characteristics of all the components, including the suction and delivery pipework, to achieve the most cost-effective solution for a given solar energy input, static head and water demand and this is assessed in items of the Specific Capital Cost (see section 4.3).

In addition to having good overall performance, a cost-effective solar pumping system, whether photovoltaic or thermodynamic, must be reliable and robust, and suitable for use in rural areas with minimum maintenance. Designs are required which can be repaired and maintained locally and in time be wholly or largely manufactured in the country where they are used, to reduce foreign exchange expenditure and build-up self reliance.

4.1.1 Photovoltaic pumping systems

A photovoltaic pumping system can be relatively simple, comprising a flat-plate photovoltaic array with associated support structure (which may be portable), a dc electric motor directly coupled to a water pump, and pipework from source to delivery point, as shown in Figure 4.1. Batteries are not normally used in continuous water pumping applications, since in the longer term reservoir storage is probably cheaper to provide and easier to maintain. More complex systems, incorporating power conditioning items such as continuous electric system optimisation, or a dc-ac inverter for an ac motor may be appropriate for particular applications.

The characteristics of the main components of a photovoltaic pumping system are shown in Figure 4.2 which illustrates how the output from one component in the system is the input to the next. The effect of the consequential interactions can be evaluated using mathematical modelling techniques: a number of interesting points emerged during the Phase I studies (Refs 9 & 10).

For static heads up to about 10m, a single-stage centrifugal pump directly coupled to a dc motor may be used. Such a motor/pump combination can be designed so that it operates close to the locus of the PV array maximum power point as the solar irradiance varies; in such instances electronic power conditioning systems are not necessary. For pumping through higher heads (>10m), many types of positive displacement pump are available, but these do not have characteristics that can be readily matched directly to the PV array. In consequence, it is generally necessary to introduce a small battery or a maximum power point tracker to overcome the impedance mismatch that would otherwise arise. Alternatively, high head pumping systems may use either a high-speed single-stage centrifugal pump or a multi-stage centrifugal pump. Some manufacturers are developing dc motors that can be submerged. thereby eliminating the need for a long vertical drive shaft. Brushless dc motors are also becoming available and these should require less maintenance than the brushed type.

4.1.2 Thermodynamic pumping systems

A solar thermodynamic pumping system consists essentially of a solar collector, heat engine, transmission and pump, and delivery pipework.

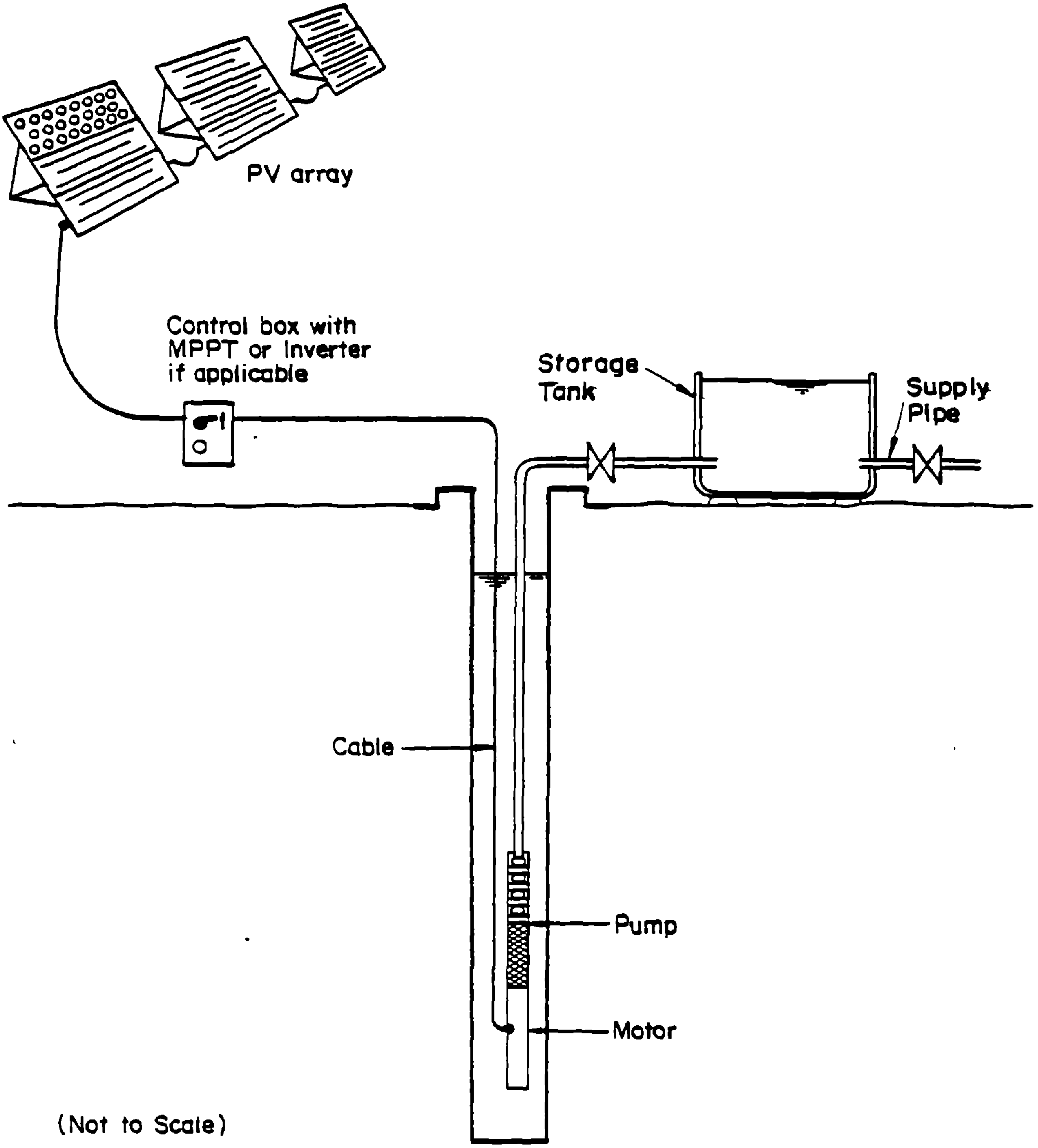


Figure 4.1 Schematic diagram of a PV Solar Pumping System

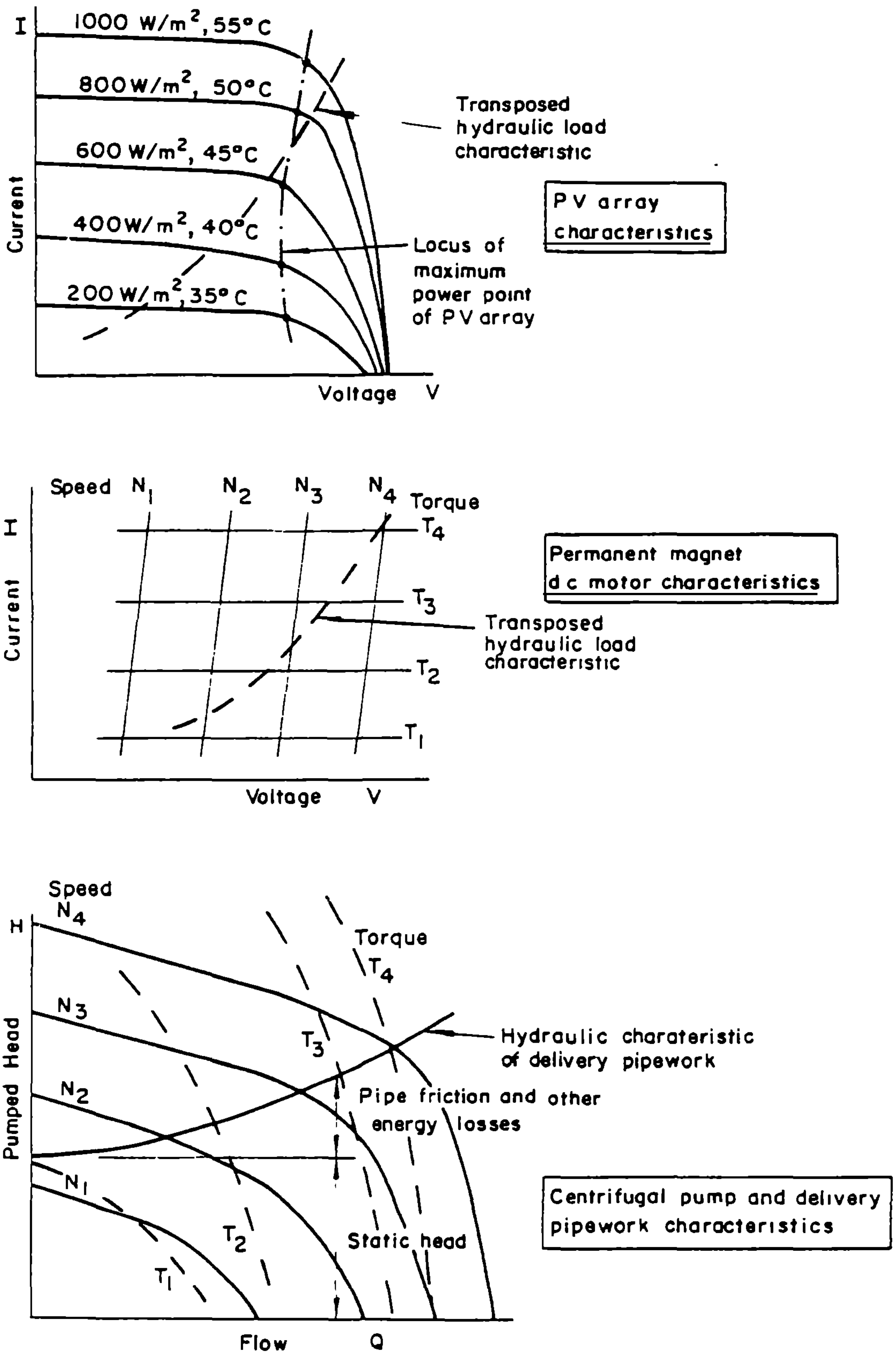


Figure 4.2 Performance Characteristics of Components of Typical PV Pumping Systems

These components are represented schematically in Figure 4.3. There is in general a wide range of options for each main component.

The solar collector may be either one of the flat plate type or employ concentrators with linear or point focus achieved either with reflecting surfaces or Fresnel lenses. Small diameter finned copper tubes have been used traditionally for transfer of heat to the working fluid in flat plate collectors, but recent developments have employed evacuated glass tubes.

The engines may utilize the Rankine (vapour) or the Stirling (gas) cycle. In the case of the Rankine cycle, the working fluid may be evaporated by heat exchange with the circulating solar collector fluid or may be directly evaporated. The fluid may be water or an organic compound where lower temperature boiling is required. The expander may be a reciprocating positive displacement type or a rotodynamic type. Systems using refrigerant 11 as a working fluid have been used successfully for low temperature energy conversion from flat plate solar collectors. The condenser may be water or air cooled.

The choice of pump is governed mainly by the speed and type of motion of the engine. Usually rotary or reciprocating positive displacement pumps are used, but some systems have employed rotodynamic pumps. The engine-to-pump transmission may be either a straightforward system of rods and levers, a more complex hydraulic arrangement, or a gearbox. Systems incorporating an electrical generator and dc motor driven pump have been demonstrated.

Some of the early commercial enthusiasm for thermodynamic pumping systems has waned, but new ideas based on a variety of design approaches are still being developed by various organisations worldwide. None are genuinely commercially available as yet, most being still at the prototype development stage. The main reason for small-scale solar thermal pumping systems being relatively less developed than photovoltaic systems is undoubtedly the high cost of developing a complete and satisfactory system. With the possible exception of the pump, few of the components are available "off the shelf" and most parts have to be purpose designed and built. Each of the many options has to be considered and the design of each component optimised.

A study was undertaken as part of Phase I of the Project to investigate the relative merits of various thermal system options. This work was continued as part of Phase II Preparation of the Project and the results of a review of recent developments and further mathematical model studies are reported in Chapter 6.

4.2 Performance Requirements

The hydraulic power output required for a specific application is given by the product of flow, fluid specific weight and pumped head. As already noted in Section 1.2, for typical small-scale irrigation applications, systems lifting water 2 to 7m and giving a peak flow of 2 to 5 l/s are required to provide a daily volume of 20 m^3 to 100 m^3 for irrigating a hectare. With a static head of 5m, the peak hydraulic power is in the range from 50 to 250 watts per hectare. For typical village water supply applications, serving populations between 500 and 1500 needing 40 litres per capita per day, the required peak flow rate is less than for irrigation, about 1 to 3 l/s, but the heads are generally higher, often more than 15m. The peak hydraulic power requirement of a village of 500 with water to be pumped through 20m is thus around 200 watts and is similar to that required for irrigation systems. However, a different type of pump would normally be appropriate and in consequence, irrigation systems cannot normally be substituted for water supply applications (and vice versa).

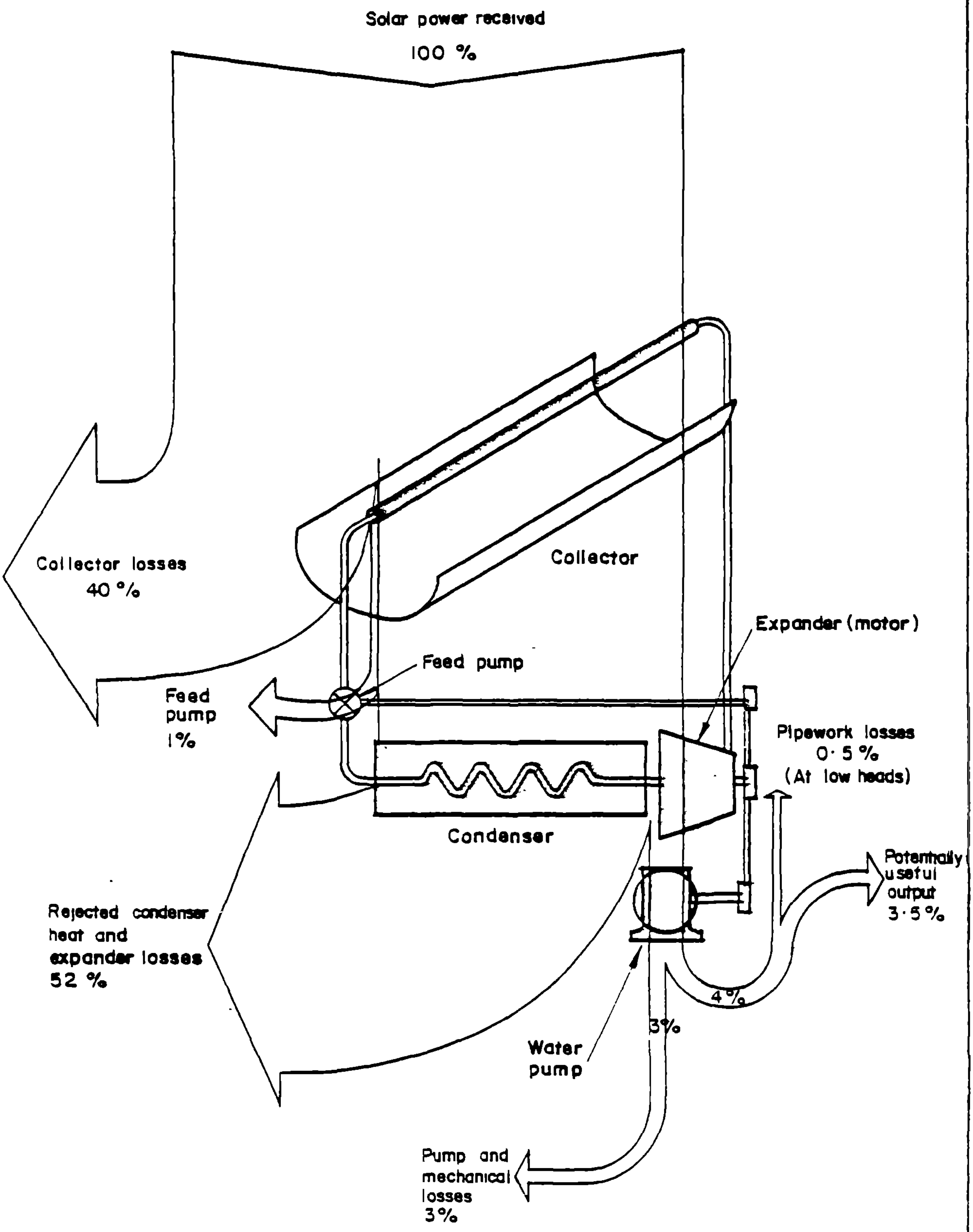


Figure 4.3 Solar Thermal Pumping System
(showing energy flows through system)

After reviewing the main pumping requirements in a number of developing countries, three main categories of solar pumping system were selected as being representative of three broad bands of hydraulic duty for irrigation and water supply applications. These were:

Category A :	intended mainly for irrigation applications: 60m^3/day output through 2m design static head.
Category B :	intended for water supply and/or irrigation applications: 60m^3/day output through 7 m design static head.
Category C :	intended mainly for water supply applications: 20m^3/day output through 20m design static head.

It was decided that these performance requirements should be met under a global solar insolation on the horizontal plane of 5.0 kWh/m^2 per day (18 MJ/m^2 per day) and an average daytime ambient temperature of 30°C. The energy incident on the array will obviously depend on its azimuth and inclination. Systems also need to operate well for conditions away from the design condition, particularly in respect of variations in static head and global irradiance. From mathematical model studies it was determined that it was feasible, although not easy, for the following requirements to be achieved by a well matched system:

a) the daily system efficiency should not be less than 75% of the system efficiency for the design conditions if the static head decreases to 75% of the design head or increases to 150% of the design head;

b) the daily system output for a daily global insolation of 4kWh/m^2 on the horizontal plane should not be less than 70% of the daily output for the design conditions (5kWh/m^2 per day).

The daily efficiency is the ratio of the hydraulic energy pumped in one day to the solar energy received by the PV array in one day. It clearly depends on the maximum instantaneous efficiency of the system, but is also heavily influenced by the part load efficiencies of the system components and the threshold irradiances at which the system starts and stops.

For certain markets it may be appropriate to modify the above performance requirements. For example, it would probably be better to adopt a daily insolation on the horizontal plane of 6 kWh/m^2 rather than 5 kWh/m^2 for countries having a desert climate.

4.3 Specific Capital Cost

A pumping system must be designed to maximise overall daily output for a given solar input. Cost-effectiveness is ultimately the determining criterion and to facilitate rapid comparison of systems, the concept of Specific Capital Cost (SCC) has been introduced to relate system capital cost to the daily hydraulic energy output. It is defined as:

$$SCC = C/\rho gVH$$

where

C = total capital cost of system (US \$)
ρ = density of water (kg/m^3)
g = gravitational acceleration (m/s^2)

V = total volume of water pumped per standard solar day (m^3)
H = static head (m)

With this definition and units, the SCC has units of dollars per joule per day, but for convenience it is expressed in this Report as dollars per kilojoule per day ($/kJ.d). Specific Capital Costs quoted in the Phase I Project Report were based on a standard solar day of 6 kWh/m^2 global insolation on the horizontal plane. It is now considered that a 5 kWh/m^2 standard solar day would be more generally appropriate and all SCC values quoted in this Report have been derived on that basis. The daily volume of water pumped by a given system under the 5kWh/m^2 condition will be some $12-20 less than under the 6kWh/m^2 condition and consequently the SCC values will be higher by a corresponding amount.

It will be noted that this definition of SCC does not take account of recurrent costs ie, operation (labour and fuel), maintenance and repair, and materials. Nor does it take account of differences in working life. Once there are reasonable data available, it will be possible to calculate the present worth of the various costs and to use this as the basis for calculation of "Specific Present Worth"; even then it will still be helpful to quote SCC values.

Values of SCC have been calculated for Project purposes on two main bases:

a) The cost of systems quoted in the tenders submitted by manufacturers to the Consultants when procuring improved PV pumping systems (the 'Tender SCC').

b) The cost of systems projected on the basis of the sum of an array cost of $5 per peak watt plus an estimate of the cost of the motors and pumps when produced in quantity (the 'Projected SCC').

The SCC values for other sets of assumptions have also been calculated to illustrate cost trends, as discussed further in Sections 5.3.7 and 5.4.

As will be appreciated, SCC values can be used to estimate the capital cost of a system required to fulfil a hydraulic performance specification written in terms of a daily volume and static head. If the static head falls into a convenient band, the SCC for that band can be converted into the cost of a system to pump a unit volume of water per standard day by the relation:

$$\text{capital cost per cubic metre per day} = \text{SCC} \times \text{Head} \times 9.81 \ (\$/m^3.d).$$

5. PHOTOVOLTAIC PUMPING SYSTEMS

5.1 Procurement of Improved Commercial Photovoltaic Systems

Under Phase I of the Project, a total of ten different photovoltaic pumping systems were subjected to field trials and laboratory tests. Each of the systems thus tested displayed shortcomings of one sort or another and, before embarking on a wider programme of field trials under Phase II, it was agreed that an intermediate phase (Phase II Preparation) was needed to see whether improved pumping system had been or could be developed to meet performance specifications developed in Phase I, and to procure and test such systems under controlled conditions. This would reduce the risk of sending unsatisfactory equipment to the countries selected for future field trials and provide an important stimulus to manufacturers and system suppliers to develop better systems.

After considering the likely markets and applications, the three categories of system referred to in Section 4.2 were introduced, with their associated requirements relating to performance for reduced solar input or changed static head. In November and December 1981, suppliers of photovoltaic pumping systems were invited to register their interest in tendering for systems in one or more of the three categories. Advertisements were placed in a number of international journals, including 'UNDP Development Forum' and 'World Solar Markets' and, in addition, the UK embassies of all the countries being considered for participation in Phase II were asked to inform local manufacturers of pumps and solar equipment. The invitation was also reported in the technical press. A total of 62 organisations responded to these approaches and invitations.

Detailed recommendations on the design and construction of photovoltaic pumping systems had been prepared as part of Phase I and these were included in the tender documents along with Instructions to Tenderers, Specification, General Conditions, Questionnaire and Schedules. Copies of the documents were issued in early January 1982 to all who had requested them. Tenders were submitted by the end of February 1982.

The number of tenders, including alternatives, received for each of the three categories was as follows:

Category A . 18
Category B : 25
Category C : 21

A list is given in Table 5.1 of the organisations who were sent tender documents and who submitted tenders and supporting information.

A detailed assessment of each tender was made under the following four headings, with the relative importance ascribed to each heading being indicated by a weighting factor·

a) Compliance with Specification - weighting 30%

- o The output of the system was assessed in relation to the relevant category, taking into account any deviations from the Specification proposed by the tenderer.
- o The overall daily efficiency of the system and the subsystem was calculated.

b) System design - weighting 30%

- o The suitability of the equipment for the intended use was assessed, taking into account operation and maintenance requirements, general complexity, safety features, potential for local manufacture and, in the case of Category A, portability.

Companies to whom documents were sent	Country	Tenders Received Date Received	No of Systems Offered System A	System B	System C	Joint Tender with	Remarks
ACEC	Belgium						
AEG Telefunken	W.Germany	1.3.82	1	1	1		
Akai Impex Pvt. Limited	India						
Ansaldo	Italy						
Arco Solar Europe	Italy						
Arco Solar Inc.	USA						
Arco Solar (FE) Pte Limited	Singapore						
Azorim	Israel						Telex tender received, then withdrawn.
Belgonucleaire SA	Belgium						
Brisu SA	France						
Brooke Crompton Parkinson Motors	Great Britain						
Central Sun Supply	USA						
ENE	Belgium	1.3.82			1		
GEC Power Eng. Limited	Great Britain						
Grundfos A/S	Denmark	1.3.82	1	2	1		
Heliodinamica	Brazil	8.3.82		1	1		
Holecsol	The Netherlands	1.3.82		1	1		
IDE	Belgium	26.2.82		1			
Insto Foundation	The Netherlands	26.2.82			1	Jansen Venneboer	
Intersol Power Corp.	USA	26.2.82		1		Star Light Energy Tech.	
Jansen Venneboer	The Netherlands						
Jyoti Limited	India						
Klein, Schanzlin & Becker	W. Germany	23 2.82	1	2			
Wm. Lamb Co	USA	26.2.82			3		
Lowara	Italy						
Lucas BP Solar	Great Britain	26.2.82		1			
A Y McDonald	USA						
Meghraj Machines Pvt. Limited	India						
Monegon Limited	USA	1.3.82	1				
Mono Pumps Limited	Great Britain						Declined to tender.
(Motorola Inc) Solavolt	USA	1.3.82			1		
Nipha Exports (P) Limited	India						
Nolte BV	The Netherlands						Declined to tender.
Omera-Segid	France	4.3.82	2	1			
Pasan SA	Switzerland						
Philips Electronic Components and Materials	Australia						
Photon Power Inc.	USA						
Photowatt International SA	France	8.3 82	1	2	1		
Pilkington Solarproducts Limited	Great Britain						
(Pompes Guinard) Solar Force	France	1.3 82	1	1	2		
Pragma SpA	Italy						
Renewable Energy Systems	USA	1.3.82	1	1	1		
Sharp Corporation	Japan						
Siemens AG	W Germany	26.2.82			1	K.S.B.	
Sofretes/Mengin	France	26 2.82			1	Solar Power Corporation	
Solact	Malta						
Solamat Inc.	USA	1.3.82	1	1			
Solapak Limited	Great Britain	26.2.82	2	3	2		
Solar Electric International	Great Britain	26.2.82	1	1		Solar Power Corporation	
Solarex Corporation	USA						
Solar Power Corporation	USA						
Solex Interantional Inc.	USA						
Solenergy International Corp.	USA						
Sun Power Co.	USA						
Sotorem	France	2.3.82	1	1			
Star Light Energy Technology	USA						
Sunpump Co.	USA						
TPK Solar Systems Inc.	Canada	1.3.82	1				
Trisolar Corp.	USA	26 2.82	3	3	3		
UP National Manufacturing Pvt. Limited	India						Offered motor/pump only
Venture Technology Limited	Great Britain						
Worthington-Simpson Limited	Great Britain	1.3.82		1			
TOTAL NUMBER OF TENDERS Sent: 62 Received: 26		NO OF SYSTEMS	18	25	21		

Table 5.1 Distribution of Tender Documents

o The equipment life was assessed with regard to bearings, brushes and other parts liable to wear and tear.

c) Specific Capital Cost - weighting 30%

o The Specific Capital Cost (SCC) was calculated for quantity production based on a photovoltaic array price of US $5.00 per peak watt and subsystem prices estimated by the manufacturer for orders of 100 units or more (the projected SCC). It was felt fairer to let each manufacturer's estimates of quantity production cost stand without any attempt by the Consultant at adjustment. This figure indicates what it is believed could be achieved for the system in question within a few years, when photovoltaic array costs have fallen further.

o The Specific Capital Cost based on the tender price (the tender SCC) was also calculated but only limited account of this was taken in the tender assessment since some manufacturers had clearly submitted subsidised prices, whereas others had included a large proportion of their development costs.

d) Overall credibility of tender - weighting 10%

o The amount and content of the information supplied to support the tender was assessed, in particular the provision of general assembly drawings and performance information.

o The experience and resources of the tenderer relevant to solar pumping technology in developing countries was assessed.

For each of the above headings, each system was rated 'Very Good', 'Good', 'Fair' and 'Poor'. An overall rating was then derived, taking into account the weighting factor, except that any tender which was rated 'Poor' against any of the first three headings was also given an overall rating of Poor. Table 5.2 gives an overall summary of the systems tendered.

The next step was to prepare a short list by selecting all systems given an overall rating of 'Very Good' or 'Good' This resulted in six systems being short listed in Category A, eight systems in Category B and six systems in Category C.

Ideally, it would have been worthwhile to test all the systems short listed, to check manufacturers' claims and determine the expected performance of the systems under the range of conditions likely to be encountered in the field (eg, varying solar energy input and water level). Budget and time constraints ruled out such an ambitious testing programme and it was necessary to identify the systems that showed the most promise or were most representative of different design approaches.

It was generally agreed that thorough testing of subsystems under controlled laboratory conditions in the UK would provide adequate data with which to determine the performance of the corresponding complete system at any location where the environmental conditions were known or could be estimated. The performance of photovoltaic arrays is well understood and in most cases the modules have already been subjected to independent testing either in Europe (at JRC, Ispra) or in the USA (at JPL, California).

After discussions with the World Bank, it was decided that six complete systems should be purchased for testing, two from each category, as originally proposed, plus a further six subsystems (complete systems less their photovoltaic arrays). All 12 systems could then be tested in a similar way using a photovoltaic array output simulator (see Section 5.2 below).

TECHNICAL FEATURES		CATEGORY A	CATEGORY B	CATEGORY C
		60m^3/d output 2m head	60m^3/d output 7m head	20m^3/d output 20m head
Rated array power range	W	105 to 792	480 to 1120	555 to 1440
Sun following arrays (non-manual)	No	1	2	0
Concentrator arrays	No	0	1	0
Surface suction pumps	No	8	7	1
Floating motor-pump sets	No	4	7	0
Submerged single or multi-stage centrifugal dc motor pump sets	No	1	3	5
Submerged single or multi-stage centrifugal ac motor pump sets	No	1	3	6
Submerged multi-stage centrifugal pump/surface dc motor	No	3	5	0
Positive displacement submerged well pump	No	1	0	9
Systems with maximum power trackers	No	5	4	7
System with batteries	No	1	2	1
TOTAL DC SYSTEMS	No	17	22	15
TOTAL AC SYSTEMS	No	1	3	6
System tender cost range (FOB)	$	2.860 to 27,800	8.440 to 31,000	7,270 to 69.750

Table 5.2 Improved Commercial Systems Tendered in 1982

To supplement and validate the subsystem testing it was agreed that, in addition, there would be sunshine testing of the six complete systems, although it was recognised that the solar irradiance levels and ambient temperature conditions in the UK would be somewhat different from tropical sites.

The final selection of equipment for testing is given in Table 5.3, which also lists the date of order and the date of delivery to the Consultants' Solar Pump Test Centre near Swindon, UK. In general only systems of proven design or from suppliers well experienced in solar pumping technology were selected, but exceptions to this principle were made in the case of two Category A systems which had features of particular interest. One of these was the TPK system which incorporated a positive displacement reciprocating pump made up largely from standard PVC pipe sections, well suited for local manufacture if the system performance met expectations. The other was the Monegon positive displacement rotary pump which offered a compact highly efficient design with very low Specific Capital Cost if its performance met the specification.

Prior to delivery, the Consultants made visits to all but one of the suppliers to witness acceptance tests on the system or subsystem. One subsystem was delivered before an inspection visit could be arranged.

It should also be noted that the Category C system offered by Wm. Lamb was accepted on the basis of an output of 15 m^3/day at a design static head of 20m, instead of the specified 20 m^3/day. This was because the system offered was a standard production model with which the supplier had reported good experience.

5.2 System Testing

5.2.1 Test facilities

Solar Pump Test Facility

One of the lessons to come out of Phase I of the Project was the strong desirability of testing solar pumping systems under controlled conditions before being sent for field trial. The initial proposal was that a suitable test site should be established in Southern Europe or possibly North Africa, but it soon became clear that the cost of equipping, maintaining and staffing such a centre would be prohibitive.

Following discussions with the World Bank, the Consultants decided in March 1982 to establish their own purpose-built solar pump test facility in the grounds of the offices of Sir William Halcrow and Partners near Swindon, UK. By the end of August 1982, the test facility was ready for use, equipped as follows to reproduce as closely as possible field conditions:

- large area for the erection of photovoltaic arrays, within an existing walled garden for security;
- 25m deep, 300mm diameter watertight borehole;
- 2m deep, 2m square sump;
- 18m high tower with suspended delivery tank for the imposition of the necessary static delivery head,
- pipework between borehole/sump and delivery tank,
- flow meters of various sizes and flow meter calibration tank;
- photovoltaic array output simulator to provide a dc current and voltage input to a subsystem matching that given by an actual array under given solar irradiance and ambient temperature conditions,

System			Array				Motor		Pump			
Supplier (Country)	Complete System Tender Price FOB (1982 $)	Claimed Output(1) m^3/day	Manufacturer (Country)	Type	No of Modules in Series (S) and in Parallel(P)	Nominal Power Wp (12)	Manufacturer (Country)	Model or Type and Spec	Manufacture (Country)	Model or Type and Spec	Date System Ordered Day/Mo/Yr	Date System delivered Day/Mo/Year
CATEGORY A												
Monegon (USA)	2860(2)	50	Solarex(2) (USA)	5300 SG	3S x 1P or 1S x 3P	105	Remond (USA)	PMDC(3)Type E25-2A 12V	Everest	Gear	5 4 82	27 5 82
Solar Electric International (Malta)	6000	140	Solar Power (USA)	LG 12-250(11)	3S x 3P	351	AEG (FR Germany)	PM brushless 360W,2735 RPM	KSB (FR Germany)	Aquasol 100 L floating centrifugal	6 4 82	13 10 82
Solamat (USA)	8965(2)	75	Arco Solar(2) (USA)	ASI 16-2300	3S x 2P	222	Honeywell (USA)	PMDC type BA 3624-3349-56	Berkeley (USA)	B11/2MPKS self priming Surface pump	20 4 82	4 8 82
TPK (Canada)	4680	60	TPK		(5)	210	Boston Gear (Canada)	90U, 194W PMDC	TPK	all plastic PDRD(6)	5 4 82	2 9 82
CATEGORY B												
AEG(7) FR Germany)	10150	62	AEG	PQ 10/20/0(8)	8S x 4P	614	Engel (FR Germany)	GNM 7045 67V PMDC	Loewe (FR Germany)	submerged centrifugal pump on floating unit	6 4 82	13 9 82
Heliodinamica (Brazil)	14360(2)	67	Heliodinamica(2) Brazil	HFP19815	5S x 9P	882	Honeywell (Brazil)	modified type SR5316-2546 PMDC	Jacuzzi (Brazil)	plastic self priming surface mounted	19 4 82	28 9 82
KSB(9) (FR Germany)	8440	60	Arco Solar (USA)	ASI 16 2300	4S x3P	480	AEG (FR Germany)	PM brushless 360W, 3450 RPM	KSB (FR Germany)	Aquasol 50 M Floating centrifugal	5 4 82	16 9 82
Solar Force (France)	22240(2)	62	France-Photon(2) (France)	G76	11S x 1P	836	Leroy-Somer (France)	M71 A 150 PMDC	Pompes Guinard (France)	Alta X F6-5-73 submerged centrifugal	5 4 82	10 11 82
CATEGORY C												
Grundfos (Denmark)	13360	31	Arco Solar (USA)	M51(11)	7S x 3P	840	Grundfos	MS 401 3 phase ac motor with inverter	Grundfos	Sp4-8 multistage centrifugal	5 4 82	19 8 82
Wm Lamb (USA)	14470	15	Arco Solar (USA)	ASI 16-2300(11)	5S x 3P	555	Honeywell (USA)	BA 3640-3412-56B 390W PMDC	Baker (USA)	reciprocating borehole	5 4 82	17 7 82
Sofretes (France)	21050(2)	20	Solar Power Corp(2) (USA)	LG 12-351	6S x 5P	990	CEM (France)	PMDC with magnetic coupling	Jellen & Mege (France)	A410Fo5 multistage centrifugal	5 4 82	3 9 82
Trisolar Corp (USA)	25500(2)	23	Solar Power Corp(2)	LG 12-351	9S x 2P	540	Honeywell (USA)	PV 5316-3597-56BC PMDC with MPPT(10)	Baker (USA)	reciprocating borehole	5 4 82	16 9 82

NOTES
(1) See Section 6 for measured performance
(2) Only subsystem ordered so array not tested
(3) PMDC = Permanent Magnet Direct Current
(4) Model 350L
(5) 3S x 2P low mode, 2S x 3P high mode
(6) PDRP = Positive Displacement Reciprocating Pump
(7) Model Swimpump 400
(8) Incorporating polycrystalline silicon cells
(9) Type "Aquasol" 50
(10) MPPT = Maximum Power Point Tracker
(11) Different from equipment tendered
(12) Powers quoted correspond to arrays delivered in case of complete systems or motor/pump suppliers recommendations in case of subsystems

Table 5.3 Equipment Selected for Testing

- instruments to record solar irradiance, current and voltage from array and to the sub-system, suction and delivery heads, static head, pump speed, flow rate and ambient and array temperatures;
- data logging and analysis equipment, based on micro-computer with disc data storage and dot matrix printer.

A schematic diagram of the test rig is given in Figure 5.1. Some general views of the test facility are shown in Figures 5.2 to 5.5.

The provision of the correct lengths of pipework and suction and delivery heads ensured that inertial effects due to acceleration and deceleration of the water columns when testing reciprocating pumps were taken into account.

Photovoltaic Array Output Simulator

The photovoltaic array output simulator was specially developed under sub-contract to the Consultants by the Department of Electrical Engineering of the Imperial College of Science and Technology, University of London. The current-voltage output (I-V characteristic) of a single photovoltaic pilot cell under conditions of constant illumination and temperature is amplified to produce the I-V characteristic that would be produced by an actual array under specified irradiance and ambient temperature. The special feature of the simulator is that it will produce the required I-V characteristics under transient conditions, thus making it possible realistically to test systems which need to 'hunt' the I-V curve (eg, reciprocating systems or those with electronic maximum power controllers). After overcoming the problems to be expected with the first prototype of a very sophisticated piece of electronic/electrical control engineering equipment, the simulator worked reliably.

The short circuit current (Isc) and open circuit voltage (Voc) of the simulator output are separately adjustable. The shape of the I-V curve connecting the Isc and Voc intercepts exactly follows the shape of the I-V curve for the pilot cell: ie, the Fill Factor remains the same. The Voc can be set to any value up to a maximum of 250V and the Isc can be set to any value up to a maximum of 27A. The Fill Factor depends on the quality of the pilot cell (several pilot cells provided by system suppliers were found to have very low Fill Factors) but for most tests a pilot cell with about 70% Fill Factor was used, close to the value expected for the actual arrays being simulated.

The Isc and Voc values for a given array for different irradiance levels are calculated using data supplied by the manufacturer for the particular modules used for his system. The typical module performance data was usually supported by independent testing carried out by the Jet Propulsion Laboratory, Pasadena, California, USA or the European Communities Joint Research Centre, Ispra, Italy.

Using NOCT (nominal operating cell temperature) data, the operating cell temperature for each irradiance is calculated for the ambient temperature specified in the tender documents, namely 30°C, using the relationship:

$$Tc = 30 + (NOCT-20)G/800$$

where

Tc = cell temperature in degrees Celsius for irradiance G W/m^2
NOCT = nominal operating cell temperature, for 20°C ambient temperature, 800 W/m^2 irradiance, 1 m/s wind speed
G = irradiance in W/m^2

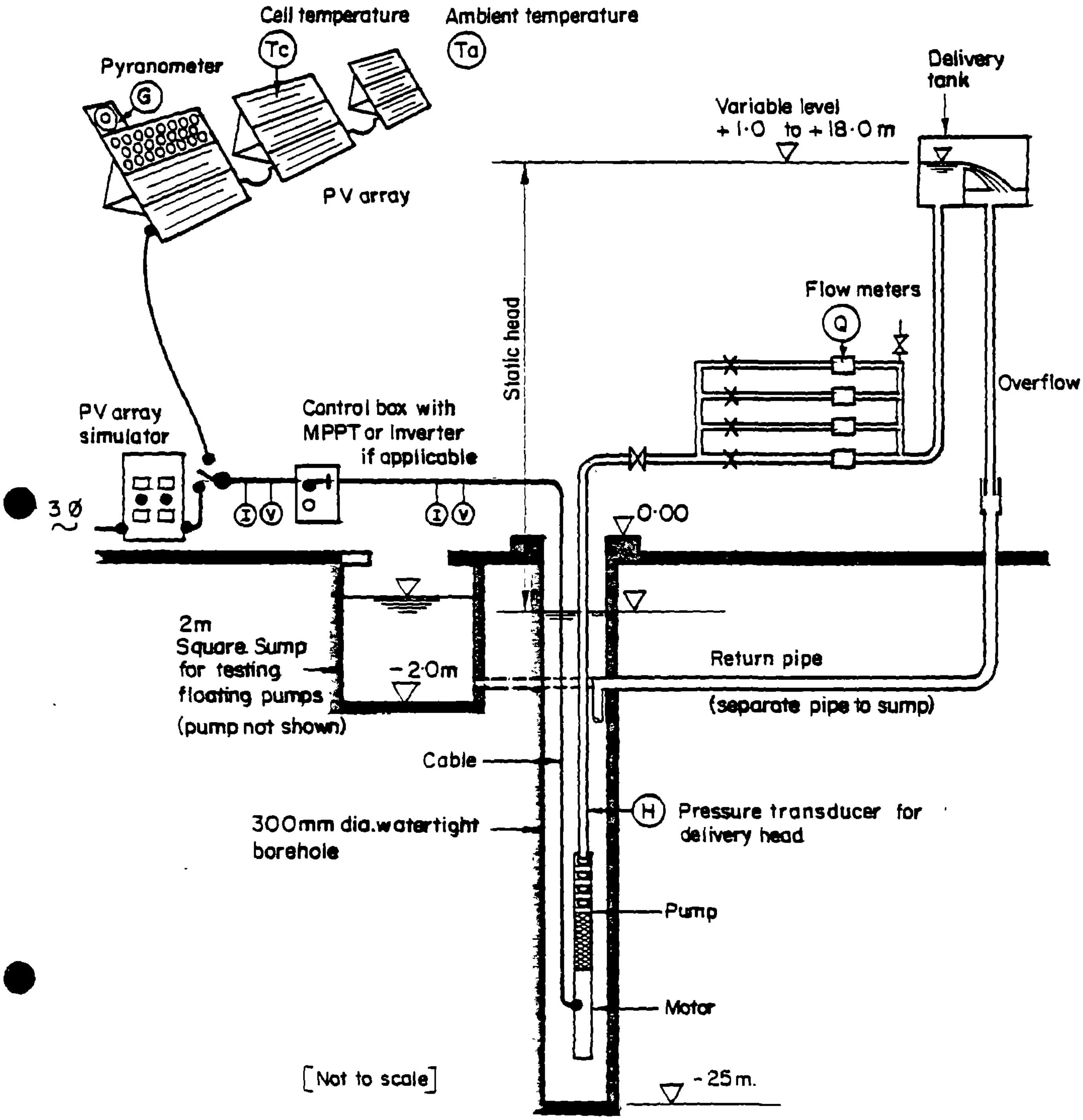


Figure 5 1 Schematic layout of Solar Pump Test Facility

Figure 5.2 Solar Pump Test Facility – Office and base of 18m high mast showing delivery tank

Figure 5.3 Solar Pump Test Facility – Pump housing for 25m deep borehole and 2m deep sump

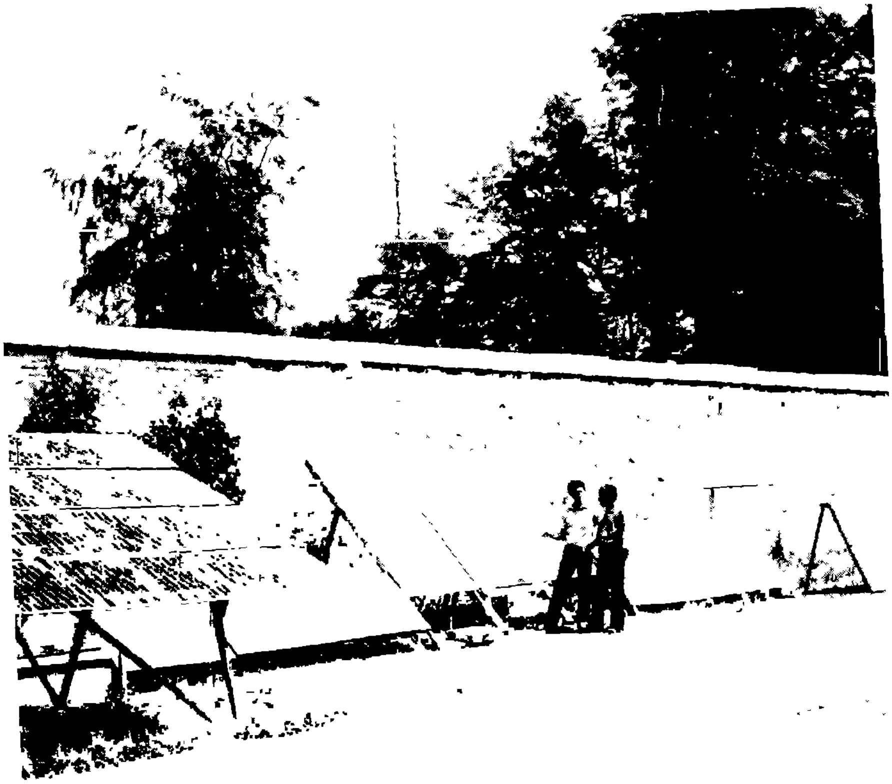


Figure 5.4 Solar Pump Test Facility – Photovoltaic arrays

Figure 5.5 Solar Pump Facility – Data Logger and analysis equipment

Module performance is normally quoted for a cell temperature of 25°C. Using the temperature coefficients given by the manufacturer, appropriate corrections were made to the Voc and Isc values to produce the I-V curves corresponding to each irradiance and associated cell temperature.

For each system, a set of I-V curves was produced for values of irradiance in the plane of the array from 100 W/m^2 to 1000 W/m^2, in increments of 100 W/m^2. The shape of the curves connecting the pairs of Isc, Voc values was based on test data supplied by the array manufacturer. A typical example of the set of curves thus produced is shown in Figure 5.6.

For each simulator test run, the simulator output I-V curve was set to give the required Isc and Voc values. In general, the shape of the curve connecting these two points differed to a small extent from that required, due to the Fill Factor of the pilot cell used in the simulator being different from that appropriate for the array being simulated. Due allowance was made for this difference by carrying out a second order correction to the irradiance value once the I and V values of the operating point were found. The basis of the correction involved is illustrated in Figure 5.7.

Validation of simulator output

It should be noted that the resulting I-V curves which were set on the simulator for each irradiance and associated cell temperature assume a perfect array, with no module mis-match losses, diode losses (other than diodes incorporated in the modules) and wiring losses. These losses typically amount to 2-3% of the nominal array power and thus the system performance predicted on the basis of simulator test results may be slightly <u>over</u>estimated as far as these losses are concerned.

In addition to this difference between the simulator and a real array, allowance must also be made for the difference between the ambient temperature assumed for the simulator setting and the actual ambient temperature obtaining during the sunshine tests.

The simulator I-V characteristics were derived on the basis of a constant ambient temperature of 30°C, whereas the ambient temperature for the sunshine tests was considerably less, on occasions as low as 2°C, and variable. As the ambient temperature and hence cell temperature rises, Isc increases slightly and Voc decreases significantly. The maximum array power is typically 5 - 8% lower for an ambient temperature of 30°C than for 15°C; thus the output of a subsystem with 30°C simulated array input will be expected to be <u>lower</u> than that of a complete system under sunshine test whose array is at a lower temperature.

These two effects counteracted each other and the simulator test results were found to be in close agreement with the sunshine test results, as may be illustrated by Figures 5.8 and 5.9, which show results for the Grundfos system for 15m and 20m heads respectively and an ambient air temperature of 30°C for the simulator test and 11-17°C for the sunshine test. The flow rates recorded in the simulator tests are within 3% of those recorded for sunshine tests.

There is apparently a much wider divergence between the simulator and sunshine results for the SEI system, as shown in Figure 5.10, but the difference can be accounted for when allowance is made for the much greater difference in ambient temperature (30°C for simulator test, 2°C for the sunshine test).

These and other similar comparisons provided the necessary evidence to validate the simulator approach. Although developed primarily for the pump testing programme, the photovoltaic array output simulator provides a convenient method of testing other photovoltaic systems such as refrigerators and battery chargers under the full range of irradiance and temperature conditions that might be encountered anywhere in the world.

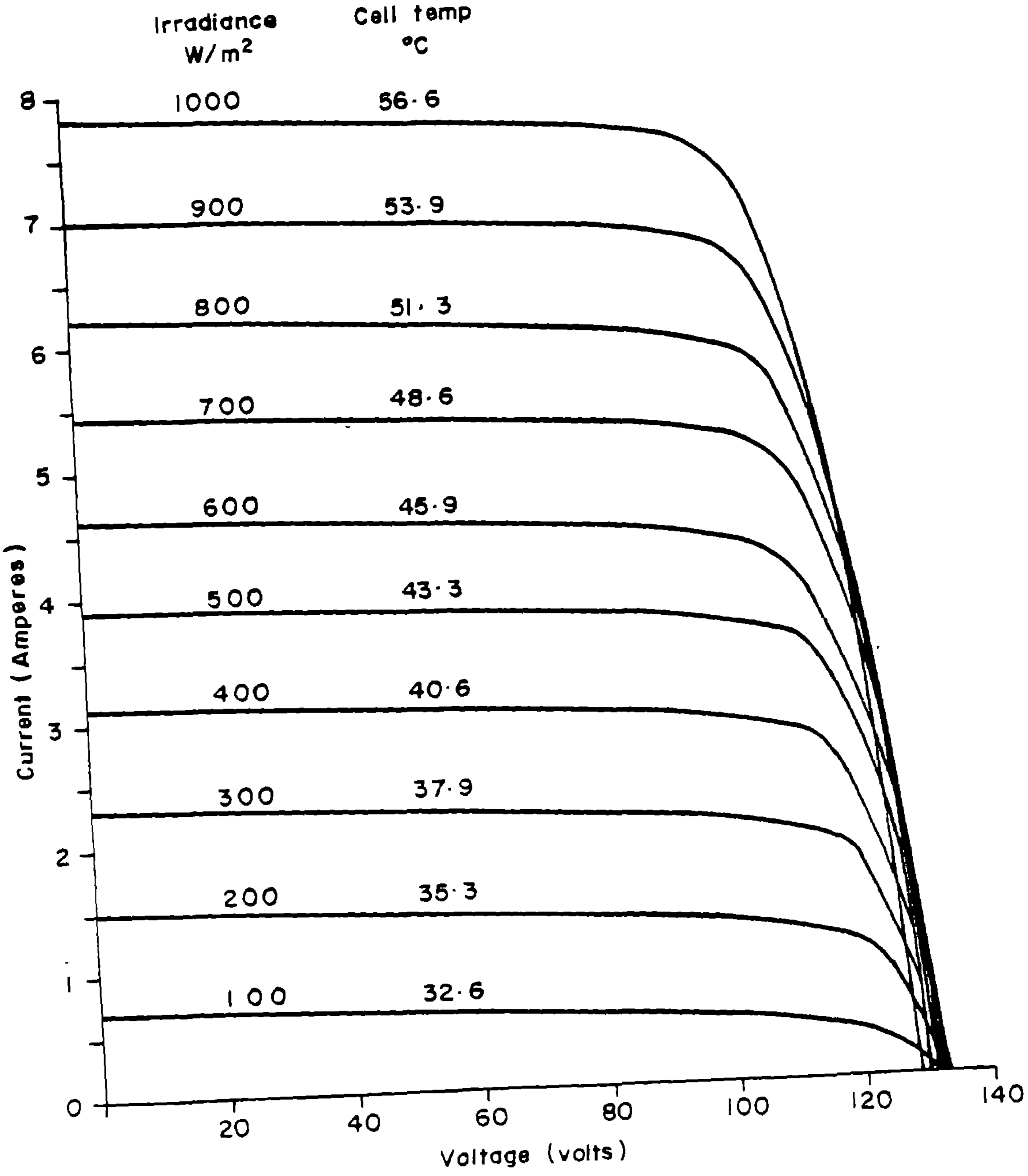


Figure 5.6 Typical set of I-V curves for complete array

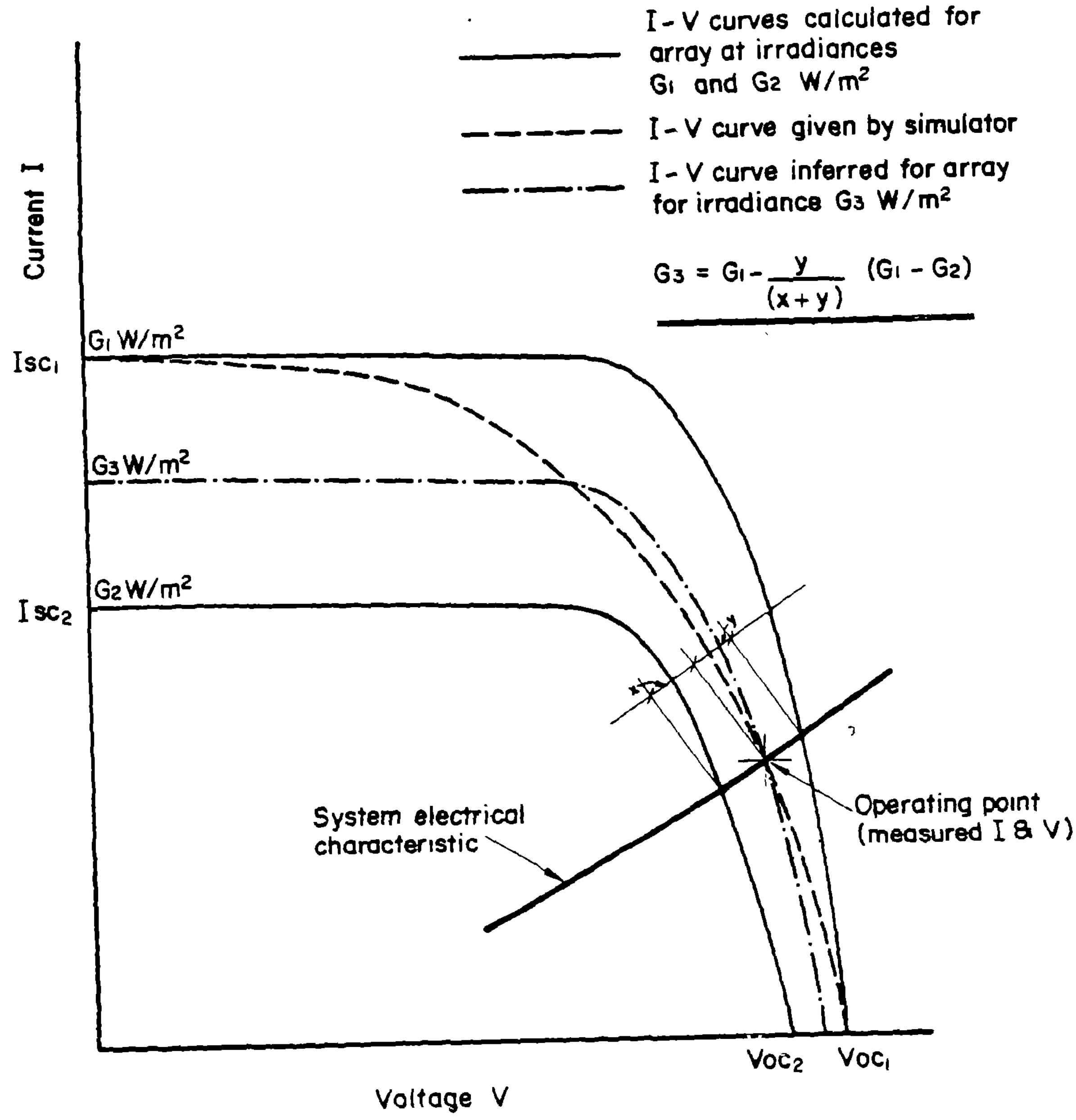


Figure 5.7 Derivation of Accurate Equivalent Irradiance Value when using Simulator

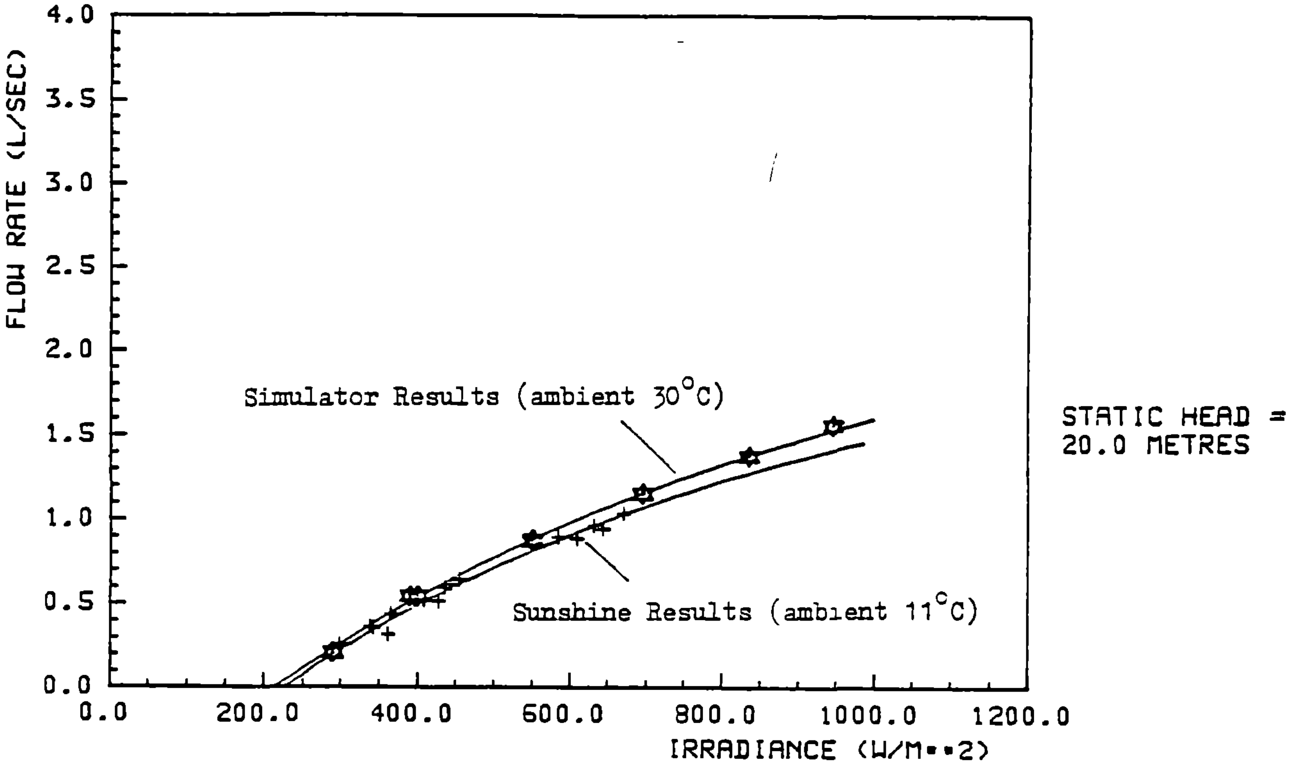


Figure 5.8 Comparison between simulator and sunshine test results for Grundfos system for 20m head

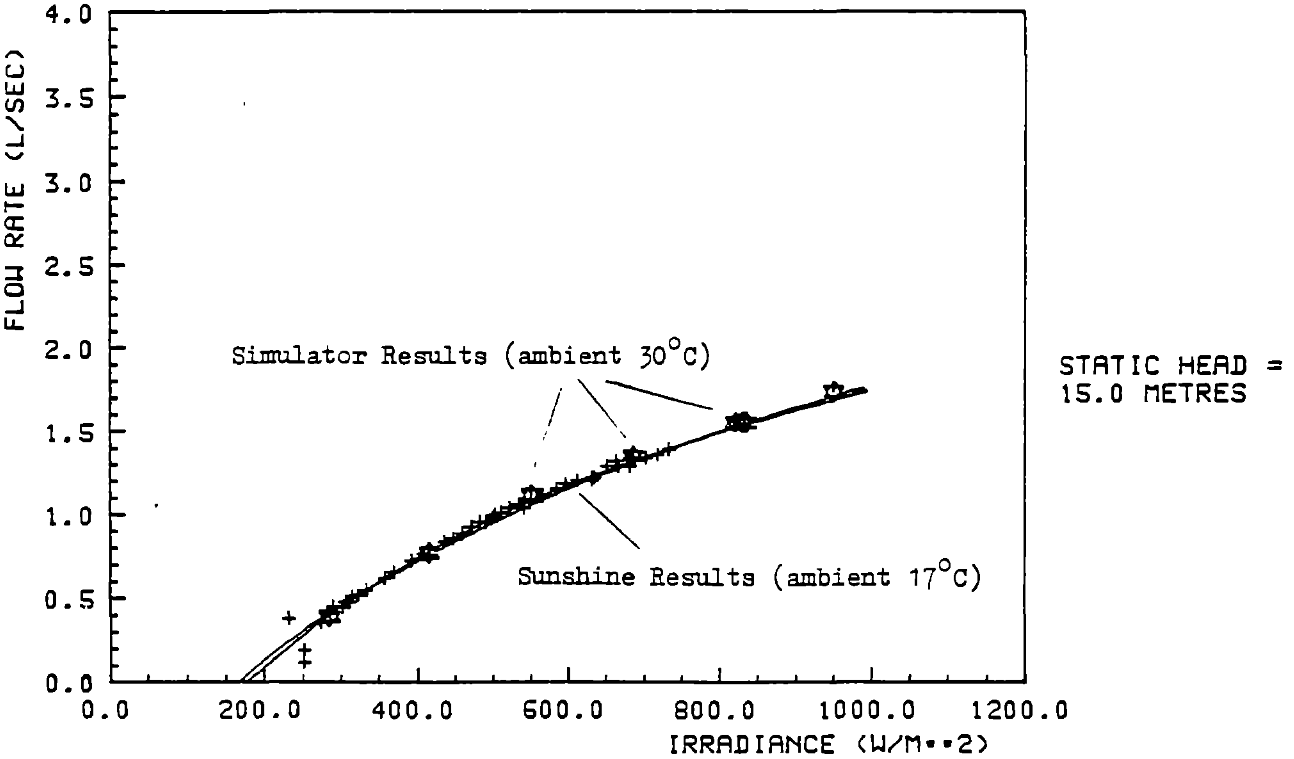


Figure 5.9 Comparison between simulator and sunshine test results for Grundfos system for 15m head

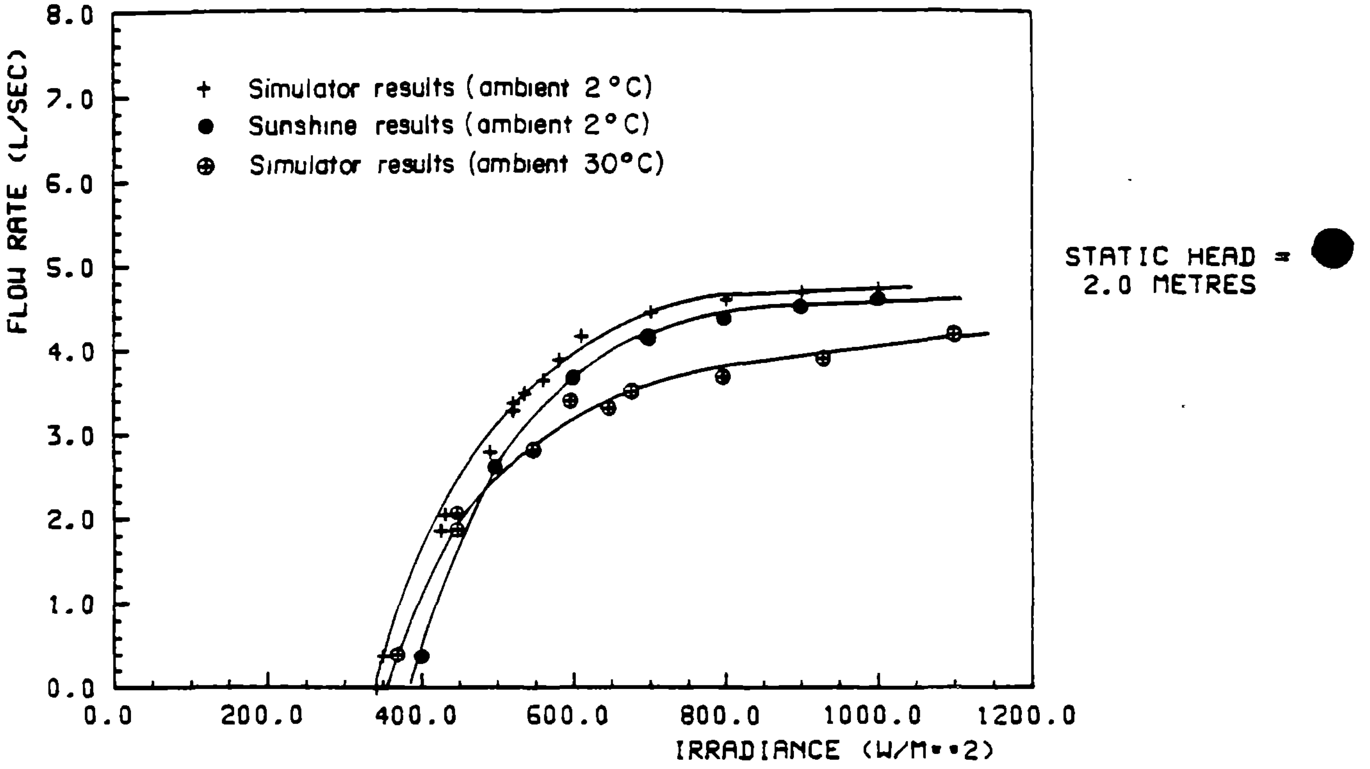


Figure 5.10 Comparison between simulator and sunshine test results for SEI system for 2m head

Motor test facility

In addition to testing complete pumping systems in natural sunlight and subsystems using the simulator, performance tests were also conducted on individual electric motors, to provide more information on subsystem performance and an insight into pump efficiencies. The motor tests were undertaken at Imperial College, London, using a modified version of the dynamometer test rig originally constructed for similar motor tests carried out in Phase I.

5.2.2 Test procedures for simulator and sunshine tests

Full details of the test procedures with simulator and sunshine are given in Supporting Document 1.

The systems were installed on the basis of the manufacturer's instructions. Every precaution was taken when setting the systems up for test to follow these instructions, but as the Consultants were, in effect, standing as proxy for potential users in remote areas of developing countries, no special attempts were made to 'fine tune' or modify systems to correct design faults or to try to improve performance. A careful note was made of any particular problems encountered during installation and operation.

Results for each system were prepared in the form of curves of Flow against Irradiance in the plane of the array for each value of static head. These curves were then used to derive the variation in flow through a Standard Solar Day assuming the array was inclined at 20^{o} (the specified latitude) and orientated North-South. (Note that 2 Standard Solar Days were used with horizontal plane insolation values of $4kWh/m^2$ and $5kWh/m^2$. Hourly values of irradiance in the plane of the array were calculated using the specified diffuse/direct irradiance values).

Curves could thus be prepared of Flow against Time of Day for:

- Design static head and $5kWh/m^2$ standard solar day
- 75% design static head and $5kWh/m^2$ standard solar day
- 150% design static head and $5kWh/m^2$ standard solar day
- Design static head and $4kWh/m^2$ standard solar day.

For each of these curves, the total volume pumped per day and overall daily efficiency (based on insolation in plane of array and gross area of the modules making up the array) was computed and the results compared with the values specified in the tender documents.

Special computer programs were developed to analyse the data gathered for each test run and to plot the curves required. Regular calibration checks were made of all instruments apart from the pyranometer, which being a WMO Class 1 instrument was assumed to remain stable for the duration of the tests. All instruments were considered to be accurate to within 1% of full scale readings: since the lowest readings were about 1/3 of full scale, an individual reading could be in error by up to 3%. The RMS value of the error in efficiency could be of the order of ± 6% at worst, but since it is not likely that all readings will have been at low scale simultaneously, the general order of error will be less than this.

5.2.3 Procedure for motor tests

Two electric motors could not be separately tested, because they required continuous water cooling or needed variable frequency ac supplies. The re-maining ten motors were mounted on a dynamometer test rig and loaded by connecting the drive shaft to an ac alternator through a pulley drive. The output from the alternator was absorbed in a simple variable resistance load.

The following parameters were logged:

- dc voltage, V (stepped in increments of about 10V from 10V to rated voltage) (Volts)
- current, I (Amperes)
- torque, T (Nm)
- speed, N (Hz or rpm)

The data were then used to derive the characteristic equations for the dc motors, generally in the form:

$$V = aN + bI + B$$
$$T = 60\,(aIN - P)/\,2\pi N$$

in which $P = c + dN + eN^2$
and V = voltage (volts)
I = current (Amperes)
N = rotational speed (Hz)
T = torque (N.m)
B = brush loss, assumed 0.7 volts
a, b, c, d and e are constants for the particular motor.

These equations were found to be entirely satisfactory for all but two motors. These two motors had higher current ratings than the rest and the equations had to be slightly modified. Full details are given in Supporting Document 1.

5.2.4 Test report and derivation of results

Appendix 2 illustrates the type of test report which was prepared for each system tested. It consisted of the following sections:

a) System description

This gives brief details of the overall system, photovoltaic array and the motor/pump unit.

b) Test runs

This lists the different static heads tested using the simulator and, where appropriate, under sunshine, with details of any special instructions followed. It also states whether the electric motor was separately tested.

c) Comments on installation and operation

This section records the test operator's comments on the adequacy of the instructions provided by the supplier, installation, operation and general construction of the system and principal components. Comments are also made regarding the factors possibly affecting the reliability of the system, recognising that long term reliability in tropical conditions can only be properly assessed by long term field trials.

d) Performance

a) Simulator

Curves of 'Flow' against 'Irradiance' for each static head tested were plotted on the one summary graph, to give a family of curves. Data points are omitted from these summary curves for clarity, but this graph is followed by separate graphs of 'Flow' against 'Irradiance' for each static head, showing the actual data points.

In most cases the test pipework was different from that specified in the tender documents. In order to make a full assessment of performance, measured flows were adjusted to take account of the different system hydraulic characteristics as illustrated in Fig. 5.11.

Using these results, curves of 'Flow' against 'Time' for various static heads were calculated from the flow-irradiance curves and either the 5 kWh/m^2 or the 4 kWh/m^2 Standard Solar Day; the total volume pumped and overall daily efficiency were then computed. The results were then tabulated to enable the simulated performance to be readily compared with the specified performance. Note that the specified requirements for volume to be pumped under 4 kWh/m^2 are expressed as 70% of the volume actually pumped under $5kWh/m^2$ (not 70% of the volume specified at $5kWh/m^2$). Similarly the daily efficiency under the low and high conditions is 75% of the measured daily efficiency.

b) Sunshine

The results for sunshine tests, where applicable, were presented in a similar format to that described above for simulator tests. However, it should be noted that the result is calculated for the ambient temperature of the test, not corrected to 30°C. Where temperatures were less than 30°C, test values will overestimate the performance to be expected under specified conditions, in some cases by as much as 5%.

e) Subsystem and motor performance

Curves of subsystem efficiency against input power to the subsystem were plotted for each static head tested (the subsystem includes any inverter or maximum power point tracker, where applicable).

The motor performance was presented by plotting contours of speed, torque and efficiency on a graph with motor current as ordinate and motor voltage as abscissa.

Pump efficiency may be inferred by dividing the subsystem efficiency by the motor efficiency for the same values of current and voltage (assuming that the temperature of the motor under test was similar to the motor when used in the subsystem).

f) Discussion of results

The test results are discussed, with comments on any anomalies and suggestions for possible improvements (refer to Section 5.25).

g) Projected Specific Capital Cost

The Projected Specific Capital Cost of the system was calculated on the basis on photovoltaic array price of $5.00/Wp and balance of system prices estimated by the suppliers for orders of 100 units or more. The volume of water pumped per day was that given by simulator tests for the design head under specified conditions and for the $5kWh/m^2$ Standard Solar Day.

h) Overall conclusions

The pumping system was assessed overall taking into account three factors:

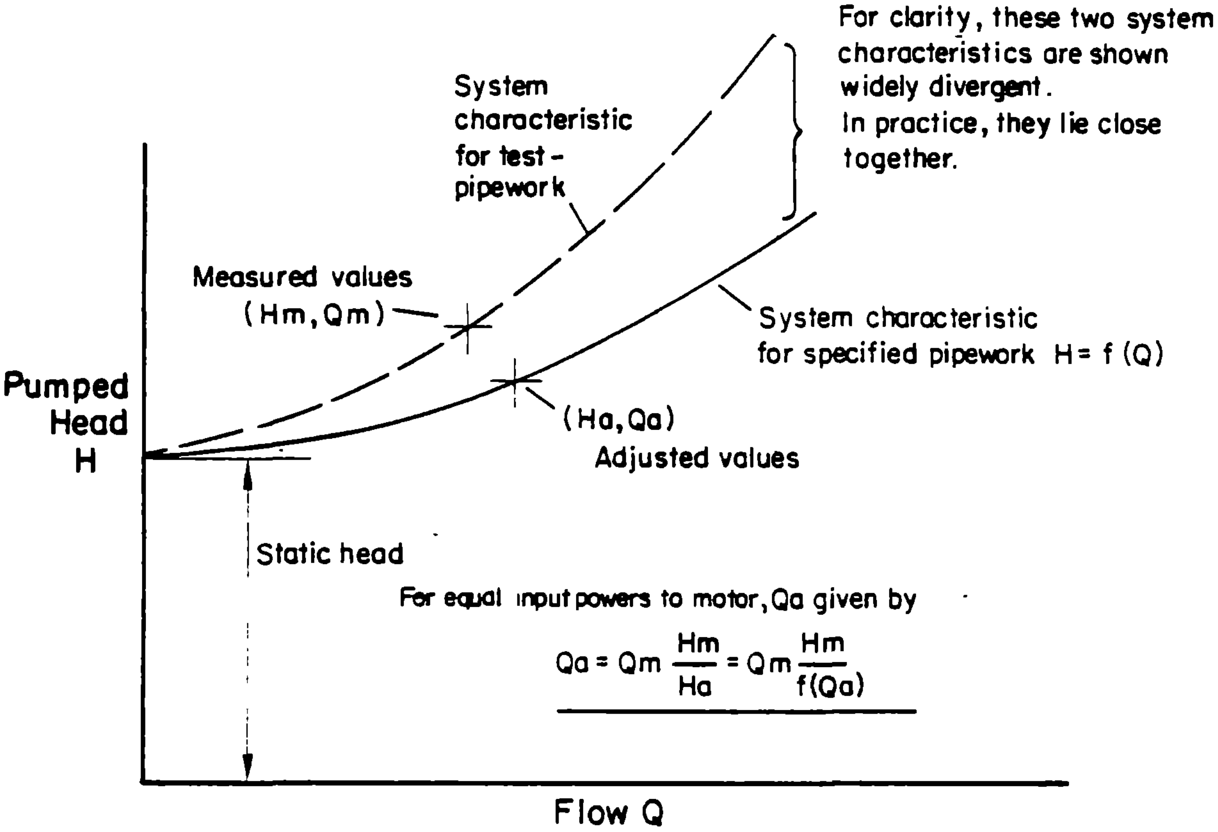


Figure 5.11 Adjustment to Measured Flow Values Arising from Differences in System Hydraulic Characteristics

a) Performance

Whether the system met the specification for:

- output for design head and 5 kWh/m^2 Standard Solar Day
- outputs for 75% and 150% design head and 5 kWh/m^2 Standard Solar Day
- output for design head and 4 kWh/m^2 Standard Solar Day

The performance of the system was clearly a function of its design, in particular the way the main components were matched.

b) Design features

Comments on the design were prepared in the light of compliance (or not) with performance specification and the Consultants' assessment of the following features:

- ease of installation and operation
- maintenance requirements
- durability, materials of construction, wiring details
- robustness, reliability and safety aspects
- suitability for local manufacture

These fell broadly into two groups; systems where the design was thought to be basically sound, but which could be improved; and systems whose design was poor and which would need to be fundamentally rethought.

c) Projected Specific Capital Cost

This was reviewed in the light of compliance with the performance specification and the system design.

5.2.5 Results

General

The views expressed in this Report about the performance, design and projected cost of systems are given in good faith on the basis of the data and results obtained from the tests described herein. Their validity is obviously limited to the range of conditions under which the tests were carried out. It should also be noted that only one example of each system was tested.

The summary graphs of flow against irradiance based on simulator test results for all systems are shown in Figures 5.12 - 5.14. Graphs for flow against head for different values of irradiance are shown for each system in Figure 5.15. A histogram comparing the overall daily efficiencies of all systems is given in Figure 5.16. Table 5.4 presents the main test results from all the systems. Full details of the procedures and results are given in Supporting Document 1.

System Performance

The performance of each system, its design features and SCC are summarised below. Values given for inferred peak pump efficiency have been derived from measurements of subsystem efficiency and motor efficiency. It should be noted that peak pump and motor efficiencies do not necessarily occur simultaneously. All peak motor and pump efficiencies quoted refer to the system operating range and do not necessarily represent the maximum efficiencies obtainable.

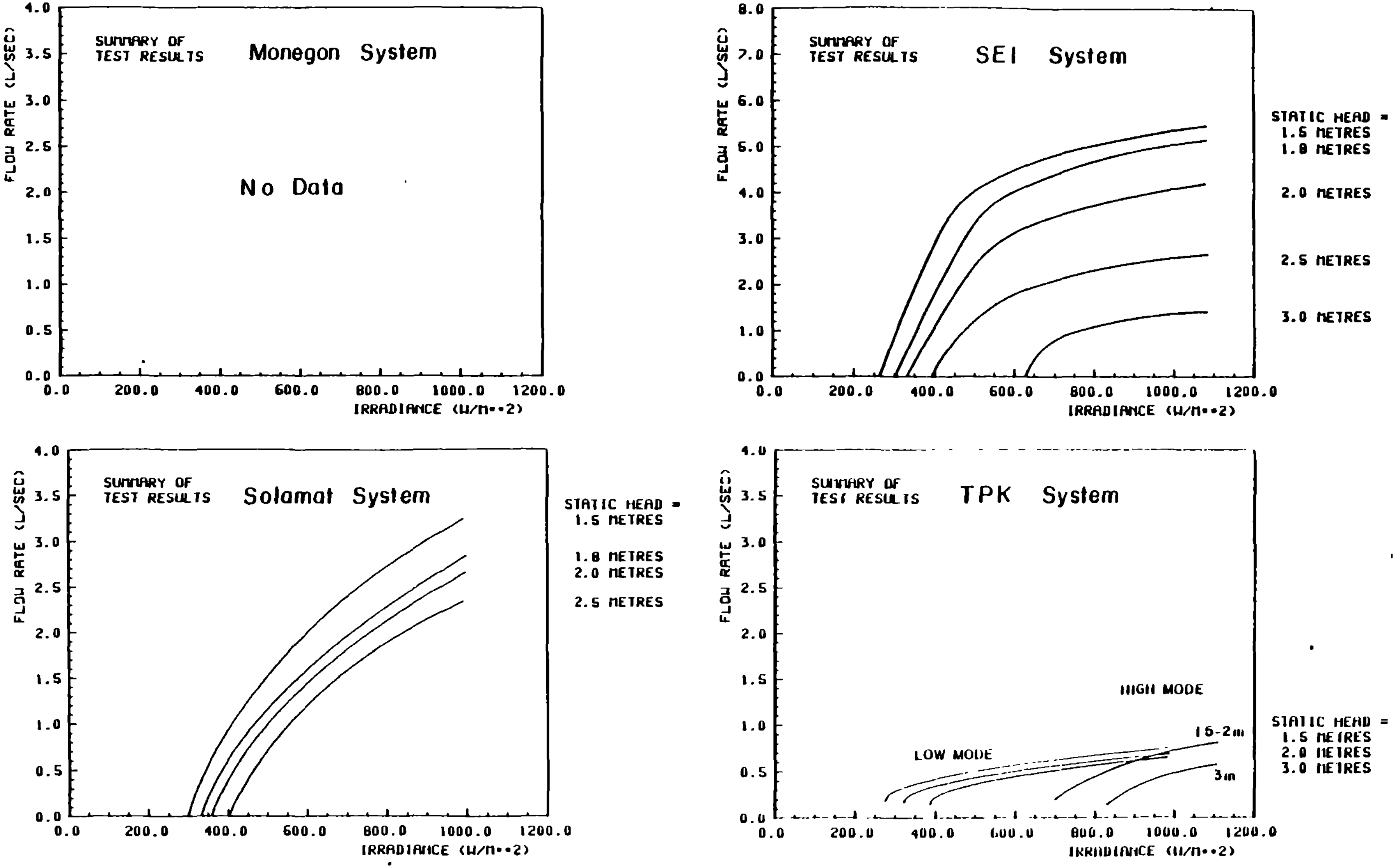


Figure 5.12 Summary of Simulated Test Results (Flow v Irradiance) - Category A Systems

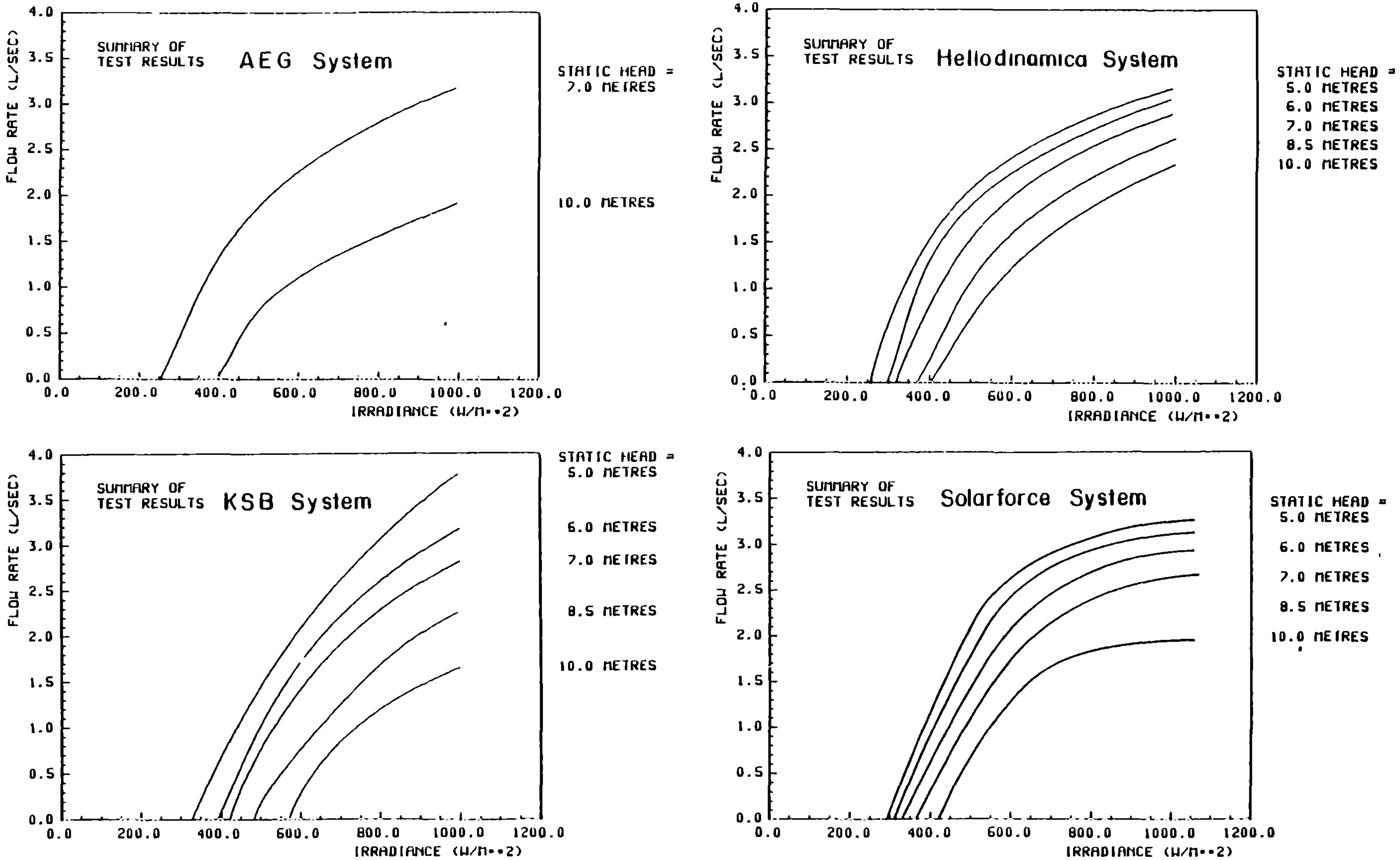


Figure 5 13 Summary of Simulated Test Results (Flow v Irradiance) - Category B Systems

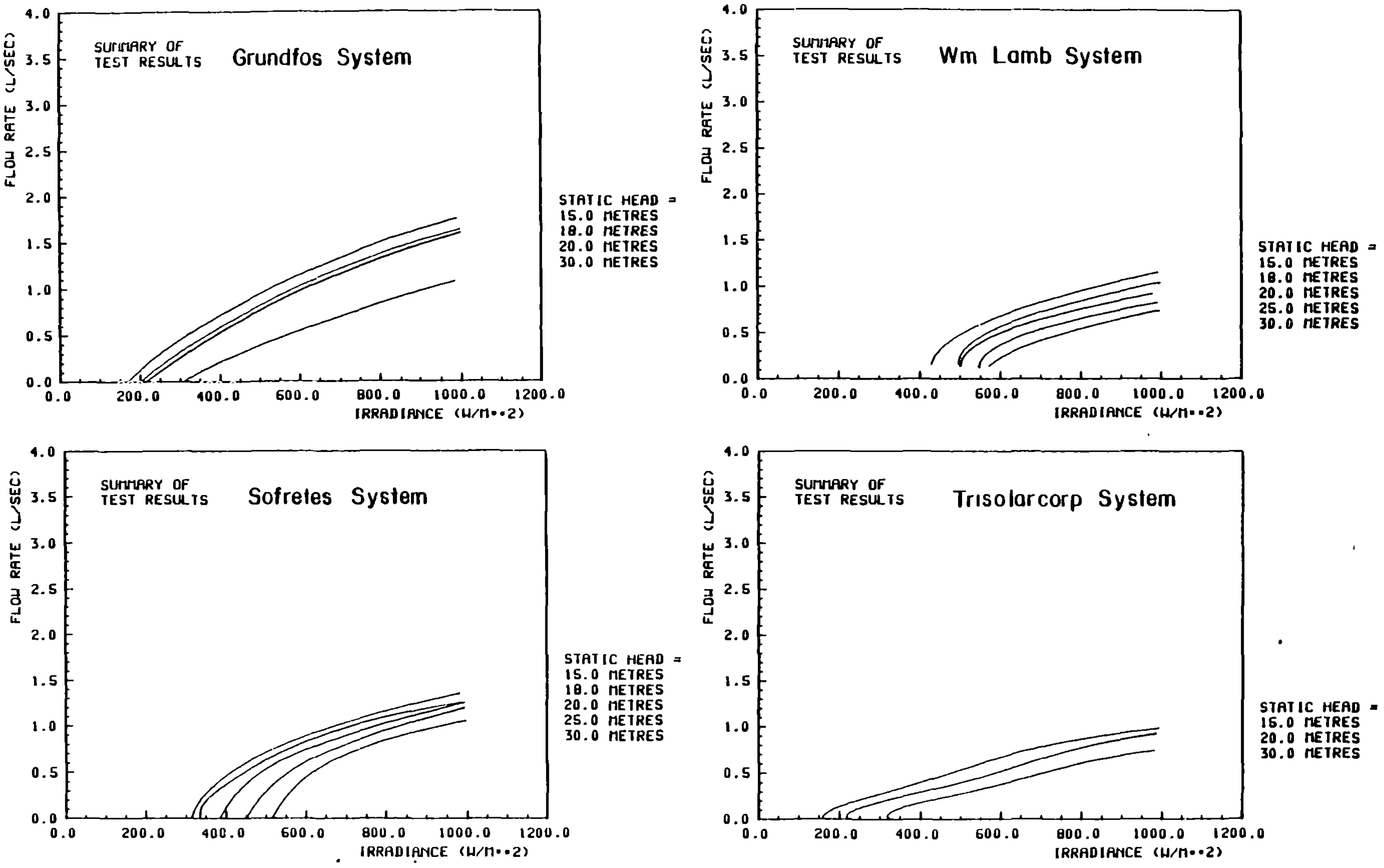
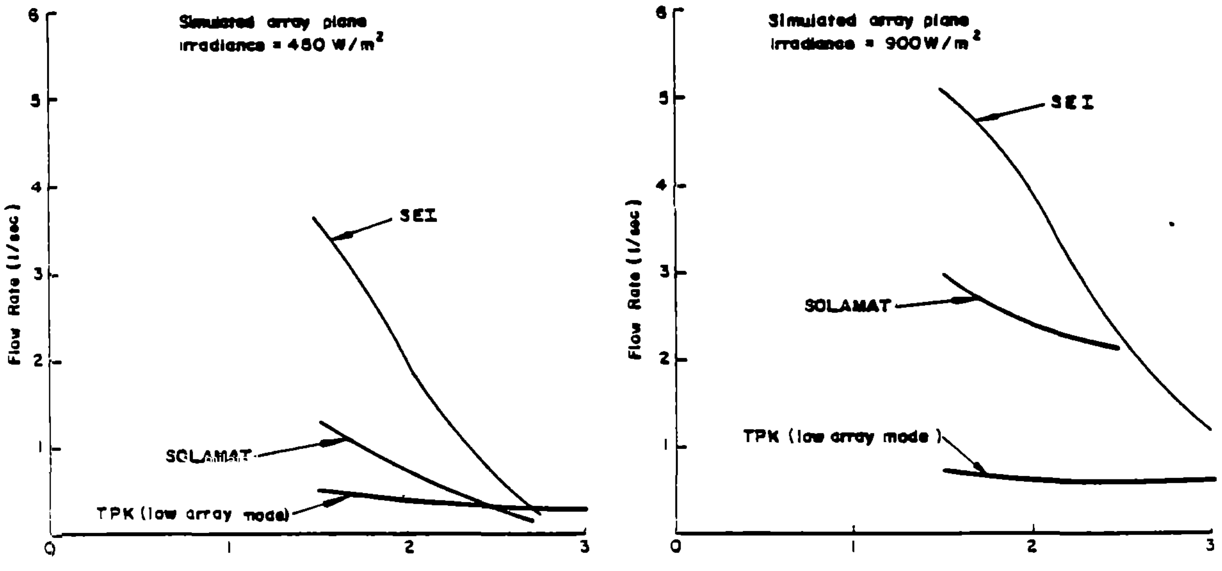
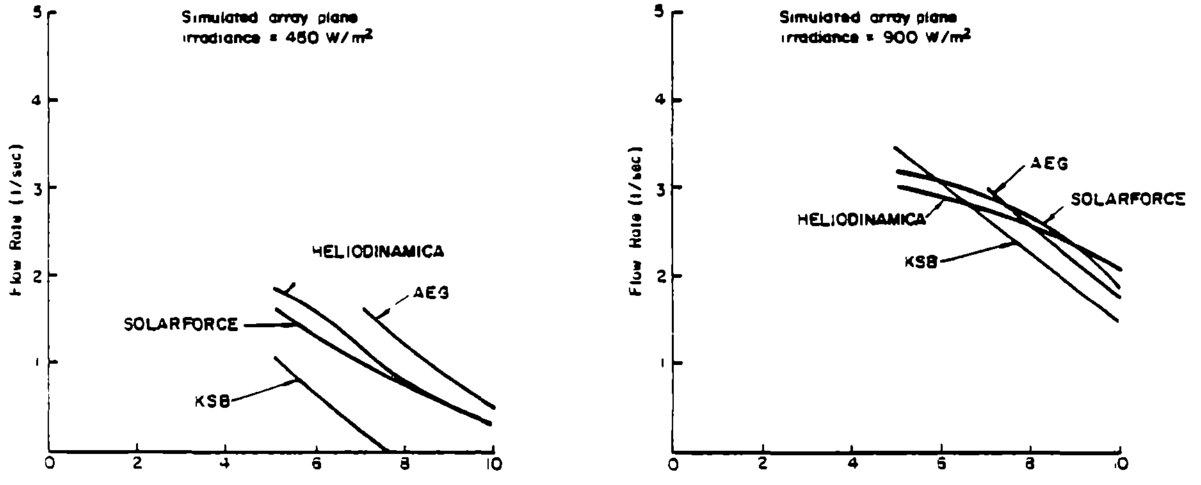


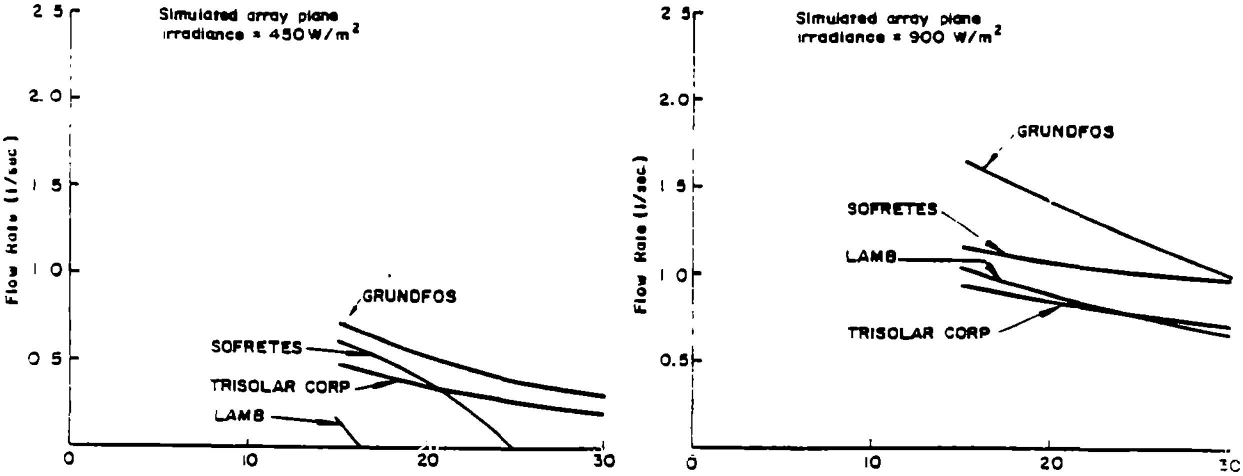
Figure 5.14 Summary of Simulated Test Results (Flow v Irradiance)
- Category C Systems



Category A Systems

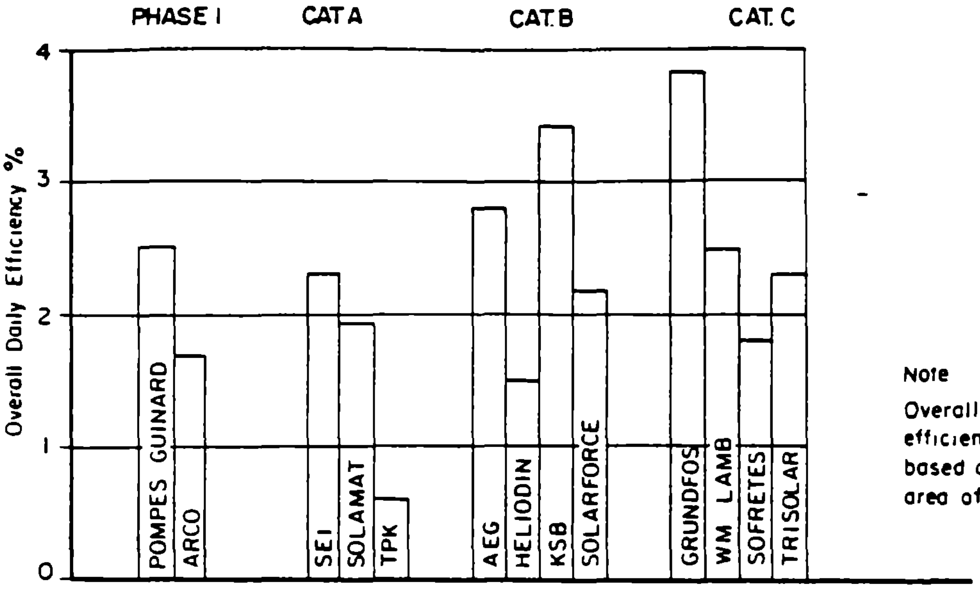


Category B Systems



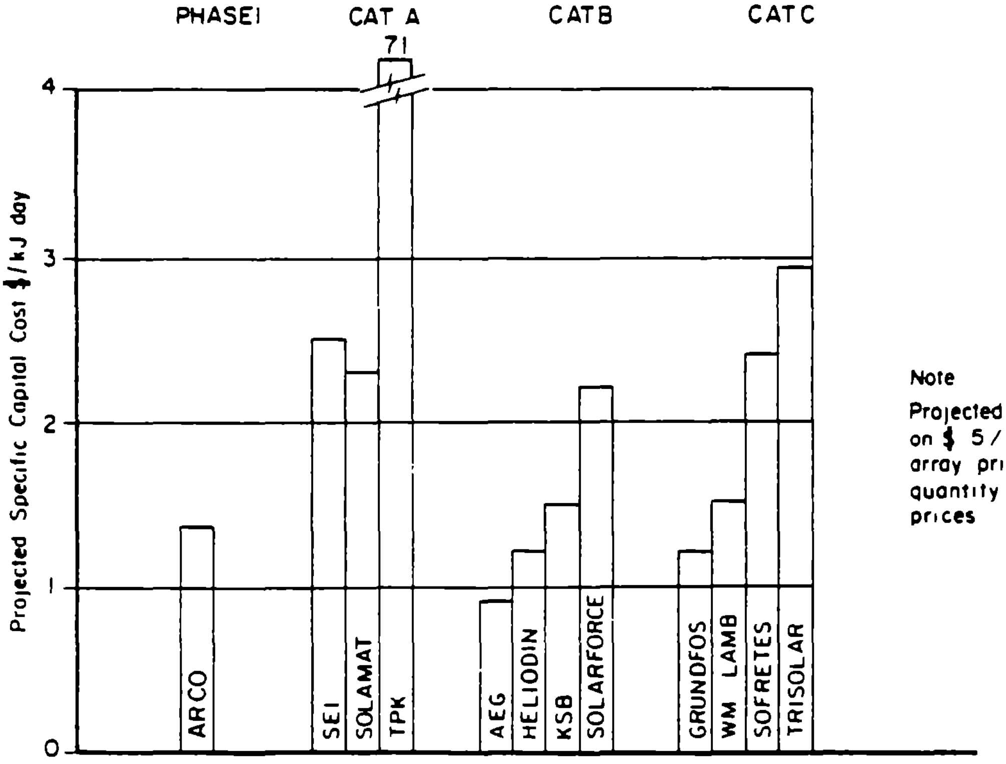
Category C Systems

Figure 5.15 Summary of Simulated Test Results (Flow v Static Head)
Categories A,B and C at irradiances of 450 and 900 W/m²



Note
Overall daily efficiency values based on gross area of array

a) Comparison of Overall Daily Efficiency Values



Note
Projected SCC based on $ 5 / Wp array price and quantity subsystem prices

b) Comparison of Projected Specific Capital Cost Values

Figure 5.16 Comparison of Test Results. Daily efficiency and Specific Capital Cost
See Table 5.4 for Summary of Results

Cat	System Supplier	Projected (5) Capital Cost $	Vol (2) del at design hd m³	Daily Efficiency (DL)% (1)			Max Subsystem Effic at Design Hd %	Projected Specific Capital Cost $/kJd	Results @ 4 kWh/m²/d at Design Hd		Remarks
				low hd (3) (75 % DH)	at Design hd (DH)	high head(3) (150% DH)			Daily Efficiency %	Vol (4) Del m³	
A	Monegon	2124									Failed to work needs further development
	SEI	4415	90	2.5	2.3	0.6*	33	2.5	1.8	63	Good system concept but could have lower SCC with better matching System best at 1.5m head
	Solamat	2150	48*	2.0	1.9	2.0	34	2.3	1.4	30*	Performance not as good as expected Flap valve in self priming tank could be unreliable and causes energy losses
	TPK	2231	16*	0.5	0.6	0.7	12	7.1	0.5	13	Interesting system but performance poor due to many losses PV array deteriorated rapidly Good scope for for local manufacture
B	AEG	4614	73		2.8	1.9	57	0.9	2.5	55	Good concept and very efficient sub-system but several minor features need to be modified to improve reliability Very low SCC Performance generally met or exceeded specification
	Heliodinamica	5276	62	1.3	1.5	1.4	33	1.2	1.3	44	Good surface mounted pumpset with self priming tank Needs more efficient pump & motor to bring SCC down to $1.0 kJ/day
	KSB	4822	48*	3.5	3.4	2.0*	53	1.5	2.2	27*	Very efficient subsystem but output below specification More suited to 5m head than 7m Good system concept
	Solarforce	9544	64	2.0	2.2	2.0	30	2.2	1.8	44*	Good system for permanent installation in borehole Pump efficiency poor Robust design but complicated to install
C	Grundfos	7812	33	3.4	3.8	3.3	44	1.2	3.2	24	Very good concept, easy to install and operate Performance met or exceeded specification in all respects Very good daily efficiency Low SCC
	Wm Lamb	4445	16(6)	2.6	2.5	2.3	41	1.5	1.6	8*	Good system provided head remains constant and daily insolation is >5kWh/m² since high threshold irradiance
	Solietes	11239	23	1.6	1.8	1.6	30	2.4	1.3	15*	Good concept and performance met specification, but efficiency poor hence high SCC
	Trisolar Corp	10770	19*	2.1	2.3	2.5	38	2.9	1.9	13	Performance just below specification MPC ensures low threshold to start Unsuitable for situations where head changes ever day Fine filter cannot be back-flushed if it becomes blocked

NOTES

(1) Based on gross array area

(2) Spec required 60m³ for A & B and 20 m³ for C for 5kWh/m² day

(3) Spec required DL at end of head ranges to be ≮75% of DE at DH

(4) Spec required vol under 4 kWh/m² d to be ≮70% of design volume under 5kWh/m² d

(5) Based on array $5/Wp plus estimate for system in quantity production. Equivalent to FOB costs, installation costs not included

(6) System accepted on basis of 15m³/day output

(7) * indicates below specified performance

Table 5.4 Summary of Test Results on PV Pumping Systems

a) **Category A Systems** (60m^3/day through 2m static head)

Monegon (subsystem)

This was an inadequately developed prototype system based on a positive displacement rotary pump. It did not work in the configuration supplied but with further development and appropriate matching of array, motor and the pump, it could possibly provide a compact, cost-effective system. The peak efficiency of the motor supplied was rather low at about 73%.

SEI 350L (complete system)

A good system, easy to install, with floating pumpset and array. System performance at the design static head and 1.5 m static head was considerably better than specified although not as good as predicted by the supplier at the tender stage. Performance at 3m static head was however, considerably below specification. The Projected SCC is high at \$2.5/kJ.d at 2m head (\$2.2/kJ.d at 1.5m head) but this could probably be reduced by better matching of the array to the pumpset. The maximum measured subsystem efficiency was 33% at the design static head of 2m (but still rising), but reached a peak of 44% for a static head of 1.5m. Higher subsystem efficiencies would be obtained at the 2m and 3m heads if the system were operated at higher power inputs or alternatively, the subsystem design was modified to provide peak efficiencies at the design and higher heads. The efficiency of the dc motor was found to be in the range of 67 - 72%, which is considered good in view of the losses associated with the electronic commutation for a brushless motor. The inferred peak pump efficiency is good at about 63%. The motor needs special protective devices if the subsystem is ever to be run from a battery power supply instead of a PV array. Local assembly of the subsystem would be feasible but local manufacture probably would not be feasible in most developing countries.

Solamat (subsystem)

This is a compact surface mounted system with self-priming chamber but still dependent on a non-return flap valve which could give reliability problems and would also contribute to hydraulic losses. The performance at the design static head of 2m was some 20% less than specified and 30% less than predicted by the supplier at the tender stage. Performance at 1.5m and 3m static heads was satisfactory. Peak subsystem efficiency was average in the range 31-36% for all heads tested. Peak motor efficiency was good at 79%, and so the inferred peak pump efficiency is rather low at about 46%. The Projected SCC was high at \$2.3/kJ.d because the daily volume is 20% below that specified, due mainly to the poor pump and also to probable losses at the flap valve. Local manufacture of the subsystem would be feasible.

TPK (complete system)

This was a prototype system incorporating a positive displacement pump of relatively simple design well suited for local manufacture. Unfortunately performance was considerably below that specified, with subsystem efficiency around 10 - 12% for the design static head. The motor efficiency was generally good, in the range 75-80%. Losses arose mainly from flexing of the support framework and poor sealing of the pump footvalve. Due to the poor overall performance, the Projected SCC is very high at \$7.1/kJ.d. It should also be noted that sunshine tests were not feasible, as the flow would vary with irradiance and it was not practical to connect the pump to a flow meter as it did not have a proper stuffing box to allow a positive discharge pressure. (The series of steady flows associated with simulator tests were measured in a calibrated tank). In addition, the encapsulant around the PV cells went opaque after about six weeks, a problem which the manufacturer says has now been solved. Although the system concept is an interesting one because of the potential for local manufacture, considerable development is needed to achieve a cost-effective, reliable design.

b) **Category B Systems** ($60m^3$/day through 7m static head)

AEG - Telefunken (complete system)

This system incorporates a compact floating pumpset and a PV array with polycrystalline silicon cells made up into relatively small (19 Wp) and convenient modules. The floating pumpset sank during testing due to water ingress, probably due to an inadequate cable gland. The simulator tests indicated that the system exceeded the volume specification by a margin of some 20% at the design static head of 7m. Performance at 10m was a little below specification. Performance in sunshine tests was well below specification, but later a faulty cable connector was found which would account for some 25% loss in array power. The array support structure was heavy and not easy to assemble and the array wiring and cable connectors were generally considered to be not sufficiently robust for small-scale systems in remote locations. The subsystem efficiency was very good (the highest of all systems tested), with a peak of 57% at the design static head of 7m and little fall-off across the head range of 5 - 10m. The motor efficiency was also good, in the range 75 - 82%. The inferred peak pump efficiency is thus about 67%, which is very good. With relatively minor improvements, this easy to operate system would be very good, with a low Projected SCC of $0.9/kJ.d. Local manufacture of the subsystem would be feasible.

Heliodinamica (subsystem)

This is a compact surface-mounted system with a large spherical self-priming chamber, obviating the need for non-return valves and their associated hydraulic losses. The pump is constructed largely from plastics, which may mean limited life if water pumped contains abrasive sediment. Performance was good, meeting the specification in all respects. After some initial problems with filling, the self- priming vessel worked very well. Subsystem efficiency was rather low with a peak of around 34% for all heads tested. Motor efficiency was poor, in the range 62-64%. The inferred peak pump efficiency was average at about 54%. The Projected SCC, already good at $1.2/kJ.d, would be further improved if a more efficient motor and pump were used, requiring a smaller PV array. This system is a good example of a surface mounted solar pump, largely made in a developing country (Brazil).

KSB (complete system)

This is a good system concept, easy to install, with floating pumpset and portable array. System performance however, was some 20% below specification at the design static head of 7m but it performed well at 5m static head. Performance in sunshine tests was not as good as in simulator tests implying that the array was performing below specification: from Fig. 5.15 it will be noted that its performance at an irradiance of 450 W/m^2 had deteriorated relative to the other systems in its group compared with its performance at 900 W/m^2. The peak subsystem efficiency was about 53% at 5m and 7m static heads but no peak was reached in the 10m test (a maximum efficiency of 40% was recorded). Peak efficiency of the brushless motor is understood to be about 67 - 72% and thus the inferred peak pump efficiency is very good at about 69%. The Projected SCC at design head is reasonably good at $1.5/kJ.d, but would be a little lower for a static head of 5m. Thus as supplied, this system is better suited to operation at the lower head. The brushless motor needs special protection if ever required to operate from battery rather than PV array. Local assembly of the subsystem would be feasible but local manufacture probably would not be feasible in most developing countries.

Solarforce (subsystem)

This system is designed for permanent installation in a borehole and is not easy to install, with many parts needing careful assembly and alignment. It is very robust however and performed well, meeting the specification in all respects. The peak subsystem efficiency was about 30% for all heads tested. The motor efficiency was good in the range 77 - 81%. The inferred peak pump efficiency is thus low at 38%, probably due in part to the losses associated with the long drive shaft. The Projected SCC is fairly high at $2.2/kJ.d. This system is well made but rather expensive to supply and install. Local assembly, but probably not local manufacture, would be feasible.

c) Category C Systems (20 m^3/day through 20m static head)

Grundfos (complete system)

This system is unusual in that the submersible multi-stage pump set incorporates a standard water-filled ac motor supplied by a variable frequency inverter. The inverter operates at constant voltage on the array (dc) side, the operating voltage being set to be close to the locus of maximum array power for varying irradiance values. This helps to achieve the very good overall daily efficiency of 3.8% at design conditions, the best of all systems tested. The complete system was easy to install and performed very well, meeting or exceeding the specification in all respects. Provided the inverter proves reliable in tropical conditions (the manufacturer advises that testing is in progress), this system appears well suited for the application. Subsystem efficiency was found to be over 40% for a wide range of input power for the design static head of 20m. Based on manufacturer's test results, the inverter efficiency is about 96%, the motor efficiency is 68 to 73% and the pump efficiency is 50 to 62%, for input power in the range 200 to 800W. (An independent check was not possible in the time and with test rigs available). The Projected SCC is low, at $1.2/kJ.d. The current cost of the system is relatively low since the pumpset is based on a standard mass produced ac unit. Local assembly but not local manufacture of the subsystem would be feasible.

Wm.Lamb (complete system)

This system incorporates a robust reciprocating positive displacement pump. The PV array is mounted on a structure that can be turned to follow the sun, but performance was evaluated on the assumption that the array was fixed, orientated North-South and inclined at 20°. The system supplied was a standard unit, designed to produce 15 m^3/day at 20m head for 5 kWh/m^2 standard solar day. The test results verified this performance, although performance at the 4 kWh/m^2 standard solar day was below specification, due to this system having a high threshold irradiance of about 500 W/m^2 (see also Fig 5.15). Performance could be improved by manually assisting the pump to start. An appropriate switching system may achieve a similar effect. The counter balance weights and the pulley size have to be changed for different operating heads, which would render this system unsuitable for boreholes where the water level changes by more than about ± 2m through the day. Subsystem efficiency was found to be about 40% for 20m and 30m static heads, but somewhat less for 15m static head. The motor efficiency was quite good in the range 70 - 77%. The inferred peak pump efficiency is thus about 52%, a typical value for a reciprocating pump of this type at the head being considered. The Projected SCC is quite low, at \$1.5/kJ.d. The array support structure needs to be strengthened to withstand high winds. The pump piston seals would need maintenance at intervals depending on the amount of abrasive suspended matter in the water. Local manufacture of the subsystem would be feasible.

Sofretes (subsystem)

This system incorporates a submersible multi-stage centrifugal pumpset with flexible delivery pipe. The brushed dc motor is in a sealed chamber and drives the pump through a magnetic coupling. The pump vibrated and was noisy at high heads, which may indicate cavitation problems if the pump is not submerged to a sufficient depth. The system nevertheless met the specification in all main respects. Subsystem peak efficiency was low at about 28% at 15m static head, rising slightly to about 30% at 30m static head. Motor efficiency could not be separately determined with the test rig available, as the motor requires continuous water cooling. The pump would need to be withdrawn at intervals of about two years for the motor brushes to be changed, but this is a relatively straightforward operation although needing care to ensure the seals were correctly replaced to prevent water ingress. The Projected SCC is quite high at \$2.4/kJ.d, mainly because of the poor subsystem efficiency. Local assembly but probably not local manufacture of the subsystem would be feasible.

Trisolar Corp (subsystem)

This system incorporates a robust reciprocating positive displacement pump and a Maximum Power Controller (MPC) interposed between the array and the motor. The support arrangement for the reciprocating shaft was not the same on the system delivered as that seen on the system inspected at the supplier's premises prior to shipment. This had to be modified by the supplier before it could work satisfactorily. The MPC is built in two parallel channels, each supplied by half the PV array. Special protective devices have to be installed if the system is to be operated from a single power source, like the Consultants' PV array simulator or a PV array not sub-divided into two sections. The system output at design head was found to be about 5% below the specification, although the MPC did enable the system to start at a relatively low threshold of about 200 W/m^2. The peak subsystem efficiency was about 38%. The very fine filter at the inlet to the pump is likely to be a source of hydraulic loss. Moreover, the filter cannot be back flushed if it gets blocked. The motor efficiency was quite good, in the range 74 to 79%. The efficiency of the MPC is claimed by the manufacturer to be at least 95%. The inferred peak pump efficiency is thus about 51%, a typical value for a reciprocating pump of this type at the head being considered. The pump piston seals would need maintenance at intervals, depending on the amount of abrasive sediment in the water not held back by the fine mesh filter. A good feature of this system is that the pump plunger may be withdrawn for seal changing without having to withdraw the riser pipe. The Projected SCC is rather high at \$2.9/kJ.d, due probably to the cost of the MPC and the modifications needed to the standard pump unit to enable it to be incorporated into the system. Local manufacture of most if not all of the subsystem would be feasible.

5.2.6 General discussion of results

It is apparent that most if not all system designers found meeting the various performance specifications quite a challenge. Not counting one Category A system, which failed to operate in the configuration supplied, eight systems met the daily volume requirement at $5 kWh/m^2$ (counting one which only just failed and one which was accepted with a lower specification). Two systems failed this requirement in Category A, one in Category B and none in Category C. Eight systems also met the daily efficiency requirement at both the upper and lower limits of the head range specified. One system failed in Category A, two in Category B and none in Category C; each of these met the daily efficiency requirement at the lower head limit (assuming the AEG would have passed in the absence of experimental data). Only six systems met the daily volume requirement at $4 kWh/m^2$, there being one failure in Category A, two failures in Category B and two failures in Category C. (It should be noted that some systems which failed one performance specification passed the others).

It is clear that in general, the low head Category A systems are the most difficult to design to meet the three performance specifications and the Category C are the easiest. This is not surprising because the peak efficiencies are the most difficult to match within the small operational head range of Category A and the losses are proportionately higher. Since solar pumps are more economic at low heads (see Part C) it is to be expected that their markets would first develop for the Category A hydraulic duties and so attention will need to be given by suppliers' manufacturers to the difficult task of improving the performance of this Category of pump.

The volume requirement at $5kWh/m^2$ did not pose a problems for the Category B and C systems, and the performance of the SEI system in Category A showed it could readily be met in that class as well. The volume requirement at $4kWh/m^2$ was obviously more difficult - the best system provided only 75% of the volume at $5kWh/m^2$ - and more attention needs to be given to the part load performance characteristics of the components; and the threshold irradiance values at which the systems started and stopped.

The daily efficiency requirement at the limits of head range posed only a relatively minor problem - all systems met it at the lower head limit - although the behaviour of one otherwise good system (SEI) showed that it was not always easy to satisfy. It is of course very important that efficiency should be maintained as the static lift varies, and these good results would suggest that the requirement could be tightened a little.

There seems no particular reason to recommend altering the general approach to these performance specifications in any particular respect, although for a particular project with known solar conditions and known water head range (both daily and seasonal), it might be appropriate to change some of the requirements, such as daily volume and daily solar input. For some locations, it would be appropriate to specify daily output for a standard solar day of $6 kWh/m^2$ rather than $5kWh/m^2$.

Compared with the systems tested in Phase I, there has been a general improvement in overall daily efficiencies. The five best Phase I systems had daily efficiencies in the range 1.3 to 2.2%. The five best Phase II Preparation systems had daily efficiencies in the range 2.3 to 3.8%. Several of the Phase II Preparation systems nevertheless still had scope for further improving daily efficiency by either better matching of components, or using a more efficient pump or motor. It is particularly satisfactory that there are systems now available where efficiency varies little with changes in static head.

Some subsystem efficiency curves (plotted against power) peaked fairly sharply (eg, SEI at 1.5m head) while with others the peak efficiency did not vary so much with change in input power (eg, Solamat and Sofretes). However, the peak efficiencies of all subsystems tested did not vary greatly with change in head. Clearly it is important that for good overall performance that the subsystem efficiency should not vary greatly with changes in head or input power.

The peak motor efficiencies quoted in the preceeding section refer to the system operating range. For comparison with Phase I it is necessary to quote the maximum efficiencies over the full range of values tested and the four best motors gave values in the range 81% - 84%, which are some 2% below the best Phase I results. Since only single examples were tested these differences are not significant and thus it is concluded that motor performance has not improved since Phase I.

Pump efficiencies were in general significantly better for the Phase II Preparation systems than for the Phase I systems. The peak efficiency of single stage centrifugal pumps has improved from about 30 to 46% to about 35 to 69%. The best multi-stage pumps have improved from around 50% to over 60%. No directly comparable reciprocating pump of the borehole type used in three of the Phase II Preparation systems was tested in Phase I, but the efficiency found for the better examples is considered to be good at over 50% at the heads tested. Higher efficiency could be expected at high heads. A good pump performance should not be reduced by unnecessary use of non-return flap valves (eg. Solamat) or ultra fine filters at the foot of the suction pipe (eg Trisolar). Further discussion of the potential for motor and pump development is given in the next section.

The design and construction of the best systems has significantly improved, with much more attention being given to reliability and ease of installation. The surface mounted pumpset supplied by Heliodinamica is well designed with an adequate self-priming chamber, although care will always be needed to avoid air leakage into the suction pipework of surface suction system of this type. A simple method of filling the self-priming chamber and checking the water level inside would be a desirable improvement. The efficiencies of its motor and pump could be improved. The plastic pump may have a short life in water containing abrasive sediment.

The floating pumpset with brushless dc motors has been well developed for the SEI and KSB systems. Neither were particularly well matched for the design conditions specified but for the static heads for which they were designed they perform very well. The pumpset for these systems consists of a moulded plastic casing and costs are relatively high. A strong competitor is provided by the AEG floating pumpset of simpler design. The AEG system still needs improving in a few respects but is potentially the most cost-effective of all systems tested.

The Solarforce (formerly Pompes Guinard) Alta X vertical system for borehole installations is soundly constructed but expensive, and moreover needs a skilled technician to install it. Once installed, it may be expected to operate reliably for many years, since the design is inherently robust. A system of this type is best suited to a permanent borehole installation for water supply applications.

Two submersible multi-stage centrifugal pumpset systems were tested (Grundfos and Sofretes). Pumps of this type are widely used for high head applications but for PV power sources special attention has to be given to the motor. If a conventional dc motor is used, the brushes need to be changed at regular intervals, requiring the pump to be withdrawn. The motor has to be in a sealed compartment and care is needed to ensure water does not enter through faulty or worn seals. The Sofretes system incorporates a dc motor with magnetic coupling to the pump, thereby avoiding a shaft seal. The pumpset is suspended in the borehole by a cable and the delivery pipe is a flexible hose, thereby facilitating withdrawal. This system worked well, although its efficiency was rather low.

The Grundfos system avoided the need to withdraw the pumpset by using a water filled ac motor of the type commonly used with electric mains supplied by an efficient variable frequency inverter. The voltage on the dc side of the inverter was preset at a value which ensured that the PV array operated at or near the locus of maximum power. The resulting daily efficiency of the system was the highest of all systems tested (3.8% for 5 kWh/m^2 day). Provided the inverter proves reliable in tropical conditions, this system has several advantages over systems with submerged dc motors, as it needs less maintenance and gives higher overall efficiency. The Grundfos system returned the highest daily efficiency in its Category.

Of the two reciprocating systems, the Trisolar with its Maximum Power Controller performed better at low irradiance levels than the Wm Lamb system, although performance was a little below specification at the design conditions. Neither of the reciprocating systems would be suitable in their present form for a situation where the water head varied widely throughout the day, since the counterbalance weights (and pulley in the case of Wm Lamb) have to be changed to suit the head.

Systems with low threshold irradiance values for start up are clearly to be preferred for sites with lower solar input (eg, places where greater cloud cover can be expected). This condition was represented in the tests by the 4 kWh/m^2 standard solar day. Systems which performed well for this condition as well as for the 5 kWh/m^2 standard solar day all had low threshold irradiance values at or below 350 W/m^2. These systems are:

Category A:	SEI	threshold 350 W/m^2 for 2m head
Category B:	AEG	threshold 250 W/m^2 for 7m head
	Heliodinamica	threshold 320 W/m^2 for 7m head
	Solarforce	threshold 340 W/m^2 for 7m head
Category C:	Grundfos	threshold 220 W/m^2 for 20m head
	Trisolar	threshold 220 W/m^2 for 20m head

It should be noted that the projected Specific Capital Cost (SCC) values are based on an array cost of $45/Wp and subsystem costs as estimated by the manufacturers for orders of 100 units or more (see Table 5.5). The SCC values are also based now on daily pumped output for a 5 kWh/m^2 Standard Solar Day, whereas in the Phase I report they were based on a 6 kWh/m^2 Standard Solar Day. Although the resulting change in any given SCC value for the lower solar input is very system specific, in general the SCC values given in the Phase I report (Ref 9) should be increased by about 12 - 20% to be comparable with values quoted now.

The main point to note is that the projected SCC values for the most cost-effective Category B and Category C systems are in the range $0.9 to 1.5/kJ.d, close to the hopes expressed for the technology in the Phase I report. Projected SCC values for the best Category A systems are somewhat higher at around $2.3 to 2.5/kJ.d, mainly due to the larger proportion of fixed costs associated with systems of relatively low hydraulic power (typical peak hydraulic power of a Category A system is about 60W compared with about 210W for a Category B system). Further discussion of SCC values may be found at the end of Section 5.4.

It should be noted that in calculating SCC values, the actual daily output of the system at the design head has been used, even though in some cases this was considerably less than or exceeded the required daily output specified. This has been done on the basis that generic types of solar pump are being evaluated, and not pumps for a specific application where possibly any extra water pumped could not be used productively, and that the SCC can be regarded as a type characteristic. When evaluating solar pumps for a specific application where the actual daily output is known and surplus output has no value, SCC values should be computed for the required daily output, neglecting any surplus. It should be noted that SCC values were calculated on the assumption that the suppliers quoted quantity production costs for a unit which gave the actual rather then specified performances.

5.3 Further Development

5.3.1 Objectives

Further development of solar powered pumping system components should be encouraged in order to improve system cost-effectiveness, to improve the reliability of the systems, and to increase the proportion of the system that can be assembled or manufactured within a developing country. This section reports on a study of the first two aspects while the third aspect is discussed in Chapter 15.

A study was undertaken with these objectives to assess the development potential of the components of solar powered pumps and whether performance improvements were possible which were cost-effective. The work is described in full in Supporting Document 3 and included the following tasks:

- a review of the state-of-the-art of solar pumping technology
- an assessment of the potential benefits of component development
- array development studies
- motor development studies
- pump development studies
- review of power conditioning
- evaluation of the effect on system performance of potential improvements using computer based models.

This activity presented the Consultants with their main opportunity to anticipate and discuss possible ways of improving the performance of PV solar pumping systems. Ideas considered ranged from technology which had been proven but was not commercially available, to possibilities of a more theoretical or speculative nature.

The study was undertaken in parallel with other Project activities, including the testing of the PV pumping systems. The mathematical model of PV pumping systems was used with basic performance data obtained in Phase I and information for the tenders for improved PV systems, plus comments and views from manufacturers and the Specialist Advisers to the Project.

5.3.2 Potential benefits of component development

The overall goal of this activity was to look at ways in which PV pumping systems might be made more cost-effective either by providing the same overall performance for reduced cost (capital or recurrent) or by improving performance at acceptable extra cost. It is important to remember that, while the search for improvements must necessarily concentrate on the components which form the system, these potential improvements must be judged by their effect on the cost-effectiveness of the system as a whole. As already explained, the Specific Capital Cost (the ratio of capital cost to hydraulic energy output) is the criterion adopted for this.

The development of individual components can have a number of potential benefits:

a) an improvement in performance (generally by increase of efficiency)
b) a reduction in first cost (capital)
c) a reduction in recurrent costs (operating and maintenance)
d) an increase in system life.

The technical aspects of the development of photovoltaic arrays, motors, pumps and power conditioning systems are discussed in the following sections, followed by a review of the effects of possible cost reductions.

5.3.3 Photovoltaic array development

The majority of commercially available solar pumps utilize flat-plate, non-tracking, mono-crystalline silicon solar cells although poly- crystalline silicon solar cells are beginning to be used too.

The Consultants have recently assessed the prospects for photovoltaic power in Europe for the Commission of the European Communities (Ref 11) and the material in this section is largely abstracted from this study. Continuing reductions in the FOB cost per peak watt of photovolatic modules can be expected as production volume increases and the technology of manufacture improves.

In 1980 $ values, historic costs and future prospects may be summarised as follows:

Year	PV module price (FOB) for large orders (1980 $) $/Wp
1975	30
1980	9
1985	3.00 - 3.50
1990	1.00 - 2.00
1995	0.70 - 2.00
2000	0.50 - 2.00

To express these figures in 1982 $ values (the year used in this report for economic evaluation) they should be increased by about 15% (ie. $ inflation 1980 to 1982). Thus, in 1982 $ values, the $5/Wp assumed for the Projected and Target cost calculations is expected to be achieved by 1985. Indeed, there have been recent reports of an order for over 1 MWp of photovoltaics for a central generating station in California at less than $5/Wp, although there may be special factors operating to achieve this low price. For small orders of around 10kWp, module prices are currently (1983) about $9 to 12/Wp FOB. (The projections prepared by the USA Department of Energy quoted in Ref. 10 are no longer maintained and the CEC figures quoted above are considered more realistic).

Recent improvements in technology include:

- low cost screen-printed process for junction and back surface field formation, anti-reflective coating and contact deposition;
- the development of ion implantation for junction and back surface field formation;
- automatic solar cell tabbing and interconnection;
- automatic module lamination.

If photovolatic module prices are ever to achieve $0.50/Wp, then a breakthrough into large area, efficient and durable thin-film solar cell technology is required. There are two main contenders in this field - cadmium sulphide/copper sulphide and amorphous silicon. The cadmium sulphide/copper sulphide cell, although invented at about the same time as the crystalline silicon cell, has developed much more slowly because of problems with low efficiency, instability and poor reproducibility. However, the University of Delaware has achieved an efficiency of over 10% in laboratory-made 'frontwall' cells (the version in which the light strikes the copper sulphide layer first) and the University of Stuttgart appear to have overcome the instability problem with a number of 7.3% efficient front-wall cells, which have shown no degradation after several years in the field. Two American firms, SES of Newark, Delaware and Photon Power of El Paso, MN, have set up pilot production lines, although SES have stated that they will close down their line in August 1983. Nukem of Hanau, Germany, who are to make a version of the Stuttgart cell have also set up a pilot production line and claim an average efficiency of 5% after 3 months operation, during which they have produced 500 kWp of modules. Commercial modules are however, not yet available.

A 1 μm thickness amorphous silicon layer can absorb as many photons as a 100 μm slice of crystalline silicon. Hence the materials and production cost of amorphous silicon cells appear attractive. Although the hydrogenated amorphous silicon solar cell was pioneered by the University of Dundee, UK, in the early 1970's, the field is now being led by Japan and USA. Recently, a group at Osaka University, working with Sanyo, claimed to have achieved an efficiency of 8% in a SiC:H/aSi:H heterojunction cells. Pursuing this idea, Sanyo have achieved 5.6% in 10cm x 10 cm modules of 9 series-connected cells on glass. They have constructed a 2 kWp demonstration array and are planning to build a 1.5 MWp/annum production plant. The cells have already found a market in pocket calculators. Recently RCA have reported the achievement of 10% efficiency in 1 cm^2 cells and Energy Conversion Devices (ECD) in the USA have announced an efficiency of 9.2% with their a-Si cells. The ECD process has been licensed to Sharp Corporation in Japan who have built a plant capable of turning out at least 3 MWp/annum. However, despite this rapid progress, doubts remain about the reproducibility and long-term stability of a-Si cells. Estimates for high volume manufacture and improved overall conversion efficiencies of 8.5% give cost projections of $0.44/Wp for the ECD a-Si process.

The use of solar concentrators to reduce the proportion of photovoltaic material required in an array appears attractive but reliability problems experienced with these devices (in particular as a result of accurate tracking requirements) and problems with non-uniformity of illumination and cell cooling suggests low concentration is more practicable.

Similarly, the use of non-concentrating sun tracking arrays (so enabling the area of the array to be reduced) has attractions, but the tracking mechanisms are not yet sufficiently reliable. Thermo hydraulic (or thermo pneumatic) mechanisms are potentially more reliable then conventional electro-mechanical systems and also require no electric power.

It was also concluded that reference conditions and methods of testing photovoltaic modules should be standardised and procedures developed to enable users readily to check module/array performance. Independent testing of modules should be encouraged, with test results made publicly available. Recognising these needs, the International Electrotechnical Commission (IEC) have recently set up a Technical Committee to study the question of photovoltaic standardisation. The Committee's first priority will be the issue of a standard for performance measurement.

5.3.4 Motor development

A review of solar powered pumps currently available confirmed that the following types of motors are mainly used in solar pumps:-

- brush type permanent magnet dc
- brushless dc
- 3 phase ac

The ac motors are specified mainly for higher power (> 700W) borehole pumping applications.

To date, brushless dc motors have been used mainly for open well installations, although it is understood that Honeywell have recently developed a submersible brushless dc motor for borehole applications.

An analysis of the energy loss mechanisms and present performance of commercially available dc and ac motors has demonstrated that improvements to the performance and efficiency of these motors are possible.

Analysis of a system tested in Phase I demonstrated that the performance of many of the more efficient pumping systems currently available can be improved if a more appropriate motor is selected from those commercially available. A 5% or more increase in pumped water delivered was typical of the improvement resulting from incorporating the most efficient motors available into a typical solar pumping system.

A number of potential ways of improving motor performance were identified, including:

- derating motors to achieve improved performance
- reducing flux densities and hence motor iron losses
- increasing rotor diameters and number of poles to reduce winding losses
- reducing current densities to reduce $I^2 R$ losses
- reducing motor speed to reduce friction loss
- improving heat transfer to reduce resistance losses
- use of improved magnetic materials such as rare earth "super" magnets
- improving dynamic balancing to increase life and efficiency
- improved bearing materials to increase life and decrease friction losses
- improved designs for reducing churning losses in water filled motors
- thinner rotor laminations
- improved design to reduce flux leakage
- improved reliability of electronics to permit brushless motors to be used and so eliminate brush maintenance requirements.

Some of the factors listed above will reduce maintenance requirements and/or increase the life of the motors, the most notable being improvement to balancing and bearing design and the use of longer life brushes or the development of brushless dc motors.

The potential cost-effectiveness of various component improvements is discussed in Section 5.3.7, although it was noted that many of these potential improvements are likely to result in larger, heavier, more expensive motors to achieve greater operating efficiency. Constraints on size exist where the motor is submerged in a borehole and these need to be taken into consideration.

From discussions with specialist advisers and manufacturers it is believed that peak operating efficiencies can be improved from their typical 80% to 85% value at present to between 85% and 90% with such improvements.

Of the design improvements considered, the following developments appear most promising:

- further development of brushless dc motors for reducing maintenance requirements, in particular for borehole applications
- derating motors for improved performance
- motor redesign to lower flux and current densities and hence reduced motor iron losses, I^2R and windage losses.

If the tested performance of ac motors and inverters is borne out in practice, advantage will flow from the fact that reliable mass produced units are already in production in many parts of the world.

5.3.5 Pump development

In the design of a solar powered pumping system it is probably the design and selection of the pump that is most crucial in achieving a good solar pumping system.

Pumps may be divided into two categories, depending on the method of transfer of energy to the fluid:

Rotodynamic (centrifugal, axial or mixed flow)

- surface suction
- single stage submersible
- multi-stage submersible
- axial flow (propellor)
- turbine

Positive displacement

- piston or plunger
- diaphragm or bellows
- lobe
- gear
- vane pump
- Archmedian screw
- progressing cavity.
- dragon spine (chain and buckets)

It was concluded early in the studies that procedures should be developed for determining pump (and motor) overall efficiencies that take into consideration part load efficiency and efficiency fall off with time in order to compare different types of pumps for solar powered applications.

A review of the type of pumps available or offered for small-scale solar powered applications showed the following pumps to be most suitable:

Low head (Category A)	-	centrifugal (self-priming or operating submerged)	
	-	axial (propeller)	
Medium head (Category B)			
	-	centrifugal (self-priming or operating submerged)	
High head (Category C)			
boreholes	-	centrifugal (multi-stage)	)
	-	positive displacement jack	) operating
	-	positive displacement	) submerged
		progressing cavity	)

The poor efficiency of positive displacement jack pumps at low heads means that these pumps are unlikely to be cost-effective for low and medium head applications.

Types of energy losses were identified for both rotodynamic and positive displacement pumps and these formed the basis for recommendations on improvements for pump efficiency. Developments for rotodynamic centrifugal pumps identified to improve efficiency included:

- selection of impeller diameter and shape to suit a particular head/flow requirement
- research into methods of reducing hydraulic loss from turbulence and friction by improving surface finishes and smoothing flow distribution.
- reduction of internal pumping arising from pressure differential in the pump by improved design including decreasing pump volume.
- reduction of leakage in wear rings after long term use
- pump redesign to reduce disc friction including smoother impellers and reducing volute/diffuser volume
- improved design of pump volute and diffuser to maximise velocity head recovery
- reduction of interstage leakage and turbulence in multistage pumps by redesign.

Of these developments, improving internal surface finishes and flow distribution in volute and diffuser are the most practicable way to achieve a significant improvement in performance over conventional pumps. Recently developed pumps for solar pumping applications are, however, already quite efficient. For example the subsystem supplied by AEG was found to have a peak efficiency of more than 55% implying a peak pump efficiency of over 65%. Further performance improvement of such pumpsets are probably limited to achieving a further 10% gain in efficiency (ie to 70-75%).

It is anticipated that future solar pumping systems will incorporate improved centrifugal pumps operating with peak efficiencies of around 72% for low to medium head applications of approximately 2 to 10 meters. Higher head multi-stage centrifugal pumps are anticipated as operating with peak efficiencies of approximately 60 to 65%. For low head applications (2m) the development of a simple construction axial flow propellor pump appears a promising approach.*

Developments for reciprocating positive displacement pumps identified included:

- careful examination of friction forces in seals and bearings with the aim of reducing these losses;
- investigation of better load levelling methods (flywheels and balances) to ensure a more constant motor load and hence motor/array impedance matching;
- reduction of pump break-away torques.

Progressing cavity pumps (rotary motion positive displacement pumps) have received attention recently for solar powered water pumping. Arco Solar installed such a solar pump at the American University in Cairo Desert Development Demonstration and Training Site between Cairo and Alexandria in Egypt. The performance of this motor/pump set pumping against 49 metres head has been measured at between 60% and 70% which implies a pump efficiency of over 70% for the Robbins and Myers progressing cavity pump. Similarly Mono Pumps Ltd, UK, have installed a solar powered pump in the UK and have claimed high pump efficiencies.

The advantages and disadvantages of progressing cavity pumps for solar pumping applications are detailed below:

advantages
- rotory motion and thus a steady load (unlike a reciprocating system)
- claimed high efficiency
- ability to pump water with suspended particles
- small diameter and hence able to fit in a 100mm borehole
- widely used in some developing countries
- better efficiency at low speeds than centrifugal pumps

disadvantages
- need maximum power controllers to ensure good matching
- high break-away torque
- wear on strator and/or rotor may reduce efficiency (but pumps which can handle solids have lower efficiencies anyway)
- relatively expensive and not easy to manufacture in developing countries
- long shaft from surface mounted motor, with associated bearing losses (but note a submerged motor/pump unit should be feasible to avoid this problem).

If the problem of high break-away torque can be eliminated without significant reduction in pump efficiency, it is considered that the progressing cavity pump appears suitable for solar pumping applications. It was a matter for regret that no progressing cavity pump was available for test during Phase II Preparation.

5.3.6 Power conditioning

Electronic power conditioners can and are being used for impedance matching, dc to ac voltage conversion, battery charge regulation and component protection.

The scope for development of impedance matching devices lies mainly in increasing their efficiency, but such improvements are likely to come about from the use of the latest solid state electronics and micro-circuitry now under development. However, because such devices consume power, add cost, and sometimes introduce reliability problems, system development should aim if possible to eliminate maximum power trackers and other impedance matching electronics by means of better motor-pump design. Nevertheless, positive displacement pumps (of all types), which are normally more efficient for high head applications, inherently involve a load mismatch with array output and such systems will probably benefit from suitable electronic power conditioning to compensate. It should be noted that as the cost of photovoltaics decreases, the improvement to cost-effectiveness of introducing these electronic units also decreases.

Within the last two years, the design of solid state dc/ac inverters has improved considerably and units are now available that are compact, fairly efficient (90-95%) and of medium cost (<$1000). With development of these inverters, cost reductions can be expected and their performance is likely to improve.

The use of a simple manual switching system to allow the user to alter the module series-parallel configuration of the array for more efficient operation or early start up is recommended for further consideration.

5.3.7 Appreciation of improvements to system cost-effectiveness

a) Basis of Comparison

In the following sections (as well as in Part C), reference is made to various combination of costs and efficiencies of PV modules, motors, pumps and complete subsystems assumed to occur at different time horizons. For reference, Table 5.5 gives details of these combinations under the titles Tender, Present, Projected, Target and Potential. The following points relating to costs should be note:

- all costs are given in terms of 1982 dollars;
- the Present case is based on an assessment of the average estimated costs of manufacturing motors and pumps in moderate quantity (100+) in mid-1982 (represented by an equation);
- the Projected case assumes module costs have halved from present levels to \$5/Wp because of increased scale of production but, since it is used for analysis of the systems purchased for test, uses the manufacturer's estimate of the cost of a particular subsystem assuming moderate quantity production, <u>not</u> average costs;
- the Target case assumes that because of increased scale of production (1000+) the average cost of subsystems (as defined by the equation) has been halved, and that module costs are at \$5/Wp;
- the Potential case is similar to the Target case, but with module costs of \$2/Wp. It could also be argued that the subsystem cost for the Potential case should be further reduced, assuming mass production (10000+) but this was considered too speculative at this stage.

Additional details of the cost assumptions necessary for the economic studies are given in Table 8.4.

The criterion Specific Capital Cost has been adopted to describe cost- effectiveness because it combines the effect of the capital cost of the system with its performance. The capital costs of systems are often quoted in terms of dollars per peak watt of array output because this appears to be a simple way of expressing and comparing costs. However, it should be noted that cost comparisons on this basis cost of systems with different subsystems efficiencies can be very misleading. For example, consider two systems, both designed to give 60 m^3/day through 7m head but the former (X) twice as efficient as the latter (Y)

	System X	System Y
Capital cost of subsystem	\$ 1000	\$ 1000
Array peak power (say)	500 Wp	1000 Wp
Total cost (@ \$5/Wp)	\$ 3500	\$ 6000
Capital cost per Wp	\$7/Wp	\$6/Wp
Specific Capital Cost \$/kJ.d	0.83	1.43

The better system (X) has a <u>lower</u> SCC (as expected) but <u>a higher</u> capital cost per peak watt simply because the array is so much smaller. This point must be borne in mind when considering the quoted values of capital cost per peak watt for different systems.

Case	Assumed Time Horizon	Module Cost $/Wp	Balance of System Costs		Daily subsystem efficiency			Remarks
			Basis of Motor/Pump Costs	Basis of other BOS Costs(7)	Basis	Value adopted in Project (2) Economic(1) Studies	System Cost effectiveness Studies	
Tender	mid 1982		Costs and efficiences as for individual systems tendered in January 1982 (3)					Prices are for one off items and will not sustain general analysis
Present	mid 1982	10	Curve representative of average costs of units produced in quantity (4) C = 530 + 1 5P	Cat A,B $3/Wp Cat C - $4/Wp	Best measured	40%	N/A	Modules available commercially for most orders irrespective of size Motor/pump costs are estimated by manufacturers for quantity production in 1982
Projected	in period up to 1987	5	Cost estimated by each supplier for quantity production		Best measured	40%	Around 40%	Calculated for individual systems on basis stated Modules not likely to be available at price quoted on regular basis until 1987
Target	1987	5	0 5 C(5)	Cat A, B - $1.5/Wp Cat C - $2/Wp	developed	50%	Cat A, B - 52% C - 50%	Module costs based on large scale production and available commercially Developed subsystem costs halved through quantity production (1000+) Improved subsystem efficiency achieved through developed components consistent with peak subsystem efficiencies of 63% for A &B, 55% for C
Potential	reached in period 1993 - 1998	2	0 5 C(6)	Cat A, B - $1 5/Wp Cat C - $2/Wp	developed	50%	Cat A, B - 52% C - 50%	Module cost based on technological improvement and large scale production

NOTES

(1) See Table 8 4 for details of costs
(2) Cell efficiency assumed to be 11%
(3) See Table 5 3
(4) See Fig. 8 3 Production runs 100+
P = Peak hydraulic power
(5) Production runs 1000+
(6) Production runs 1000+ but further reduction to (say) 0 25 C possible for production runs of 10000+
(7) Covers pipework, wiring, power conditioning (if any) and array support structure

Table 5.5 Basis of Costs and Efficiencies of PV Pumping Systems for Study of Cost-Effectiveness and Economics

Another complicating factor when comparing systems is that, as the costs of the arrays get lower, the proportion of total system cost due to the balance of system gets larger, and variations in balance of system cost from one supplier to another may make the costs per peak watt appear to vary erratically.

b) Initial Sensitivity Analyses

As indicated in Section 5.3.2, improvements to components can result in four kinds of benefit: improvement in efficiency; reduction in capital costs; reduction in recurrent costs; and increase in system life.

A preliminary analysis to confirm the relative importance of these factors for the pumping system *itself* was carried out on a Category B pumping system using the simple economic model developed in Phase I (Ref 4). The assumptions used and the results obtained (in terms of cost of unit volume of water) are shown in Fig. 5.17. The sensitivity analysis confirmed the following main points:

- system capital cost has a major effect an output costs, the dependence being linear, whether the costs are higher or lower then the base value of $12/Wp adopted for this preliminary study.
- a reduction in subsystem efficiency below the base value of 40% increases the output cost substantially and non-linearly, while an increase in subsystem efficiency is nearly as effective in reducing output costs, but the improvement is not linear. This simple analysis takes no account of the increase in capital cost of more efficient subsystems and there will be clearly be a limit to the cost effectiveness of improvements in daily subsystem efficiency over (say) 55%.
- a reduction in life below the base value of 15 years results in a marked increase in output costs whereas the benefit of an increase in life is not of great significance.
- since recurrent costs are relatively small, any reduction in these costs makes only a small contribution to reduction in output costs (depending on their value relative to the capital cost); any increase in recurrent costs similarly results in a relatively small increase in the output costs.

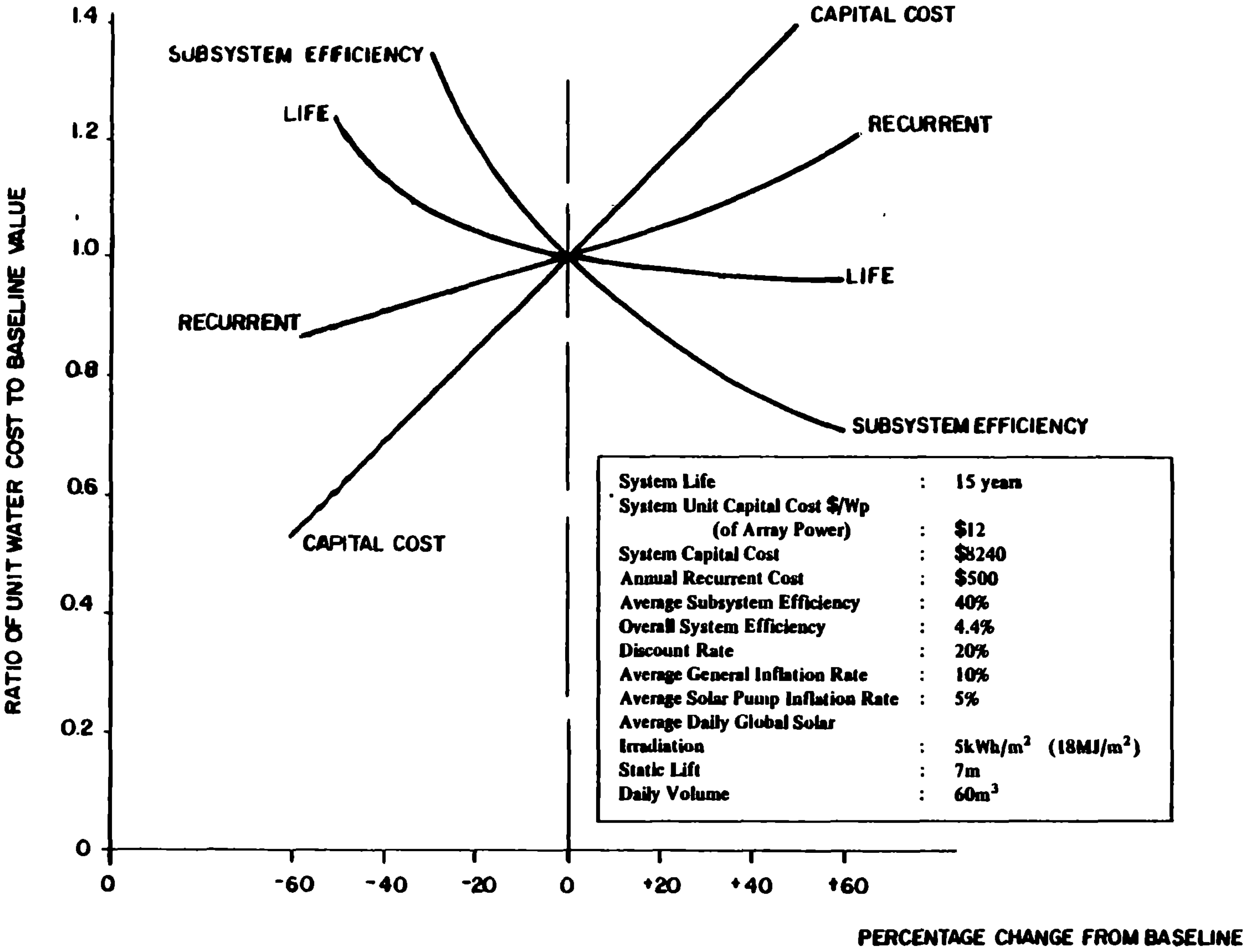
The overall conclusions to emerge regarding the relative importance of these factors are that:

- a reduction in capital is of greatest importance (whatever its level)
- an improvement in subsystem efficiency is also very important, provided it is not outweighed by increases in the capital cost of the subsystem;
- system lives should not be less than 10 years, but increase over 15 years are not of great significance; and
- a reduction in recurrent costs is helpful (whatever the level), but of lesser significance than the preceding three items.

It should be noted that, when the costs of infrastructural components are included, the proportionate effect of these changes will be less than indicated in Fig. 5.17.

c) Effect of improvements in the performance of components on system cost-effectiveness

A detailed study was then carried out into the effect on overall system performance and cost-effectiveness of possible improvements to the individual performance of the motors and pumps.



System Life	:	15 years
System Unit Capital Cost \$/Wp (of Array Power)	:	\$12
System Capital Cost	:	\$8240
Annual Recurrent Cost	:	\$500
Average Subsystem Efficiency	:	40%
Overall System Efficiency	:	4.4%
Discount Rate	:	20%
Average General Inflation Rate	:	10%
Average Solar Pump Inflation Rate	:	5%
Average Daily Global Solar Irradiation	:	5kWh/m^2 (18MJ/m^2)
Static Lift	:	7m
Daily Volume	:	60m^3

Figure 5.17 Sensitivity Analysis on a Category B Solar pump

Changes expressed as ratio of pumping system costs only (infrastructure costs not included)

The studies utilised the full mathematical model developed in Phase I to simulate the complete performance characteristics of a PV pumping system. The performance data obtained from a Phase I system giving output equivalent to a Category B system were used because the equivalent data from Phase II Preparation were not available in time. Full performance data were important in order to take account of the part load characteristics of each component and the interactions between components consequent upon changing any one parameter. The use of Phase I performance data in no way reduces the validity of the exercise, the main value of which was to assess the incremental improvements to system cost-effectiveness (expressed by Specific Capital Cost) resulting from incremental changes to component performance. Water flow rates were calculated for each system configuration at a number of levels of irradiance with a threshold of approximately 250W/m^2, and the volume pumped each day was obtained by integration using the standard solar days in the performance specification.

The costs used in the study were the sum of the array at \$5/Wp plus a balance of system cost based on an average of the costs estimated for quantity production of the four Category B systems (\$2500); this figure is roughly equivalent to the installed costs used in the economic studies for the Target case (including installation).

Table 5.6 gives the results of the seven principal runs carried out in the study. The performance characteristics of the improved and developed components were obtained by estimating an increased peak efficiency (through discussions with manufacturers and advisers as described in preceding sections) and then applying the same proportional increase to the part-load efficiencies at other operating points.

The investigations demonstrated that a developed Target case Category B subsystem with peak pump efficiency of 72% and peak motor efficiency of 90% (equivalent to a peak subsystem efficiency of around 63% and an average daily subsystem efficiency of around 52%) would require only 430Wp of photovoltaic array to deliver 60 cubic metres through 7 metres head. This compared with an estimated 505 Wpk required for the best Category B subsystem tested under Phase II Preparation to achieve the same output. Hence a potential 15% saving in array power was demonstrated.

The Specific Capital Cost improved from \$1.8/kJ.d for the baseline case with typical present motor and pump efficiencies to \$1.1/kJ.d for the Target case, an improvement of about 40%, no account being taken of any increase in cost for the more efficient components. The best Projected Specific Capital Cost of the Category B systems obtained from the performance measurements was \$0.9/kJ.d (AEG) (Table 5.4). Direct comparison with the SCC obtained from run 4 (\$1.1/kJ.d) is misleading because the Projected capital cost of the AEG system does not allow for miscellaneous costs including installation. If these are allowed at \$3/Wp (the Target case value), the SCC of the AEG system becomes around \$1.25/kJ.d. The difference between this figure and that for run 4 (in Table 5.6) is due to the fact that the AEG subsystem efficiency, although very good, is not quite as high as the values adopted for the Target case analysis.

The capital cost of the developed system used for run 4 (which pumped 72.5m^3 through a static lift of 7m) at an SCC of \$1.1/kJ.d is \$5350. This is equivalent to an installed system capital cost of \$9.4/Wp, close to the Target levels (see Table 8.4) and just over half the capital cost used in the baseline economic studies reported in Part C.

The above analysis assumed that there was no increase in cost for the developed motors and pumps, whereas in fact they may be somewhat more expensive. Improvements to the efficiency of the subsystems will only be cost- effective if developed versions can be manufactured for a

Run	Description	Daily Output (m^3)	Specific Capital Cost[1] ($/kJ.d)	Comments
1.	PV system based on characteristics of good Phase I performance. 7 metres static head, global solar irradiation 5 $kWh/m^2/d$ 5% electrical losses, stationary array at optimum tilt.	44.1	1.8	Baseline case: 570 Wp output (5) parallel/series connections optimised, 77% peak efficiency motor; 48% peak efficiency pump (2)
2.	System as for run 1, but with improved commercially available motor incorporated	47.5	1.6	Peak Motor efficiency increased to 86%, 7.7 % gain in daily water output from baseline case
3.	System as for run 2, but with developed pump	71.8	1.1	Peak pump efficiency increased to 72%, 63% gain in daily water output from baseline case.
4.	Systems for run 3, but with developed motor This configuration represents a system with developed components with array parallel/series connection optimized.	72.5	1.1	Peak motor efficiency increase to 90%. Average daily subsystem efficiency then 52%. 64% gain in daily water output from baseline case.
5.	Output at 4 $kWh/m^2/d$ investigated with developed system (as run 4)	59.8	1.3 (3)	
6.	Output at 6 $kWh/m^2/d$ investigated with developed system (as run 4)	81.6	1.0 (4)	
7.	Array size for daily output at 60 cubic metres/day determined with developed system and irradiation of 5 $kWh/m^2/d$	60.0	1.1	430 Wp (5) array required, saving $700 on baseline case at array cost of $5/Wp.

NOTES:

(1) FOB SCC values are calculated for $5/Wp array cost and at $2500 from an average of subsystem costs (based on the estimates for quantity production costs of Category B systems: AEG, Heliodinamica, KSB and Solarforce) and other balance of system costs, including installation

(2) Peak efficiencies are quoted, but system model takes full account of part load characteristics.

(3) Based on solar input of 4 $kWh/m^2/d$.

(4) Based on solar input of 6 $kWh/m^2/d$.

(5) Under standard conditions of 1000 W/m^2 and 28°C ambient

Table 5.6 Results of Studies on Effect of Improvements to Performance of PV System Components unit price which is increased by an amount which is less than the saving in array costs. The extra price which it is worth paying for developed motors and pumps at two different array prices is shown in Table 5.7 - the higher the array cost the more it is worth paying for a more efficient subsystem. At $10/Wp for arrays, the increases quoted in Table 5.7 (taking motors and pumps together) range from about 67% of the estimated quantity production costs of motor/pump units for Category A systems, to over 100% for Category B and over 200% for Category C systems. At array costs of $5/Wp these percentages will be halved. They indicate there is considerable scope for overall improvement to system cost-effectiveness by investment in components with improved efficiency.

Clearly the costs quoted will depend on the assumptions on which the analysis are based but these figures provide a reasonable first guide. In further work on this aspect, it will be necessary to obtain manufacturers' views on what could be achieved within these price increase constraints.

e) Target and Potential Specific Capital Costs

For each of the three system categories, capital costs and SCC values have been calculated and compared for the following cases:

- The best system tendered in 1982;
- Projected costs for these best systems;
- Target costs for further improved systems;
- Potential costs for further improved systems.

The results are shown in Table 5.8. Details of the assumptions regarding costs and component efficiencies used for these four cases are set out in Table 5.5, while the basis of calculation of the capital costs and SCCs are explained in the notes on Table 5.8.

It should be noted that the Target Specific Capital Cost of Category B systems at $0.8/KJ.d are a little lower than the SCCs for Category A (at $1.0/kJd)and Category C (at $0.9/kJd). This is because, at 7 metre head, very efficient low cost surface suction or floating units have been developed, whereas for Category C multi-stage units or reciprocating pumps have to be used and these are not as efficient or cost-effective. The Target Specific Capital Costs of Category B systems are lower than Category A systems because at low heads the balance of system costs do not decrease in proportion to the hydraulic output. Thus they become a larger proportion of the total cost, and so the total capital cost decreases proportionately less then the output, with corresponding effect on the Specific Capital Cost. This point may be of importance when reviewing the applications for which solar pumps will first become competitive.

The Target Specific Capital Costs are 20% to 27% of the Tender Specific Capital Costs (based on prices of systems bought in 1982 and the specified hydraulic outputs). The reduction will be brought about by a combination of reduction in the capital cost of the systems (principally by lower array costs) and improvement in system efficiencies as indicated on Table 5.6.

The Potential Specific Capital Costs are about 60% to 66% of the Target Specific Capital Costs, the reduction being entirely due to the lower PV array price assumed. Even lower Potential Specific Capital Costs may be feasible, if solar pumps are mass produced (over 10000 units per annum per production unit), when subsystem costs could reduce to less than half the values at present assumed for the Target and Potential cost estimates.

Category	Best efficiency from test results	Developed component Target peak efficiency	Approximate increase in unit price justified for developed component	
	%	%	Array @ $10/Wp	Array @ $5/Wp
A	80	90	190	95
B	82	90	610	305
C	79	90	860	430

a) Motors

Category	Best efficiency from test results	Developed component Target peak efficiency (%)	Approximate increase in unit price justified for developed component	
	%	%	Array @ $10/Wp	Array @ $5/Wp
A	63	70	210	105
B	69	72	290	145
C	62	70	800	400

b) Pumps

NOTE: From the above, it has been assumed that the concomitant peak subsystem efficiencies are 63% for Categories A and B, and 55% for Category C (allowing for losses in ac systems).

Table 5.7 Limit to Increase in Prices for Developed Motors and Pumps in PV Pumping Systems

Category	Parameter	Unit	Tendered (mid 1982)	Projected (period up to 1987)	Target (1987)	Potential (1993 - 98)
A 60m^3/d	Capital Cost	$	4440	2760	1150	765
2m lift	SCC	$/kJ.d	3.70	2.30	0.96	0.64
B 60m^3/d	Capital Cost	$	13020	3780	3370	2010
7m lift	SCC	$/kJ d	3.10	0.90	0.80	0.48
C 20m^3/d	Capital Cost	$	17600	4800	4030	2680
20m lift	SCC	$/kJ.d	4.40	1.20	1.01	0.67

NOTES: 1. Tendered: The SCC value quoted is an average of the SCC values for systems rated 'very good' and 'good' in the tender evaluation (see Section 5.1). These SCC values were based on the manufacturers tender price and the performance quoted by the manufacturer in the Tender document. The capital costs tabulated were calculated from the SCC value for the specified hydraulic output.

2. Projected The SCC value quoted was that of the tested system with the lowest SCC in each category, calculated on the basis of the hydraulic performance measured in the Consultants tests and the Projected Capital Cost (from the manufacturers estimates for moderate quantity (100+) product and an array cost of $ 5/Wp - see Table 5.5 for details). The Capital Costs tabulated were calculated for the SCC value for the specified hydraulic output.

3. Target. A system with a developed subsystem was sized to provide the specified hydraulic output and its capital costs were then calculated for the Consultants estimates for large quantity (1000+) production and an array cost of $ 5/Wp (see Table 5.5 for details). The SCC values tabulated were calculated for the capital cost for the specified hydraulic output.

4. Potential: As for Target, but with an array cost of $ 2/Wp.

N B. Table 5.5 gives definitions of the cost and efficiency bases adopted for the Tender, Present, Projected, Target and Potential cases. Note that the costs do not include instalation, and that a direct comparison cannot therefore be made with the results given in Table 5.6.

Table 5.8 Tendered, Projected, Target and Potential Capital Costs and Specific Capital Costs

Comparisons may be drawn between the results in Tables 5.6 and 5.8: for example the SCC values for Run 1 in Table 5.6 and the Projected case in Table 5.8; and for Run 4 in Table 5.6 and the Target case in Table 5.8. However, these results are not directly comparable. In the first comparison the efficiencies, the volumes delivered and the costs are all different, while in the second case, although the efficiencies are both of Target case systems, the volumes and the costs are still different. It will be noted that the costs used in Table 5.6 allow for installation, whereas those in Table 5.8 do not make this allowance.

To make allowance for the cost of installing the systems about $350 should be added to the Target cost for Category A systems and about $1250 for Category B and C systems. The resulting total installed Target cost for a Category B system would thus be about $4520, equivalent to $10.9/Wp, which broadly corresponds to the Target case values taken for the sensitivity analyses in the economic studies. It must be emphasised however that, for the purpose of the economic studies, the Target costs were built up on the basis set out in Table 5.5 (and amplified in Table 8.4) and so care must be used in comparing results on the single basis of $/Wp.

5.4 Summary of Present Status and Prospects for Photovoltaic Pumping Systems

5.4.1 Improved commercial systems

As the summary of test results given earlier in this chapter indicates, there are several well developed systems available, although there is still scope for improvement even on most of the best systems. For Category A and Category B applications, systems with floating pumpsets or self-priming surface-mounted pumpsets are available which perform well and should prove reliable in practice, provided the various improvements recommended for some of them are made. The best of these systems performed well at a range of heads either side of the design head.

For Category C applications, systems with submersible multi-stage centrifugal pumpsets are now available either with ac or dc motors. These perform well and are tolerant of changing heads (an important feature for many borehole installations). Systems with positive displacement pumps are also available that perform well. One is based on a standard pump and has a low projected SCC. The other incorporates a Maximum Power Controller which improved performance, especially at low irradiance levels, but its projected SCC is rather high. Neither of the positive displacement systems would be suitable for boreholes where the head is likely to change significantly through the day because of the need to change pulleys or counterweights. On balance, systems with multi-stage centrifugal pumpsets seem likely to prove more cost-effective and more tolerant of head changes than systems with positive displacement pumps, although it should be noted that the progressive cavity type of positive displacement pump may prove to be a strong competitor.

5.4.2 Prospects for further improvements

Regarding prospects for improving the performance of the present generation of photovoltaic pumping systems, it is clear that there is some, albeit limited, scope for improvement of the best systems available today. The cost-effectiveness of several systems tested could be substantially improved by either the use of a more efficient motor or a more efficient pump, or both. In some cases, better matching of the PV array to an already efficient pumpset would result in better cost-effectiveness.

The efficiency of the best pumps tested was found to be in the range 60 to 70% and only little further improvement can be anticipated, say to 72 to 75%. The efficiency of the best dc motors tested was found to be in the range 75 to 82%. There would appear to be scope for improving this to around 85 to 90%, without incurring a disproportionate increase in capital cost that would outweigh the saving arising from the associated smaller PV array.

The higher motor efficiencies referred to above related to brushed permanent magnet dc motors. The optimum efficiency of brushless dc motors would be somewhat less, probably around the present 67 to 72% although higher efficiencies are probably technically feasible. The reduced efficiency results in the need for a larger PV array with associated higher cost, which has to be set against the need for reduced maintenance. At current PV array prices, this extra cost is significant and hard to justify but as PV array prices fall, and more solar pumps are distributed to remote rural areas where maintenance presents problems, the use of brushless motors should prove on balance to be an advantage. It must be noted however, that in the event of array failure (or cloudy days), a brushless motor must not be connected directly to a battery power supply without first providing special protective devices.

On the assumptions that life of system, maintenance costs and solar input are similar, the cost-effectiveness of a system may be represented by the Specific Capital Cost (SCC). Based on an assumed PV array cost of $5/Wp and estimates of the cost of the subsystem if manufactured in quantity (at least 100 units), Projected SCC values have been derived for each of the improved commercial photovolatic pumping systems tested. Projected SCC values for the best Category A systems are around $2.3/kJ.d, whereas Projected SCC values for the best Category B and Category C systems are around $0.9 and 1.2/kJ.d respectively. (Category A systems are relatively more due to a higher proportion of balance of system costs). The corresponding FOB Projected capital costs are $ 2760 for Category A systems; $3780 for Category B systems; and $4800 for Category C systems.

Assuming more efficient motors and pumps will become available with large quantity production at half current prices and again taking a PV array cost of $5/Wp, Target SCC values have been derived, which indicate what could perhaps be achieved within a few years, given quantity production. These Target SCC values are $0.96/kJ.d for Category A systems, $0.80 for Category B systems and $1.01 for Category C systems. The corresponding FOB Target capital costs are $1150 for a Category A system, $3370 for a Category B system and $4030 for a Category C system. These figures indicate what possibly could be achieved by 1987, given good design using more efficient components and cheaper PV arrays.

The Target capital costs given above are some 25 to 50% of current system costs, based on the 1982 tender prices. The reduction arises from a combination of improved overall system efficiency, greater volume of production and reduced cost of photovoltaic arrays. Based on nominal peak power of the associated array, the FOB Target capital costs are equivalent to $9/Wp for Category A systems, $7/Wp for Category B systems and $9/Wp for Category C systems. Care is needed in interpreting these $/Wp figures, since in general the more efficient the system, the higher the $/Wp value, even though the corresponding total capital cost is lower than less efficient systems. In the economic evaluation studies reported in Part C the cost figures taken are broadly equivalent to $18/Wp for 'Present' system cost and $9/Wp for 'Target' system costs, although the actual numbers are built up as indicated in Table 8.4.

5.4.3 Systems for the proposed Phase II field programme

The value of testing solar pumping systems before sending them overseas to field sites has been clearly demonstrated. All the systems procured under Phase II Preparation were claimed by their suppliers to be improved commercial systems, complying with the Consultants' Specification in all major respects. Testing has shown that only about four systems justified in full the confidence their suppliers had in them. Several systems show considerable promise and with relatively minor modifications could be brought up to standard. Others proved to be prototypes which had not been tested in any rigorous way before being despatched.

To save time and expense, and to avoid the bad publicity associated with unsatisfactory solar systems in the field, the Consultants strongly advise that all solar pumps of new design are subjected to thorough testing and evaluation under controlled conditions before being despatched to the field sites for which they are intended.

Of the twelve systems supplied for test, ten would be suitable for deployment in the proposed Phase II field programme of technical evaluation and operational assessment without further testing, provided only relatively minor changes were made to correct unsatisfactory features as noted. If major changes were proposed, complete re-testing would be advisable.

Two systems, namely the Monegon and TPK, would need to be fully re-tested after they had been further developed by their respective manufacturers before they could be considered for deployment in the Phase II field programme.

Systems from other manufacturers, not included in the Phase II Preparation testing programme could also be considered, provided they had been independently tested to a similar extent and standard as the systems reported herein.

The final choice of systems for the proposed Phase II field programme would depend on the actual conditions obtaining for the various sites envisaged, taking into account water requirements in relation to time of year, solar insolation, static head variation, physical conditions of well or borehole, etc.

5.4.4 Specifications for solar pumping systems

The importance of having concise and comprehensive tender documents, which include a clear performance specification that relates the required daily output to static head and solar insolation cannot be overemphasised. The specification should also indicate how the performance may vary when the static head increases or decreases, or when the solar insolation varies. In addition to defining the performance the specification should also include general requirements and recommendations regarding individual components and the system as a whole, with particular emphasis on:

- ease of installation, operation and maintenance
- long working life of all components
- reliability and robustness
- safety.

To facilitate evaluation of tender proposals, potential suppliers should be required to complete technical schedules giving details of the overall systems and main components.

To illustrate the above recommendations, a model specification with technical schedules is included in Supporting Document 1. Appropriate modifications must of course be made to suit specific circumstances but the main features should prove generally applicable.

6. SOLAR THERMODYNAMIC PUMPING SYSTEMS

6.1 Background

At the end of Phase I of the Project it was concluded that it would be premature to discuss solar thermodynamic systems as having no future prospects. Although no reliable solar thermal pump was commercially available, the Phase I design studies showed that existing working prototype system had the potential for quantity production at costs comparable with photovoltaic systems. In addition the Phase I studies showed that small-scale systems utilising concentrating solar collectors and improved Rankine or Stirling cycle heat engines could well be produced at costs competitive with forecast photovoltaic pump costs. A decision to manufacture large numbers of units would, however, be required to achieve competitive costs.

The objectives of the thermodynamic work in the Phase II Preparation Project were to review the developments of solar thermodynamic systems since the conclusion of Phase I, and to undertake further studies based upon recently reported system and component performances and costs.

These objectives are in line with the recommendations of the World Bank/UNDP/Philippines Ministry of Energy Workshop on "Solar Pumping in Developing Countries" held in Manila, Philippines, in June 1981 (Ref 8). Further details are shown in Supporting Document 4.

6.2 Developments since Phase I

6.2.1 General

The activities of over 40 organisations listed in Table 6.1 working on the development of solar thermal pumps were reviewed. The material in this Chapter is based upon discussions or correspondence with these organisations, including their response to a questionnaire prepared to evaluate recent developments.

The response to the Consultants' enquiries indicates that, in general, progress in the development of small-scale solar-thermal systems since the conclusion of Phase I has been slow. A number of organisations reported no further development and some have ceased their activities in this field. It also appears that many organisations have been concentrating development on large-scale systems of 10kW or more.

Little further development of the equipment tested in Phase I of the Project, has taken place, with the exception of Domier Systems GmbH which has installed a second prototype solar pump in Hyderabad, India. No further development of the Sunpower free piston Stirling Engine Pump was reported, although a 4kW Stirling Engine to be powered by burning biomass is being developed. The 100 watt (hydraulic) Solar Pump Corporation System tested in Sudan under Phase I of the Project, has received little further development and only one further installations of this system (in Mexico) was reported.

Reported installations of complete small scale solar thermodynamic water pumping systems in developing countries include those of Sofretes (France) Solar Pump Corporation (USA), Domier (Germany), Technical University of Denmark, Jyoti Limited (India), Hindustan Brown Boven (India), BHEL (India) and Birla Institute of Technology (India). These installations are summarised in Table 6.2.

Field trials commenced in February 1983 on the solar pump developed by Wrede Ky (Finland) and are due to commence on the system developed by the Cranfield Institute of Technology (UK). Other progress reported since Phase I includes systems developed to the prototype level by J Vanek (USA) and Foster Miller Corporation (USA).

ORGANISATION/INDIVIDUAL	SCOPE OF ACTIVITIES	COMMENTS
EUROPE		
Technical University of Denmark	Solar pumps with displacement tanks	Demonstration pump under test in Tanzania
Wreda Ky, Finland	300 W ORC solar pump	Prototype completed. Field trial in Egypt commenced March 1983.
Ensam, France	Heat engine research	No reply to our enquiries received
Irrisun, France	Complete ORC irrigation systems	No reply to our enquiries received
Sofretes, France	10 kW ORC complete systems offered	Systems of 10 kW or more commercially available
University of Lyon France	Simple solar pump	Small prototype built
Dornier, Germany	1 kW ORC complete system	2nd prototype under test in India (with BHEL)
M.B.B. Germany	Complete systems offered	Mainly large scale
German Appropriate Technology Exchange	Solar engine using expansion wax	Development suspended
Bomin Solar, Germany	Solar powered Stirling engine pump	No reply to our enquiries received
Politecnico di Milano, Italy	Solar pump research	No reply to our enquiries received
Maboain s.a.s, Italy	Complete ORC systems offered	Status of previous installations not known, no recent installations.
Cranfield Institute of Technology, UK	5 kW Solar pump with multi-vane expander	Pilot installation planned for Egypt in 1983
ITDG, UK	Steam engine development	Development continues
Reading University, UK	Research into heat engines	Research continues
Redpoint Associates, UK	Fluid overbalancing engine	Work believed to be discontinued
I.S.C. Chemicals, UK	Simple liquid piston pump research	Work discontinued
Twente University, Holland	Research into solar pumps	Research continues mainly with solar ponds and displacement tanks
INDIA		
Birla Institute of Technology and Science, Pilani,	Solar pump with displacement tanks	Development continues
Bharat Heavy Electricals Limited, Hyderabad	1 kW solar pump	Prototype under test (in assoc. with Dornier Systems)
Central Salt & Marine Research Institute, Bhavangar	ORC solar pump	Prototype under test
Central Mechanical Research Institute, Durgapur	Bellow activated solar pump with displacement tank	No reply to our enquiries received
Delhi College of Engineering, Delhi	Bellow activated solar pump	No reply to our enquiries received
Metal Box (India) Ltd, Calcutta,	Fluidyne Stirling engine pump	No solar version yet demonstrated
Hindustan Brown Boveri, Baroda	Solar pump with displacement tank	Development discontinued
Jyoti Limited, Baroda	Solar powered steam engine pump(s)	2 prototypes built
Indian Institute of Technology, Madras	Research	No reply to our enquiries received
Indian Institute of Technology, Kanpur	Solar pump with liquid piston	No reply to our enquiries received

Table 6.1 Organisations Contacted for Solar Thermal System Review (Sheet 1 of 2)

ORGANISATION/INDIVIDUAL	SCOPE OF ACTIVITIES	COMMENTS
INDIA (Cont.)		
Indian Institute of Technology, Delhi	Research into solar pumps	No developments reported
National Physical Laboratory, New Delhi	Solar pump with spiral expander	No reply to our enquiries received
Tata Energy Research Institute, Pondicherry.	Research into solar pumps	No reply to our enquiries received
NORTH AMERICA		
Concordia University, Montreal (Canada)	Studies on fluid overbalancing engines	No reply to enquiries received
Barber-Nichols Inc.	Heat engines for large scale solar thermal power plants	Large scale systems outside scope of project
Fischer Solar Engines America Inc.	Internal vapourization steam engine	Not available under 10kW
Ford Aerospace	Large scale solar thermal power systems	Large scale systems outside scope of project
Foster Miller Corporation	Direct acting Rankine cycle engine/pump	Prototype built
Garett/A. Research	Large scale Brayton cycle (gas turbine) development	Engine power outside scope of project
L O'Hare	Bellow actuated pump (patented)	Design only
Robbins Engineering Inc	1 kW ORC solar pump	Design only
Solar King	Solar engines development reported	No reply to our enquiries received
Solar Pump Corporation	100W complete ORC solar pump	10 prototypes build. Tested in Phase I and further development recommended
Special Metals Corp	Nitinol engine under development	Development continues
Sunpower Inc	Free cylinder Stirling engine pump	Tested in Phase I further development recommended
Sunpower Systems Inc	10kVA ORC engine-generators	No solar power systems reported
C J Swet	Displacement pump using heated air	Design only
University of Massachusetts	Rubber heat engines	No reply to our enquiries received
University of Florida	Solar powered Stirling engine pump	No reply to our enquiries received
J Vanek	Solar powered steam displacement pump	Prototype built
OTHER COUNTRIES		
Ormat Turbines Ltd, Israel	ORC turbine engines	Mainly large scale systems with solar ponds
University of Tokyo, Japan	Reciprocating ORC engine	No reply to our enquiries received
Grinakers Equipment Ltd, S Africa	Fluid overbalancing beam engine	No performance data available
Asian Institute of Technology, Thailand	small-scale solar pump	Small model prototype built, no recent developments

Table 6.1 Organisations Contacted for Solar Thermal System Review (Sheet 2 of 2)

SUPPLIER	TYPE	LOCATION	HYDRAULIC POWER	COMMENTS
Sofretes (France)	flat plate collector, ORC engine (reciprocating expander)	50 installed globally	1kW approximately	The majority abandoned or not working
Solar Pump Corporation USA	flat plate collector, ORC engine (reciprocating expander)	1 in Mexico 1 in Soba, Sudan	100w approximately	Status of Mexico installation not known Sudan installation performance not satisfactory
Dornier Systems, GmbH	flat plate collector, ORC engine (reciprocating expander)	Hyderabad, India	300w approximately	Operation reported as satisfactory
Birla Institute of Technology and Science, India	flat plate collector, ORC engine with displacement tanks	Pilani, India	4 prototypes up to approx. 100 W	Status of prototypes not known
Jyoti Limited, India	parabolic trough collector/steam engine (reciprocating)	Baroda, India	500w approximately	2 prototypes with steam engines rated at 6000 W and 2000 W shaft output
Technical University of Denmark	flat plate collector (reflector boosted)/simple steam engine	Mpera, Tanzania	not known	change of working fluid under consideration

Table 6.2 Small Scale Solar Thermodynamic Pumping Installations in Developing Countries (December 1982)

None of these systems has entered production and they cannot therefore be considered to be truly commercially available.

6.2.2 Developments by manufacturers

Seven commercial manufacturers appear to be maintaining a serious involvement in the development of small-scale solar thermodynamic water pumps, and these companies are developing relatively conventional and fairly complex systems as given below.

a) Dornier Systems GmbH in association with BHEL (India)

The first prototype of the Dornier Solar Powered Water Pump was evaluated during the first phase of the Project (Ref 10). Since the completion of Phase I, Dornier have installed in Hyderabad, India, a second prototype (built in Germany).

With 25 m^2 of direct evaporating solar collectors the system has a maximum hydraulic power of approximately 400 to 500 watts. The organic Rankine cycle (ORC) engine has a two cylinder reciprocating expander with a potential maximum output of 1.2 kW claimed.

Bharat Heavy Electricals Limited, India are currently evaluating the second prototype to establish its suitability for local manufacture and assess its performance in India. Preliminary results indicate an output of $40m^3$/day pumping through 15m - 20m head.

b) Wrede Ky, Finland

A 300 Watt (hydraulic) solar ORC pumping system has recently been designed and tested by Wrede Ky, Finland, three prototypes having been built.

A schematic diagram of the engine pump is shown in Figure 6.1. The system has the potential for improved efficiency over many other designs in as much as it employs a parabolic trough solar collector and also a working fluid condenser 'after cooler' to ensure a high operating temperature difference (high Carnot efficiency). Other features that may enhance performance are the use of a double acting reciprocating expander and double acting water pump.

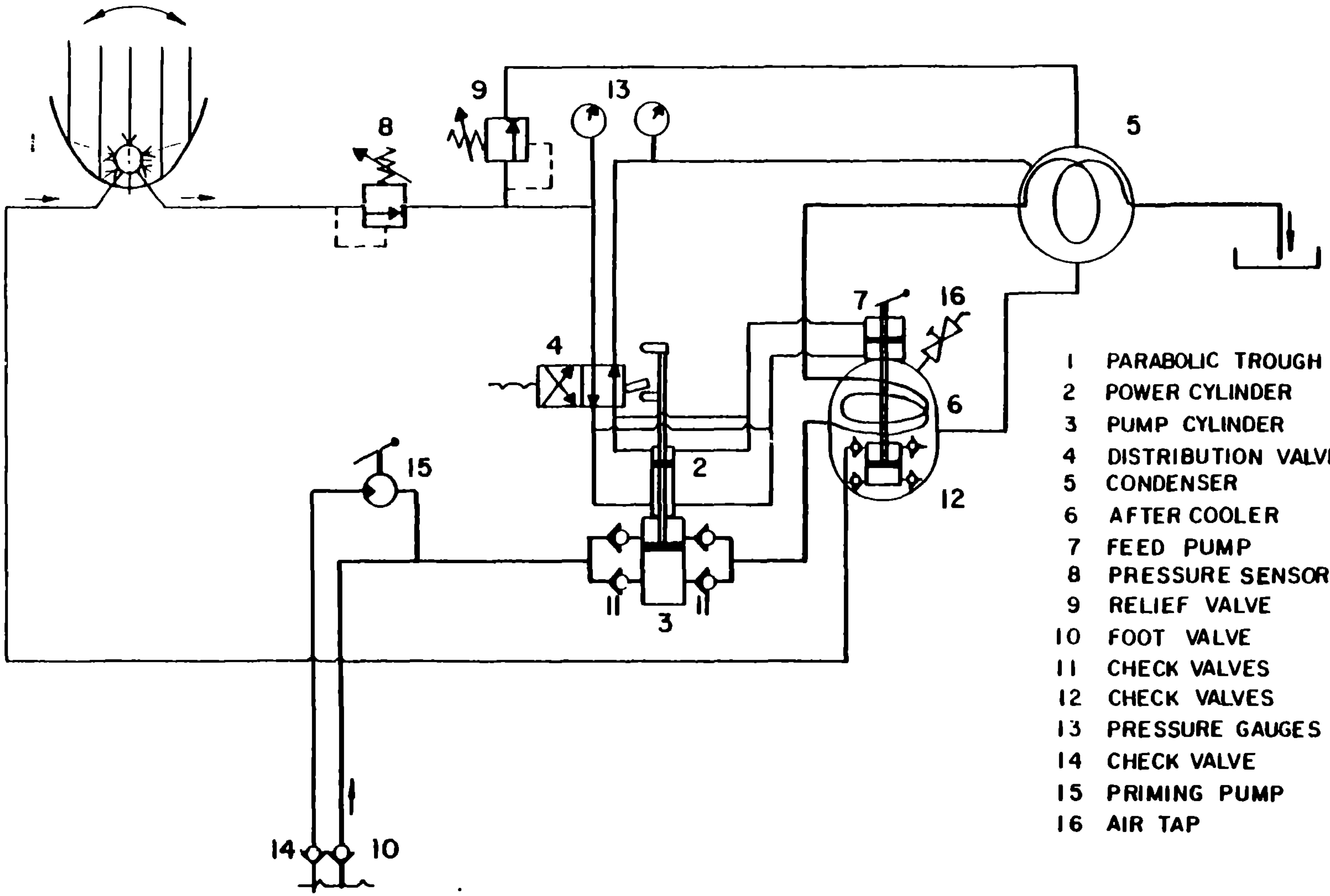
Field trials by Wrede Ky of the prototype started in Egypt in February 1983. Preliminary results indicate that when operating with a 4m total head and under $970W/m^2$ solar irradiance, a hydraulic output of 90W with an instantaneous overall system efficiency of 0.84% can be achieved. With further development the manufacturers expect to achieve a peak instantaneous overall system efficiency of 1.5%.

c) Solar Pump Corporation

A 100 W prototype of a flat plate collector/organic vapour Rankine cycle system was tested in Phase I (Ref 9). This system appears to need further development to achieve effective condensation of the working fluid with high groundwater temperatures and to overcome leaks and other reliability problems before being tested again. However, it appeared to have the potential to work properly.

d) Sunpower Inc (also working with Bomin-Solar)

A prototype free cylinder Stirling Engine Pump supplied by Sunpower Inc was tested under Phase I of the Project.



1 PARABOLIC TROUGH COLLECTOR
2 POWER CYLINDER
3 PUMP CYLINDER
4 DISTRIBUTION VALVE
5 CONDENSER
6 AFTER COOLER
7 FEED PUMP
8 PRESSURE SENSOR VALVE
9 RELIEF VALVE
10 FOOT VALVE
11 CHECK VALVES
12 CHECK VALVES
13 PRESSURE GAUGES
14 CHECK VALVE
15 PRIMING PUMP
16 AIR TAP

Figure 6.1 Schematic Diagram of Escomatic 10 Thermodynamic Pump designed by Wrede Ky, Finland.

Sunpower have not undertaken further development of this system although they are continuing to work on Stirling Engine development (including a 4kW shaft rice husk burner powered engine).

The system appears to be in need of further development to overcome the reliability problems experienced during testing in Phase I.

e) Jyoti Limited. India

Jyoti Limited has developed, to the prototype stage, a 6000 watt (shaft) and 2000 watt (shaft) reciprocating steam engines, powered by glass strip reflector parabolic trough solar collectors with a concentration ratio of approximately 25 to 1.

f) Foster Miller Incorporated

A direct acting Rankine cycle engine pump has been developed by Foster Miller in the USA. An organic fluid, refrigerant 11 or similar, is evaporated in a solar collector and admitted into the expansion cylinder where it acts on the piston. It pumps water out through a non-return valve. Some energy is imparted to a piston spring and near the end of the piston travel the valve is opened. The spring then returns the piston to its start position and the expanded working fluid is exhausted. The cycle is then repeated.

g) Cranfield Institute of Technology/Denco/GEC

A multivane expander developed at Cranfield for outputs of 3 kW or more is to be given a field trial in Egypt as part of an organic vapour Rankine cycle engine system. The system is rather complex, uses evacuated glass tube solar collectors and may not be appropriate for small-scale solar water pumping applications of less then 1000 watts hydraulic output.

6.3 Simple system designs

Four organisations are seriously involved in the development of simple systems which might be better suited for local manufacture in developing countries. The performance of these systems has yet to be established. Much will depend on whether they function sufficiently reliably and whether any loss of efficiency is compensated for by lower costs.

a) J. Vanek, USA

A parabolic trough collector attached to a steam pump (based on the Savery Pump designed in 1698) has been demonstrated, but the performance of the system has not yet been comprehensively investigated. The reliability of the engine timing and tracking mechanisms, which are linked to a pendulum device, needs to be demonstrated under field conditions as does the durability of the concentrating solar collector.

The results of tests organised by the developer indicated a maximum instantaneous thermodynamic efficiency for the engine/pump of 1.78% when pumping throught a head of 17m with a flow rate of 0.16 l/s.

b) Technical University of Denmark

A system using flat plate collectors with planar reflectors to power a simple steam engine is under field trials in Tanzania. Comprehensive performance data are not yet available but might be obtained by independent laboratory testing or by observation of the field trials. However a potential output of $10m^3$/day when pumping through 5m head is claimed by the developers.

c) **Birla Institute of Technology and Science, India**

Flat plate collectors have been used to power four displacement tank prototype pumps in India. Efficiencies determined from the field trials so far have been disappointing, but work is continuing.

d) **Grinakers Equipment Company, S. Africa**

A system based on flat plate collectors and a rocking beam version of the fluid over-balancing engine, is reported to be close to commercialisation. Performance data are not available.

6.4 Design Studies

Some basic investigations by mathematical modelling of different solar collector/heat engine configurations were carried out in Phase II Preparation. The performance and cost assumptions adopted for this work are given in Table 6.3 and the results of studies on eight different system configurations are given in Table 6.4.

The results indicate that higher temperature solar collectors result in lower system costs for a given output. Single axis tracking solar collectors, such as parabolic trough or linear Fresnel lens with Rankine cycle engines, are shown to have potentially lower system cost than flat plate systems, and are, in some cases, nearly as well developed. They are also less influenced by environmental parameters such as engine sink temperature and air temperature.

The use of thermohydraulic collector tracking systems appear appropriate for these concentrators as such tracking devices require no electrical power. These devices are now available commercially.

The use of evacuated compound parabolic collectors appears potentially to be a cost-effective approach for a collector array as no tracking is required, although vulnerability to breakage and poor potential for local manufacture are disadvantages. These devices are now commercially available.

The least cost approach appears to be point focussing - 2-axis tracking solar collectors with a Stirling or high pressure Rankine Engine. Except for manually tracked low concentration collectors, these systems are, however, furthest from commercial development.

The capital costs of thermodynamic systems, if quantity produced, are believed to be competitive with current and projected capital costs of photovoltaic systems. However, no proven thermal systems are either quantity produced or commercially available and the investment required to achieve success is likely to be large.

It is likely that solar thermodynamic pumping will be more cost-effective in large scale systems rather than in small scale systems. As the size of the system is increased the fixed cost proportion of any installation becomes less significant. In addition development costs for a small system may well be similar to those for a larger system. A larger system may also justify the cost of attendance of a local person to maintain and operate it.

Solar ponds may be a cost-effective option for collection in large scale systems, but do not appear to be suitable for small scale water pumping: at present their costs are unattractive and they require a large area of land.

Type of Collector	Efficiency when fluid at same temperature as ambient (1)	Heat Loss coefficient U W/m^2.K	Cost(2) $/m^2
Flat Plate Matt Single Glazed	0.75	7.5	110
High Performance Flat Plate	0.67	3.0	150
Evacuated Tubular Compound parabolic Collector	0.63	0.75	200
N-S Tracking Parabolic Trough	0.72	0.67	300
E-W Tracking Fresnel Concentrator	0.67	0.78	300
Parabolic Dish	0.72	0.3	400
Power Tower Central Receiver	0.72	0.3	300
Solar Pond	10% operating efficiency		50

a. Collectors

Component	Efficiency (%)	Cost
Engine	30% of Carnot	$3 per output Watt
Transmission	90% to 95%	included in engine
Pump	40%	$3 per output Watt

b. Engine transmissions and pumps

NOTES:

(1) In effect this indicates the optical losses due to absorption and reflection from surfaces.
(2) Based on estimates of costs of quantity products

Table 6.3 Performance and Cost Data used in Studies of Alternate Thermodynamic Pumping Systems

SYSTEM CONFIGURATION		CATEGORY A 60 cubic metres/day - 2m Head			CATEGORY B 60 cubic metres/day - 7m Head			CATEGORY C 20 cubic metres/day - 20m Head		
Collector Type	Engine Type	Collector Area m²	Average overall daily Efficiency %	SCC(1) $/kJ.d	Collector Area m²	Average Overall daily Efficiency %	SCC(1) $/kJ.d	Collector Area m²	Average Overall daily Efficiency %	SCC(1) $/kJ.d
Solar Pond	Organic Rankine Cycle	34.2	0.2	2.8	120	0.2	2.3	114	0.2	2.2
Flat Plate Single Glazed	Organic Rankine Cycle	15.6	0.3	2.8	57.5	0.3	2.3	54.8	0.3	2.3
Flat Plate High Efficiency	Organic Rankine Cycle	8.0	0.7	2.4	29.4	0.6	1.8	28.0	0.6	1.8
Evacuated Tubular Compound Parabolic	Organic Rankine Cycle	3.2	1.6	1.8	11.7	1.5	1.3	11.2	1.5	1.3
N-S Tracking Parabolic Trough	Rankine Cycle	4.1	1.8	2.3	15.0	1.7	1.8	14.2	1.7	1.8
E-W Tracking Fresnel Concentrator	Rankine Cycle	3.4	1.7	2.0	12.4	1.6	1.4	11.9	1.6	1.4
Parabolic Dish 2 axis tracking	Stirling Cycle or Rankine Cycle	1.4	3.4	1.6	5.2	3.2	1.0	4.9	3.2	1.0
Central Receiver 2 axis tracking	Stirling Cycle or Rankine Cycle	1.4	3.4	1.5	5.2	3.2	0.9	4.9	3.2	0.9

NOTES

(1) SCC - Specific Capital Cost based on estimate of costs of quantity production

Table 6.4 Results of Studies of Alternative Thermodynamic Pumping Systems

6.5 Future Prospects

From this review of solar thermodynamic pumps it is concluded that current activity in small-scale solar thermodynamic water pumping systems is still at the development prototype stage and that performance and cost data on solar thermodynamic pumps are limited.

The design studies show however, that the potential capital cost of some solar thermodynamic pumping systems could be competitive with photovoltaic powered pumps, as shown in Table 6.5.

It is concluded that it is premature to abandon development work on solar- thermodynamic systems. However, in selecting systems for future development, it would seem appropriate to investigate further those configurations identified in the design studies as being the most likely to lead to cost-effectiveness (see Table 6.4). The more recently developed systems (eg Wrede Ky) appear to conform with the more cost-effective configurations and employ tracking parabolic concentrating collectors and improved efficiency heat engines. Reliability in thermodynamic pumping systems remains a cause for concern.

In addition, the potential for local manufacture of some of the simplest thermodynamic systems is an attractive advantage, but in the absence of comprehensive performance data it is not yet clear whether locally produced simple systems will be more cost-effective than conventional thermodynamic or photovoltaic systems. There is a risk that simple designs may result in low efficiency and hence in large collector areas, high overall system costs and poor reliability or life.

Field experience is still extremely limited, although it is understood that several manufacturers are planning to undertake more field trials. System reliability and long term performance should be monitored on those systems which have been shown to perform well in laboratory or works tests. A series of satisfactory field trials are needed to build confidence in thermodynamic systems.

SYSTEM	Category A 60m^3/d - 2m head		Category B 60m^3/d - 7m head		Category C 20m^3/d - 20m head	
	System Cost($) (1,2)	SCC ($/kJ.d)	System Cost($) (1,2)	SCC ($/kJ.d)	System Cost($) (1,2)	SCC ($/kJ.d)
THERMAL						
Flat Plate Single Glazed Collector ORC Engine	3320	2.8	9530	2.3	9120	2.3
Evacuated CPC Collector ORC Engine	2180	1.8	5320	1.3	5120	1.3
N-S Parabolic trough Collector Rankine Engine	2730	2.3	7360	1.8	7060	1.8
Parabolic Dish Collector Rankine/Stirling Engine	1880	1.6	4220	1.0	4070	1.0
PHOTOVOLTAIC						
Two best in category from test results (see Table 5.4)	2690 - 2940(3)	2.3 - 2.5	3790 - 5110(3)	0.9 - 1.2	4730 - 5560(3)	1.2 - 1.5

NOTES

(1) Thermal system costs are estimates for quantity production
(2) PV system costs calculated on basis of $5/peak watt array plus costs of motor and pump in quantity production
(3) Capital costs pro rated in ratio of actual output to specified output.

Table 6.5 Comparison of Photovolatic and Thermodynamic Pumping System Cost Projections

PART C

Economic Evaluation of Solar Water Pumping

PART C: ECONOMIC EVALUATION OF SOLAR WATER PUMPING

7. INTRODUCTION

7.1 Philosophy Underlying Study

This Part of the Report outlines a study in which the economics of solar pumping systems were compared with four alternative techniques used in developing countries for water supply and irrigation purposes. It is believed to be one of the first studies on this subject in which mathematical modelling techniques have been used to give structure and definition to the task of comparing complex alternatives, and in which the technical and cost characteristics of the systems have been defined in some numerical detail.

It is hoped that the methodology adopted for these analyses will commend itself to others and that this work will be the forerunner of similar studies which will extend and refine the analyses carried out as part of the Project. The Consultants have used their best judgement in the selection of the many numerical values required: these have been fully tabulated in the hope that this will stimulate correction and refinement, not for uncritical repetition.

Full details of the background to the work are in Supporting Document 2.

7.2 The Study in Context

It is the view of the Consultants that the responsible development of solar pumping technology for the good of the prospective end user in developing countries requires a clear understanding and appreciation of the technical and economic circumstances in which solar pumps will become viable. It was the objective of this aspect of the Project to examine several scenarios in realistic detail, so as to make a major contribution to enlarging the existing understanding of these aspects. It is believed that the results and conclusions will be of value as a guide to those with responsibility for appraising, selecting and financing development technologies, often using public funds. The results will also be of interest to suppliers and prospective purchasers of pumping systems.

So far as small-scale energy systems are concerned, technology choice has been difficult for a variety of reasons, the more important of which are as follows:

- much technical expertise has resided with those having a vested interest in the technologies, and decisions may have been hampered by lack of an objective assessment and independent data on the cost- effectiveness of systems in the application for which they are proposed.
- some of these technologies, particularly solar photovoltaics, are developing quickly; it is important therefore to reappraise the situation at regular intervals. The results of this study are important in their own right, but in addition a methodology has been created which will provide the framework for future evaluations.
- the criteria for judging when solar pumps are ready for general use had not been clearly established and agreed. To make such judgements also required a greater knowledge than has been generally available on the alternatives to solar pumps.
- it has been surprisingly difficult to compare the new technologies with traditional alternatives that have been in use for decades. Little reliable information exists on, for

example, the actual field performance and costs of running the very small sizes of diesel-powered pumping systems used for small scale irrigation in developing countries. Manufacturers' claimed performance figures are generally optimistic and not to be relied on as the sole source of information.

- to get the new technologies right, it is important for designers, manufacturers and suppliers to obtain information on the actual performance of the systems under working conditions in the field and on the experience of users with the equipment over a period of time. However, no mechanism exists to arrange for such feed back, and information gained is either as the result of such studies as this or the enterprise and enthusiasm of individuals.

The study is virtually unique in having set out to collect "first-hand" and up-to-date data, and in using it as the basis of a techno-economic comparative evaluation of solar pumps over a range of alternative water lifting options. It is hoped that the results of the work will reduce some of the uncertainties and difficulties listed above.

The acceptability of non-traditional pumping techniques for rural development may well depend on satisfying more than technical and economic feasibility and non-technical factors may be very important. The widespread adoption of solar pumps by individual farmers or small villages could have far reaching social and institutional implications and these would need to be identified before the technology was introduced on a commercial scale. The Consultants' recommendations for Phase II (see Chapter 13) include study of these aspects and so attention in Phase II Preparation was concentrated on obtaining a clear view of the economic prospects for solar water pumps.

7.3 Applications

There are three main applications, all small-scale with hydraulic output power requirements typically in the 100 to 800 W range, for which solar pumps have been compared with alternative lifting devices:

- irrigation systems where water is raised through static lifts in the range 2m to 10m to suit land areas in the 0.25 to 4ha range. Systems for these duties at the lower end of the range of land area correspond to Categories A and B purchased for testing;

- village water supplies where water is raised through static lifts in the range 15m to 30m to serve populations typically of 375 to 1500 people. Systems for these duties broadly correspond to Category C purchased for testing, depending of course on per capita consumption;

- livestock water supplies where water is raised through static lifts in the range 15m to 30m for herds of 1000 to 4000 animals. Systems for these duties will require a hydraulic power output some four times the output of the Category C systems.

Due to variations in crop evaporation during the growing cycle, combined with variations in monthly rainfall, there is generally a large month-by-month variation in the net irrigation water requirement, with no water at all required in some months. The peak water demand of the crop itself may be 6mm/day or $60m^3$/ day per hectare and, at a field application efficiency of 50%, the peak hydraulic power required to lift the required flow to the field (before distribution) through 7m (say) would be around 380 watts/hectare.

The two water supply system types are very similar: 30m^3/day of water would typically supply either a village of 1000 people at a per capita consumption of 30 l/day or a herd of 750 cattle at a consumption of 40 litres/head/day. These types of system will have a relatively even month by month water demand which contrasts with water requirements for agriculture. The hydraulic power required to lift 30m^3 per 8 hour day through 20m would be around 280 watts.

A proper comparison of alternative pumping systems demands that they be considered in conjunction with water sources, storage and distribution methods, since these will significantly influence the total efficiency and cost-effectiveness of the water lifting and delivery process. In other words a systems approach is required when analysing the situations in which solar and other types of pumps may be used.

7.4 Value of Water

The upper limit that is acceptable economically for the unit cost of irrigation water is dictated by the benefits gained, or the marginal value of extra crops resulting from irrigation. The global target for this upper limit, based on world food market prices, agricultural input costs, etc, quoted in the Phase I Reports, was estimated by World Bank irrigation specialists at about US 6 cents/m^3 (1982) of water delivered to the field, assuming a field application efficiency of around 60%. Where the cost is based on the value of water received by the crop itself, as is convenient when field distribution systems of different efficiencies are to be considered, this norm becomes about US 10 cents/m^3 (due to the removal of the assumption on distribution efficiency). This figure is therefore used as a basis for judging whether an irrigation system, for the purposes of this study, is potentially economically viable. Obviously, the value of US 10 cents/m^3 is only a guide: in many cases, where high value crops are being grown, it might readily be exceeded, while in other places where food is cheap, it may be necessary to place a lower value on the water. Even if a solar pump meets this criterion for irrigation water, there may also be other pumping system prime-mover options which can deliver water more cheaply. Also, unit water costs are only one criterion for judging a system's merits; other factors such as first cost, ease and flexibility of operation and reliability will figure in the minds of potential users and therefore must be considered too once the main economic picture is clear.

So far as rural water supplies for personal consumption and immediate domestic use are concerned, a generally applicable figure for the economic value of water is not so easily defined. As was pointed out in Section 1.2 on a domestic level water can often be purchased in small quantities of a few litres at high costs equivalent to several dollars per cubic metre in areas where good water is scarce or difficult to extract from the ground.

On the other hand the value of water for commercial livestock has a definite upper limit which corresponds to the value of the stock for milk, meat, and other uses. In either case, the procedure adopted for the economic studies has simply compared the relative costs of water delivered to the user by the different pumping methods.

7.5 Scope of Study

This section outlines the scope of the work and the analysis which were undertaken.

7.5.1 System comparisons

The systems to be analysed and compared were defined with some care in order to provide a reasonable variety and range of conditions without incurring the penalty of a very large number of model runs.

The systems studied are shown graphically in Figs 7.1 and 7.2: each complete 'route' across the figure corresponds to a different alternative.

Six water-lifting technologies were compared:

- solar photovolatic pumps;
- wind pumps;
- diesel engine pumps;
- kerosene engine pumps;
- animal-powered pumps;
- hand-pumps.

For irrigation, the baseline models consisted of the six different pumping devices coupled with appropriate selections from the three different conveyance and field distribution methods as shown in Fig.7.1. The baseline models were run at two pumping heads of 2m and 7m representing respectively, low-head pumping and a more typical head for pumping. This led to a total of 60 irrigation baseline models. Each baseline model was run for irrigated areas between 0.25 to 4.0 hectares.

For rural water supplies, the baseline models consisted of four pumping devices (animal and kerosene excluded) with and without a storage and distribution system (as shown in Fig. 7.2) all operating at 20m static head, giving a total of 9 village water supply and 4 livestock water supply systems. Each baseline model was run for village populations between 375 and 1500 and for livestock herds of 1000 to 4000 animals.

7.5.2 Types of analysis

Three basic analyses were carried out:

a) Baseline studies

The baseline scenarios were chosen to represent what are believed to be "typical" technical and economic conditions, in order to provide a general comparison between the different pumping system options.

The technical parameters were based on average conditions for small farms and villages, while the cost and economic data were drawn as far as possible from world market data and were free of the influence of taxes and subsidies. The optimum distribution methods were selected for each pumping device to show each option applied under conditions which were fair to it.

b) Sensitivity analyses of baseline scenarios

Sensitivity analyses were carried out by systematically changing the parameters used in the baseline scenarios and running the models to find the effects on unit water costs. This was done to indicate the relative sensitivity of the various parameters and assumptions included in the baseline models.

c) Country specific case studies

Many factors other than purely economic ones affect the perceived cost-effectiveness of solar pumps. Because of this, in addition to comparing solar pumps with other options in economic terms using world market prices, the work included case studies of conditions in Bangladesh, Kenya and Thailand.

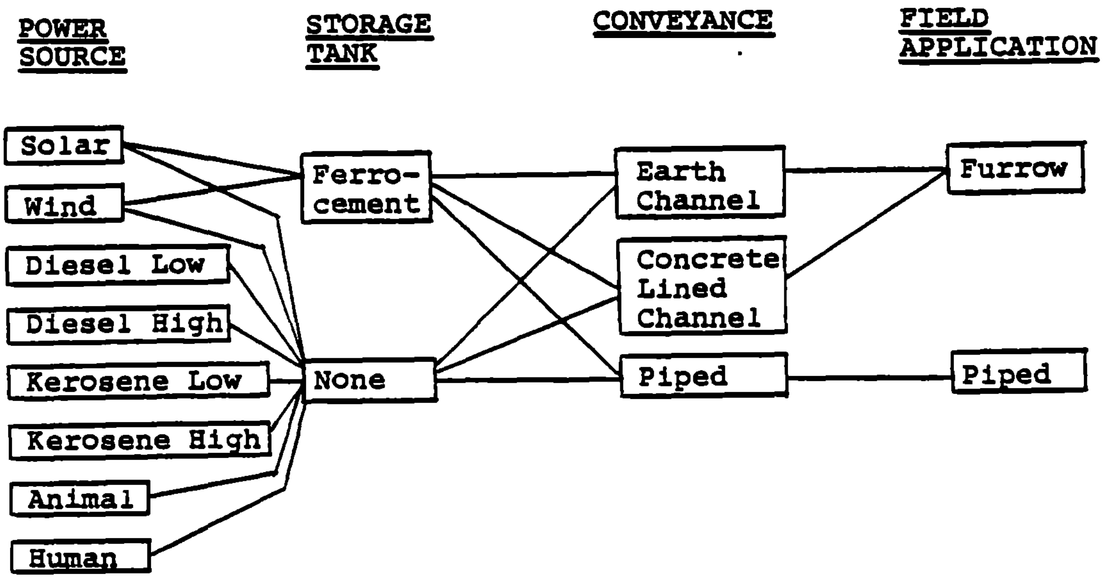


Figure 7.1 Alternative irrigation systems compared in economic studies

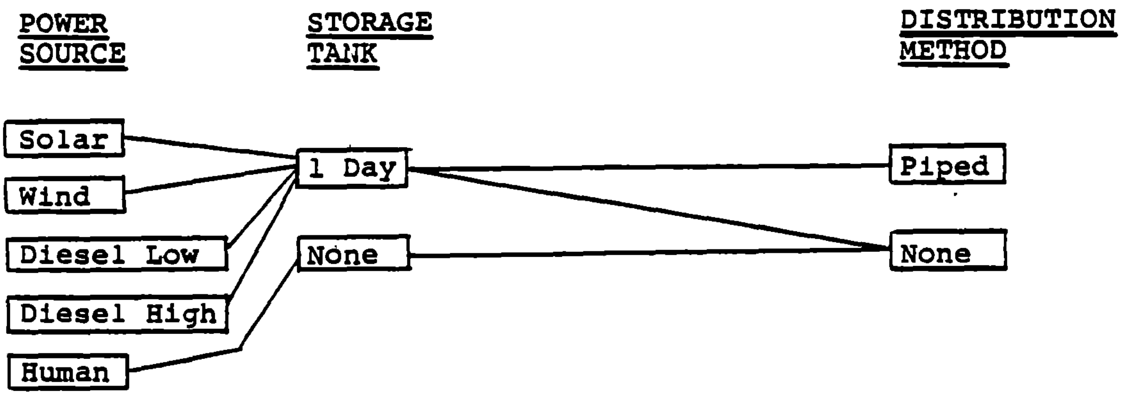


Figure 7.2 Alternative village water supply systems compared in economic studies

Note: The livestock water supply system is similar to that shown in Fig. 7.2 except that the option with no storage tank and piped distribution is not considered).

The objective of the case studies was to investigate how local conditions in the countries selected might influence the competitiveness of solar pumps compared with other techniques being analysed.

The three countries chosen for case study were selected from those short listed by the World Bank to be considered for participation in Phase II (see Chapter 14). Their conditions were representative of those visited during the Project and for which it was possible to obtain the data needed at a reasonable cost. In so far as the three countries were included in the short list of countries to be assessed, it may be assumed they were believed to be more rather than less suitable for solar pumps: in fact they provided a range of conditions for analysis; this was completely consonant with the object of the study, which was to analyse varied situations, not only those most favourable to solar pumps.

These country studies were based on recent financial cost data - there was no opportunity to assess and allow for the effects of taxes, subsidies, etc.

7.5.3 Collection of data

Much of the technical data for the baseline and sensitivity analyses were obtained from standard sources, modified if necessary after discussions with the specialist advisers to the Project.

A Bibliography on cropping patterns and meteorological data, pump performance and costs is included with the References, and individual works on these matters have not been cited in the text unless they were needed in other contexts.

Information on water use and practice and associated financial costs for Bangladesh, Kenya and Thailand was obtained through the use of detailed questionnaires prepared especially for this exercise. Arrangements for completion of the questionnaires differed from country to country: in two a firm of local consultants was entrusted with the work while in the third interested professionals familiar with the water pumping scene provided the data (see Acknowledgements). The data obtained was checked and then reduced to a form suitable for analysis in the mathematical model.

7.6 Development of Mathematical Models

7.6.1 Structure

Two computer based mathematical models were developed, one for irrigation systems and one for rural water supplies. Two models were needed because of the different characteristics of the two systems, particularly in relation to the nature of the water demand and the methods for conveying water. A modular approach was used for both models utilising components for water source, power source, pump, water storage unit, conveyance or distribution method and field application method (the last only for the irrigation model).

The computer models of the irrigation and water supply systems allow for the specification of technical and cost features of each of a range of components, the most important being:

- different types of lifting devices: solar, wind, diesel-engine, animal and human;
- systems with or without storage

- drawdown in the water source,

while the irrigation model only has:

- three different types of water conveyance: earth channel, concrete lined channel and pipes
- two different method of application to the crop: furrows or trickle pipes
- allowance for the head loss in the channels and pipes

and the rural water supply model only has:

- the appropriate number of water points or pumps calculated from the specified water point spacing and/or peaking factor (ratio of maximum daily demand to mean daily demand)
- piped distribution to water points or single outlet,with allowance for head losses in distribution pipework.

The technical and cost parameters specified are given in Section 8.1 and 9.1 for irrigation and water supply, respectively.

7.6.2 Calculation procedures

The procedure followed to calculate the unit water cost is outlined below:

a) The input data are specified and fed into the model. These fall into four main groups:

   - technical and cost specifications for each component eg. component efficiency, channel seepage rates, operating norms, cost coefficients, etc.
   - meteorological factors eg. values of mean daily irradiation for each month (on the horizontal plane), wind speed, ambient temperature, latitude of site and tilt of array in critical month.
   - water use specifications eg. static head, drawdown, water supply area, values of monthly mean daily water demand (expressed as annual mean daily demand and values of peak demand factor for each month),
   - economic parameters eg, period of analysis, discount rate, local cost ratios, shadow exchange rate.

   The parameters required to calculate mean daily net crop water requirements are fed into the model on a monthly basis.

b) The critical month is determined. For the solar and wind systems this is the month with the minimum ratio of energy available to hydraulic energy required. The pumping system is then sized to meet the mean daily water requirement during this month. For animal and human powered systems it is the month with the maximum mean daily demand. The diesel and kerosene engines adopted were the minimum sizes available commercially and no single month was critical.

c) From the individual component efficiencies, the size of the prime-mover (in the cases of solar, wind, animal and human power), pump storage tank (where considered) and water distribution system are calculated. Because the total system head depends on the flow rates in the system and the flow rates depend on the pump size, this stage of calculation involves an iterative procedure. Since the minimum size of the engines adopted were greater than that needed, the times for which they would need to operate are calculated.

d) For each component there is a size-dependent cost function, described in section 7.6.3.

Hence once the size is calculated the capital cost can be found. The total system capital cost is found by a summation of the individual component capital cost functions.

e) The lifetime (in years) of each component is calculated from the input data on the number of operational hours the system components will run before needing replacement. The discounted replacement costs over a given period of analysis (after allowing for any differental inflation specified) are then calculated. The yearly maintenance and repair costs are determined from the annual operating hours. The fuel and/or other recurrent operating costs, such as food for animals or labour (opportunity) costs for human inputs, are calculated from the input energy requirements to the system. For all these recurrent costs any presumed value of differential inflation can be allowed for, as required.

f) Capital and recurrent costs of various kinds (replacement, maintenance and repair, and operation) are thus obtained and these will probably constitute an irregular stream of cash flows over the period of the analysis. In order to calculate an average cost per unit volume of water provided by each system, this irregular cash stream is first discounted to the present day at an appropriate discount rate, the sum of the different cost components being the Present Worth (PW)* of the life cycle costs. This Present Worth is then converted to an equivalent uniform annual sum for the discount rate and period of analysis adopted, by use of the capital recovery factor. (The importance of discount rates in this procedure is discussed in section 8.3.5).

g) The model can also take account of the proportion of total cost incurred in local currency and can use a shadow exchange rate factor to give a better estimate of shadow prices.

h) The average unit cost of water delivered (either to the crop or the water point) is then calculated by dividing the uniform annual sum by the volume of water pumped on average each year. Note that, since in irrigation practice it has been usual to calculate water costs delivered to the field, the costs given in the Report will appear high because they are for the water delivered to the crop.

7.6.3 Capital and Recurrent Costs

The lifecycle costs of the individual components in each of the alternative systems studied consist of the sum of capital cost and the Present Worth of recurrent costs (for a specified discount rate and life). These are added to give the total lifecycle costs for the system concerned and then converted to uniform equivalent annual costs as described in section 7.5.2.

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*used in preference to Present Value (PV) to avoid obvious confusion with Photovoltaic (PV)

The cost elements are defined as follows:

a) **Capital costs**

For each component the capital cost is assumed to be of the form:

$$C = C_o + C_1 S^b$$

where S is the size of the component (eg peak watts for a PV array), C_o is a fixed cost, C_1 is a size related cost, and b is an exponent. Thus values of C_o, C_1 and b are required for each component. This definition assumes size varies continuously, whereas it may change in discrete steps. Due to limited data, C_o and b may take on the values 0 and 1 respectively for the minor components, which means the capital cost per unit size becomes independent of size. An allowance has been made in the value of C_1 for transport and installation costs.

It should be noted that in those instances where capital costs per unit size (or output) vary with size (i.e. $C_o \neq 0$), costs per unit size can only be quoted for a specified size.

b) **Recurrent costs**

For each component recurrent costs are calculated in three parts:

Replacement - this is allowed for at the intervals calculated by the model according to the lives or operating durations specified. A differental inflation rate, i_c, is required to allow for any relative movement between the replacement costs of a particular component and the general movement of prices (eg the cost of PV arrays is expected to fall in real terms).

Maintenance and repair - wherever possible, for moving mechanical devices, these are specified in dollars per 1000 operating hours, M, and this value is used with the total operating hours to calculate the annual maintenance and repair costs. For static devices (eg arrays) the cost is assessed simply on an annual basis. A differential inflation rate, i_m, may be specified if required.

Operating - these are fuel costs, animal feeding costs, or labour charges for operation and for attendance, c_f, calculated on the basis of the input energy requirements of the system. A differential inflation rate, i_f, may be specified if required.

There may be occasions when, for the purpose of economic analysis within a country, it is necessary to use shadow prices. The model user can allow for this for each of the cost elements listed above through the local cost factor, L, which is the proportion of total cost incurred locally. A shadow exchange rate factor can then be used on the local costs to weight these relative to the value of the foreign expenditure component.

7.7 Economic Analysis

The economic comparisons have had regard to the classical distinction between economic evaluation and financial planning (see for example Ref. 12). The former approach seeks to make comparisons based on a measure of the real resources committed to or resulting from an investment decision and is used to judge between alternatives. Once a decision is made the financial consequences in terms of loans, interest rates, taxes, subsides etc. are then calculated.

In the framework of economic evaluation a general movement of prices has no effect on the relative merits of different alternatives and inflation per se does not need to be taken into account. However, if the price of particular goods or services increases (or decreases) at a rate which is different from the general movement of prices, then this differential inflation does need to be allowed for in the discounted cash flow analysis. In these studies the two main examples of differential inflation were a negative value of 7% per annum for PV module costs and a positive value of 3.5% per annum for cost of diesel fuel (see Appendix 3).

The cost data used for the baseline and sensitivity studies were 'international' and deemed to be free of the distorting effects of taxes, subsidies etc. The basis on which these data were derived is given in Table 7.1. The cost data collected from Bangladesh, Kenya and Thailand were known to include taxes and subsidies and have been termed 'financial' cost data - generally these prices reflect what farmers or villagers in those countries would pay.

Normal discounted cash flow (DCF) methods have been used for the comparative analyses whether international economic data or country specific financial data were used. The model requires the user to specify the general discount rate, 'i,'and the overall period of analysis, 'n' in years. For economic analysis the discount rate should reflect the real returns gained from investment in excess of the general level of inflation and a real rate of 10% was adopted. The period of analysis strictly should be a whole multiple of the different replacement periods, but these are not known in advance. To minimise the slight errors introduced by this a period of analysis of 30 years was adopted - this is also about twice the minimum period at which the life assumed for a PV pumping system ceases to have a major influence on the economics of the complete system.

Finally the shadow exchange rate factor was set to unity and no attempt was made to assess shadow prices in these initial studies.

1 Water Source

Costs based on an average for Bangladesh, Kenya, and Thailand.

2 Power Source

Solar	based on prices quoted internationally for modules
Wind	based on cost data obtained by IT Power in survey of windmills under separate project within UNDP GLO/80/004 (excluding taxes)
Engines	based on data from Thailand and UK (excluding taxes)
Animal	based on data from Bangladesh, Kenya and Thailand

3 Pumps

Photovoltaic	based on UK costs (excluding taxes)
Engine driven	based on UK costs (excluding taxes)
Wind	based on IT Power data
Animal	based on data from Bangladesh, Kenya and Thailand
Handpumps	Capital costs (excluding taxes) from UNDP/World Bank Handpump Programme Maintenance costs based on international reference material moderated to give reasonable totals for multiple installations.

4 Storage Tanks & Channels

Costs based on data from Bangladesh, Brazil, India, Kenya and Thailand.

5 Pipes

Costs based on data from Bangladesh, Kenya and Thailand and a survey of UK sources.

NOTES.

1. All data is deemed free of taxes and subsidies.

Table 7.1 Basis of Generalised International Cost Data

8. IRRIGATION STUDIES

8.1 Systems Considered

8.1.1 Agricultural aspects

A schematic layout of the irrigation system is shown in Fig. 8.1 and its technical characteristics are listed in Table 8.1. A square two hectare field was adopted for the baseline scenario: the effects of a change in the area supplied by a single pump were investigated as part of the baseline studies. As noted previously six types of prime mover were studied.

The following types of irrigation water distribution system were considered:

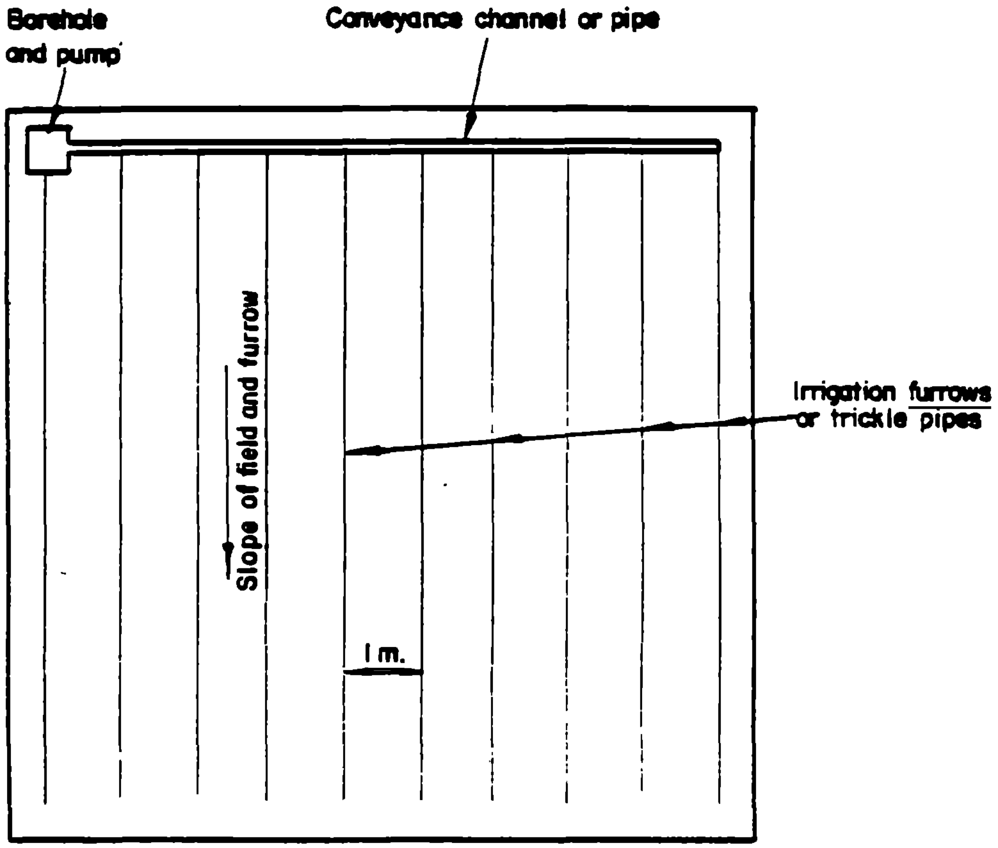
- open channels (lined or plain earth) to convey the water from the pump to the field, with furrows to distribute the water to the crops. Typically the application efficiency of the earth channels is 50%.
- a main conveyance pipe coupled to an array of trickle pipes, which cover the entire irrigated area, with a typical application efficiency of about 85%.

Open water was assumed as the source for the 2m lift (i.e. a canal, river or pond), while a borehole or well was assumed for 7m lift applications. Both sources were assumed to have the same drawdown characteristics for these initial studies and this aspect will require refinement in further work.

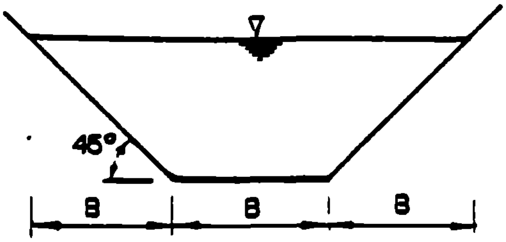
The two renewable energy sources (solar and wind) which differ from the other options in not always being available on demand, were also considered in conjunction with a storage tank capable of storing from half to one day of the peak water requirement. The purpose of the store is to even out diurnal fluctuations in the water delivered, to provide a little emergency cover, and to obtain more flexible water management practices. The importance with which storage is viewed will depend to a large extent on existing farming practices: although many would regard storage as a desirable feature, there are many areas of the world where renewable systems could be used successfully without storage. It will be appreciated that impracticably large storage would be required to cope with longer term resource constraints, but detailed considerations of this were beyond the scope of the study.

The net crop irrigation water requirement for the baseline cropping pattern is shown in Figure 8.2 and has a peak requirement of 6mm/day (see Bibliography). This is derived from Kenyan practice and is based on two main cropping periods - cotton in the first, and a mixture of groundnuts, maize and cowpeas in the second - and represents the type of demand for which solar pumps would first be used. Figure 8.2. also includes data on the energy available from solar and wind energy resources. The critical month for solar energy availability is May when the ratio of energy available to that required for pumping is a minimum: a mean daily solar irradiation of $20.8MJ/m^2$ ($5.78kWh/m^2$) on the horizontal plane has been assumed. This is what would be expected in a relatively sunny (perhaps semi-arid) tropical or sub-tropical region and would represent the kind of region where solar pumps might first be expected to become economically viable for irrigation applications.

The critical month for wind is February when the average wind speed is 2.5m/s. This is rather a low wind speed and is perhaps more typical of inland tropical regions with moderate winds than of regions which look attractive for applying wind power (such as coasts, certain desert fringes and islands).



LAYOUT



CROSS SECTION OF CHANNEL/FURROW

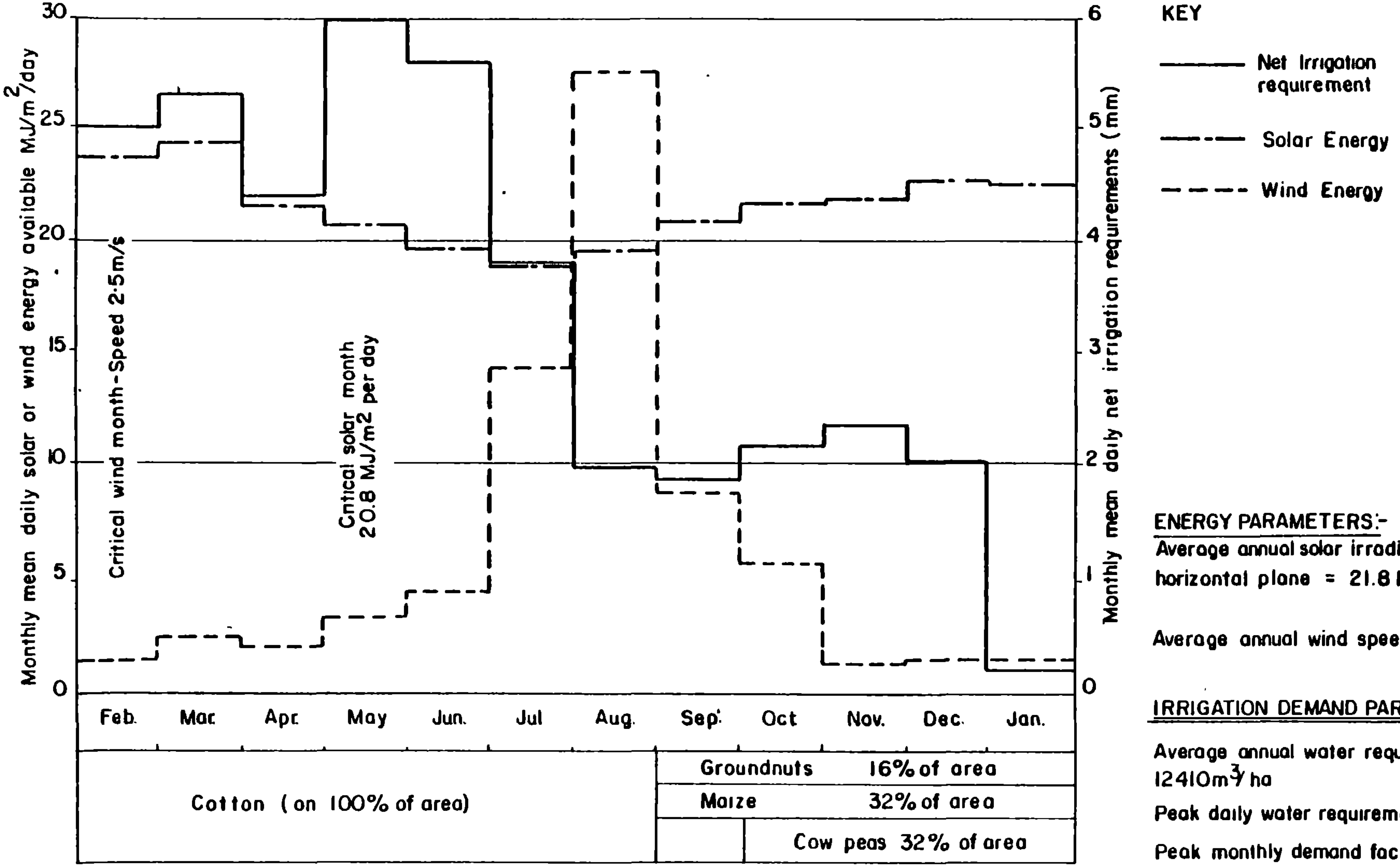
Figure 8.1 Schematic Layout of Irrigation System Field Pattern for Baseline Model

Irrigated Area	
Area	2 hectares
Shape	square
Conveyance channel	along side
Water Source	
(a) open well static head (1)	2 metres
drawdown	0.1m per l/sec
(b) borehole static head (1)	7 metres
drawdown	0.1m per l/sec
Storage tank	
Store size	0.5 days of the peak water demand
Store height	height = ½ diameter
Material	Ferrocement
Storage efficiency	100%
Application time	2 hours with open distribution 8 hours with piped distribution
Lifetime	30 years
Earth channel	
Slope	1%
Shape	trapezoidall side slope 45° Top width = 3 x invert
Manning roughness coefficient	0.020
Seepage rate	8×10^{-3} lit/sec per m^2 of wetted surface
Lifetime	5 years
Cement/Soil channel	
Slope	1%
Shape	trapezoidall side slope 45° Top width = 3 x invert
Manning roughness coefficient	0.018
Seepage Rate	0.7×10^{-3} lit/sec per m^2 of wetted surface
Lifetime	10 years
Conveyance Pipe	
Diameter	0.075 m
Material	PVC
Darcy resistance coefficient	0.02
Efficiency	100%
Lifetime	10 years
Trickle pipe	
Diameter	0.013 m
Material	PVC
Darcy resistance coefficient	0.02
Efficiency	0.85
Spacing	1 metre
Lifetime	10 years
Furrow	
Application efficiency	50%
Additional head required	0 metre (assumed to be at overall field slope)
Spacing	1 metre

NOTES.

(1) Defined for purposes of economic studies as the difference in elevation between the water surface at the source and the ground level adjacent to the storage tank or conveyance channel or pipe. It does not include the extra head required to raise the water to the storage level in the tank nor the head required to overcome energy losses in pipes or channels nor drawdown. These are calculated and added to the static head to give total pumped head.

Table 8.1 Technical Characteristics of Source, Storage, Conveyance and Field Distribution Systems - Irrigation Baseline Scenario



ENERGY PARAMETERS:-

Average annual solar irradiation on horizontal plane = 21.8 MJ/m^2/day

Average annual wind speed = 3 5 m/s

IRRIGATION DEMAND PARAMETERS -

Average annual water requirement 12410 m^3/ ha

Peak daily water requirement 6 mm

Peak monthly demand factor 1 76

Figure 8.2 Cropping pattern and meteorological data - baseline scenario

8.1.2 Technical specifications for pumping systems

As previously noted in section 5.3.7, the combinations of future costs and efficiencies used in these economic studies are given in Table 5.5. The technical specifications for the pumping systems are given in Table 8.2 Note that the static head is the difference in elevation between the water surface of the source and the ground level adjacent at the head of the conveyance system (or storage tank if used). All flow dependent energy losses are calculated and added to the static head, drawdown and storage tank height (if used) to give the total pumped head.

The solar pump specification corresponded with the performance obtained from the best systems tested so far under the Project and is considered that systems giving this performance in the field will be available very shortly. (Note that the value of PV array efficiency quoted is based on gross cell area). The site was assumed to be at a latitude of 20^{0} with the array tilted at the same angle.

An average daily subsystem efficiency of 40% was taken for the baseline studies. This value is based on the best system daily efficiencies obtained in the tests (3.4% and 3.8%) which, when converted to cell area (4.5% and 5.1%) and using a cell efficiency of 11%, produce daily subsystem efficiencies in the range 41% to 46%. Since the model did not permit daily efficiency to vary with static lift an average figure for all the baseline studies of 40% was adopted. The figure is also supported by analysis of the measured peak subsystem efficiencies. For analysis of the target case it was assumed that average daily efficiencies of developed systems would be around 50%.

The windpump specification similarly reflects the current state-of-the-art for windpumps (see Bibliography). Better efficiencies are likely to be possible from new developments, but it was decided to model what is attainable at present from the best commercially available products.

There is conflicting information on the performance and operating costs of very small engine-powered pumps operating under conditions prevalent in developing countries. Manufacturers' performance claims are often optimistic compared with almost all the very limited available results actually measured in the field. This is because, in practice, diesel pumps are rarely run near their optimum speed (indeed they usually need to be derated to attain an adequate life) and often they spend a fair proportion of their useful lives running in a poor state of "tune". Therefore, two cases were considered for diesel pumps; a 'high' recurrent cost case with a 6% diesel/pump system efficiency and a 'low' recurrent cost case with a 9% diesel/pump efficiency. It should also be noted that the very smallest sizes of diesel engines have been considered and these are inherently less efficient than the larger engines.

It is believed that the former - the diesel 'high' case - more nearly represents the realistic performance of small engine pumps under normal field conditions, while the latter - the diesel 'low' case- represents the best which can be expected under good conditions in a developing country context. These are some instances of small diesel pump systems giving far worse overall system efficiencies than 6%, so this does not by any means represent a very badly run diesel system.

Because kerosene powered pumping systems are widely used for irrigation in some countries, they were also briefly investigated in order to confirm that they are less economic than diesel systems; therefore diesel was used as the prime example of the use of petroleum fuels as it represents the most cost-effective method for using such fuels. (The results of this analysis on the use of kerosene pumps is also given later).

Solar pump	
Tilt	20 degrees
Critical Radiation level(daily ave)	250 W/m^2
PV array efficiency	11% (4)
Array lifetime	15 years
Motor/pump efficiency(ave)	40% (3)
Motor/pump lifetime	20,000 operating hours or 10 years maximum (1)
Windpump	
Cut in wind speed	Mean wind speed of least windy month
Rated wind speed	10 m s^{-1}
Furling wind speed	12 m s^{-1}
Efficiency at rated wind speed	9%
Pump lifetime	40,000 operating hours or 10 years maximum (1)
Tower/Rotor lifetime	30 years
Diesel pump (high case)	
Size (Rated shaft power)	2.5 kW
Engine efficiency	10%
Engine lifetime	3700 operating hours or 7.5 years maximum (1)
Pump efficiency	60%
Pump lifetime	40,000 operating hours or 10 years maximum (1)
Diesel pump (low case)	
Size (rated shaft power)	2.5 kW
Engine efficiency	15%
Engine lifetime	5000 operating hours or 10 years maximum (1)
Pump efficiency	60%
Pump lifetime	40,000 operating hours or 10 years maximum (1)
Kerosene pump (high case)	
Size (rated shaft power)	1.1 kW
Engine efficiency	3%
Engine lifetime	2700 operating hours or 5 years maximum (1)
Pump efficiency	60%
Pump Lifetime	40,000 operating hours or 10 years maximum (1)
Kerosene pump (low case)	
Size (rated shaft power)	1.1 kW
Lifetime	3700 operating hours or 5 years maximum (1)
Engine efficiency	5%
Pump efficiency	60%
Pump Lifetime	40,000 operating hours or 10 years maximum
Animal pump	
Mean animal power rating	350 W
Length of working day per animal	5 hours
Pump efficiency	60%
Pump lifetime	15 years maximum
Animal lifetime	10 years
Hand pump	
Human power rating	60W
Length of working day	8 hours social) irrigation only 5 hours actual)
Pump efficiency	60%
Pump lifetime	20,000 operating hours or 10 years maximum (1)
Peak flow rate (2)	(at 2m static head) = 1.83 lit/s (at 7m static head) =0.52 lit/s (at 20m static head) = 0.18 lit/s

NOTES:

(1) · Unit replaced at whichever limit is reached first.
(2) · Extrapolated from data from 'Performance Index for Man Powered Pumps' by A R O'Hea, Appropriate Technology Vol 9 No. 4, March 1983 assuming 36 watt output maintained for duration of 10h.
(3) . Based on ratio of hydraulic energy output to energy input when pump is working
(4) . Based on gross cell area (not array)

Table 8.2 Technical Characteristics of Pump Prime Movers - Irrigation and Rural Water Supply Baseline Scenario

Data on the performance characteristics of hand and animal powered pumps were very limited. Human power figures were based on long duration power output data (Refs 3 and 13) and extrapolated from handpump performance data. It was assumed that the human output power was even at about 60W. The performance of animal pumps was based on a published draught animal power measurements (see Bibliography).

Overall the technical specifications have been chosen to represent what it is believed would be very good performance from the latest equipment currently available, given reasonably good operational procedures, but not assuming perfection.

8.1 3 Cost and economic data

a) General

Full details of the origins of the cost data and their analysis are given in Supporting Document 2. The information used for the derivation of the cost factors outlined in section 7 6 3 was obtained from a variety of sources (see Bibliography)·these included published material, private written sources, individuals met on overseas visits, manufacturers (tender importation and other) and the project questionnaires completed for Bangladesh, Kenya and Thailand. The costs can be regarded as those current in mid-1982. local currencies have been connected to US dollars at the exchange rates ruling in August 1982.

The various cost factors, coefficients and parameters needed to define and derive the capital and recurrent costs for each component are given in full for the international baseline scenarios and for the country specific case studies in Appendix 3. Since some of the costs per unit size (or power) are size dependent it is not always possible to quote generally applicable figures for costs per unit power (as is done with arrays for example). As an illustration of the use of the cost factors, the international capital and recurrent costs have been worked out for typical sizes of the pumping systems and these are given in Table 8.3.

This data is amplified for PV pumping systems in Table 8.4 (explained in more detail below). Table 8.5 gives illustrative cost data for the infrastructural components of the irrigation (and water supply) scenarios.

It should be noted that the cost of those items of equipment presently originating in the developed countries also include an allowance for the costs of transport and installation and thus are broadly comparable with the costs of local produced items.

In all the baseline studies a real discount rate of 10% and a period of analysis of 30 years were adopted. The choice of the discount rate can be controversial and the effects of changes in the rate have been examined in the sensitivity analyses.

b) PV pumping systems

The way in which the capital costs of the PV pumping systems themselves are handled requires special mention. The derivation of these costs will first be explained and then the approach used to estimate costs at different time horizons will be outlined. For mathematical economic studies it is very helpful (if not essential) to have continuous smooth functions by which to express the cost relations The general equation for capital costs given in Section 7.6.3 involved a fixed cost (C_0), a size related cost (C_1) and an exponent (b). The unit capital costs of arrays are not size dependent and are usually quoted simply in terms of dollars per peak watt and it was therefore simple to set Co to zero and b to unity. For mid-1982 a cost of 10 dollars per peak watt was adopted.

System	Hydraulic Rating of Pump (watts)	Capital Cost of Pumping Systems	Maintenance Cost		Operating Cost
			$ per yr	$ per 1000 operating hours	
Solar	100-400	$17.1-18.7 Wp of array output(3)	50(2)	12	0(4)
Wind	N/A	$300 per m² of rotor (for 1m <dia <10m)	50(2)	6	0(4)
Diesel - low	1.5 kW	$850 per kW engine shaft output	-	200	40¢ per litre(5)
Diesel - high	1.5 kW	$850 per kW engine shaft output	-	400	80¢ per litre(5)
Kerosene - low	550	$400 per kW engine shaft output	-	200	40¢ per litre(5)
Kerosene - high	550	$400 per kW engine shaft output	-	400	80¢ per litre(5)
Animal	210	$5.2 per hydraulic Watt output(1)	10(2)	-	$2.25 per animal day
Handpump	36	$6-$8 per hydraulic Watt	50(2)	-	$1 per man day

NOTES.

(1) On the basis that one animal generates 350 watts
(2) Probably low for one pump alone, but when groups of pumps are involved total cost is reasonable
(3) See Table 8.4 for details
(4) Values will be small and in absence of firm data costs have been set to zero
(5) Costs of attendance on engine not included

Table 8.3 Illustrations of Pump Costs for Selected Hydraulic Outputs
(Based on data in Appendix 3)

Case	Hydraulic rating of pump hydr. watts	Motor/Pump Costs (FOB)		Module Costs FOB	Miscellaneous Costs(5)	Total installed solar pumping system cost
		$ per peak hydr watt	$ per peak watt array output	$ per peak watt	$ per peak watt	$ per peak watt
Present (mid 1982)	100	6.80(1)	2.70(3)	10	6	18.7
	200	4.15	1.70			17.7
	400	2.82	1.10			17.1
Target (by 1987)	100	3.40(2)	1.70(4)	5	3	9.7
	200	2.80	1.40			9.0
	400	1.41	0.70			8.7
Potential (1993-1998)	100	3.40(2)	1.70(4)	2	3	6.7
	200	2.08	1.04			6.0
	400	1.41	0.70			5.7

NOTES.

(1) From equation C = 530 + 1.5P (Fig 8.3)
(2) From equation C = 0.5 (530 + 1.5P (Table 5.5)
(3) Assumes average subsystem efficiency of 40%
(4) Assumes average subsystem efficiency of 50%
(5) Covers pipework (excluding riser pipe in borehole) foundations, array support, shipping, transport and labour

Table 8.4 Cost Assumptions for PV Solar Pumping Systems for Economic Studies

Component	Size	Capital Cost	Maintenance Cost ($ per year)
Well	2m	$ 3 per metre	) deemed to) be included) in pump maintenance costs
Borehole	7m	$56 per metre	
Pipework in borehole(1)	-	$25 per metre	0(2)
Storage Tank	30m³	$16.2 per m³	0
Earth Channel	100m²	$0.6 per m²	50
Lined Channel	100m²	$3 per m²	35
Furrow	-	0	0(2)
75mm Ø PVC pipe	N/A	$12 per metre	0(2)
12mm Ø PVC pipe	N/A	$0.4 per metre	0(2)

a) Irrigation

Component	Size	Capital Cost	Maintenance Cost ($ per year)
Borehole	20m	$52 per metre	deemed to be included in pump cost
Pipework in borehole(1)	-	$25 per metre	0(2)
Storage Tank	30m³	$58 per m³	0(2)
50mm Ø PVC pipe	N/A	$4 per metre	0(2)

b) Water supply

NOTES.

(1) Added to cover costs of riser pipe within borehole for all systems. In case of solar this is extra over the pipework provided as part of the pumping system under miscellaneous costs item - ref. Table 8.4.

(2) Values have been small and in absence of firm data costs have been set to zero

Table 8.5 Illustrations of Costs of Infrastructural Components for Irrigation and Water Supply Scenarios (Based on data in Appendix 3)

It was suspected that the unit capital cost of the motor pump units would be size dependent in some way and a plot of capital cost per rated hydraulic watt output was prepared, (see Fig. 8.3), the costs being based on the manufacturers/suppliers estimates of the cost when produced in quantity. (In fact the manufacturers quoted a rated motor output and hydraulic power output was obtained by use of an estimated pump efficiency of 60%). It was to be expected that such a plot, based on estimates for a new technology, would demonstrate considerable scatter and therefore regard was paid to the systems purchased when drawing the curve deemed to be representative of average costs in mid-1982. The equation of this unit cost curve is $C = 530 + 1.5P$ (where C is in US$ and P is in hydraulic watts output) and demonstrates that capital cost per peak hydraulic watt can only be quoted for a particular hydraulic power. (For example, for a motor/pump unit with an output of 100 watts hydraulic, the cost per watt is around 6 8 dollars, and hence the capital cost is 680 dollars; for a motor/pump unit with an output of 200 watts hydraulic, the cost per watt is 4 dollars and the capital cost is therefore 800 dollars).

It will be noted that for a motor/pump unit of 50% efficiency the cost of the motor and pump expressed in terms of dollars per peak watt array output is half these figures. The practice of quoting motor pump costs in terms of array output is inherently confusing and not to be encouraged.

It will also be seen that the effect of static lift is not taken explicitly into account in the costings for the motor/pump units, although some influence is implicit in Fig. 8.3 which is based on the prices quoted for the three categories of system.

The third element in the total installed cost of PV pumping systems is the sum of the miscellaneous cost of pipe work, foundations, array support structures, shipping, transport and labour. These are difficult to estimate and it was decided to input these on the basis of array output power because many of these costs will be linked to the size of the array. For mid-1982 a cost of 6 dollars per peak watt was adopted. (The extra costs of the more expensive riser pipework for the 7m and 20m lifts have been added to the borehole costs and apply to all the alternatives).

The 'Present' costs are quoted in the top part of Table 8.4 for hydraulic outputs of 100, 200 and 400 watts. The size of pump, motor and array are calculated in the model for the particular circumstances in which they are being used. It was noted that the calculated costs of the motor/pump unit are sometimes lower than the prices paid for them in systems with similar quoted outputs: this is because either the manufacturer has provided a motor pump unit which is slightly larger than that needed or else that its efficiency is less than 50%

As previously explained, estimates were also made of costs at two time horizons: the first at around 5 years (1987) and the second in the range of 10-15 years (1993-1998). The costs at 5 years were described as 'Target' costs and for these the arrays were assumed to be available commercially at 5 dollars per peak watt, the reduction from present price level being mainly due to the increased scale of production.

For the motor/pump units a comparison between the present day costs of ac motors and pumps and dc motors and pumps suggested that, because of the increased scale of production, real costs could be halved and the costs of d.c. motors and pumps for use in the projected cost analyses were taken as 50% of that given by the equation above (details are in Supporting Document 2). This curve forms the lower bound to the costs plotted in Fig 8.3. Similarly, the miscellaneous costs of site work, transport and labour were taken as 3 dollars per peak watt of array output.

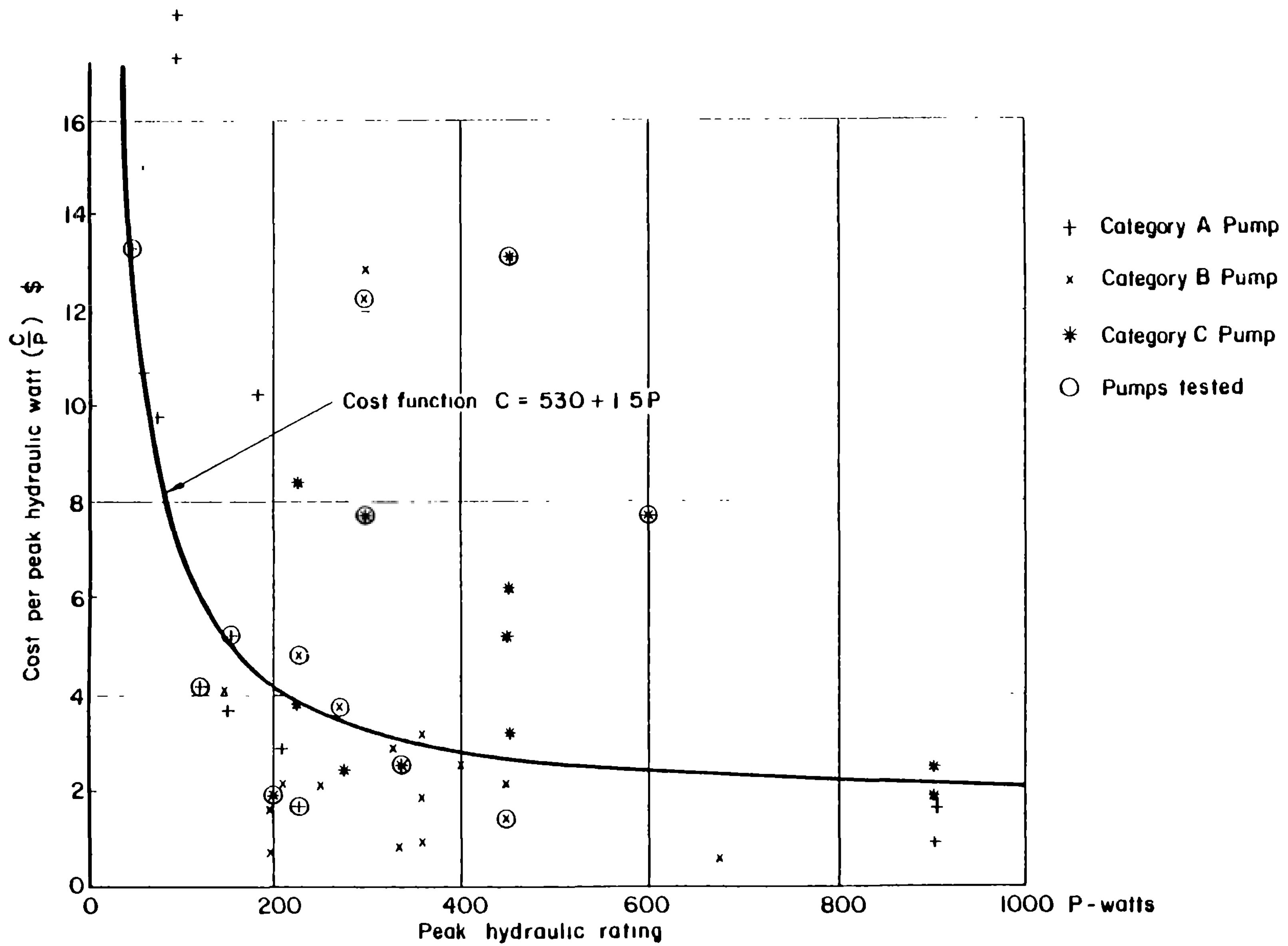


Figure 8 3 Costs of dc motor/pump units

For an estimate of 'Potential' costs in 10-15 years time, a figure for the arrays in the range of 2 dollars per peak watt was assumed on the basis of a significant technological improvement to the process of manufacture, but the costs of the motors and pumps were assumed to remain at their projected levels on the basis that the scope of further cost reduction due to increase in scale of production was limited and that no major technical innovations were likely. The miscellaneous costs remained at 3 dollars per peak watt.

These costs and figures are all illustrated in Table 8.4 for system hydraulic output powers of 100,200 and 400 watts. For easier comparison with other evaluations this table also gives the equivalent figures for total system installed cost as $/Wp.

c) Diesel engine pumps

The maintenance costs allowed for technical servicing at intervals of about 250 hours running time, but the operating costs did not include any provision for the cost of time spent checking and starting the engine, topping up fuel and stopping it. The way this is done in an irrigation context will differ widely from country to country and in many areas the farmers themselves will undertake these tasks. Strictly the value of the time spent is an input cost and if allowance had been made it might be expected to increase the output cost of the water by one or two cents/m^3, depending on the time spent and the daily wage.

d) Windpumps and handpumps

The figure used for windpump costs of $300/m^2 of rotor area is typical of American-manufacturered farm windpumps and is somewhat on the high side as an international norm. This fact emerged as a result of subsequent work completed under another contract for a related UNDP Global Project (see Bibliography); for example, Australian windpumps built in larger numbers with cheap steel, and indigenous designs in certain developing countries like Thailand, India or Sri Lanka cost typically as little as $100 to $150/m^2 of rotor area.

It should also be noted that for the baseline studies it has been assumed that it is correct to value the time spent by farmers operating the handpumps on the basis that the time devoted to pumping could have been spent productively on other agricultural tasks.

e) Maintenance costs

For solar, wind, animal and human powered pumps there are insufficient data to relate the annual maintenance cost of a single pump to a group of similar pumps. This relation may be especially important for handpumps (and to a lesser extent for animal pumps) which will usually be used in groups, on which maintenance needs to be carried out regularly and where the logistical component of the total cost is a large fraction of the total. What are recognised to be low values for handpump annual maintenance costs have been adopted ($50 per pump p.a) so that the total maintenance costs for a group of pumps on a small farm or village are of the right order. Informed estimates for handpump maintenance have put the figure at up to $500 p.a., but at a UNDP seminar held in Malawi in December 1982 it was reported that the target maintenance costs for handpumps have been reduced from $200 p.a. to $50 p.a. (Ref. 14).

8.2 Baseline Studies

8.2.1 Presentation of results

With eight pumping systems (including diesel and kerosene, high and low), two storage options, three means of conveyance and two methods of field application (as illustrated in Fig.7.1)the number of baseline irrigation scenarios studied was 30. Each scenario was analysed at two static heads, 2m and 7m, for a baseline irrigated area of two hectares, although as already explained, analyses were carried out over a range of irrigated area from 0.25 to 4.0 hectares. This work has thus produced a wealth of information which has had to be summarised in this Main Report. Examples of the results have been included so that the reader can appreciate the type of results which were obtained.

The output obtained from a typical computer run is shown in Table 8.6. Data of this type contributed just one point on graphs of unit water cost against irrigated area, a typical example of which is shown in Fig 8.4. This figure demonstrates the relationship between unit water cost and irrigated area for solar pumping systems operating with and without storage and distributing the water via earth lined channels and trickle pipes with characteristics, as listed in Table 8.1. Similar plots were prepared for the other pumping technologies.

8.2.2 Basis of comparison

As illustrated in Fig 8.4 the unit cost of solar pumped water has a minimum value for irrigated areas in the range 0.75 to 1.5 hectares.

This type of result was also obtained from windpumps and to some extent for animal pumps, but not for the diesel units because their size was fixed well above the minimum needed. The unit output costs of the kerosene engine pumps did increase because, as they were not oversized for the larger areas, their running times increased and they needed replacement more often. An optimum area was not found in case of handpumps because the area irrigated was limited by the input power which was assumed to be 60W for day long effort. The limiting area was usually less than 0.2 hectares. This behaviour is explained below in Section 8.2.3.

In order to make a fair comparison between the pumping methods, the method of distribution which gave the lowest unit cost of water and the irrigated area for which it was a minimum (the optimum area) were first determined and then this data were used as input to a further analysis of the unit water costs for supplying water to the baseline 2 hectare plot. The supply area for the individual system was chosen so as to divide into 2 hectares by a whole number. The results of this set of analyses are given in Tables 8.7 and 8.8 for static lifts of 2m and 7m respectively. Note that because a solar water pump is at its optimum cost-effectiveness at around one hectare, two solar pumps are used to irrigate 2 hectares. On a similar basis 2 animal pumps and 10 handpumps are needed for the baseline area (at 2m lifts). On the other hand, although the unit cost of water supplied by a diesel pump continues to fall slightly as the area increases from 2 to 4 hectares, a single diesel pump still has to be used for the 2 hectare plot. Thus the 2 hectare baseline area is the smallest that could be adopted without unfairly handicapping diesel powered units. Of course, in many countries, small farms of less than 2 hectares are common and diesel engines on these will give considerably greater output water costs.

The optimum unit costs of water delivered to the crop by all the water lifting systems considered are compared in the histograms plotted in Figs. 8.5 and 8.6 for static lifts of 2 and 7m respectively. The global target for economic water cost delivered to the crop (10 cents/m^3) is also indicated.

8.2.3 Discussion of results

Overall the most significant point to emerge is that, for realistic input technical and cost parameters, at 2m static lift solar channel distribution systems without storage deliver water for around 8.8 cents/m^3 (and wind without storage for 5.3 cents/m^3) which is comparable to the

DATA FILES

Location
Water demand
Water Source
Power Source
Pump
Store
Conveyance
Field Application
Economic

SYSTEM SPECIFICATION

1. Input Parameters

Irrigation Area	2 hectares
Water static lift	7 metres
Average Annual Crop Water requirements	12410 cubic metres per hectare
Peak daily crop water requirements	6mm (equivalent to 60m^3 per day per hectare)
Peak monthly demand factor	1 76
Oversizing factor	1
Number of pumps	2
Discount Rate	0 1
Period of Analysis	30 years
Shadow Exchange Rate factor	1

2 Calculated Parameters

Total head	8 3 metres
Store head	0 metres
Conveyance head	0 6 metres
Field application head	0 4 metres
Overall energy efficiency	0 044
Overall volumetric efficiency	0 85
Overall system efficiency	0 037
Overcapacity ratio	1 602
Mean no of operating hours per day	8
and in peak month	11 1

3 Component Sizes (per pump)

Component	Type	Lifetime years	Size
Power Source	Solar	15	635 6 peak watts
Pump	M/Pump	6 9	254 peak hydraulic watts
Store	NONE	30	0
Conveyance	75mm PVC	10	100m
Field Application	12mm PVC	10	10000m

COSTS IN 1982 $

		Total $	Total $
1	Capital		
	Water Source	1130	1130
	Power Source	20341	3814
	Pump (1)	1823	0
	Store	0	0
	Distribution	2400	1800
	Field Application	7400	5550
	Total	33094	12294
2	Recurrent		
	Annual Maintenance	175	140
	Annual Operating	0	0
	PW of Replacements	8707	4234
3	Summary of Life Cycle Costs (over 30 year period of analysis at discount rate of 10%)		
	Total Capital	33094	12294
	PW of Maintenance	1815	1452
	PW of Operating	0	0
	PW of Replacement	8707	4234
	Total Life Cycle (PW)	43616	17980
	Equivalent Annual Costs ($pa)	4206	1733
	UNIT WATER COST ($/m^3)	0 169	0 070

NOTES

(1) includes motor with PV system

Table 8 6 Typical Data Output for Analysis of Baseline Irrigation Scenarios

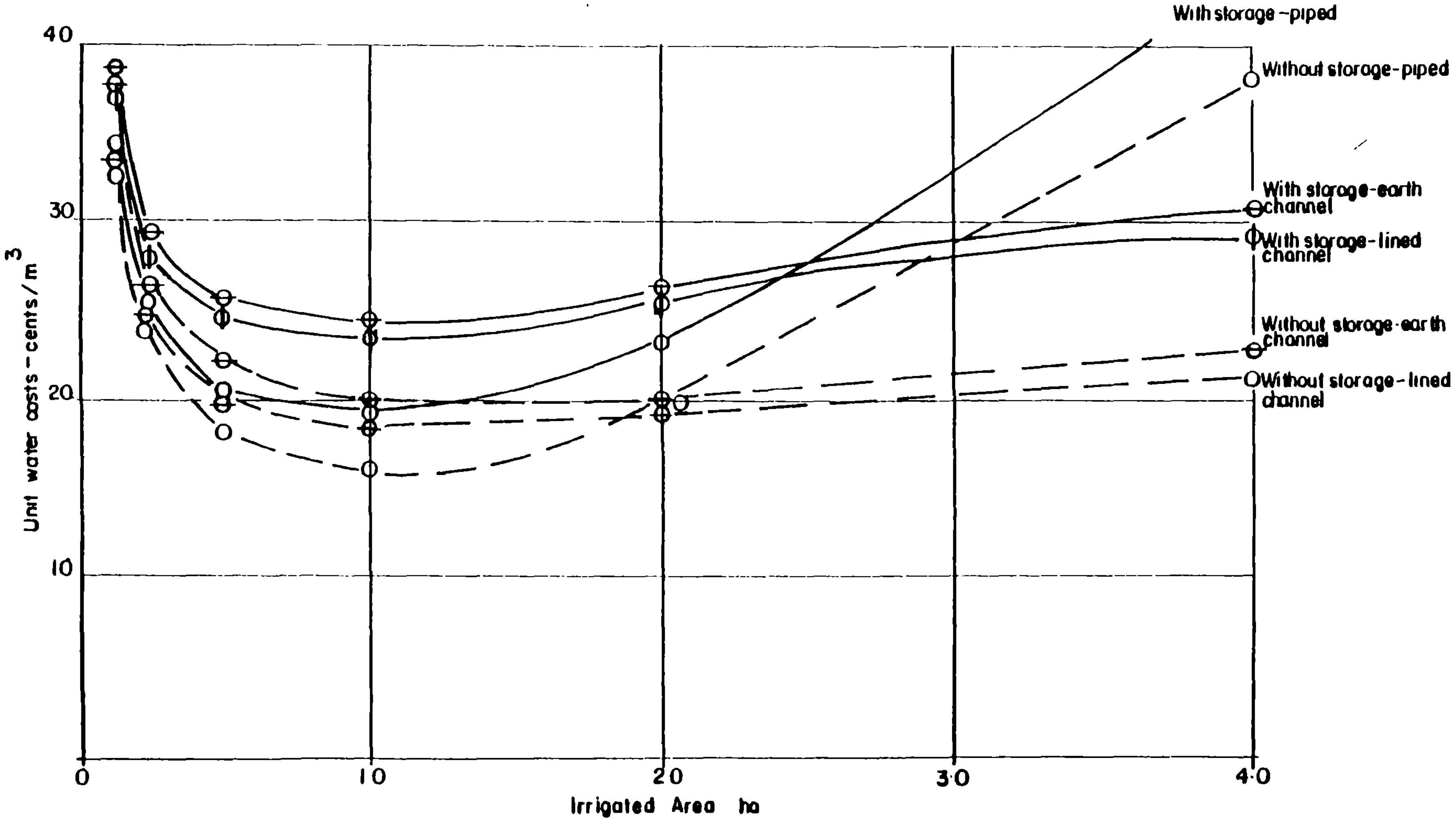


Figure 8.4 Cost of irrigation water for a solar pump - 7 metre static lift (Baseline scenario)

Pump	Optimum Supply Area	Optimum Distribution Method	Number of Pumps	Power Source Size per pump	Actual Lifetime		System Capital Cost	PW of re-placements	Annual Running Costs	Annual Maint Costs	Life Cycle Costs (PW)	Unit Cost of water to crop
					Power Source	Pump						
	hectares				yrs	yrs	$	$	$	$	$	cents per m³
Solar	1	lined channel	2	425 Wp (2)	15	6 9(7)	17060	3074	0	245	22676	8 8
Solar + Store	1	lined channel	2	468 Wp (2)	15	6.9(7)	26106	7909	0	175	35831	13 9
Wind	1	lined channel	2	18 6 m²(3)	30	10	11071	730	0	187	13742	5 3
Wind + Store	1	lined channel	1	32 7 m²(3)	30	10	20958	1103	0	187	23998	9 3
Diesel - low	> 4	lined channel	1	2 5 kW(4)	9 1	10	2470	1525	451	241	11169	4 3
Diesel - high	> 4	lined channel	1	2 5 kW(4)	6 7	10	2470	2079	1352	441	23147	9 0
Kerosene - low	2	lined channel	1	1 1 kW(4)	3 6	10	715	1138	1097	142	14699	5 7
Kerosene - high	2	lined channel	1	1 1 kW(4)	3 6	10	715	1138	2193	243	27119	10 5
Animal	1	lined channel	2	350W/animal(5)	10	10	3632	1036	755	90	13427	5 2
Handpump	0 2(1)	lined channel	10	60W/person(6)	-	10	3756	1975	2048	650	33712	13 1

NOTES

(1) Not optimum, but limited by pump output
(2) Array output
(3) Rotar area
(4) Shaft output
(5) Assumed output per animal
(6) Assumed input power maintained over 5 working hours
(7) Includes electric motor

Table 8.7 Results for Optimum 2 hectare Irrigation Baseline Scenarios: 2m static lift (6mm per day peak; annual crop water requirement 24820m³; peak monthly demand factor = 1.76; critical solar month = 20.8 MJ/m²; critical wind month = 2.5 m/s, i = 10%, n = 30 years).

Pump	Optimum Supply Area	Optimum Distribution Method	Number of Pumps	Power Source Size per pump	Actual Lifetime		System Capital Cost	PW of replacements	Annual Running Costs	Annual Maint Costs	Life Cycle Costs (PW)	Unit Cost of water to crop
					Power Source	Pump						
	hectares				yrs	yrs	$	$	$	$	$	cents per m^3
Solar	1	piped	2	636 Wp (2)	15	6.9(7)	33093	8707	0	175	43615	16.9
Solar : Store	1	piped	2	802 Wp (2)	15	6.9(7)	39734	9336	0	175	50885	19.8
Wind	1	lined channel	2	46.2 m^2(3)	30	10	27892	1461	0	187	31295	12.2
Wind + Store	1	piped	2	31.2 m^2(3)	30	10	29830	6063	0	117	37107	14.4
Diesel - low	> 4	lined channel	1	2.5 kW(4)	5.5	10	3014	2561	748	241	15828	6.1
Diesel - high	> 4	lined channel	1	2.5 kW(4)	4.0	10	3014	3537	2243	441	34384	13.4
Kerosene - low	1	lined channel	2	1.1 kW(4)	1.9	10	2450	1986	1982	282	27192	10.8
Kerosene - high	1	lined channel	2	1.1 kW(4)	1.9	10	2450	1986	3969	482	50537	19.6
Animal	1	piped	3	350W/animal(5)	10	10	14110	6036	971	20	30425	11.8
Handpump	0.12(1)	piped	16	60W/person(6)	-	10	26684	9425	3176	800	77337	30.0

NOTES:

(1) Not optimum but limited by pump output
(2) Array output
(3) Rotar area
(4) Shaft output
(5) Assumed output per animal
(6) Assumed input power maintained over 5 working hours
(7) Includes electric motor

Table 8.8 Results for Optimum 2 hectare Irrigation Baseline Scenarios: 7m static lift (6mm per day peak; annual crop water requirement 24820 m^3; peak monthly demand factor = 1.76; critical solar month = 20.8 MJ/m^2; critical wind month = 2.5 m/s, i = 10%, n = 30 years).

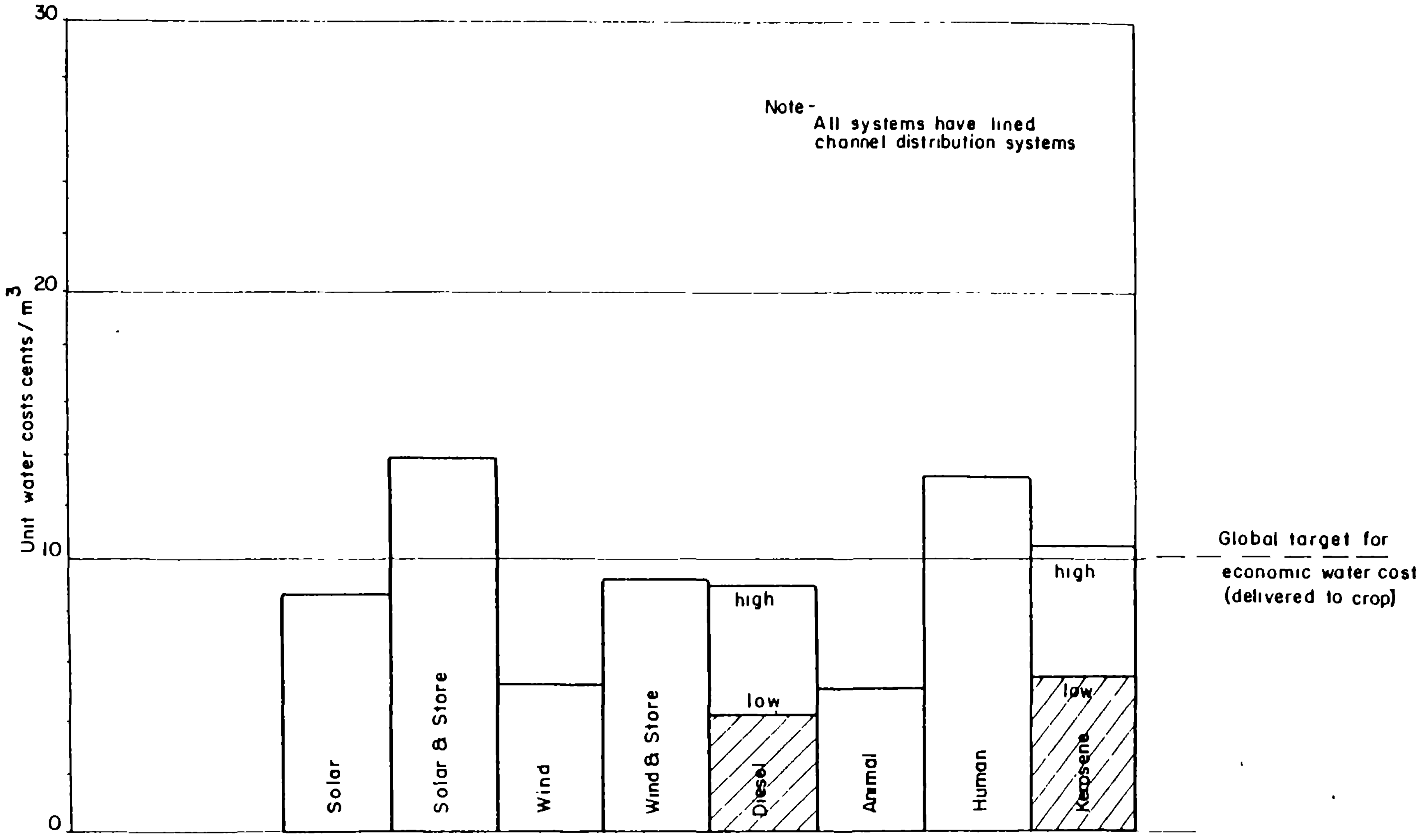


Figure 8.5 Histogram showing optimum irrigation water costs for alternative pumping methods to supply 2 ha at a 2 metre lift with peak water requirements of 6mm per day (using baseline models)

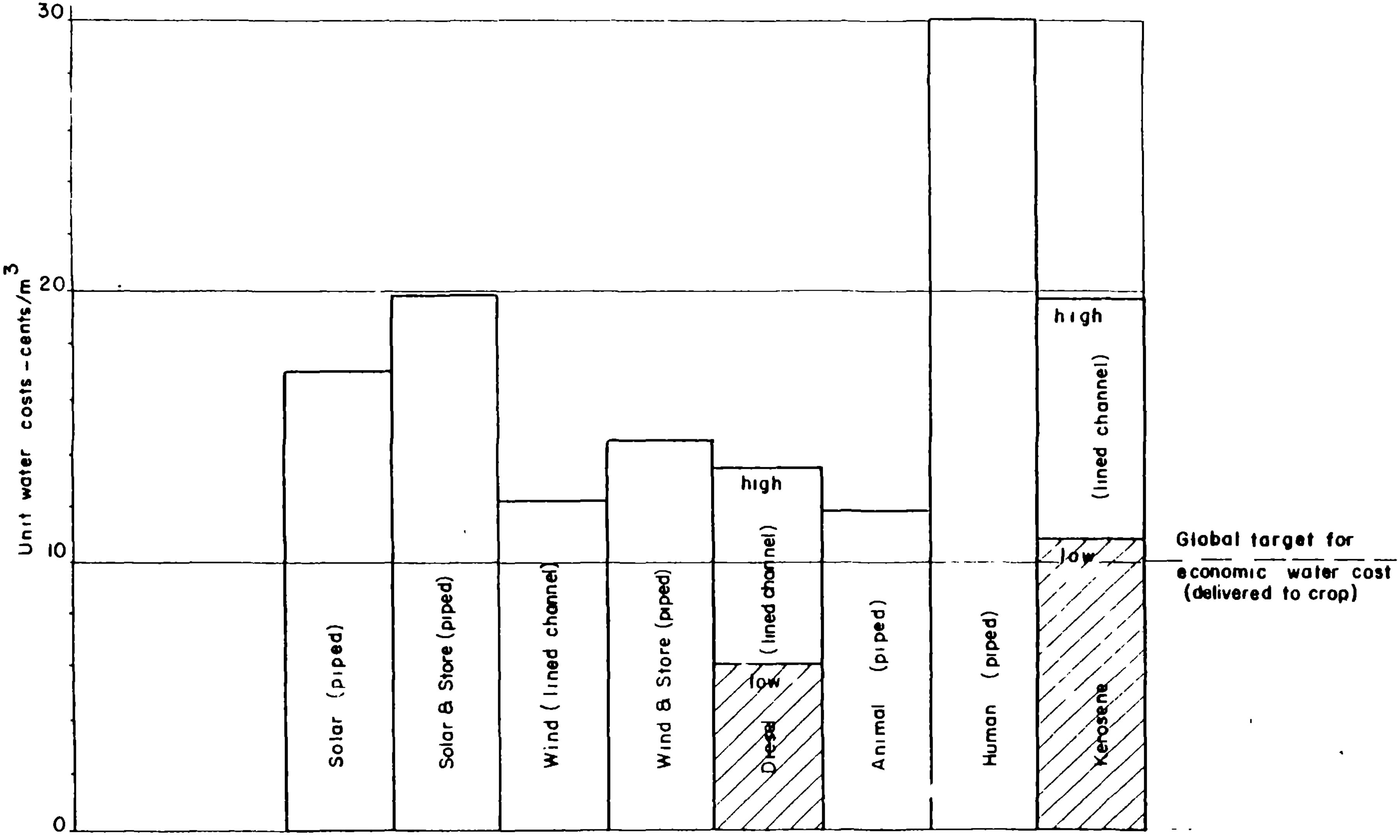


Figure 8.6 Histogram showing optimum irrigation water costs for alternative pumping methods to supply 2ha at a 7 metre lift with peak water requirements of 6mm per day (using baseline models)

high case diesel systems studied. To be competitive with low case diesel, solar system output costs will need to drop to around 50% of their present levels (equivalent to the 'Target' case defined in Tables 5.5 and 8.4).

At a lift of 7m, solar pipe distribution systems without storage are cheaper than systems with channel distribution and deliver water for around 17 cents/m^3, 3.5 cents/m^3 more than high case diesel at 13.4 cents/m^3 (see Fig. 8.6). Wind systems deliver for 12.2 cents/m^3. Since the diesel analysis made no allowance for attendance costs (and also bearing in mind the general accuracy of the data used) the solar and high case diesel may be regarded as broadly comparable. To be competitive with low case diesel, solar system output costs will need to drop to around 36% of their present levels (roughly equivalent to the Potential case).

It is considered that the high case diesel systems studied are representative of the real costs of the smallest diesels working under normal conditions in developing countries and so it can be concluded that even at present prices, solar pumping systems without storage are close enough to being competitive with diesel to make it worth while evaluating each alternative in detail for the application proposed.

The future cost trends of solar must be downward in real terms whereas the trend for fuel engines must be upward. Thus the outlook for solar powered pumps over the next decade should steadily improve.

The use of tanks to store half the daily volume pumped adds considerably to the flexible management of solar pumped water. However such tanks increase the output cost by 5 cents/m^3 at 2m lift and 3 cents/m^3 at 7m lift which make solar unattractive at present cost levels. Thus solar systems will first have to be applied to situations in which storage is not regarded as an essential facility.

It has already been noted that a particular feature of Fig. 8.4 is that the unit cost of solar pumped water has a minimum value for irrigated areas in the range 0.75-1.5 hectares. The initial decrease in unit water costs at small irrigated areas (from 0.25 to 0.75 hectares) is due to economies of scale, as with all other pumping systems. The unit costs increase for larger areas because in these baseline studies the shape and gradients of the channels and the diameters of the pipes used to distribute the water were invariant. Thus as flows increased with the area irrigated, the hydraulic gradients and total head increased and this was reflected in the capital cost of these capital intensive systems. The effect is greater with pipes than channels because the head loss is proportional to the square of the flow and the diameter was fixed, whereas for channels the increase is due to the inability to alter the overall gradient to give optimum hydraulic conveyance. (The importance of pipe diameter was demonstrated in the sensitivity analyses). The systems without storage were cheaper than those with storage by some 2.5 cents/m^3 for piped systems and some 5 cents/m^3 for channel systems. In both cases the optimum supply area was little greater for systems without storage because without the capital cost of the store it is economic to put more investment into the distribution system needed for the larger areas. It will also be noted that for the systems studied concrete lined channels delivered water for a fractionally lower cost than those with unlined channels. This was principally because the concrete channels had a much lower seepage loss and thus to deliver a given volume to the crop the volume to be pumped was less, the pump and channels were smaller and the savings in them more than offset the higher cost of the channel lining.

Comparison of the relative increases in the unit costs of water delivered for the 2m and 7m lift cases shows that the diesel costs increase by a lower factor then the others eg. diesel low from 4.3 to 6.1, a factor of 1.4, diesel high from 9.0 to 13.2 a factor of 1.5 while solar without store increases from 8.8 to 16.9 a factor of 1.9. On the other hand solar with store increases from 13.9 to 19.8 a factor of 1.4. This is because the diesel is under utilised at the lower heads and to provide the volume required at the higher head it simply has to work for longer hours, with only the operating cost increasing significantly. On the other hand the installed power of the capital intensive solar system has to be increased and this is reflected directly in higher cost increases. A solar system with store increases less in proportion because the pump is a lower proportion of the total cost, and the static lift changes less in proportion.

Although the costs assigned to windpumps are on the high side, the effect of this is partly offset by the safety margin in sizing needed to cover any uncertainty over windspeeds. Hence the wind system output costs are probably not too far from what might be expected in areas with light winds (i.e. annual means of around 3 to 4m/s) but are probably rather higher (say 2 cents/m^3 at 2m and 6 cents/m^3 at 7m lift) compared with those for even a moderately windy location with mean annual wind speeds of about 4.5m/s or more. It so happened that for the costs chosen for this model, the baseline windspeed represented roughly the breakeven requirement between solar and wind systems; more favourable wind parameters (such as higher mean wind speeds or lower windpump costs or higher windpump efficiency) would give wind the economic advantage and vice-versa.

One of the cheapest methods of water pumping, especially at low lifts, is an animal pump; the main snag with animal pumps is in areas where land is scarce, since animals require land to be devoted to the production of feed, but this would normally be reflected in the cost of the feed. It should be noted too that animals are not normally used for irrigation pumping in the three countries which were investigated, and that in countries where animals are used the tendency is for farmers to seek to mechanise and replace them with engines. This study would suggest that the economics of animal powered pumping ought to be reassessed and the present trend towards mechanisation reconsidered.

Human powered pumps are cheap if no value is assigned to human labour, but if a notional wage as low as $1.00/day is included, as in the baseline model, handpumps become the highest cost option due to the relatively poor productivity of people as prime movers. Indeed, handpumped power at wage rates of $1/day is so expensive that pipes are justified in place of channels because of the savings they bring in the terms of pumped output. It is considered reasonable to assign an opportunity cost to labour for irrigation pumping, because the use of human power diverts resources which would be probably better employed performing other agricultural tasks. The figure of $1 per day is typical of field labour costs in Bangladesh or Kenya, but in Thailand the daily rate would be nearer $3.00. The cost of handpumped water drops to the level of solar or high case diesel when the daily wage rate is under $0.6 per day (for 2m lift) but at 7m lift handpumped water is only competitive when the daily wage rate is nil. Handpumps are further handicapped when borehole costs are high because of the need for a greater number of handpumped sources.

These results illustrate the inefficiency of human power as a prime mover and are of great significance for handpump irrigation programmes. It is considered that the real economics of this type of pumping should be re-evaluated in detail for the conditions where irrigation handpumping is widely practised.

A point of particular interest lies in the comparison between diesel and kerosene pumps. At 2m lift the kerosene engine (low and high cases) delivers water at only a cent or so higher than the diesel, whereas at 7m lift the low case kerosene engine pumps water at 4 cents/m^3 more than the low case diesel and the high case kerosene engine delivers water for some 6 cents/m^3 more. The main reason for the comparatively large differences between the two engine systems, particularly for the high case, is that as the efficiencies of kerosene engines are low (one third of diesel) they have to work longer hours and hence have a shorter operating life, and need replacement twice as often (see Tables 8.7 and 8.8).

A point of some general interest is that, for the baseline scenario conditions, at 2m static lift all the systems (with the exception of solar with store and the handpump), deliver water for a cost equal to or less than the global target economic water cost of 10 cents (to the crop). At 7m static lift only the low case diesel delivers water for less than the norm. This point is interesting, because the global economic target relates simply to the crop and its value to the farmer and is not dependent on head in any way. For the particular situations analysed, as defined by the input technical and cost parameters, it is clear that the costs of water delivered equal the global target figure for a lift in the region of 5m (depending on pumping system) and farmers needing to pump water through higher lifts will need to be subsidised in some way. No single global figure can be representative of many actual situations and, to carry this analysis further, it would be necessary to check on the economic value for water appropriate to the situation being considered.

When interpreting the results it is most important to remember that small changes in the assumptions underlying the baseline model can quite significantly change the unit water costs. Therefore, technologies should on no account be judged purely on the basis that the baseline model for one is a cent or two better or worse than another, but sensitivity analyses in which the consequences on unit water cost of changes in one or more of the input costs or technical assumptions must be carried out, or the situations corresponding more exactly to particular applications must be evaluated. Such sensitivity analyses and country specific case studies for irrigation application are described in the remainder of this chapter.

8.3 Sensitivity Analyses of the Baseline Irrigation Scenarios

8.3.1 General

Four groups of parameters in the baseline model were varied :

Group A	Climate
Group B	Agricultural and technical factors
Group C	Costs
Group D	Economic

A 2 hectare irrigation area was used for the study of each group. As before, each method was compared on the basis of the optimum method of distribution and the irrigated area for one pumping system as given in Tables 8.7 and 8.8 (for 2m and 7m heads respectively). All the sensitivity analyses were carried out for the combination of optimum supply area and distribution methods shown in the tables. This means that for a lift of 7m for example, results are not available for solar pumps with channel distribution. The storage options were not examined either, because they were always more expensive, but the output water values for these will normally be around 3 to 5 cents/m^3 more than the systems without storage.

The major parameters which were thought to influence the unit water costs in each group and which were studied in the sensitivity analyses are set out in Tables 8.9 and 8.10 for 2m and 7m lift respectively. These tables also show the percentage change caused in unit water costs by varying the various parameters listed, individually, by ± 50% from the international norm baseline model. Not all the parameters chosen for sensitivity analysis have an equal chance of increasing or decreasing by 50%, but for a first assessment it was a reasonable set of changes to make. In a few cases a change of this magnitude was a physical impossibility and these are noted in the tables. Graphs illustrating some of the more interesting results for the 7m head case are included and will be referred to in the following sections. Full details, including results for the 2m heads are in Supporting Document 2.

Group		Parameter	Percentage change in unit water cost when value of parameter reduced by 50%						Percentage change in unit water cost when value of parameter increased by 50%					
			Solar	Wind	Diesel Low	Diesel High	Animal	Human	Solar	Wind	Diesel Low	Diesel High	Animal	Human
A	Climate	Wind (mean velocity)		1389						-49				
		Solar (Irradiation)	134						-28					
		Peak Demand Factor	-41	-42	0	-3	-6	-8	47	45	7	4	27	14
		Peak Water Requirement	19	17	56	32	31	43	-2	-2	-14	-10	4	-9
B	Agricultural/ Technical	Pipe Diameter/Channel Slope	-43	-11	-2	-6	-6	50	43	13	5	6	8	-5
		Field Application Efficiencies(3)	98	94	60	71	90	53	-27	0	-14	-23	-25	-19
		Component Lifetimes	32	21	19	10	13	34	-8	0	-2	-3	-4	-8
		Subsystem efficiency (4)	24						-14					
C	Costs	Capital costs												
		- well	0	0	0	0	0	0	0	0	0	0	0	0
		- Pumping system	-43	-40	-16	-9	-15	-2	43	42	16	9	15	5
		- Distribution	-1	-2	0	-1	-2	-24	1	4	2	1	2	27
		Operating costs												
		- labour (1)						-63						-31
		- Animal feed					-29						29	
		- Fuel			-21	-30					21	30		
		Maintenance	-6	-6	-9	-10	-4	-1	6	8	12	10	4	0
D	Economic	Discount Rate(5)	-24	-26	0	4	-8	-8	50	58	7	-2	17	26
		Period of analysis(6)	8	8	0	-4	2	0	-2	2	2	2	0	0
		Shadow exchange rate factor(2)	-19	-57	-14	-10	-75	-63	-12	-38	-9	-7	-50	-41

NOTES Parameters altered by ±50% except for·
(1) for zero labour costs and 50% of full labour costs
(2) for shadow exchange rate factors of 0 5 and 0 75
(3) to a maximum of 100%
(4) for 30 & 50%
(5) for 5 & 20%
(6) for 20 & 40 years

Table 8.9 Summary of Results of Sensitivity Analyses of the Baseline Irrigation Scenarios; 2m static lift (Peak requirement of 6mm/day). For baseline values see Tables 8.1 and 8.2.

Group		Parameter	Percentage change in unit water cost when value of parameter reduced by 50%						Percentage change in unit water cost when value of parameter increased by 50%					
			Solar	Wind	Diesel Low	Diesel High	Animal	Human	Solar	Wind	Diesel Low	Diesel High	Animal	Human
A	Climate	Wind (mean velocity)		1272						-53				
		Solar (irradiation)	145						-21					
		Peak Demand Factor	-30	-44	-7	-6	-29	-18	41	45	15	10	23	20
		Peak Water Requirement	41	11	36	21	-10	20	-6	-3	-7	-4	-1	-5
B	Agricultural/ Technical	Pipe Diameter/Channel Slope	204	-6	-3	-5	-18	10	-5	5	5	4	2	0
		Field Application Efficiencies(3)	47	92	79	88	99	-42	-18	-30	-21	-27	-35	-17
		Component Lifetimes	43	20	20	12	20	20	-11	-1	-5	-4	-6	-6
		Subsystem efficiency (4)	17						-10					
C	Costs	Capital costs												
		- well	-1	-2	-2	-1	-3	-6	2	2	3	1	3	6
		- Pumping system	-29	-44	-13	-8	-18	-3	30	43	15	7	18	4
		- Distribution	-17	-2	0	-1	-1	-14	18	1	2	0	1	14
		Operating costs												
		- labour (1)						-43						-21
		- Animal feed					-16						17	
		- Fuel			-26	-34					26	34		
		Maintenance	-2	-3	-7	-7	-3	-3	2	2	8	6	3	3
D	Economic	Discount Rate(5)	-22	-31	2	5	-10	-10	49	63	5	-4	22	21
		Period of analysis (6)	6	8	-2	-5	1	1	-1	1	3	3	0	0
		Shadow exchange rate factor(2)	-31	-56	-13	-9	-75	-68	-20	-37	-8	-6	-50	-46

NOTES: Parameters altered by ± 50% except for:
(1) for zero labour costs and 50% of full labour costs
(2) for shadow exchange rate factors of 0 5 and 0 75
(3) to a maximum of 100%
(4) for 30% 50%
(5) for 5 & 20%
(6) for 20 & 40 years

Table 8.10 Summary of Results of Sensitivity Analyses of the Baseline Irrigation Scenarios; 7m static lift (Peak requirement of 6mm/day) for baseline values see Table 8.1 and 8.2.

The usual caveat relating to the analysis of percentage changes is needed in that a large percentage change on a small base figure can often be a smaller absolute cost increase (or decrease) than for a much smaller percentage change on a larger base figure. However, the studies do highlight those parameters which stand out as being either particularly influential (or passive) so far as water costs is concerned.

8.3.2 Climate

Fig 8.7 shows the considerable effect on unit water cost of changes in the available solar and wind energy for both 2 and 7m static lift cases. The output costs of solar systems show a steadily reducing trend as the critical month mean daily solar irradiation increases. The solar curve should not be extrapolated beyond around 25 MJ/m^2 (7 kWh/m^2) since the solar energy that might be received anywhere will be unlikely to exceed this value on average. The unit cost of water nearly doubles from 10-20 $cents/m^3$ (for 7m lift) as the critical daily irradiation falls from 5 kWh/m^2 to 4 kWh/m^2, demonstrating clearly that there is little point in proposing solar pumps for regions where the solar regime is poor.

The curves of wind energy are even more dramatic: for the critical average speeds less than the baseline value of 2.5 m/s the unit cost of water increases very rapidly. As the graph shows, for heads in the 2m to 7m range, solar pumps are more competitive than wind for speeds less than around 2.25 m/s. This breakeven speed will also depend on the peak monthly demand factor. It should be noted that, whereas there is a limit to the solar energy receivable, wind speeds two or three times the baseline value are quite common.

Fig 8.8 shows the relatively small influence of peak daily crop water requirement on unit water costs. There are indications that for all systems the unit cost increases as the volume of water delivered gets less, much as would be expected (the animal pump line does not appear to show this, because the output costs are constrained by the use of integer numbers at constant power output). The graph of the 2m case (not shown) indicates that the increase is greater for the diesel than solar because the diesel becomes progressively more oversized, and the same trend is present at the 7m lift. This result was for the baseline value of peak monthly demand factor ie the monthly distribution of volume delivered remained the same.

Fig. 8.9 shows how variation in the peak monthly demand factor affects unit water costs. The effect is most pronounced for the solar, wind and animal pumping systems and very slight in the case of the diesel. An increase in peak monthly demand factor means that the daily demand in the peak month increases relative to the average annual demand (which stays the same). Thus the capacity of a solar pump and its cost have to increase to accommodate the peak, but the volume of water delivered in the year remains the same. A diesel pump which is already oversized simply works for more hours each day in the peak month and uses more fuel. The very important implication of this analysis is that solar pumps are better suited to demands which are relatively even throughout the year.

In summary, solar pumps are more competitive when solar irradiation is high, and water demand is relatively steady.

8.3.3 Agricultural and Technical Factors

Fig. 8.10 demonstrates the major effect of increase of static lift on unit water costs. This is one of the most important variables and affects all pumping systems. In general the unit costs increase more for the solar, wind and animal pumps because the installed capacity and hence

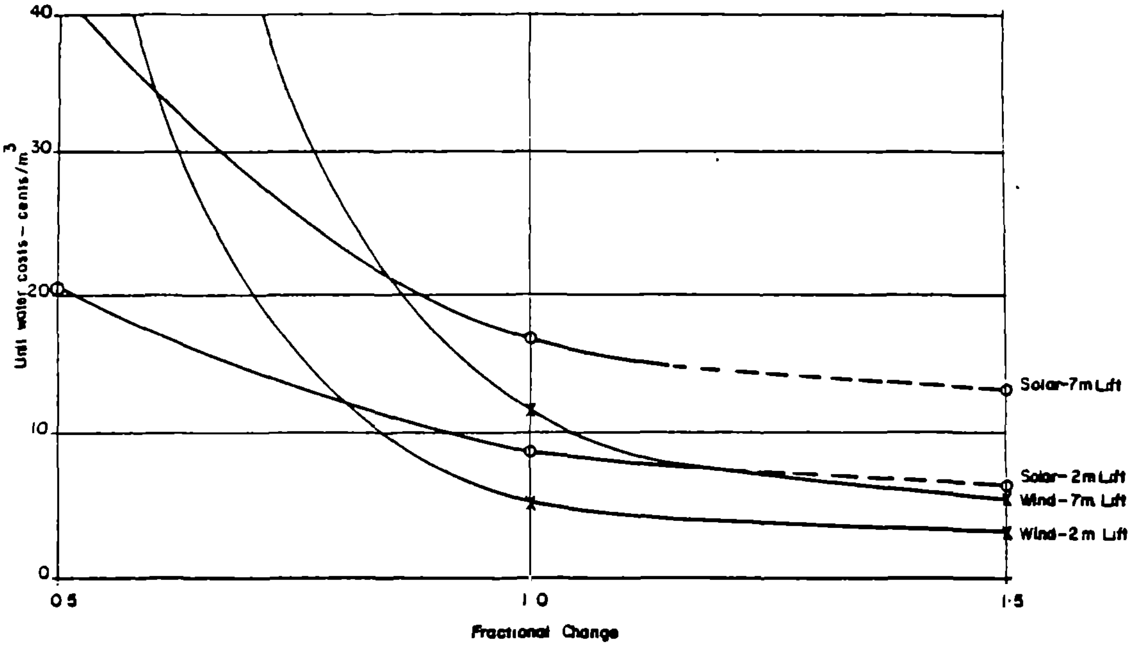


Figure 8.7 Effect of Climatic Conditions
(Baseline irrigation scenario - no storage)
Base Case: Mean wind speed 2.5m/s; critical month mean daily solar irradiation 5.5 kWh/m²

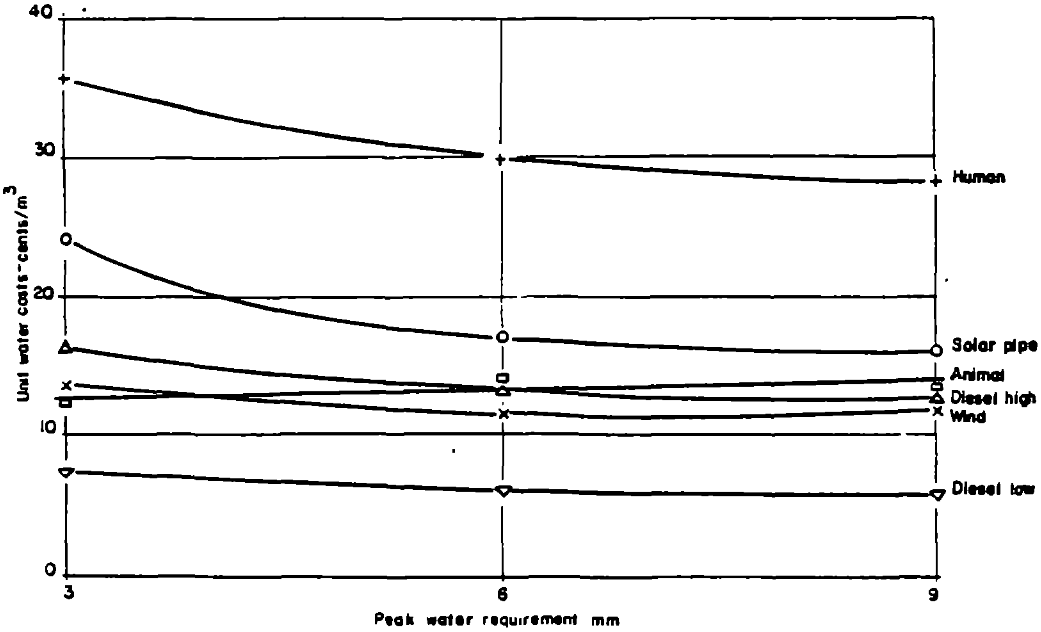


Figure 8.8 Effect of Peak Crop Water Requirements - 7m static lift
(Baseline irrigation scenario - no storage)
Base Case: 6mm per day

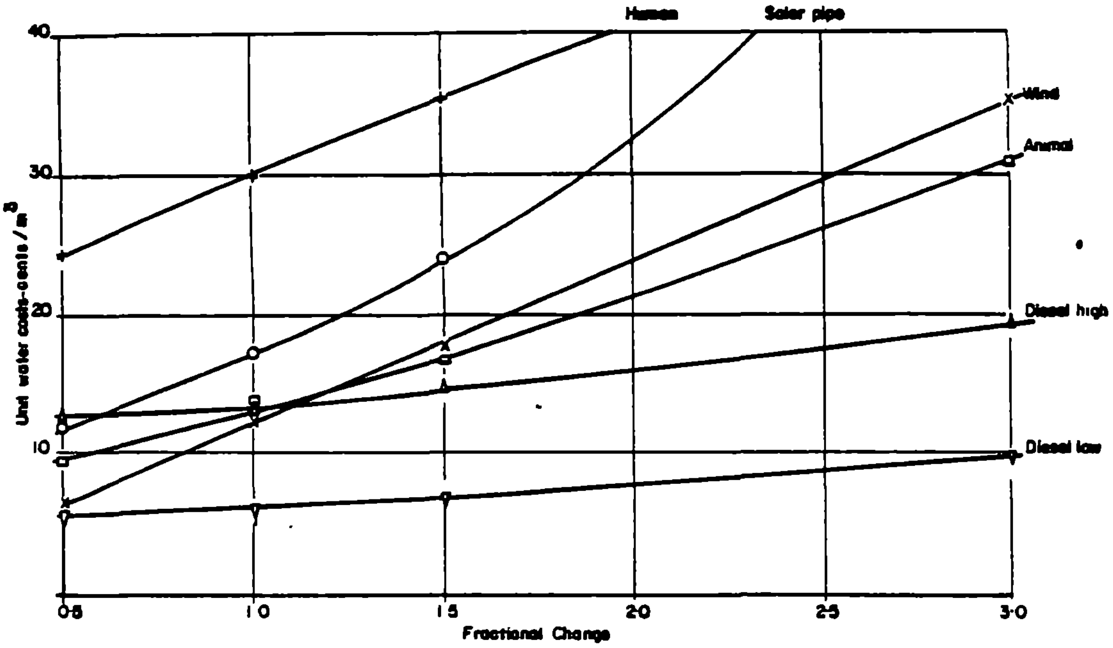


Figure 8.9 Effect of Peak Monthly Demand Factor - 7m static lift
(Baseline irrigation scenario - no storage)
Base Case: Peak Monthly Demand Factor 1.76

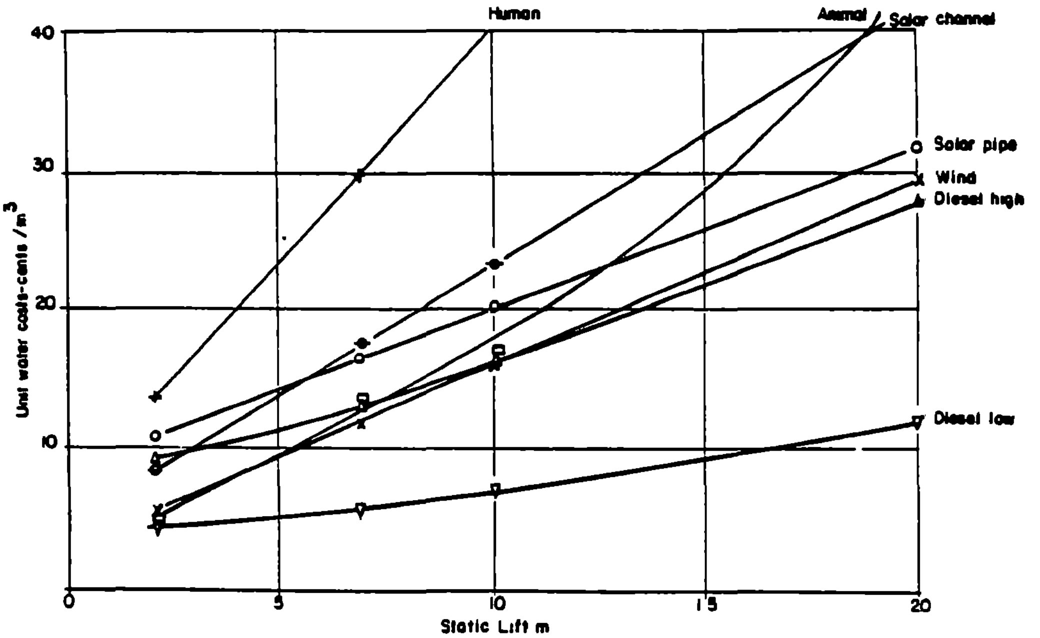


Figure 8.10 Effect of Static Lift on Unit Water Costs
(Baseline irrigation scenario - no storage)

capital cost has to increase in direct proportion to the head. This graph demonstrates how, for static lifts less than about 4.5m, a solar pumping system with channel distribution results in lower output costs than systems with piped distribution, whereas for lifts greater than 6m, piped distribution is cheaper. There are two basic reasons for this: firstly, for a given crop water demand a piped distribution system requires a smaller pumped volume than a channel distribution system (because less water is lost) and secondly, as static lift increases the proportion of the total cost of the pump and irrigation system attributable to the pumping system alone increases. Thus the savings in pumped power due to the smaller volume of water required for the pipe distribution case increase in importance and so the channel and pipe cost lines on Fig 8.10 diverge. The head at which they cross over depends of course on the particular values of the technical and cost parameters adopted.

For diesel pumps, as long is the engine is oversized the consequence of increase in head (reduction in flow rate) can be made up by the engine working longer - this is not relatively as expensive as the increase in installed power needed by the other systems. The 'present' case solar systems deliver water a few cents/m^3 more than do high case diesel. For low heads the difference is only 2 cents/m^3 and hardly significant in terms of the assumptions made for the study as a whole, while at 20m lift the difference is around 4 cents/m^3.

Animal powered pumped water appears to increase in cost with lift more than any other system (apart from hand). With limited power outputs and a restricted time of working each day the numbers of animals employed and the cost of their feed combines to increase the cost non-linearly (probably as a step function). The cost of hand pumped water is greater than for any other system and increases most rapidly with increase in lift. As comparison between the results for 2m and 7m shows, delivery falls as the lift increases, the number of handpump sources has to increase and if these are boreholes the total cost rises dramatically.

Fig. 8.11 shows the dramatic effect on solar system output costs of undersizing the diameter of the conveyance and distribution pipes (below 75mm for the conveyance pipes and 12mm for the trickle pipes) and is a salutary reminder that pipe diameters which are too small simply waste the energy obtained. Channel slope was also investigated but, as Fig. 8.11 shows, the costs of all types of pumping systems varied only a little. This is because the head at the upstream end of the channel needs to change relatively very little to maintain the same flow as the slope changes.

Fig 8.12 shows the serious effect of changes to field application efficiency. All systems are affected as the efficiency falls below 50% for furrows and 85% for pipes and the volumes to be pumped increase substantially. Solar systems show a greater proportional fall in unit water cost as the field application efficiency improves.

The importance of subsystem efficiency in relation to the cost of the pumping system itself was demonstrated in Fig. 5.17 and the influence of this factor on water output costs from the baseline systems was also investigated. As explained in section 8.1.2, a daily subsystem efficiency of 40% was adopted for the baseline scenarios, and so in these sensitivity analyses the effects on unit costs of water of daily subsystem efficiencies of 30% and 50% were studied for static lifts of 2m and 7m. The results are shown in Fig. 8.13. The higher value was chosen to demonstrate the benefits of systems near to the practical limit of development, while the lower value was chosen to illustrate the cost penalty to solar pumping systems with subsystems of only average or poor efficiency. The percentage reduction in the unit cost of water at 7m lift as the subsystem efficiency increases from 30% to 50% is 30%, while at 2m lift it is 41%. Although important in their own right, these percentage changes are not as dramatic as those shown in Fig. 5.17 because they are based on the total costs of the pumping system plus infrastructure.

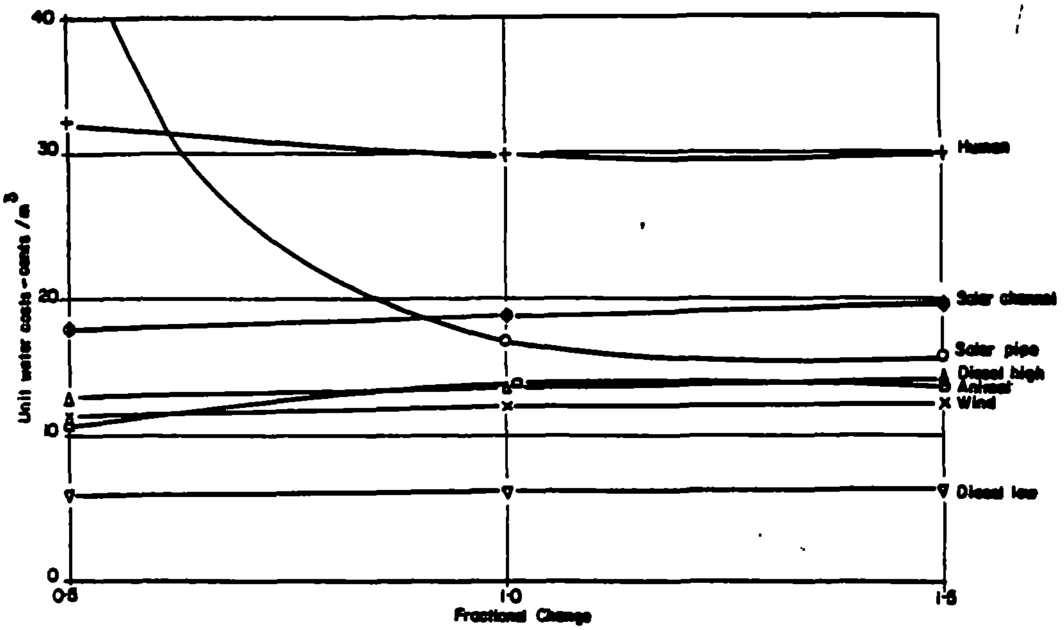


Figure 8.11 Sensitivity to Pipe Diameter or Channel Slope - 7m static lift (Baseline irrigation scenario - no storage)
Base Case: Channel 1% slope; conveyance pipe 75mm; trickle pipe 12mm

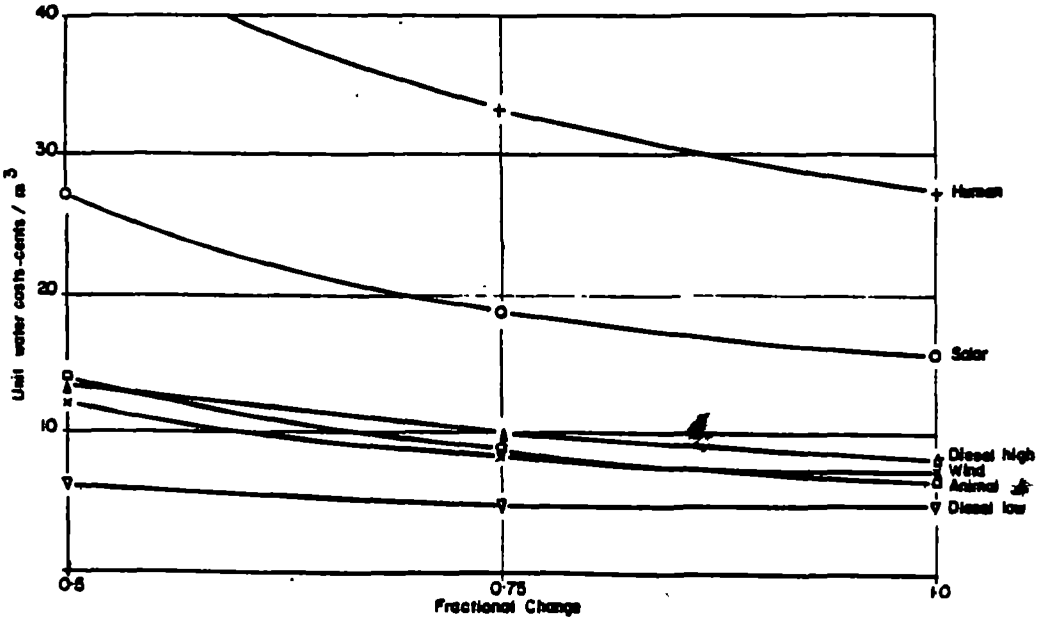


Figure 8.12 Sensitivity to Field Application Efficiency - 7m static lift (Baseline irrigation scenario - no storage)
Base Case: Furrows 50%, pipes 55% efficiency

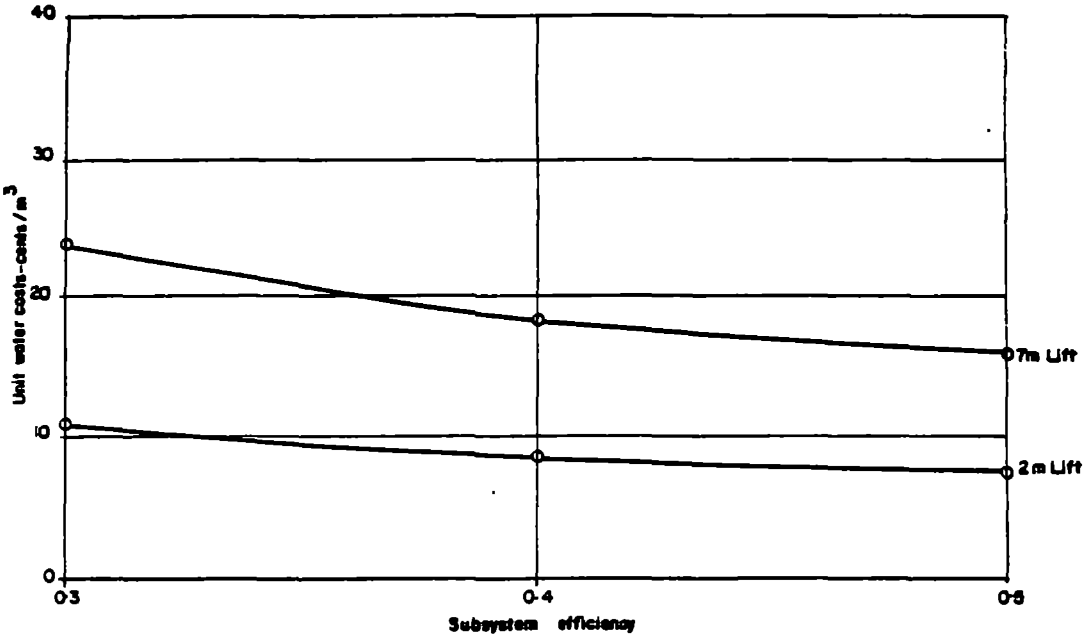


Figure 8.13 Sensitivity to PV Subsystem Efficiency
(Baseline irrigation scenario - no storage)
Base Case: Subsystem efficiency 40%

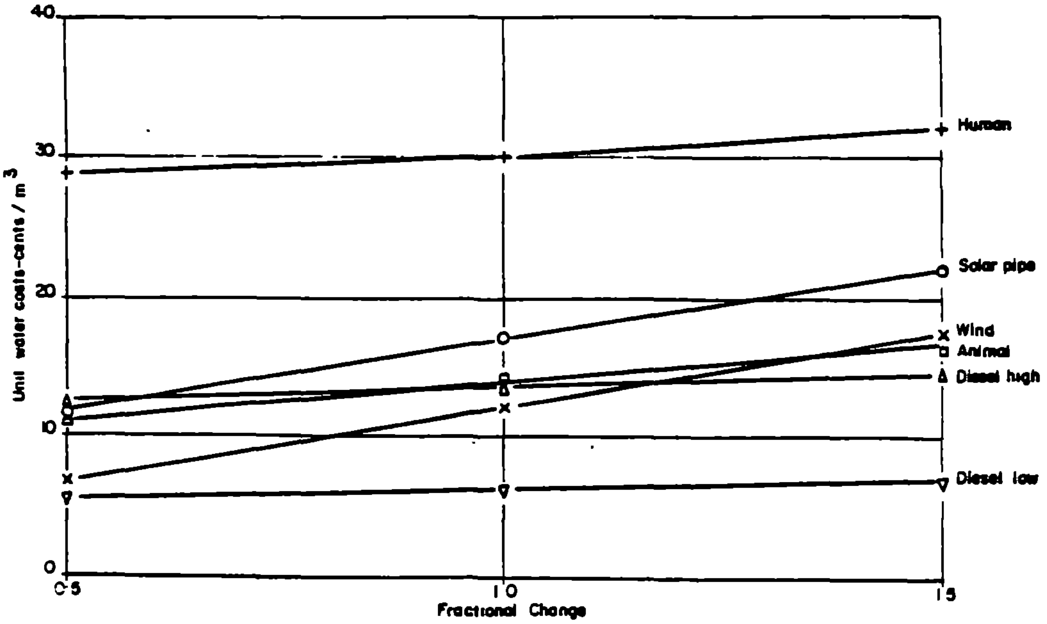


Figure 8.14 Sensitivity to Pumping System Capital Cost - 7m static lift
(Baseline irrigation scenario - no storage)
Base Case: See Tables 8.7 and 8.8

The effect of component lifetimes was also examined and it was confirmed that there was no great advantage in seeking to provide components with lifetimes longer the limits given in Table 8.2. However, the costs of solar and wind systems started to increase more significantly when lives are less then those limits.

In summary, for economy solar pumps require adequately sized pipework for conveyance and distribution, high efficiency field application networks, low static lifts, efficient subsystems and long lives. Actual values will depend on circumstances.

8.3.4 Costs

It is generally accepted that significant cost reductions in solar water pumps can be expected through improved manufacturing technology and increased scale of production during the next five years. An assessment was therefore made as to the likely effect of such cost reductions on unit water costs.

Fig. 8.14 shows the consequence of changes in the capital costs of each pumping system for a static lift of 7m. The renewable systems change most because the capital cost of these systems is the predominant constituent in the makeup of the unit cost of water. This graph demonstrates the competitive edge which solar will gain as its costs decrease in real terms while diesel increases. Solar and diesel high costs cross over when solar capital costs fall to about 55% of present values. This will possibly take about five years or more and in that time the real costs of diesel engines would have increased. Note that, because 'Present' case solar with piped distribution is cheaper than solar with channel distribution for the baseline at a lift of 7m (see Fig. 8.10), the former has been used in the sensitivity analyses to demonstrate the effect of changes in capital cost.

Table 8.4 gives the cost assumptions used to construct the 'Present', 'Target' and 'Potential' solar pumping system cases. These produce systems at price levels of around \$18/Wp, \$9/Wp and \$6/Wp respectively. The main prospect for future reduction in cost lies in the arrays and it is estimated that these prices will be at a level of \$5/Wp on a regular commercial basis (instead of being occasionally quoted as a loss leader for prestigious orders) within five years. This level contributes to a total system cost of around \$9/Wp. It is impossible to predict when systems might be available commercially for \$6/Wp. To reach that level array prices would need to fall to the region of \$2/Wp and this must depend on the developments in PV technology discussed in section 5.3.3.

Fig. 8.15 compares the output costs of 'Present', 'Target' and 'Potential' case solar systems with the other systems over a range of heads, all for the baseline model assumptions. 'Target' case solar systems (without storage and utilising pipe or channel/furrow distribution) lie between the high and low case diesel lines. * 'Target' case solar systems with channel distribution provide water to the crop for under 10 cents/m^3 for lifts up to about 9m more economically than any other alternative, other than low case diesel. Thus within five years the best solar pumping systems should be establishing themselves as the economically preferred option in circumstances similar to the baseline scenarios and where the global target economic water cost is applicable.

The 'Potential' case solar pumps are competitive with all other systems including low case diesel and are able to deliver water for less than 10 cents/m^3 at heads up to 14m. The fact that the costs of the 'Target' and 'Potential' case solar systems increase apparently linearly over the range of head studied from 10m to 20m should not be taken to mean that at much greater heads, they will remain as competitive with diesel: by influence from the general behaviour of diesel engines, it would be expected that at much higher heads economies of scale would make diesel more competitive.

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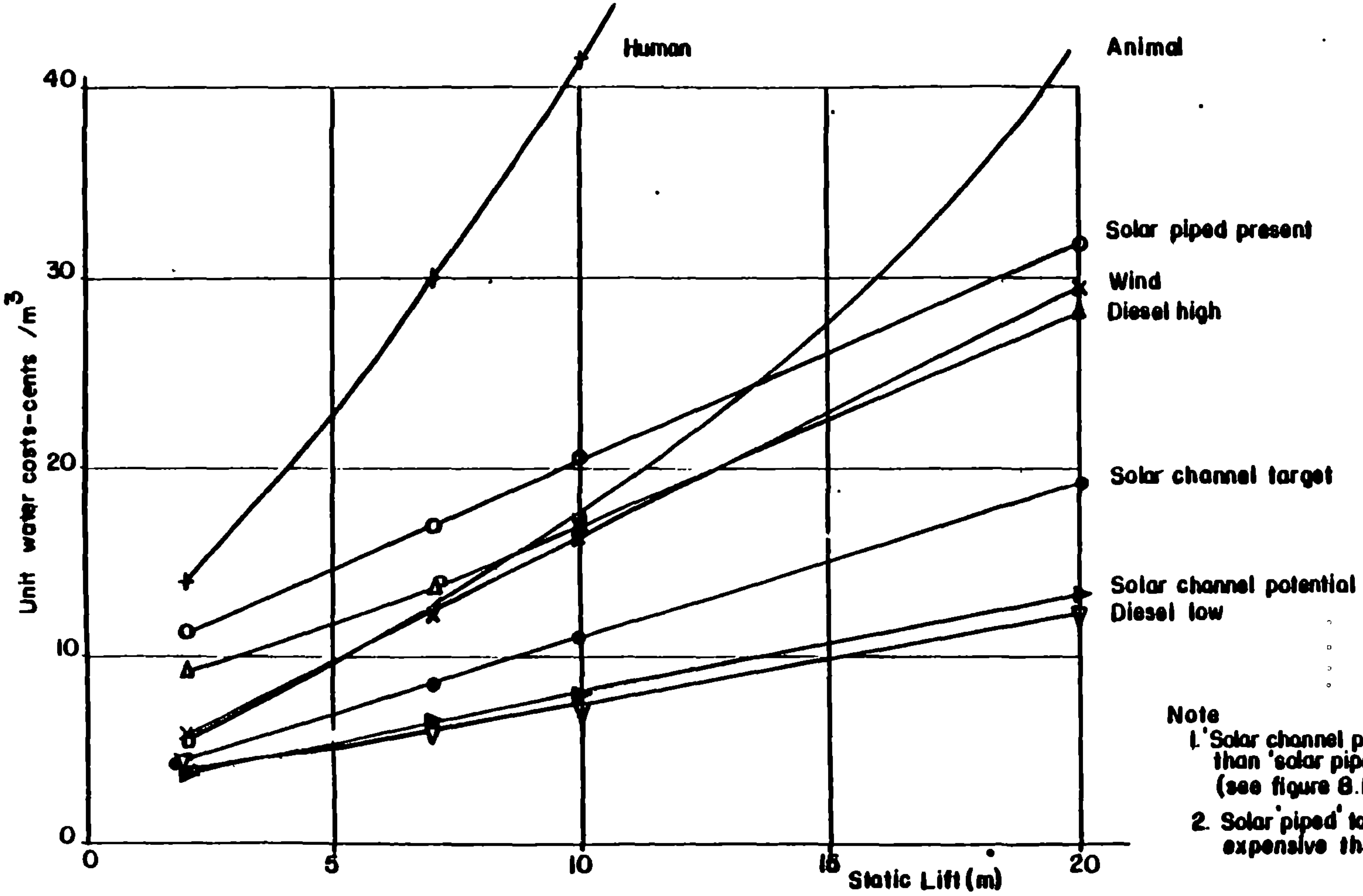
*For clarity the line for Target case solar with pipe distribution is not shown on Fig. 8.15 as it is always more expensive than the case with channel distribution.



Note

1. 'Solar channel present' more expensive than 'solar piped present' and not shown (see figure 8.10)
2. Solar 'piped' target and potential more expensive than channel and not shown.

Figure 8.15 Effect of Reduced PV Solar Pumping System Capital Costs in Comparison with Alternatives as a Function of Static Lift (Baseline irrigation scenario - no storage)

Changes in the values of distribution system costs, operating costs, and maintenance costs all have consequential effects, but these were not of great significance for the values used and details are in Supporting Document 2. One point worth mentioning is the considerable effect of wage rates on the costs of handpumped water. The value to be placed on the time spent operating handpumps may be a question of debate, but in the Consultants' view it is misleading to compare handpumps used for irrigation purposes on the basis of zero value of labour. Fig. 8.16 demonstrates the very considerable effect which inclusion of wages has on output costs: for a 2m lift a wage of $0.50 per day (instead of the baseline value of $1 per day) doubles the unit cost of water over that calculated for zero wage rates, while at 7m the same wage increases the output costs by a factor of 1.43.

In summary, since the capital cost of solar systems accounts for some 75% of the lifecycle cost of the total pump and irrigation system on the basis of the cost assumptions in Table 8.4 the PV module FOB cost accounts for some 55% of the capital cost (and more when installation is considered), any reduction in PV array costs has an immediate and beneficial impact on unit water costs. Target case solar pumps without storage should have good prospects for lifts up to about 9m. Maintenance costs are small and variations in them have comparatively little effect on output costs.

8.3.5 Economic Factors

The effect of discount rate on unit water cost is shown in Fig 8.17. The response of the various systems demonstrates the classic difference between lower capital - higher recurrent cost systems (eg diesel) and higher capital- lower recurrent cost systems (eg solar). High discount rates inevitably favour the lower capital - higher recurrent cost systems since the future recurrent cost are heavily discounted, while low discount rates favour capital intensive solar and wind systems. The output costs of human powered systems also increase with rise in discount rate because of the capital cost of the many boreholes needed.

Fig 8.17 shows that 'Present' case solar without storage at 7m lift is more economic than high case diesel for discount rates less then around 6% but there is no real discount rate at which it is more economic than low case diesel. It may be estimated that 'Target' case solar powered systems will be more economic than high case diesel for discount rates of around 15%.

Selection of the appropriate discount rate for economic analysis is never easy. It depends on the real return on capital expected, the risks involved and the general demand for capital (interest rates used in financial planning also have to allow for the effect of inflation). Historically there is evidence that, in settled economic times, discount rates of around 2.5 to 3% were acceptable for investments of low risk,. However in many developing countries the real opportunity cost of capital is very much higher, sometimes in excess of 10% (Ref. 15), and in situations where capital resources are scarce it would be difficult to justify taking a lower value for the appraisal of water pumping systems intended for regular use and not simply demonstration.

Thus the seriousness with which solar pumping systems are considered in relation to conventional and other non conventional systems depends very much on the achievement of 'Target' case solar systems with costs and efficiencies assumed in Tables 5.5 and 8.4.

In circumstances in which mutually exclusive alternatives are being compared, it may be more helpful to consider the outcome of the analysis in terms of cross-over discount rates. On that basis, if the real opportunity cost of capital is below the cross-over discount rate, solar is to be preferred.

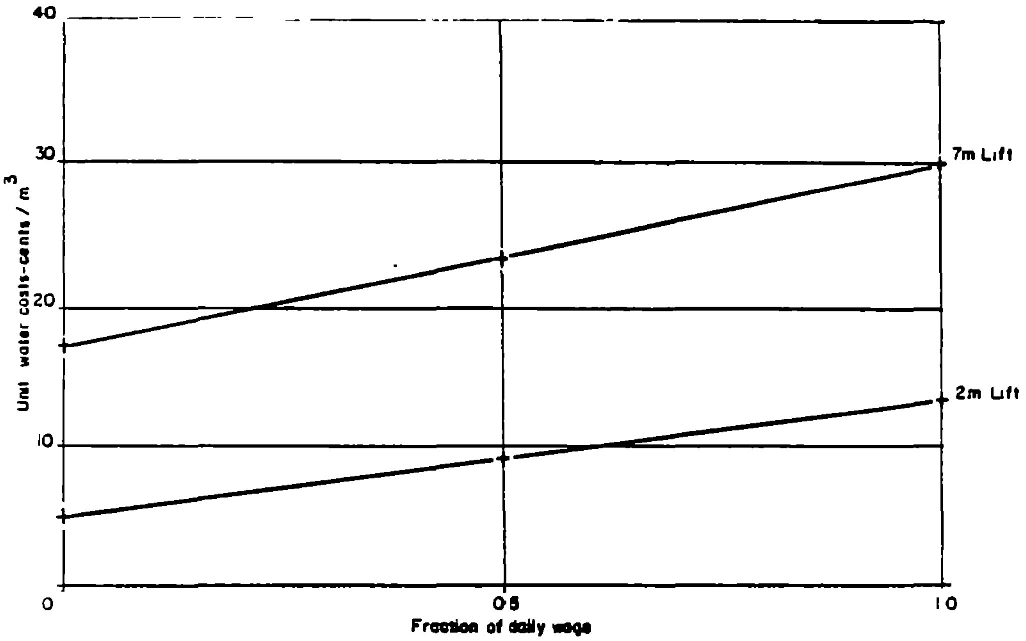


Figure 8.16 **Effect of the Value of Labour Costs on Cost of Irrigation Water Pumped by Hand (Baseline scenario)**
Base Case: Wage $ 1 per day

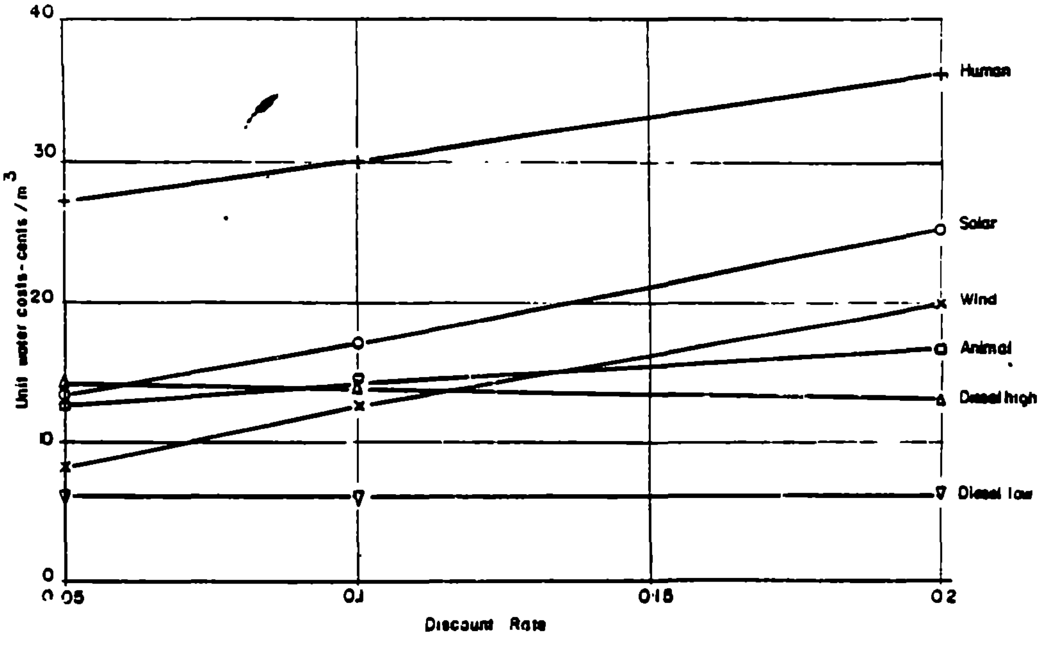


Figure 8.17 **Effect of Discount Rate on Irrigation Costs - 7m static head (Baseline irrigation scenario - no storage)**
Base Case: Discount rate 10%

The effect of the period of analysis was also investigated and this confirmed that at a discount rate of 10%, there was little difference in unit water costs for periods of analysis in excess of 30 years and that 20 years could be taken with little loss of accuracy. Use of lower discount rates would increase the importance of longer periods of analysis, while higher ones would reduce it. The model permits the calculation of the local cost component of total expenditure and then the use of a shadow exchange rate factor to adjust the value of the local component in relation to the foreign component. The effect of variation of the shadow exchange rate factor will be greatest in the case of systems with a high proportion of local cost. At the moment the question is somewhat academic for solar water pumps since the bulk of their expenditure is incurred outside the developing countries, but as moves are made to encourage local manufacture, the shadow exchange rate facility will become important.

In summary, solar pumps are favoured by lower discount rates and, on the basis of the assumptions used for the present analysis, solar becomes competitive with high case diesel for discount rates less than around 6%. The period of analysis need not be longer than about 20 years where the discount rate is 10%.

8.4 Country Specific Case Studies

8.4.1 Procedure

Many factors influence the perceived cost-effectiveness of solar water pumps and it was thought it would add point to the 'international' economic evaluations to compare solar pumps with the other water lifting technologies under the specific conditions in three of the countries visited in connection with their possible involvement in Phase II of the Project. Bangladesh, Kenya and Thailand were chosen.

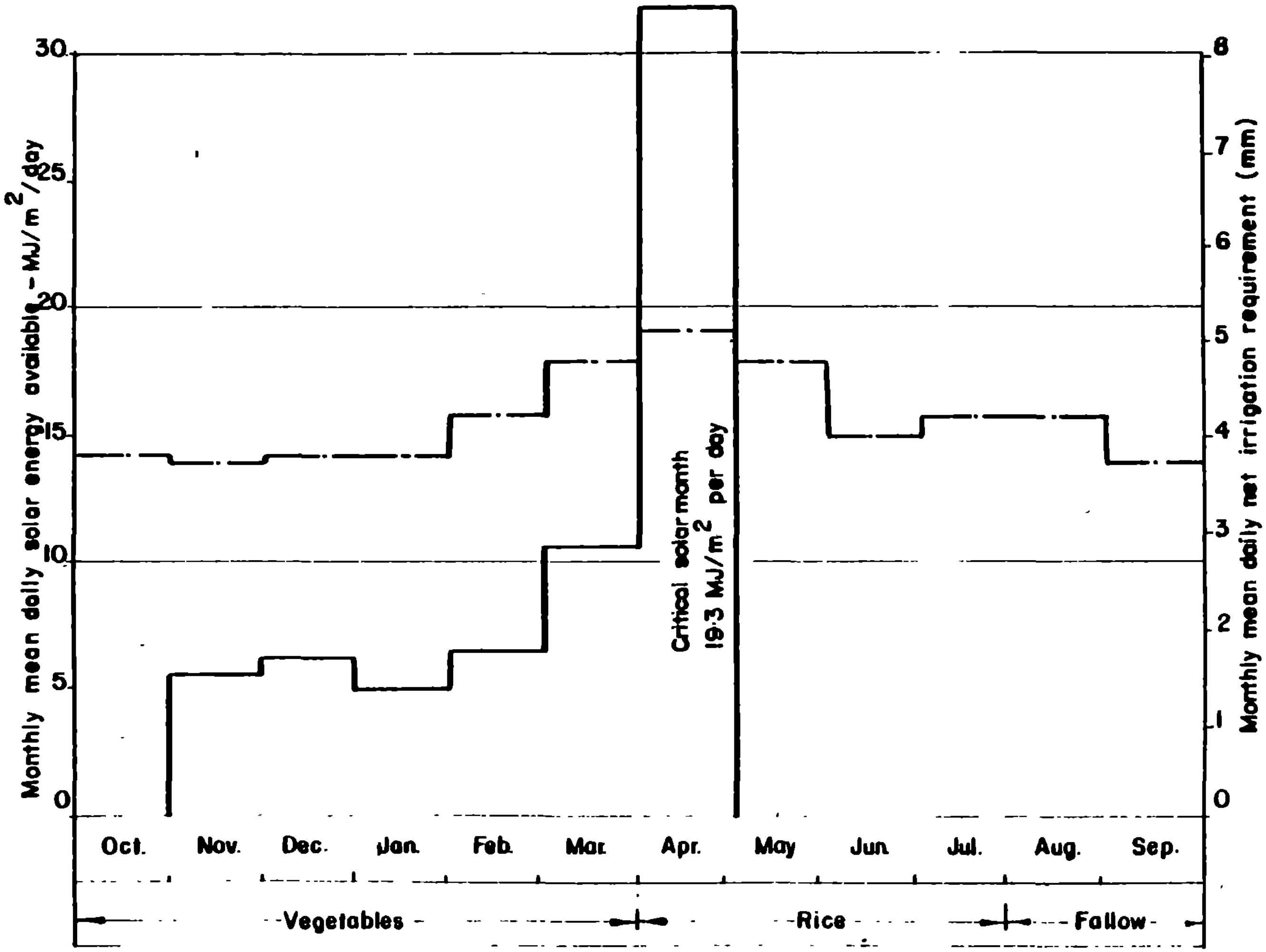
For each of the selected countries, local cost data, cropping patterns and meteorological data were used to examine the comparative economic of solar water pumping. This data were obtained through the use of questionnaires especially prepared for these studies. The cost factors are listed in Tables in Appendix 3.

The general technical characteristics of the irrigation system (Table 8.1) and the pumps (Table 8.2) were similar to these adopted for the baseline scenarios, except where data obtained from the three countries superseded the more general values. The cropping patterns adopted for the base studies are illustrated in Figs. 8.18, 8.19 and 8.20. The irrigation demand parameters are also given on these figures.

The general procedure adopted for the case studies was the same as for the baseline analyses. The variation of unit water cost with area was plotted and the optimum area and distribution system for the pumping system was determined. This was then used to evaluate the cost of irrigating a two hectare plot by each of the five systems.

8.4.2 Results

The results have been summarised into two histograms, one for 2m static lift (Fig 8.21), the other for a 7m static lift (Fig 8.22). Each histogram shows costs of water per unit volume delivered to the crop by each of the pumping systems evaluated for the technical, cost and cropping conditions adopted for each of the three countries. Since the types of results obtained have been explained in reasonable detail in connection with the baseline and sensitivity analyses this detail is not repeated here-it may be found in Supporting Document 2.



KEY

——— Net irrigation requirement

—·—·— Solar Energy

Note. Wind not shown as it is not a viable source in Bangladesh.

ENERGY PARAMETERS:-

Average annual solar irradiation on horizontal plane = 15.7 MJ/m²/day

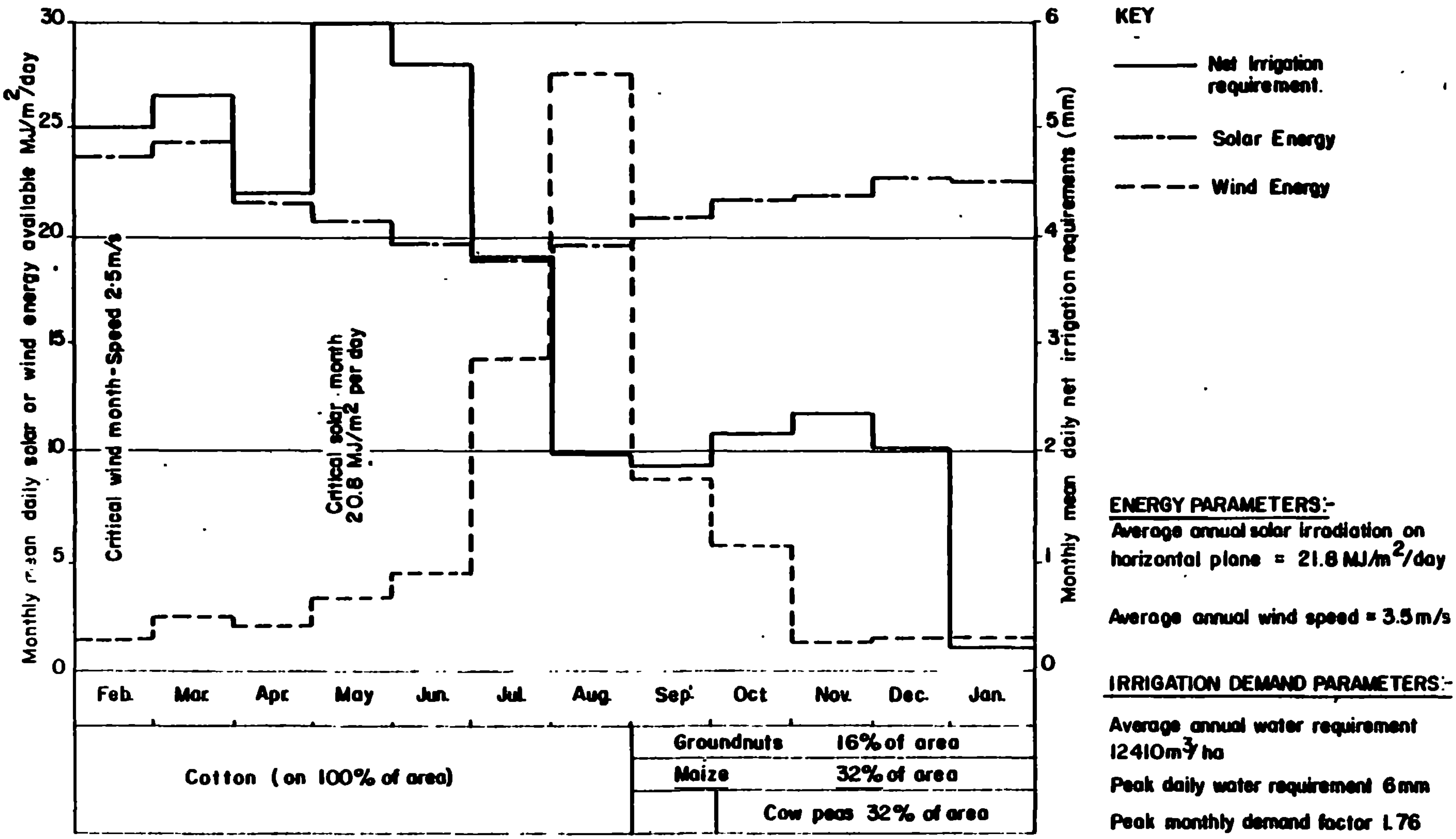
IRRIGATION DEMAND PARAMETERS:-

Average annual water requirement 5110 m³/ha

Peak daily water requirement 8·5mm

Peak monthly demand factor 6.02

Figure 8.18 Case study cropping pattern and availability of solar energy for Bangladesh



ENERGY PARAMETERS:-

Average annual solar irrodiation on horizontal plane = 21.8 MJ/m²/day

Average annual wind speed = 3.5 m/s

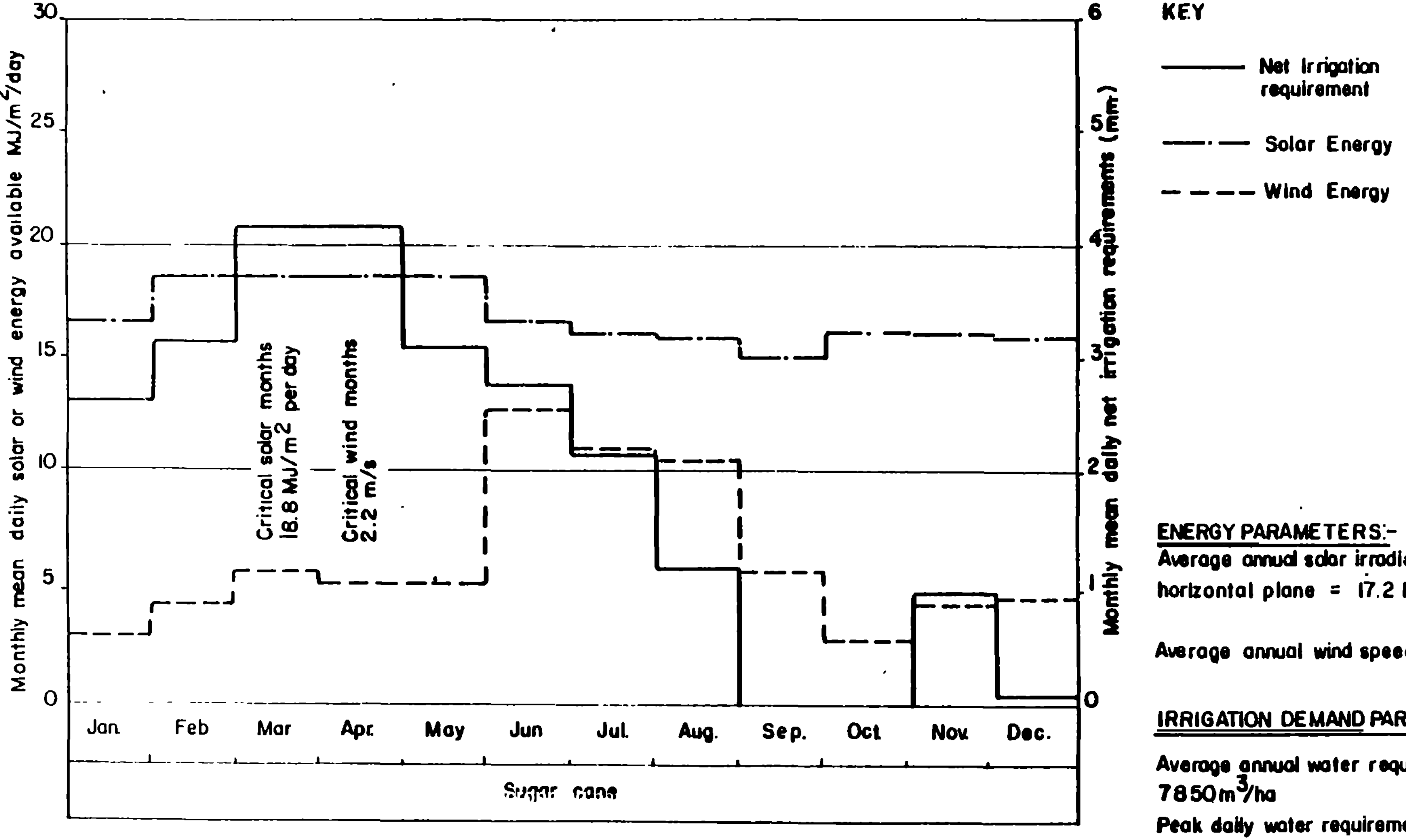
IRRIGATION DEMAND PARAMETERS:-

Average annual water requirement 12410m³/ha

Peak daily water requirement 6 mm

Peak monthly demand factor 1.76

Figure 8.19 Case study cropping pattern and availability of solar and wind energy for Kenya



ENERGY PARAMETERS:-

Average annual solar irradiation on horizontal plane = 17.2 MJ/m^2/day

Average annual wind speed = 3.9 m/s

IRRIGATION DEMAND PARAMETERS:-

Average annual water requirement 7850 m^3/ha

Peak daily water requirement 4.2 mm

Peak monthly demand factor 1.95

Figure 8.20 Case study cropping pattern and availability of solar and wind energy for Thailand

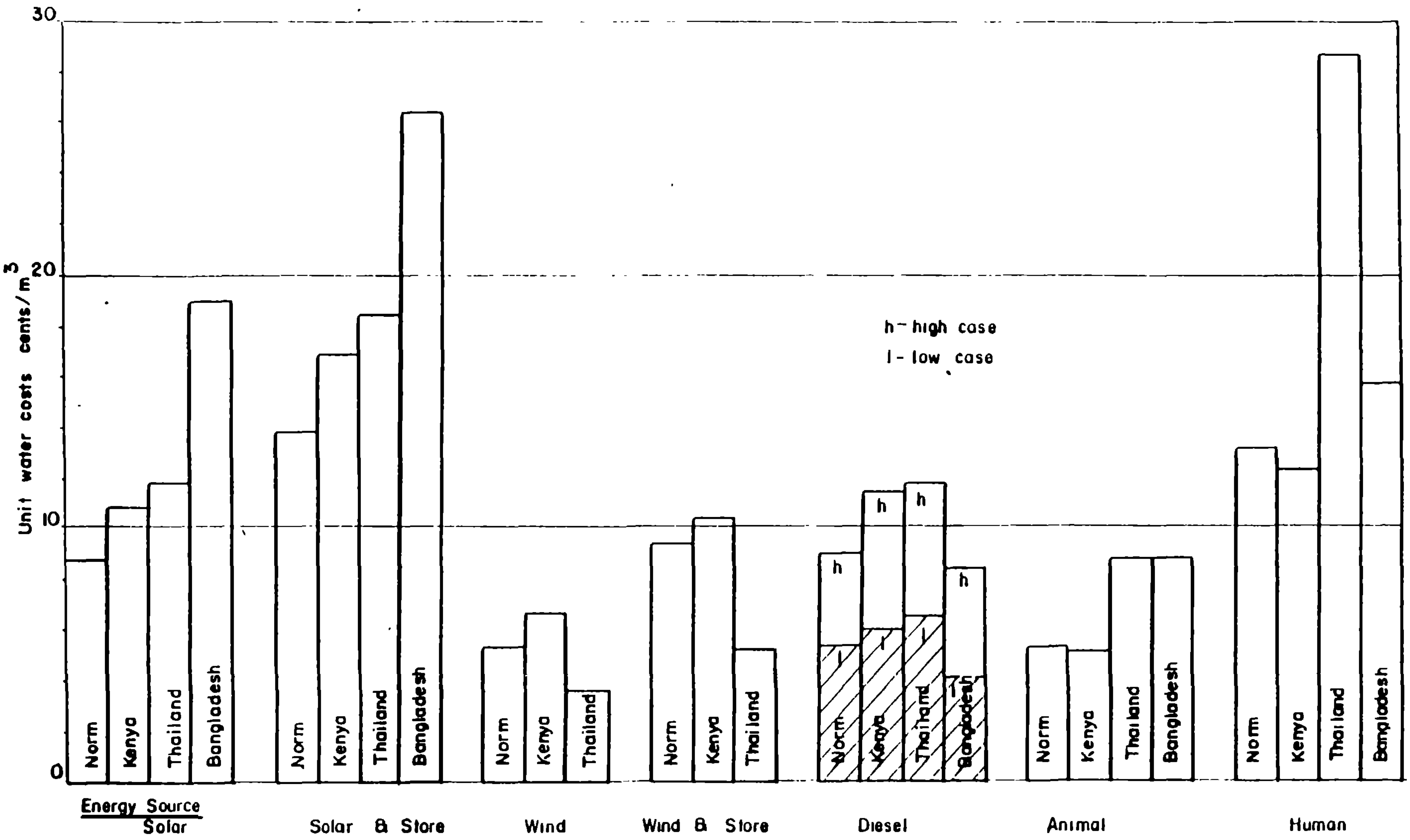


Figure 8.21 Histogram showing optimum irrigation water costs for alternative pumping methods to supply 2ha at a 2 metre lift with peak water requirements of 6mm per day
Technical characteristics as Tables 8.1 and 8.2 Climate, cropping patterns and water demands as Fig 8.18, 8.19 and 8.20

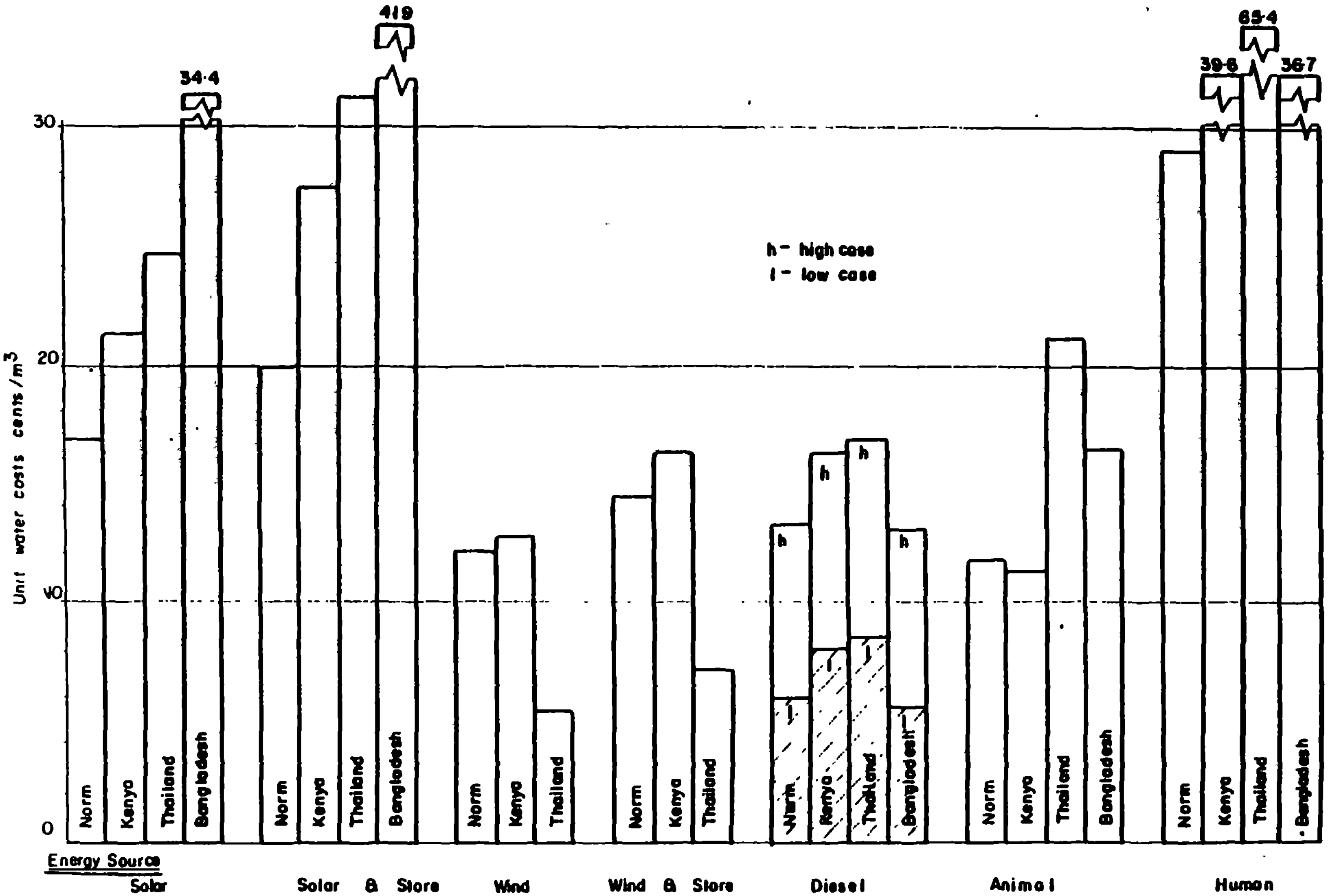


Figure 8.22 Histogram showing optimum irrigation water costs for alternative pumping methods to supply 2ha at a 7 metre lift with peak water requirements of 6mm per day Technical characteristics as Tables 8.1 and 8.2. Climate, cropping patterns and water demands as Fig. 8.18, 8.19 and 8.20.

8.4.3 Discussion of results

Some of the variations illustrated by the sensitivity studies reappear under the case studies, where data specific to the three selected countries of Bangladesh, Kenya and Thailand has been used. For example there is an optimum supply area for solar and windpumps, and this is location dependent. In Kenya the optimum area for a solar pump is 1 ha. while in Bangladesh it is nearer 0.5ha.

It must also be remembered that specific conclusions depend on the local costs and technical conditions assumed. In Kenya, for example, the cost of PVC pipes is comparatively high, with the result that lined channels work out as the more cost-effective distribution method for a solar pump. The results for Thailand have been calculated on the basis of a sugar cane crop and different answers would have emerged from a study of another cropping pattern, with a more evenly distributed water requirement and lower peak monthly demand factor.

The reasons for the variability in costs for different countries are complex, but some of the principal ones are as follows:

- solar pumps seem more cost-effective for irrigation in Kenya because, for the region of Kenya considered, there is little rain and consequently the peak monthly demand factor is lower than for Thailand or Bangladesh; Bangladesh seems poor by comparison precisely because a high dry season crop water demand is combined with a long rainy season, leading to a very adverse peak demand factor for solar pumps which have to meet a maximum water requirement six times the average. Solar pumps also appear more attractive in Kenya because of the high cost of diesel engines there.

- solar pumps are competitive with high case diesel pumps in Kenya and Thailand at lifts of 2m. At 7m lift solar delivers water for around 5 cents/m^3 and 8 cents/m^3 more than high case diesel for Kenya and Thailand respectively.

- wind is not considered for Bangladesh, because the limited wind data available suggested that the mean wind speeds are too low for windpower to be viable. Wind comes out as a very low cost option in Thailand, because cheap, locally manufactured windpumps are manufactured and used for irrigation in that country, even though mean wind speeds are not particularly favourable. Wind pumps are also manufactured in Kenya, but they are intended for borehole pumping and turn out rather expensive when used on low head irrigation applications. However, they still appear to be competitive with high case diesel.

- diesel engines are below world market prices in Bangladesh and above them in Kenya and Thailand.

- animal pumps are cheaper in Kenya than in Bangladesh, primarily because the lower peak monthly demand factor allows fewer animals to be used in Kenya to irrigate a given land area. Higher feed costs are responsible for higher unit costs using animals in Thailand.

- handpumps are barely competitive at 2m lift but become prohibitively expensive everywhere at 7m lift due to the high actual or opportunity cost of labour when converted into energy. They are particularly expensive in Thailand for a 7m lift because labour costs there are three times higher than in the other two countries and boreholes are more expensive to drill in Thailand.

Clearly these indicative conclusions can only apply to the specific conditions examined in the country case studies. The great advantage of this type of modelling procedure is that it can be used to compare a wide range of conditions quickly and easily, and it is hoped that it will be so used to explore the complexities of the situation in each country in more detail.

The impact of extensive utilisation of solar pumps on the foreign exchange and balance of payments positions might warrant special study when it is clear that solar pumps are poised to achieve significant market penetration. This could affect the development of facilities for local manufacture.

9. RURAL WATER SUPPLY STUDIES

9.1 Systems Considered

Two water supply end uses were studied: for people living in villages in rural areas and for livestock. The village supply case is described first.

9.1.1 Village water supply aspects

The village population was assumed to be in the range 375 to 1500 people and 750 was taken as the baseline value. The population density was taken as 75 persons per hectare. The effects of changes in village population were investigated as part of the baseline studies. Four types of pump prime mover were studied: solar, wind, diesel and human. Animals do not seem to be used much for powering village water supply pumps and so they were not included in the comparisons. The technical characteristics of the water source, storage and distributions systems, together with water use data are listed in Table 9.1.

Two public standpoint village water supply arrangements were considered with mechanised pumps: the first with a single centrally located borehole, pump and storage tank and the second, with this central facility augmented by pipes distributing water radially to a number of water points (schematically represented in Fig. 9.1)* . The former centralised arrangement has a number of disadvantages, particularly for the larger villages eg longer distances to walk, possible congestion at the central tank and longer queuing times leading to lower per capita consumption and lower standards of health (although such a situation could be improved by provision of a number of outlet from the tank). The latter arrangement with distribution provides for water standpoints at spacings which reduce these disadvantages, encourages the use of less polluted sources and so leads to an increase in the per capita consumption and an improvement in health. The investment required in the systems with standpoint distribution is substantially higher than for those with a single outlet point, because of the extra pipework involved and the cost of the energy lost in the distribution system. Clearly for villages where no pumped supply existed previously and finance is limited, it is sensible to proceed in stages and to provide initially for a single central water point storage with multiple outlets.

The arrangements utilising human powered pumps were somewhat different. No central storage facility was provided and the pumps were distributed in the village to satisfy the criteria for maximum distance and the peak flow demand (described below).

Quoted per capita consumptions range from 10 litres/day to 100 litres/day depending on distance and convenience of source (Refs. 2,3,4). It was decided to adopt a baseline value for both the central storage and distributed systems of 40 litres/capita per day which corresponds to design practice for public standpoint supplies and to investigate the effect of variation to this figure in the sensitivity analyses. For the range of population considered this per capita consumption results in total daily volumes in the range from 15m^3 to 60 m^3.

The economics of standpoint connections to individual houses were not considered: this will obviously occur at a somewhat later stage of development and will be associated with very much higher per capita water consumption figures for which different supply arrangements may be appropriate.

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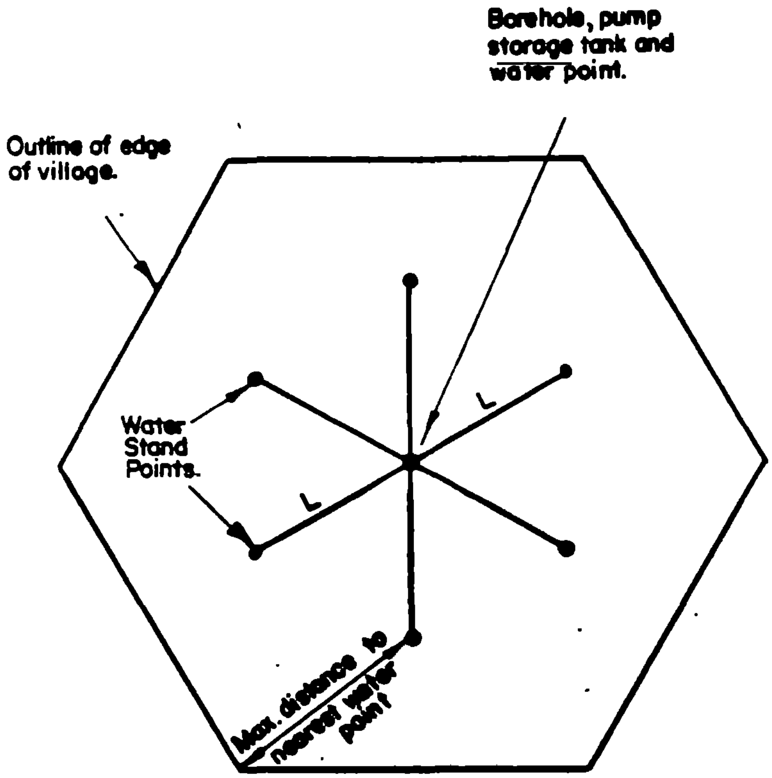
* Fig. 9.1 shows six water points fed by distribution pipes but the number is calculated within the model to match the constraints imposed.

Water demand	
(a) Village	
Population	750
Population Density	75 people per hectare
Per capita consumption	40 litres per day
Daily Peaking factor	0.15
Maximum distance from household to standpoint	100m
(b) Livestock	
Livestock population	2000
Animal consumption	40 litres/head/day
Water Source (borehole or well)	
Static lift	20 metres
Drawdown	0.1 m per lit/sec
Storage tank	
Store size	1 days demand
Store height	height = ½ diameter
Material	Concrete
Storage efficiency	100%
Lifetime	30 years
Distribution Pipework	
Diameter	50mm
Material	PVC
Darcy Resistance Coefficient	0.02
Conveyance Efficiency	100%
Lifetime	10 year

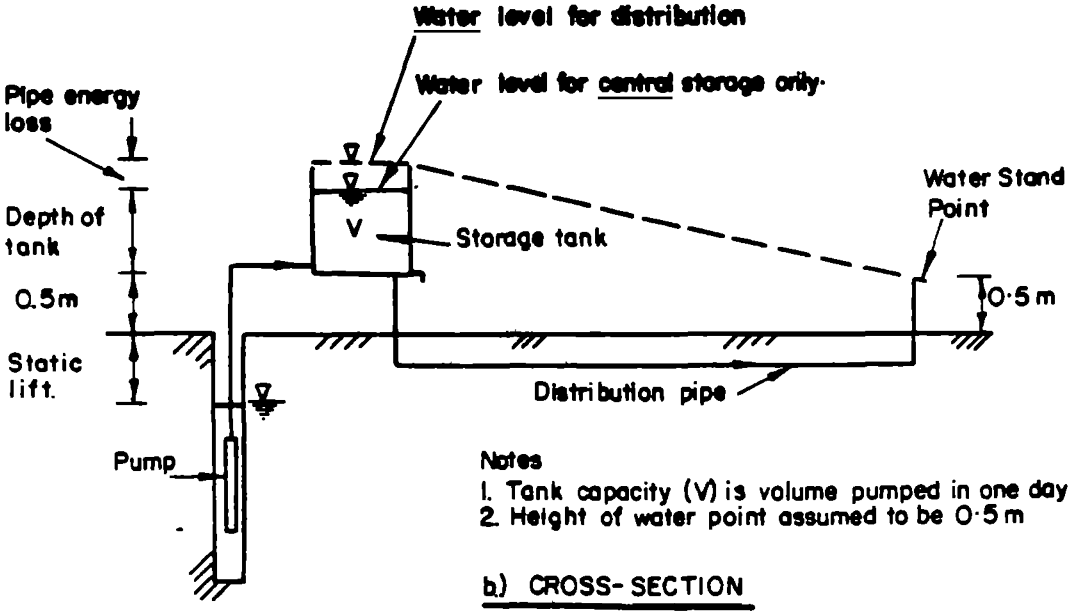
Table 9.1 Technical Characteristics of Water Demand, Source, Storage and Distribution Systems - Baseline Water Supply Scenarios



Notes

1. Total length of pipework = 6L
2. Max. distance to nearest water point is L for the configuration shown.
3. Distribution of hand pumps will not necessarily coincide with layout of water points.
4. The actual number of water points is chosen by model to match constraints.

a) PLAN



Notes
1. Tank capacity (V) is volume pumped in one day
2. Height of water point assumed to be 0·5 m

b) CROSS-SECTION

Figure 9.1 Schematic Layout for Village Water Supply System with Piped Distribution

The number of water points required was based on comprehensive studies on the patterns of water consumption made by Ahmed (Ref 16) for villages in Bangladesh. This data have been used to set the maximum distance from a household to a water point (100m) and the maximum rate of flow which has to be provided with distributed systems. (Note that on the distribution model shown in Fig. 9.1 the maximum distance limitation occurs on the outside of the village, the centre being relatively better catered for). This is related to the number of people wanting to use the standpoint at any one time, the volume of water each takes and the time they are prepared to queue; these studies allowed for 15% of the total daily demand to be abstracted in the peak hour. Although the Bangladesh data may not not apply strictly to other countries, they are uniquely well documented and similar trends should be evident elsewhere.

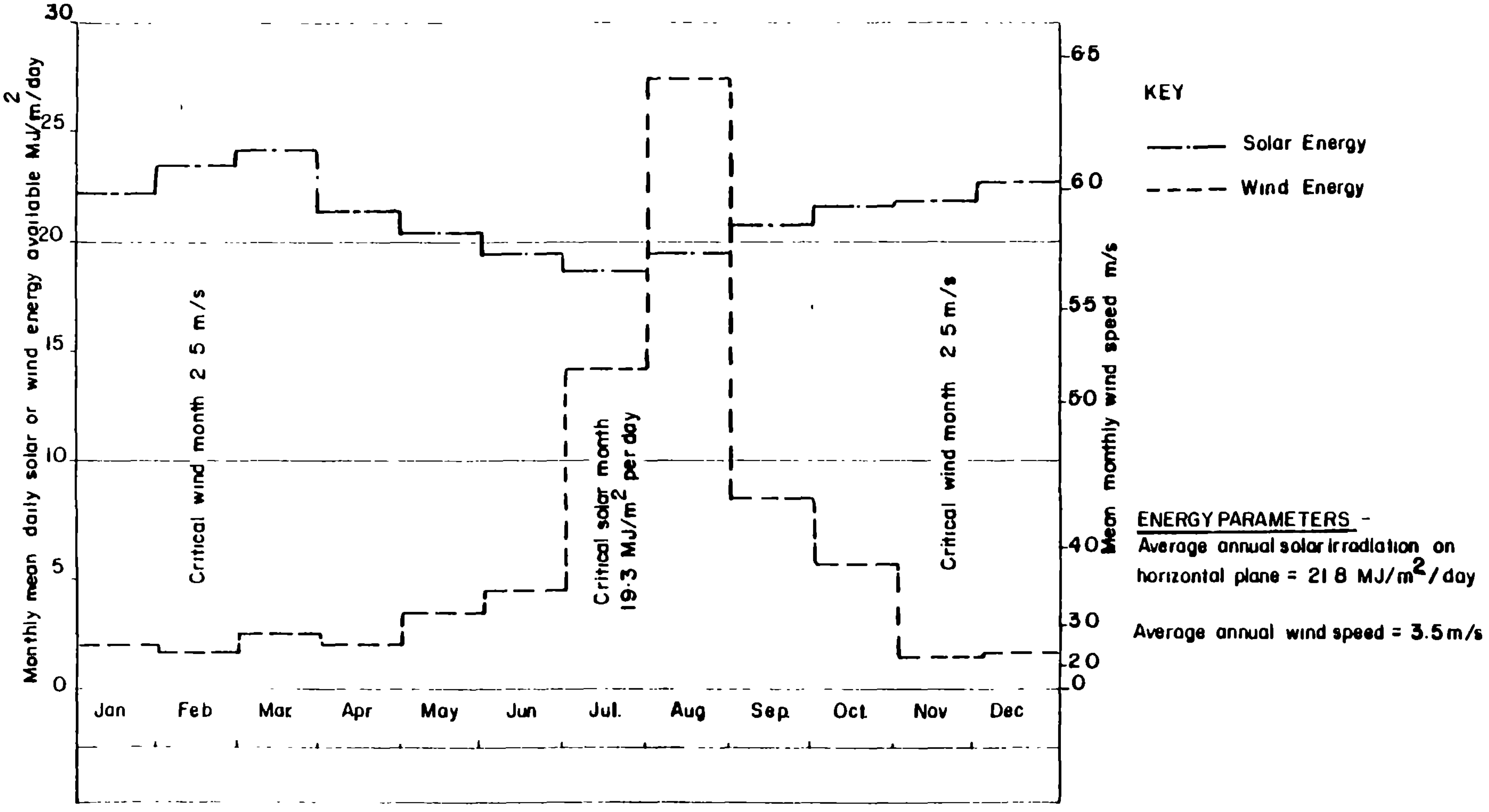
Taken together, the maximum distance from a household to a water point the peak hourly demand rate, and the population density determine the number of water points on the layout shown in Fig. 9.1. There is clearly a limit to the size of village that can be economically served by such an arrangement with respect to particular numerical values of the distribution criteria, and at the limit an additional hexagonal distribution system will need to be introduced.

For all mechanised methods of pumping, storage at the borehole equal to one days supply was provided. The purpose of the store was to provide some capacity to cover for changes in the pattern of daily water consumption and more importantly, minimum cover against the effects of breakdown in the pump or for periods of low sunshine or wind. The whole question of reliability of water supply systems is one which has to be taken very seriously and in many instances it may be felt that more comprehensive measures would be appropriate. These could include, for example, storage of two (or more) days supply or the provision of back-up pumping capacity. In the case of solar pumps such back-up could be provided by a handpump. A related question is that of utilisation: for the present studies it was assumed that all systems and sources give full utilisation throughout their working lives and clearly those will be occasions when this is not so. These are matters which can be explored in greater depth in subsequent studies. Water from some sources will require treatment, but this will apply equally to all pumping systems and so no special note was taken of this in these studies.

A borehole or well was assumed to be the water source in all cases, and the baseline static lift was taken as 20m. The static lift is the difference in elevation between the water surface at rest in the well (or borehole) and the ground level adjacent to the storage tank. The total pumped head is the sum of static lift, plus drawdown, plus height from ground to water surface in storage tank (the base of the tank is assumed to be 0.5m above ground level and the volume is set equal to the daily volume required). This height will be increased by the flow dependent pipe energy losses when the water is distributed to stand points (see Fig. 9.1).

The distribution pipework was assumed to have a diameter of 50mm. These is clearly some need for suboptimisation of pipework diameter but this was beyond the scope of this initial study. Because the pipe runs were simple and short it was assumed that there was no leakage: this is obviously optimistic and the baseline value of 100% conveyance efficiency would have to be varied in sensitivity studies of actual sites.

The solar and wind energy assumed to be available are shown in Fig. 9.2. These are based on Kenya data, as were the inputs for the irrigation studies (shown in Fig. 8.2). As the daily demand for potable water is assumed to be the same throughout the year, the critical month for which the renewable energy systems have to be designed is the one for which the solar or wind energy is a minimum: for solar this is July with a mean daily solar irradiation of 19.3 MJ/m^2 (5.36 kWh/m^2) on the horizontal plane, while for wind is in February or November, both of which have average wind speeds of 2.5 m/s.



ENERGY PARAMETERS -

Average annual solar irradiation on horizontal plane = 21 8 MJ/m²/day

Average annual wind speed = 3.5 m/s

Figure 9 2 Meteorological data used for baseline rural water supply scenarios (based on Kenya)

9.1.2 Livestock water supply aspects

This water supply system is very simple, consisting of a borehole or well, a pump, and a storage tank. No major distribution system is required. One water point was reckoned to serve from 1000 to 4000 head, a baseline number of 2000 being adopted for the study. Cattle were considered to be typical livestock and a daily water consumption of 40 litres/head was adopted: a pump servicing 2000 head will thus need to deliver 80 m^3 per day. Clearly arrangements will need to be made for the provision of tanks of appropriate shape for the convenient access of this number of cattle, and a very small distribution system may be required: no attempt was made to model this.

Three types of pump prime movers were compared: solar, wind and diesel. Handpumps were not included in the analysis of livestock application (they will be identical to those of a village without distribution for equal daily volumes). Identical values to the village supply case were adopted for static lift and renewable energy inputs.

The basic methodology was otherwise identical to the village supply case with no distribution system.

9.1.3 Technical specifications for pumping systems

The combinations of future costs and efficiencies used in these economic studies are given in Table 5.5. The technical specifications for the pumping systems were identical to these adopted in the irrigation studies and this information is listed in Table 8.2.

The discussion about engine performance in Section 8.1.2 also applies to these water supply scenarios. As before "high" and "low" case diesel engines have been included in the evaluation.

The input power to a handpump was assumed to be 60 W (as for the irrigation studies). Such data as exists (Ref. 13) indicates that, for shorter durations, human power can be around 200 W over 2 minutes: the effect of this was studied in a sensitivity analysis but it should be taken into account in detail in subsequent studies.

9.1.4 Cost and economic data

Full details of the origins of the cost data and its analysis are given in Supporting Document 2. The costs can be regarded as those current in mid-1982: local currencies have been converted to US dollars as the exchange rates ruling in August 1982.

The various cost factors, coefficients and parameters needed to define the capital and recurrent costs for each component (as outlined in Section 7.6.3) are given in full for the international baseline scenarios in Appendix 3. Illustrative capital and recurrent costs for the pumping systems are given in Tables 8.3 and 8.4 and for infrastructural components in Table 8.5.

Other remarks in section 8.1.3 apply to the water supply studies, with the exception of the treatment of the valuation of time spent by people operating the handpumps. In the context of normal village use it is not felt to be appropriate to place a value on this time and a zero value has been adopted for the baseline scenario. The effect of wage rates on the cost of water has been examined in the sensitivity analyses, however.

As with the irrigation studies, a real discount rate of 10% and a period of analysis of 30 years has been adopted for the baseline scenarios.

9.2 Baseline Studies

9.2.1 Presentation of Results

With five pumping systems (including diesel high and low) two storage options, and two distribution methods (as illustrated in Fig 7.2) nine village water supply baseline scenarios were studied. Each scenario was analysed for the baseline static lift of 20m and a village of 750 people. Baseline analyses were carried out over a range of village populations from 375 to 1500.

For the livestock water supply case, four baseline scenarios were studied, comprising four pumping systems (including diesel high and low)each with storage. The baseline number of livestock was taken as 2000 but the head of cattle were varied from 1000 to 4000.

A wealth of information has been obtained and only a summary can be given in this Main Report. Examples of the results have been included so that the reader can appreciate the type of information that was obtained.

The output obtained from a typical computer run is shown in Table 9.2. The results from the analyses of the baseline scenarios for village and livestock applications are given in Tables 9.3. and 9.4. From this type of data plots of unit water cost against village population for the alternative lifting techniques examined were prepared: typical examples are shown for 20m static lift in Figs. 9.3 and 9.4 for village systems with central storage only and with piped distribution arrangements, respectively. Costs of hand pumped water are shown in both figures. The unit cost of water for livestock is shown in Fig. 9.5.

Fig. 9.4 shows that there was a minimum in the solar and wind curves of unit cost of water against population for the distributed case, although the effect was not very great: this occurred for a population of around 1000 people. The procedure adopted for the irrigation studies (see Section 8.2.2) was not used therefore, and the output costs in 1982 US cents were compared simply for the baseline population and livestock values in the histograms shown in Figs. 9.6 and 9.7 respectively. Fig 9.6 includes the village water supply cases with and without piped distribution and with human powered pumps.

9.2.2 Discussion of results

Village Water Supply

For the baseline scenario village of 750 population without distribution the cost of water delivered by solar and high case diesel systems are identical at 21 cents/m^3. Low case diesel, wind and human power deliver water at costs of 11.4, 13.8 and 15.4 cents/m^3 respectively (see Fig. 9.6).

Fig 9.3 shows the effect on unit water cost of increase in village population for the central storage-no distribution case with a static lift of 20m. Normal economies of scale apply to all systems as the volume required per day increases. This is particularly marked in the case of diesel pumps, because they are considerably oversized for populations less than around 1000 (equivalent to 40 m^3 per day). It will also be noted that the cost of handpumped water falls by a few cents as the population increases from 375 to 750. For low populations the maximum distance criterion (not the peak demand criterion), was the limiting factor in determining the number of handpumps and small increases in population could be accommodated without an increase in the number of handpumps needed. At higher populations the daily peaking factor became limiting because the number of handpumps was then related directly to the population and so the unit cost ceased to fall and became constant.

DATA FILES
Location
Water Demand
Water Source
Power Source
Pump
Store
Distribution
Economic

SYSTEM SPECIFICATION

1 **Input Parameters**

Village population	750
Village area	10 hectares
Population density	75 persons/hectare
Water static lift	20 metres
per capita consumption	40 litres/day
Mean daily water demand of village	30 cubic metres
Daily peaking factor	0.15
Oversizing factor	1
Number of pumps	1
Number of water points	3
Discount Rate	0.1
Period of Analysis	30 years
Shadow Exchange Rate Factor	1

2 Calculated Parameters

Total head	24.8 metres
Store head	3.3 metres
Distribution head	1.3 metres
Max. Distance to nearest water point	99 metres
Overall energy efficiency	0.014
Overall volumetric efficiency	1
Overall system efficiency	0.011
Overcapacity ratio	1.11
Mean no. of operating hours per day	10.1

3 Component Sizes (per pump)

Component	Type	Lifetime years	Size
Power source	Solar	15	974.1 peak watts
Pump	M/Pump	5.3	390 peak hydraulic watts
Store	Concrete	30	30 m^3
Distribution	50mm PVC	15	297 m

COST IN 1982 $

		Total $	Total $
1	Capital		
	Water Source	1540	1540
	Power Source	15585	2922
	Pump(1)	1114	0
	Store	1742	1306
	Distribution	1188	891
	Total	21169	6659
2	Recurrent		
	Annual Maintenance Costs	98	75
	Annual Operating	0	0
	P.W. of Replacements	3113	448
3	Summary of Life Cycle Costs (over 30 year period of analysis at discount rate of 10%)		
	Total Capital	21169	6659
	P.W. of Maintenance	1017	777
	P.W. of Operating	0	0
	P.W. of Replacements	3113	448
	Total Life Cycle (PW)	25299	7884
Equivalent Annual Costs ($ pa)		2439	760
	UNIT WATER COST ($/$m^3$)	0.223	0.069

NOTE

(1) includes motor with PV systems

Table 9.2 Typical Data Output from Analysis of Baseline Village Water Supply Scenario

Pump	No. of Pumps	No of Water points	Population per water point	Power Source size per pump	Actual Life-times Power Source yrs	Pump yrs	System Capital Cost $	P.W. of Replacements $	Annual Running Costs $	Annual Maintenance Costs $	Life Cycle Cost $	Unit Water Cost cents per m³
With piped distribution												
Solar	1	4	187	974 Wp(1)	15	5.3(5)	21169	3113	0	98	25301	22.3
Wind	1	4	187	40.7 m²(2)	30	10	16038	823	0	59	17469	15.4
Diesel 'low'	1	4	187	2.5 kW(3)	9.9	10	6649	1549	414	206	14629	12.9
Diesel 'high'	1	4	187	2.5 kW(3)	7.3	10	6649	2063	1242	406	25806	22.7
Without distribution												
Solar	1	1	750	944 Wp(1)	15	5.3(5)	19849	1017	0	98	23273	20.5
Wind	1	1	750	39.4 m²(2)	30	10	14500	522	0	59	15629	13.8
Diesel 'low'	1	1	750	2.5 kW(3)	10	10	5641	1164	402	206	12932	11.4
Diesel 'high'	1	1	750	2.5 kW(3)	7.5	10	5461	1641	1206	406	23832	21.0
Handpump	7	7	107	60W (4)	-	10	12796	1077	0	350	17497	15.4

NOTES

(1) Array output
(2) Rotor area
(3) Shaft output
(4) Assumed input power maintained over 5 hours
(5) Includes electric motor

Table 9.3 Results of Analyses on Village Water Supply Pumping Systems
(Population 750, consumption 40 litres per capita per day, static lift 20m, population density 75 per hectare, critical solar month = 19.3 MJ/m², critical wind speed = 2.5 m/s, i = 10% n = 30 years).

Pump	Power Source Size	Actual Lifetimes Power Source	Pump	System Capital Cost	P.W. of Replacements	Annual Running Cost	Annual Maintenance Cost	Life Cycle Cost	Unit Water Cost
		years	years	$	$	$	$	$	cents per m^3
Solar	2681 Wp(1)	15	5.3(4)	49845	1017	0	98	57341	18.9
Wind	2 x 61 m^2(2)	30	10	36722	1489	0	59	38868	12.8
Diesel -low	2.5 kW(3)	3.6	10	6982	3821	1126	282	25410	8.4
Diesel - high	2.5 kW(3)	2.7	10	6982	5308	3379	557	53098	17.5

NOTES

(1) Array output
(2) Rotor area
(3) Shaft output
(4) Includes electric motor

Table 9.4 **Results of Analyses** on Livestock Water Supply Pumping **Systems**
(2000 livestock, consumption 40 litres per animal per day, static lift 20 metre, critical solar month = 19.3 MJ/m^2, critical wind speed = 2.5 m/s; i = 10%, n = 30 yrs)

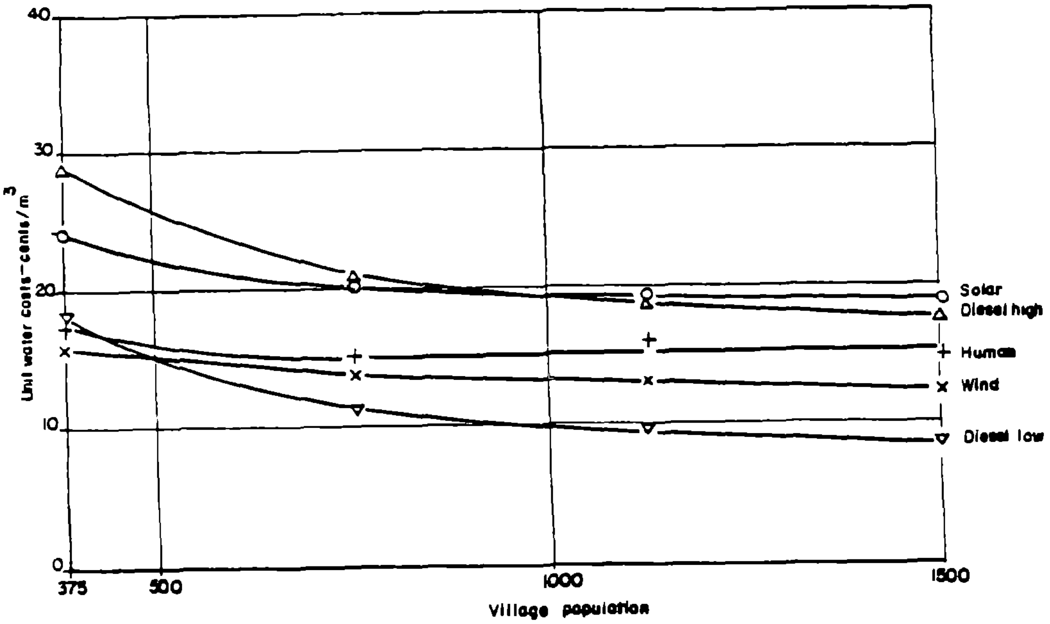


Figure 9.3 Cost of Water for Village Water Supplies - no distribution (Baseline scenario - 20m static lift)

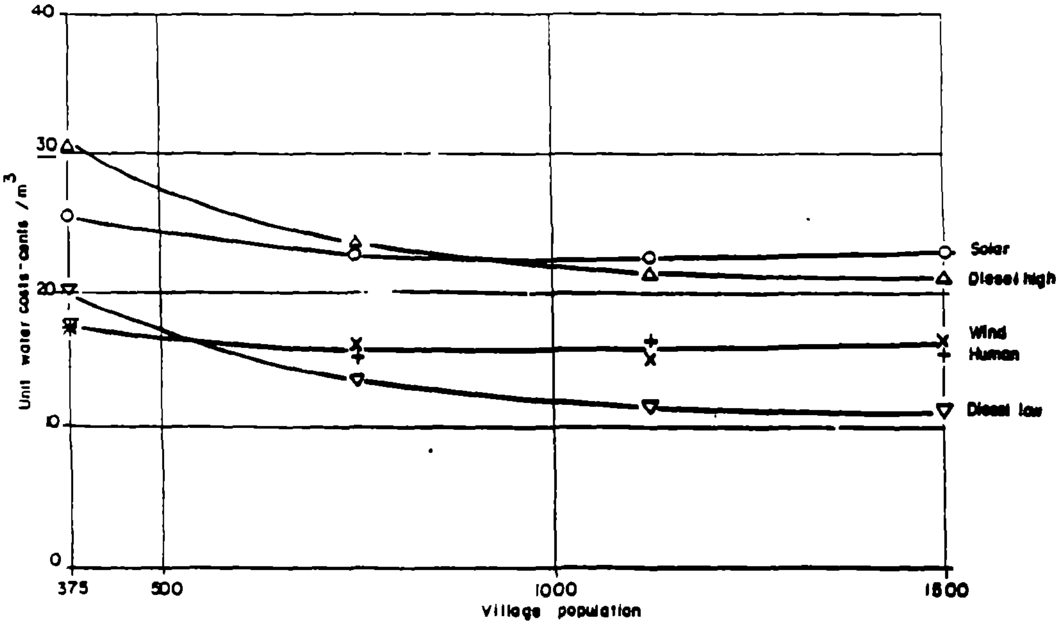


Figure 9.4 Cost of Water for Village Water Supplies - piped distribution (Baseline scenario - 20m static lift)

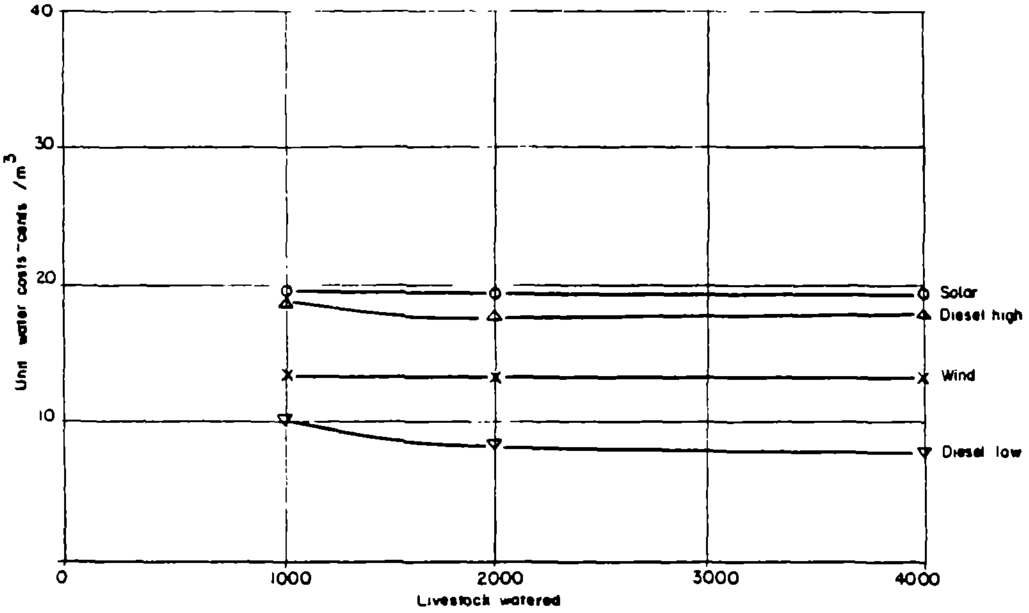


Figure 9.5 Cost of Water for Livestock (Baseline scenario)

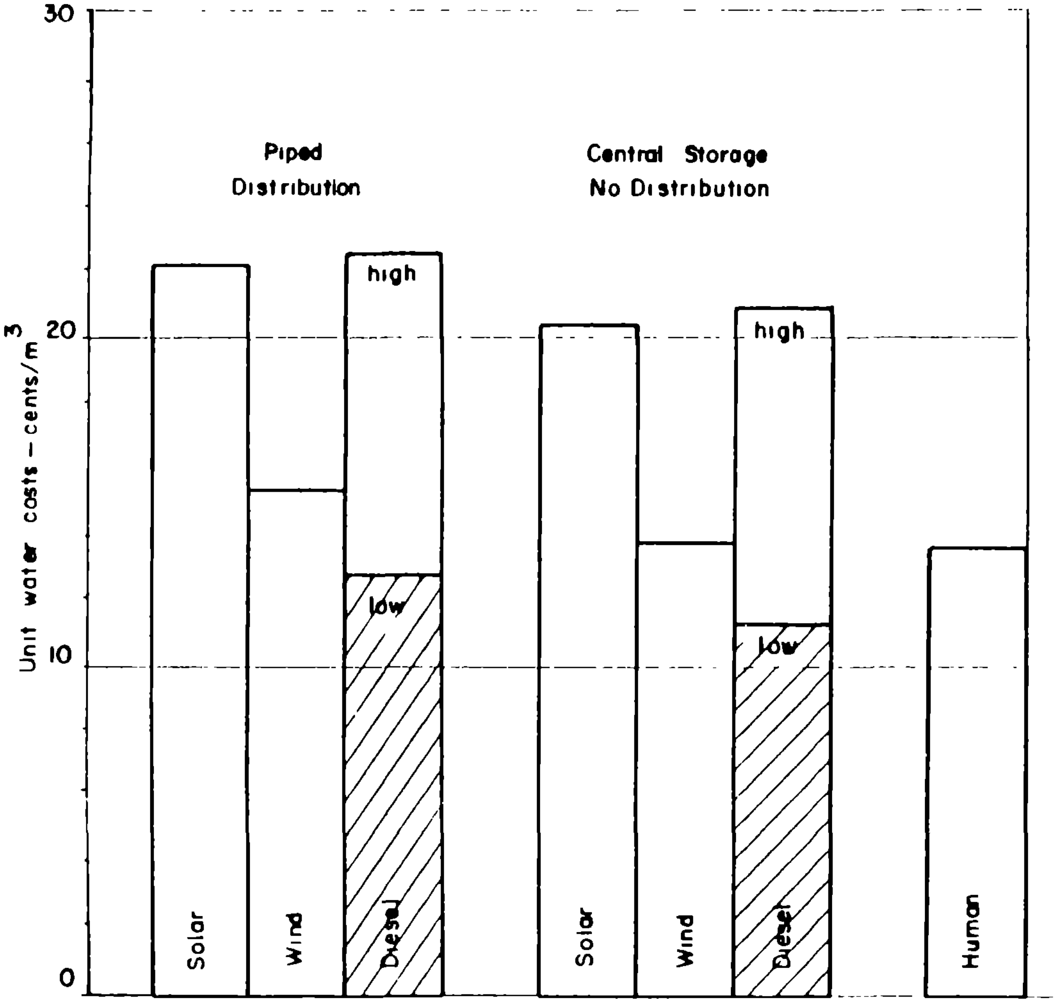


Figure 9 6 Histogram showing unit water costs from studies of village water supply baseline scenarios (population 750 at a 20 metre lift, 30m³ per day)

Note

The number of handpumps is derived from its own supply characteristics and the demand pattern, and is not usually the same as the number of water points in a piped distribution system

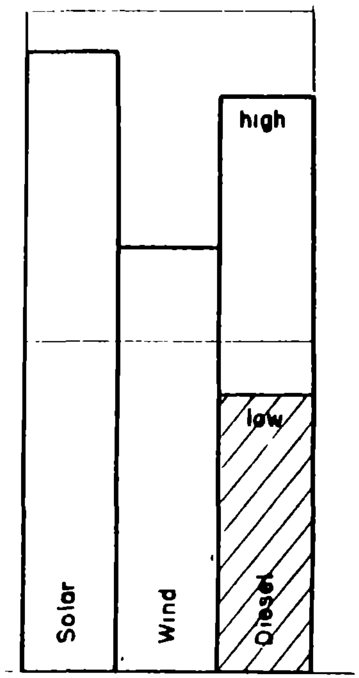


Figure 9 7 Histogram showing unit water costs from studies of livestock water supply baseline scenarios (2000 cattle at a 20 metre lift, 80m³ per day)

At a population of 1500 there appears to be little further scope for falling output costs due to economy of scale and, from the point of view of costs, villages of larger populations could be served very nearly as cost- effectively from two supply centres.

For populations above 500, low case diesel is cheaper than any other option, delivering water for about 10 cent/m^3. However high case diesel is the most expensive option for populations below around 1000, above which it is comparable to solar at just under 20 cents/m^3. The general validity of this conclusion obviously depends on the real cost of maintenance and operation and these would need to be examined very carefully before opting for diesel. At around 13 cents/m^3 wind is about 4 cents/m^3 more expensive than low case diesel and 6 cents/m^3 cheaper than solar, but could be cheaper in better wind regimes. If the wind regime were very poor and diesel were excluded because of maintenance or fuel supply problems, solar is the only remaining mechanised option: the delivered cost of solar pumped water of around 20 cents/m^3 is still very much less than is paid for it in many parts of the world. The only remaining method of lifting water are human powered pumps which, on the basis of the assumptions made, delivers water for a little more than 15 cents/m^3. Factors tending to increase that cost include, for example, maintenance (a low value was assumed), the cost of multiple boreholes (if other factors increase the total number of handpumps required) and any charge for the time spent pumping. A factor tending to reduce the cost of handpumped water is the greater power output from a person for limited durations. Some communities might consider it was worth 4 cents/m^3 to be free of the toil of pumping water and this result is sufficiently good for solar to encourage further field trials in appropriate circumstances.

Fig 9.4 illustrates the effect on the unit cost of water for the piped distribution case of an increase in village population. Although the picture is similar to the central storage situation it differs in two main respects: a) all options (apart from handpumps), are more expensive than in the central storage - no distribution case by around 2 to 3 cents/m^3 and b) the renewable energy systems display cost curves having minima at populations of between 700 to 1000. Piped systems are always more expensive because of their higher capital costs, combined with the higher power requirements needed to overcome pipe friction and/or the extra static head involved. Initially the cost of the renewable energy systems fall with increase in the population served, because the pipes are oversized and do not consume too much energy. However, as the population and flows continue to rise, pipe friction increases, the head developed by the pumps has to increase and so the installed power and the total costs go up.

The handpump line on Fig 9.4 is the same as on Fig 9.3 and so is nearly coincident with the wind curve. Low-case diesel is increasingly competitive as the size of village increases, while for populations over about 1000 wind and solar get progressively more expensive with the fixed diameter pipe distribution system studied, delivering water for not less than 16 and 22 cent/m^3 respectively at a population of 1500.

Wind could be a cheaper in more favourable wind regimes-the assumed mean wind speed for the baseline model of 2.5 m/s in the least windy month would be exceeded in many places. It should also be noted that, as explained earlier in the discussion on the irrigation results, the assumptions behind the windpump cost parameters were on the pessimistic side.

The low case diesel could not be any cheaper than indicated, but could (and probably normally would) be more expensive than indicated by these studies. This is so, partly because no separate allowance has been made in these water supply studies for the costs of attendance of a person responsible for the operation and maintenance of the engine. The maintenance cost included in the analysis allow for technical servicing at intervals of about 250 hours running time, but not for checking and starting the engine, topping up fuel and stopping it. The costs of attendance are location specific and it was difficult to make any reasonable assumptions for the international case. For every dollar per day paid for attendance, the delivered cost of water at 40 m^3 per day increases by 2.5 cents/m^3 so this item can be significant in relation to the other factors which influence output costs. It is possible that in some places the villagers could arrange to do it for themselves (much as the farmers are assumed to do) but that in other places it would be virtually impossible to organise this function. This could well be a material factor contributing to a lack of use of diesels for small village pumping.

The other factors contributing to an increase in costs for the low case diesel are, as discussed previously, more expensive routine maintenance and/or higher costs of breakdowns and more expensive fuel.

In summary, where the wind is unsuitable and the real costs of diesel approximate to the high case, solar water pumps may offer the only viable way to mechanise the pumping of water for small villages. The physical task of handpumping 30 m^3 of water per day from depths of 20m (or more) should not be underestimated and the likelihood is that the village would have to make do with considerably less. The premium of 5 cents/m^3 for solar pumped water over handpumped water would therefore have to be weighed against the improvements to health which would result from the regular supply of a greater volume of water. Although a piped supply is always more expensive for populations up to 750 or so, it is only around 2 cents/m^3 more and the people concerned may deem this extra sum worth paying.

As with the irrigation studies, it is important to remember that changes in the assumptions for the many technical and economic criteria can cause significant changes to the unit costs of water. For a more complete understanding of the factors which influence the baseline costs it is necessary to do sensitivity analyses in which the consequences on unit water cost of change to one or more of the inputs can be systematically examined.

Livestock water supply

The histogram in Fig. 9.7 indicates the relative costs of mechanised water supplies for 2000 livestock. Fig 9.5 shows how the unit cost of water pumped by the three alternatives vary with the number of livestock watered. Not surprisingly the curves are strongly reminiscent of the scenario for village water supply without distribution and the unit costs at the upper end are very close. Here, under ideal conditions, diesel is the least cost option, but if more typical conditions are assumed (the diesel high case) then it becomes nearly as expensive as solar at 18 cents/m^3. No allowance has been made for attendance, or for providing a safe and secure storage for fuel in what may often be locations some distance from human habitation, and these inputs will further increase the cost of diesel pumped water.

It will be appreciated that the livestock case is simply an extension of the village case (without distribution) and that the curves on Fig. 9.5 are but an extension of those in Fig. 9.3. Since there was evidently little economy of scale, the cost of providing solar pumped water for 2000 livestock at 18 cents/m^3 is only a little less than providing water for 750 people at 21 cents/m^3. (other conditions being equal).

Thus windpumps will be competitive with diesel and solar pumps for this duty at a delivered cost of around 13 cents/m^3, and will offer additional operational advantages over diesel. Windpump technology which, unlike solar pumps, has been long established, is therefore quite widely perceived as technically and economically viable for livestock water supply duties in Australia, Southern Africa, Argentina and parts of the USA, although it is still rarely used in most developing countries.

Since the tropical belt is often less windy that the regions where windpumps are already in use, solar pumps may be an equally attractive technology for duty in those areas where diesel is not feasible, as it is less sensitive to site specific factors than windpumps.

9.3 Sensitivity Analyses of the Baseline Village Water Supply Scenarios

9.3.1 General

Four groups of parameters in the baseline model were varied

Group A Climate
B Water Supply Factors
C Costs
E Economic

A village with a population of 750 was used as the basis for all the studies, some with piped distribution and some without. Since the livestock water supply case is so similar to that of a village without distribution, separate sensitivity analyses were not carried out into this application.

The major parameters which were thought to influence unit water costs in each group and which were studied are set out in Table 9.5. This table also shows the percentage change caused in unit water costs by varying the various parameters listed, individually, by ± 50% from the value taken for the baseline scenario. Graphs illustrating some of the more interesting results are included and will be referred to in the following sections. Full details are given in **Supporting Document 2.**

9.3 2 Climate

Fig. 9 8 shows the considerable effect of change in the available solar and wind energy. Although the model does not represent these features, it should be noted that an increase in average daily solar irradiation means longer sunshine hours, higher peak irradiance, less interruption from clouds and probably a more even distribution over the year, all of which help to increase the daily system efficiencies of solar water pumps. Even a modest reduction from the baseline value of 5.5 kWh/m^2 to 5 0 kWh/m^2 causes an increase in unit water cost for the systems without distribution from about 20 cents/m^3 to 23 cents/m^3 while at 4.0 kWh/m^2 the cost rises to 30 cents/m^3 The changes for the pipe distribution case will be greater because more energy is consumed.

The proportional effect of changes in average wind speed is even more marked than for solar the change from 2.5 m/s to 1.8 m/s causing the cost to rise from 15 cents/m^3 to 30 cents/m^3

These results serve to remind those responsible for decisions on investment in renewable energy technologies of the great importance of collecting good basic data on these energy resources. Without these data it is virtually impossible to make correct judgements.

9.3.3 Water supply factors

Fig. 9.9 shows the effect of change of per capita water consumption for the central storage - no distribution case. The result is similar to that shown in Fig. 9.3 for an increase in population, because both lead to increases in total volume pumped and some reduction in unit cost of water. For the case of piped distribution, the picture will be similar to the one for increase in

Group		Parameter	Percentage change in unit water cost when value of parameter reduced by 50%					Percentage change in unit water cost when value of parameter increased by 50%				
			Solar	Wind	Diesel Low	Diesel High	Human	Solar	Wind	Diesel Low	Diesel High	Human
A	Climate	Wind Regime		246					-46			
		Solar Regime	110					-27				
B	Water Supply	Per Capita Consumption	17	14	58	37	14	-5	-4	-16	-10	5
		Population Density*	5	8	8	5	0	-2	-3	- 4	-2	0
		Distance to Water Point*	4	7	9	5	0	0	-1	-2	0	0
		Peaking Factor*	-2	-3	-3	-2	-43	3	3	2	2	57
		Storage Tank Capacity	-5	-6	-5	-4	-	3	4	4	3	-
		Component Lifetime	32	20	17	11	15	-7	0	0	-2	0
		Static Lift	-35	-36	-18	-26	-60	35	36	24	28	105
		Subsystem efficiency (3)	23					-14				
		Human power output (4)					61					-57
C	Costs	Capital										
		- well cost	-3	-5	-6	-3	-31	3	4	6	3	31
		- Pumping system cost	-41	-38	-13	-8	- 8	41	37	13	8	9
		- Distribution cost*	-7	-10	-12	-7	-	8	12	13	7	-
		Operating										
		- cost of labour (1)					203					101
		- fuel cost			-16					16		
		Maintenance cost	-2	-2	-9	-9	-10	2	1	8	9	10
D	Economic	Discount Rate (5)	-28	-33	-10	-1	-25	57	67	24	8	51
		Period of analysis (6)	37	46	8	1	33	-2	1	2	3	1
		Shadow exchange rate factor(2)	-21	-56	-24	-17	-75	-14	-38	-16	-11	-50

NOTES Parameters altered by ± 50% except for
(1) for 50% and 100% of full labour costs
(2) for shadow costs factors of 0 5 and 0 75
(3) for 30 and 50%
(4) for 40 & 200W
(5) for 5 & 20%
(6) for 10 & 30 years
* Piped distribution

Table 9.5 Summary of Results of Sensitivity Analysis of Baseline Village Water Supply Scenarios (20 metre lift)

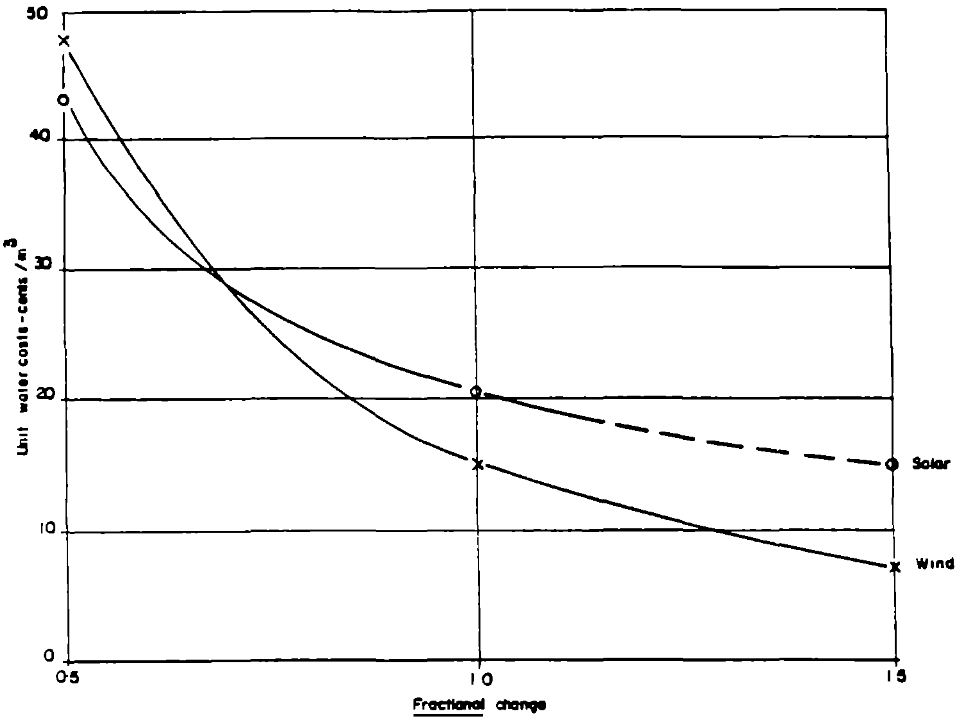


Figure 9.8 Sensitivity to Climatic Conditions
(Baseline village water supply scenario - no distribution)
Base Case: Mean wind speed 2.5m/s, mean daily solar irradiation 5.5 kWh/m^2

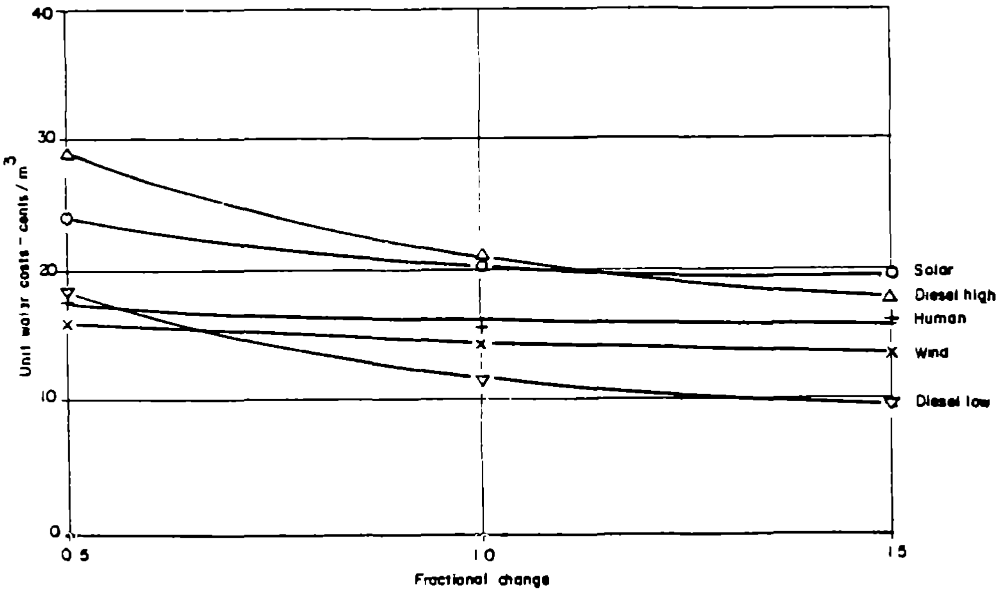


Figure 9.9 Sensitivity to Per Capita Consumption
(Baseline village water supply scenario - no distribution)
Base Case: 40 litres per person per day

population (Fig. 9.4). The slight difference stems from the fact that whereas population growth meant a large village and more flow through longer pipes, increase in per capita consumption means a greater flow through pipes of the same length.

Fig 9.10 demonstrates what happens when population density increases for piped distribution systems (this is not to be confused with increase in per capita consumption). For all systems except handpumps (which are independent of distribution pipes) the unit cost decreases by up to 1.6 cents/m^3 as the population density trebles from 37.5 to 102.5 persons per hectare. This is because for a fixed population the village is smaller, the pipes are shorter and cheaper, and the energy loss in pipe friction is less. The cost of handpumped water stays the same because the number of handpumps is determined by the daily peak demand factor.

The effect of an increase to the maximum distance a villager has to walk to the nearest water point is very similar to population density increases (Fig. 9.10). As the maximum distance increases, the pipe lengths decrease and there is a small decrease in output cost as a result.

Fig 9.11 shows that only the handpumped water costs change appreciably when the daily peaking factor increases in a system with distribution. This is because, once the maximum distance to water point criterion ceases to be limiting, the number of handpumps is directly linked to the demand factor, so as to ensure that the necessary volume of water can be provided in the peak hour. The effect on the other systems is limited to the consequences of pumping a larger flow during the peak demand hour. As usual the installed power and cost of the renewable energy systems increases a little, while the diesel system simply consumes more fuel.

Fig. 9.12 demonstrates the importance of PV subsystem daily efficiency as it varies from its assumed value of 40% over the range from 30% (the minimum which should accepted) to 50% (which is assumed to be achievable in the target case). Over the range of subsystem efficiencies examined, the delivered cost of water falls from 25 to 18 cents/m^3 a change of 34% of the value at 40% efficiency. Subsystem efficiency is important because it directly determines the actual volume pumped each day and consistently good subsystem efficiency will have a beneficial effect on every scenario in which solar systems are used. In these studies, it was not possible to model the relation between efficiency and lift and the consequences of this link should be examined in further work.

Fig. 9.13 illustrates the dramatic effect on the costs of water delivered by human powered pumps of increases in the power which can be applied by the operator from 60W to 200W In the majority of village situations the pump will be operated separately by each of the people needing water who may be expected (for the short durations involved) to work at considerably greater power outputs than those assumed for day long irrigation applications. The pump power input of 60 W assumed for the baseline studies corresponds to the long term output sustainable from an adult and for durations as short as 2 minutes, 200W is feasible from a male operator (Ref 13). Of course women and children do a lot of the pumping for domestic purposes and their outputs will not reach these levels. As the power applied increases the daily peaking factor criterion becomes less limiting, fewer pumps and boreholes are needed (because their output is greater) and so the output costs reduce very significantly from 15 to 7 cents/m^3. The curve flattens at the end because the maximum distance criteria becomes limiting and further increases in power do not lead to reductions in numbers of handpumps. The proportional reduction would have been even greater if the value of labour had been included.

Fig 9.14 demonstrates the great importance of static lift. The output cost of all systems increases significantly, but none more so than handpumps whose output water cost increases from 6.0 cents/m^3 at 10m to 32 cents/m^3 at 30m. This is because at the baseline power input of 60W the human power output is very limited and, as the delivery flow rate drops, the number

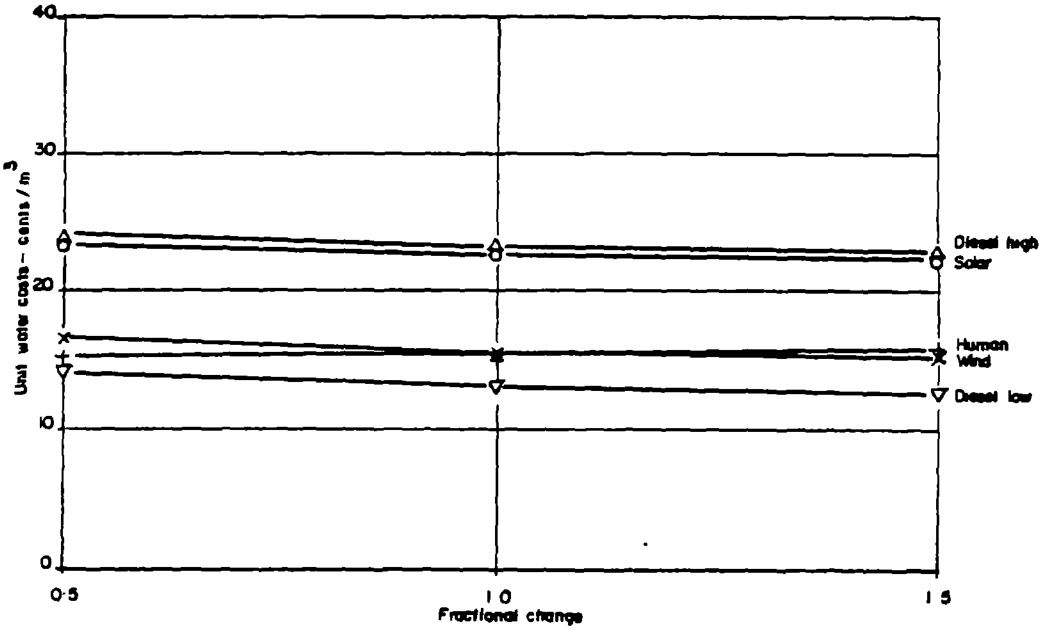


Figure 9.10 Sensitivity to Population Density (Baseline village water supply scenario - with piped distribution)
Base Case: 75 people per hectare

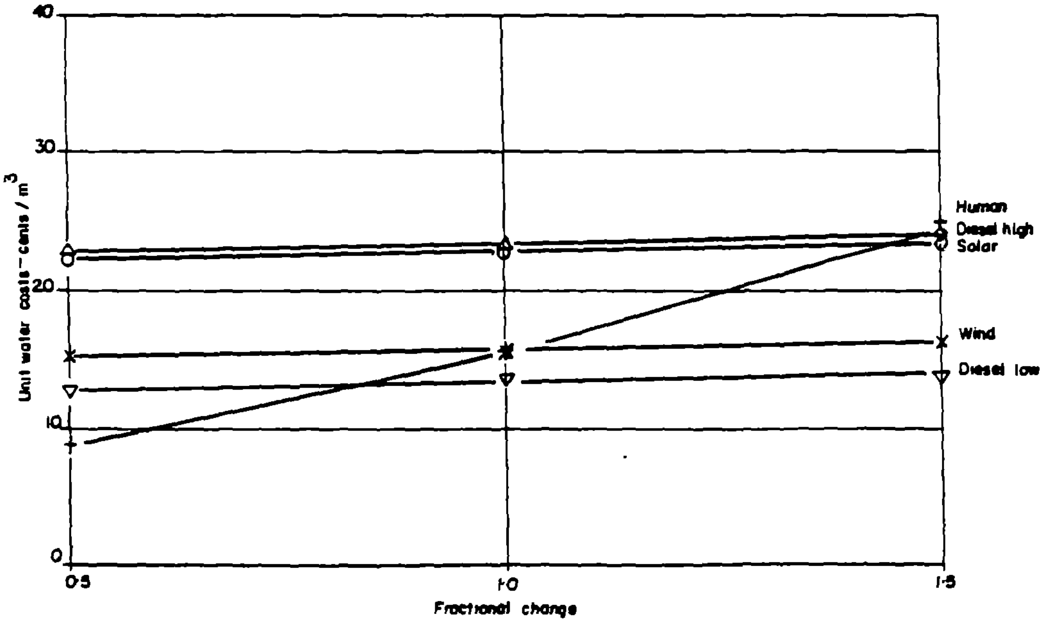


Figure 9.11 Sensitivity to Daily Peaking Factor (Baseline village water supply scenario - with piped distribution)
Base Case: Peaking factor 15%

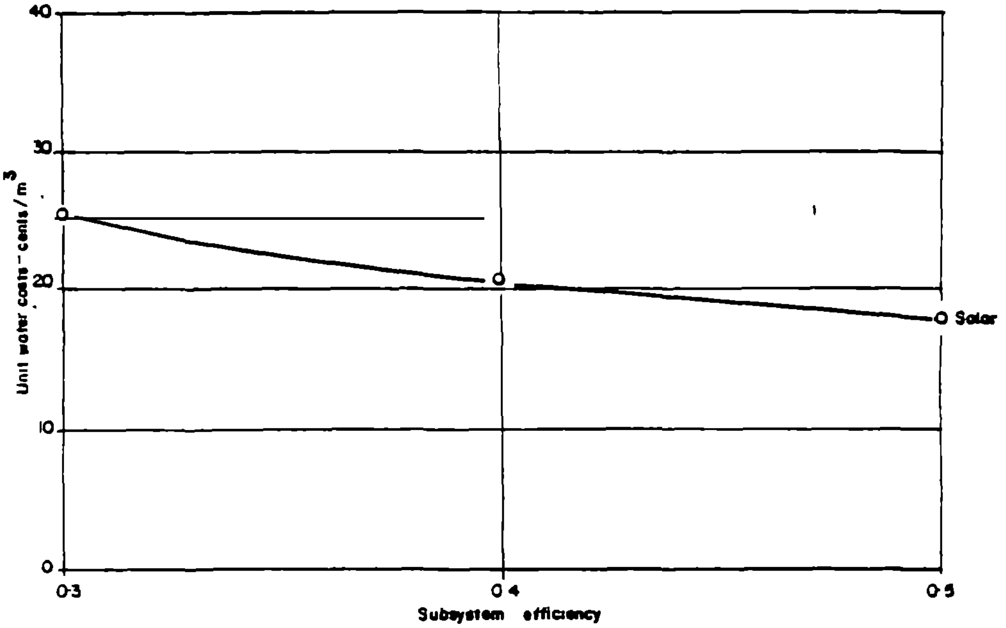


Figure 9.12 Sensitivity of PV Subsystem Efficiency (Baseline village water supply scenario - no distribution)
Base Case: Subsystem efficiency 40%

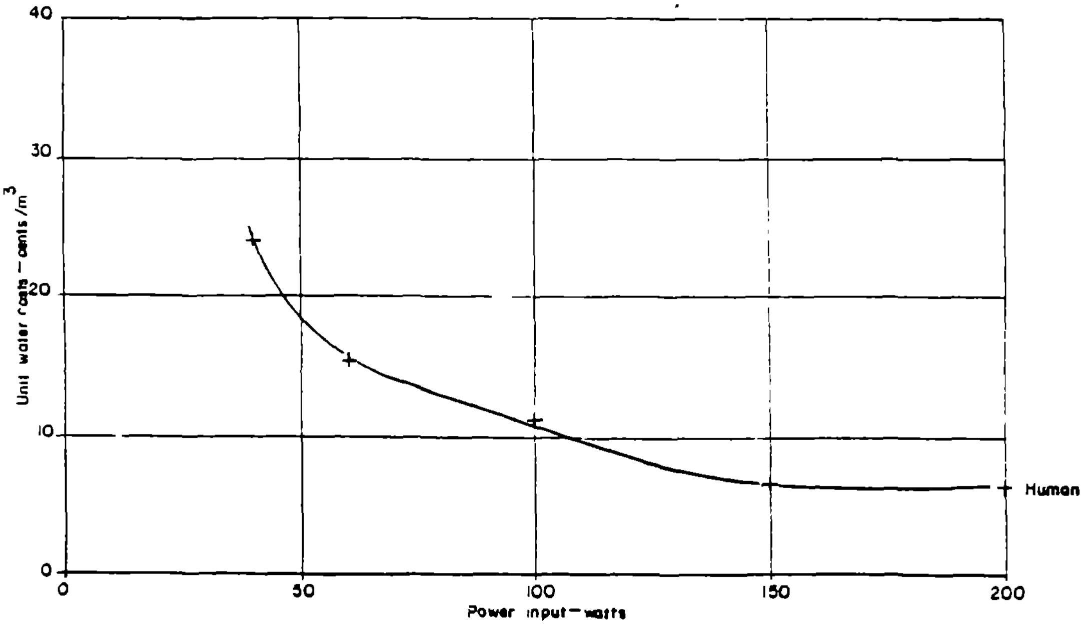


Figure 9.13 Sensitivity to Power Applied to Handpumps (Baseline scenario)
Base Case: Power input 60W (efficiency assumed at 60%)

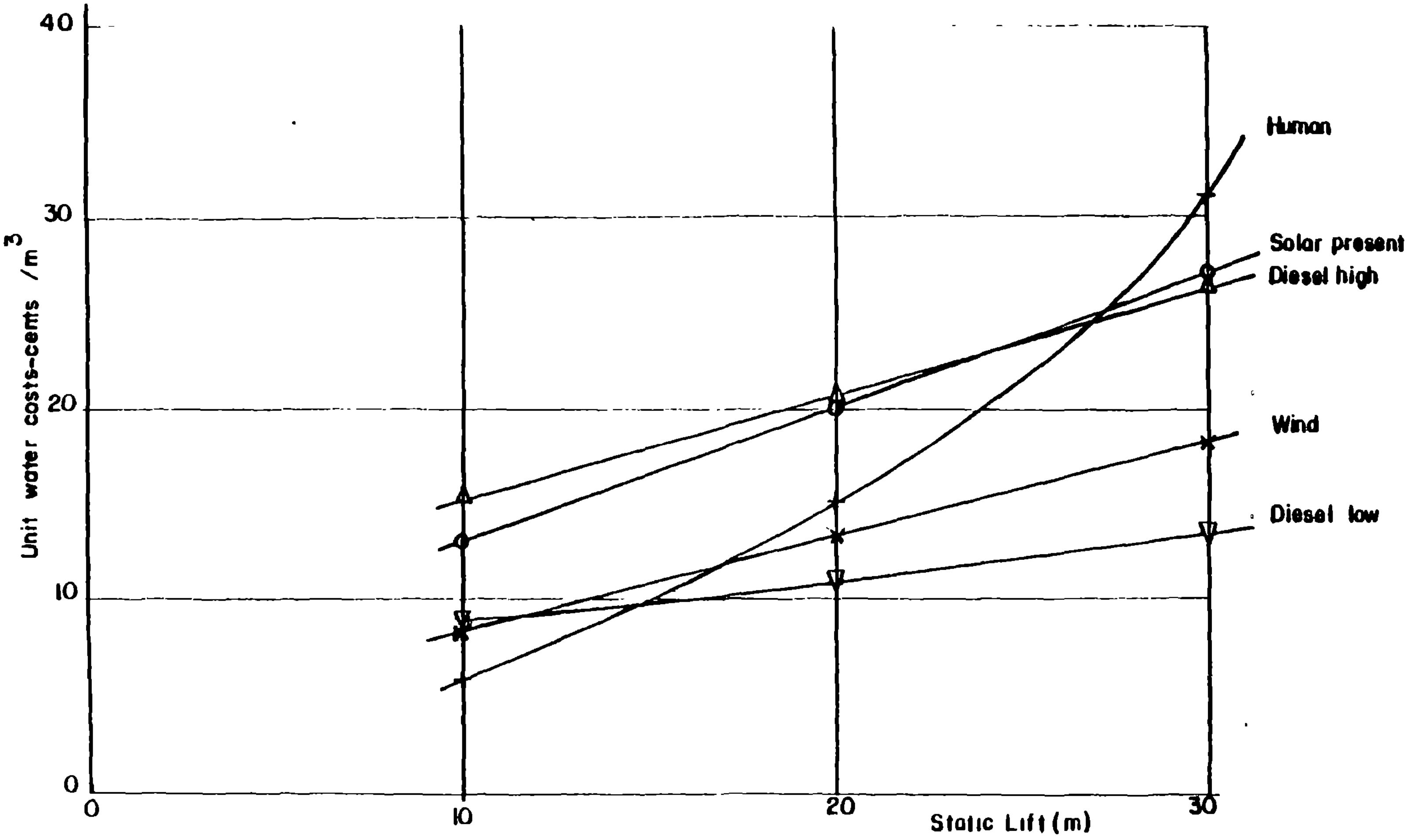


Figure 9.14 Effect on Static Lift on Cost of Water for Village Water Supplies
(Baseline scenario - population 750 - no distribution)

of handpumps has to be increased to meet the peak flow requirement: each handpump needs a borehole and this forms a larger proportion of cost as the static lift increases. It may well be impractical to consider handpumping through static lifts of much more than 30m but, even if that were not a restriction handpumps lose their position as the cheapest option for lifts in excess of 15m. This is with zero value for time spent pumping; the inclusion of a wage would make handpumps totally uneconomic at these high heads. High case diesel output costs match solar closely over the whole range of lift from 10 to 30m. Wind is similar to low case diesel at a lift of 10m (output cost is 10 cents/m^3) but increases more as the lift increases until at 30m, and output costs at around 17 cents/m^3 are 4 cents/m^3 more than low case diesel. Diesel high case costs increase more than diesel low, basically because part of the increase in cost comes from increases in fuel consumed in pumping at greater power outputs for longer periods. These remarks apply to the no distribution case, but the case with piped distribution will be similar.

Changes in the capacity of the storage tank by ± 50% only change the output cost by ± 6% and this has implications from the point of view of reliability, particularly for the renewable systems.

Changes in component lifetimes showed that there was significant increase in cost only when the lives of solar pumps were reduced below the baseline maximum values (array 15 years; motor/pump 10 years).

In summary, for all the mechanised systems for a given population the most important variable is static lift; with per capita consumption influencing the renewables and diesel but population density, daily peaking factor and maximum distance to nearest water point producing only very small changes. PV subsystem efficiency is important for solar pumps. Low case diesel is the cheapest of the present systems over the entire range of lift (apart from handpumps for less than 15m). Human powered pump output costs are most influenced by static lift, daily peaking factor and power applied.

9.3.4 Costs

Fig 9.15 shows the effect of changes in the capital cost of the pumping systems for the baseline static lift of 20m. As with the irrigation studies, the greatest response was from the capital intensive renewable energy systems. A 50% reduction in these capital costs yielded output costs for solar which were about 3 cents/m^3 more than low case diesel and for wind about 2 cents/m^3 less than low case diesel.

Fig 9.16 shows the effect of allocating a cost to the time spent hand- pumping. The increase in output cost is dramatic, from 15 cents/m^3 when the wage rate is nil to 31 cents/m^3 when the wage is $0.5/hour. It is clear that all the previous comparisons will be invalidated should those who spend time pumping be reimbursed. For baseline conditions, handpump output costs will equal those of solar and high case diesel (at 22 cents/m^3) if the daily wage rate is around $0.22.

Fig. 9.17 compares the output costs of 'Present', 'Target' and 'Potential' costs (see Section 5.3.7 and Tables 5.5 and 8.4) with the other systems over a range of lifts. The 'Target' case solar system would provide water as cheaply as low case diesel and more cheaply than all than other mechanised systems for heads in the 10-30m, range and cheaper then the handpumps above a head of about 12m. The output cost varies from about 7 cents/m^3 at 10m lift to 14 cents/m^2 at 30m lift. As discussed in Section 8.3.4, the achievement of Target case solar system capital costs are largely dependent on reductions in the costs of PV modules to around $5/Wp array output (from around $10/Wp at present) and improvements in subsystem efficiency. It is anticipated that these price levels will be attained within 5 years. 'Potential' case solar water

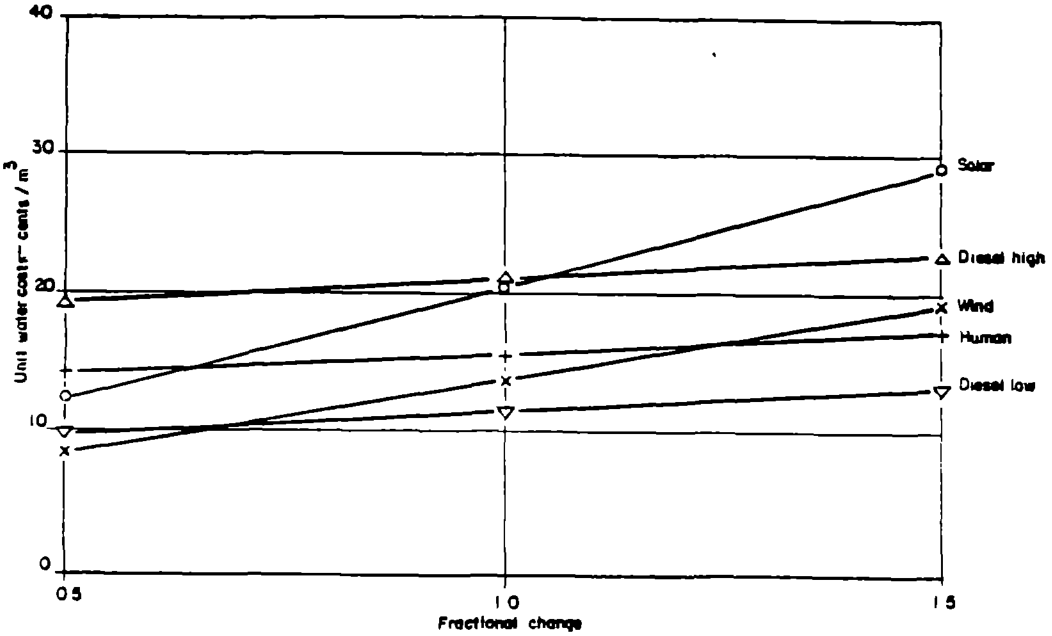


Figure 9.15 Sensitivity to Pumping System Capital Cost
(Baseline village water supply scenario - no distribution)
Base Case: See Table 9.3

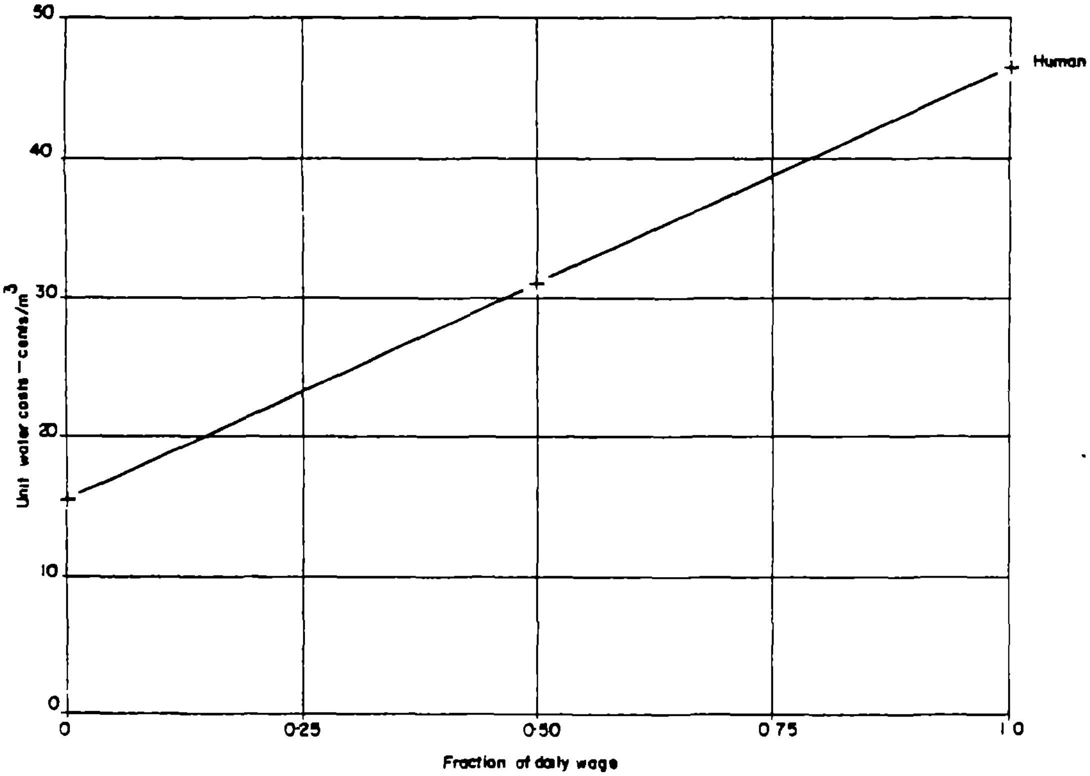


Figure 9.16 Effect of the Value of Human Time on Cost of Water for Village Water Supplies
(Baseline village water supply scenario - no distribution)
Base Case: Wage $ 1 per day

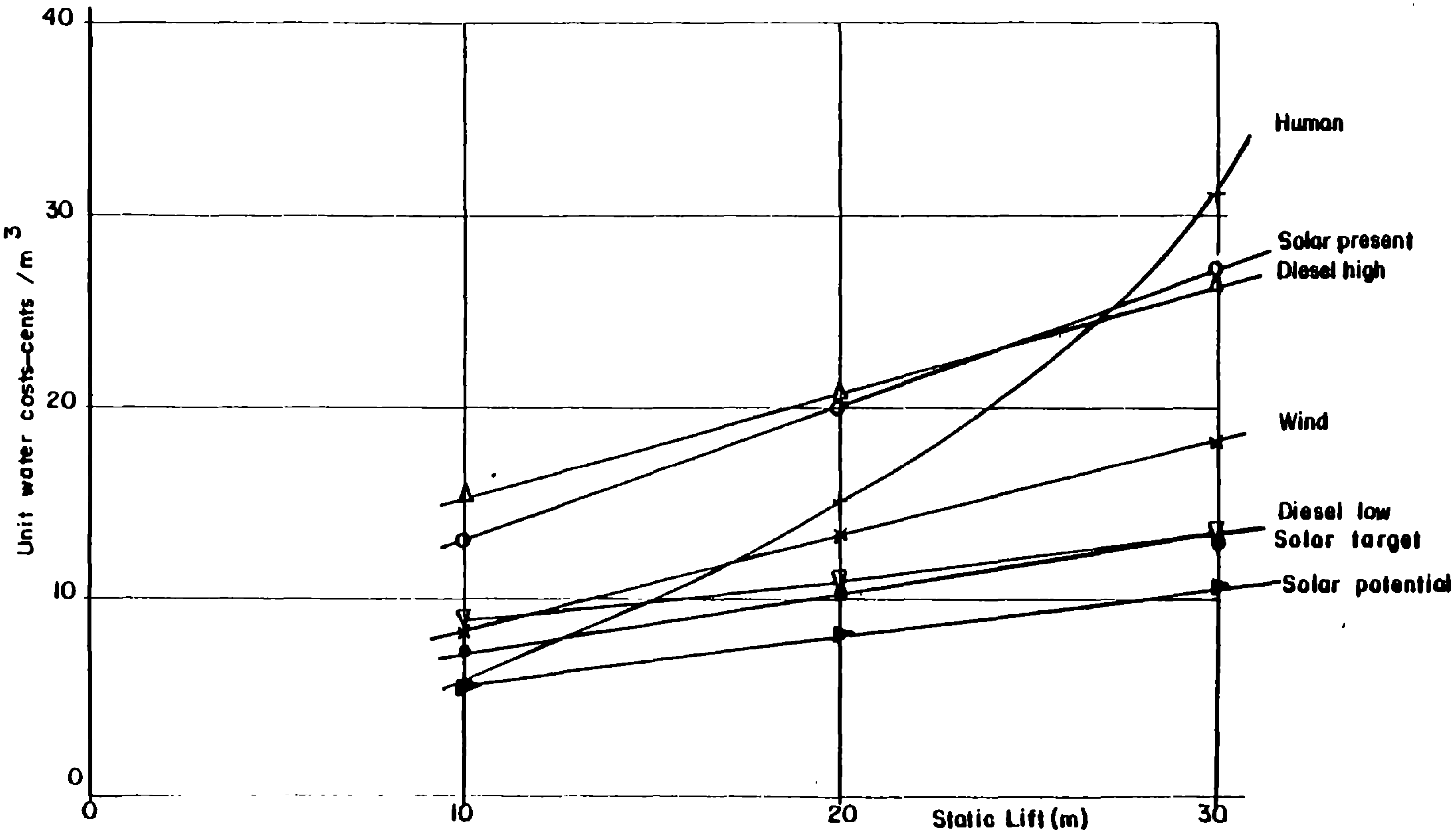


Figure 9.17 Effect of Reduced PV Solar Pumping System Capital Costs in Comparison with Alternatives (Baseline village water supply scenario - no distribution)

pumps can deliver water more economically than any other method over the full range of static lift from 10 to 30m, but as this depends on modules being available for $2/Wp it is only possible to conjecture that state of affairs will be reached in the period 1993 - 1998.

As expected, changes in the costs of boreholes affected only the handpump option, because only with handpumps does the number increase with population served. Maintenance costs were also varied but, as maintenance did not account for a large proportion of the total cost, the overall effect of the changes appeared small. Handpump projects have run into difficulties because of maintenance problems and this point warrants more detailed study.

More extensive or complicated distribution systems may have a greater proportion of their costs tied up in pipework and in such situations changes to factors like maximum distance to water point may well influence output water cost more than was evident in these studies.

In summary, the most significant changes are produced by reductions in the capital cost of the renewable energy systems: whereas it is hard to see how this could happen for wind pumps, there is a reasonable prospect of this in the case of solar pumps. When Target case solar pumps are available, they will be competitive with low case diesel. Handpumps are competitive only for 10m lift and even without a charge allocated to the time spent pumping are not competitive with any of the mechanised systems under any of the conditions studied.

9.3.5 Economic factors

The effect of discount rate on unit water cost for the no distribution case is shown in Fig. 9 18. The same general remarks apply as were made for the corresponding irrigation analysis - high discount rates favour the lower capital cost - higher recurrent cost systems since future recurrent costs are heavily discounted, and vice versa.

The figure demonstrates that for the input data used in the analysis, solar pumps are more economic than high case diesel for discount rates less than about 10% (it is a coincidence that this is the baseline value). The crossover discount rate is higher than for the irrigation application (6.0) because, although the proportion of recurrent expenditure in the case of the solar water supply system actually reduces slightly compared with the irrigation application, the decrease of recurrent expenditure in the case of diesel engine systems is proportionately more than in the case of solar ie relative to diesel, a larger proportion of the total cost of solar water supply systems originates in recurrent expenditure.

The period of analysis was also investigated and this confirmed that at a discount rate of 10% there was little difference in unit water costs for periods in excess of 30 years and that 20 years could be adopted with little loss of accuracy.

9.4 Country Specific Case Studies

9.4.1 Procedure

Case studies of the village and livestock water supply applications were carried out for Bangladesh, Kenya and Thailand. While the meteorological and cost data were the same as for the irrigation studies the water supply data were obtained through the use of questionnaires especially prepared for the Project. The cost factors are given in Appendix 3. the solar and wind energy inputs are included in Figs 8.16, 8.17 and 8.18.

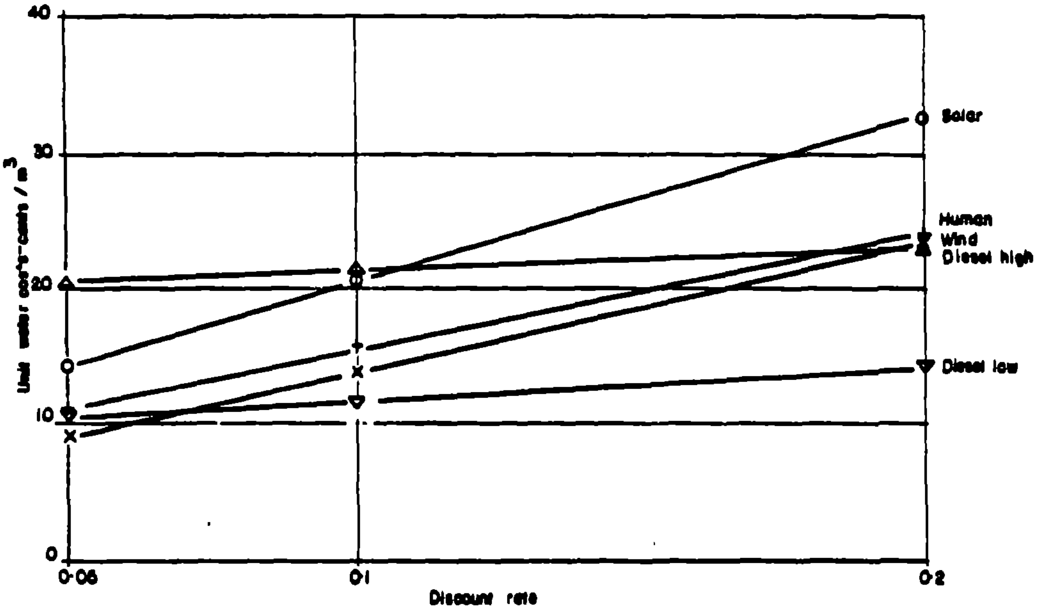


Figure 9.18 Effect of Discount Rate
(Baseline village water supply scenario - no distribution)
Base Case: Discount rate 10%

The general technical characteristics of the water supply systems used in the baseline studies (see Table 9.1) were adopted for the country studies, except where local data superseded the more general values. The pump characteristics were as given in Table 8.2.

The computer based mathematical models were run exactly as for the baseline analyses: for the village case the populations ranged from 375 to 1500, with per capita consumption of 40 litres/day, and a static lift of 20m; for livestock, the number of cattle ranged from 1000 to 4000, the consumption was 40 litres/head/day and the static lift was 20m.

9.4.2 Results for the village and livestock applications

The results have been summarised for comparison into two histograms: in Fig. 9.19 the output costs for village water supply have been plotted for a village population of 750 while in Fig 9.20 the output costs for livestock water supply have been plotted for 2000 head of cattle. Each histogram shows output costs for conditions in Bangladesh, Kenya and Thailand and also the international norms.

9.4.3 Discussion of results

The main cost trends, for systems with and without piped distribution, are similar to those obtained in the baseline studies, the main differences being in the output costs of the various alternatives. Some of the general reasons for the variations in costs between countries for irrigation water, set out in Section 8.4.3, equally apply for water supply costs. There are other factors however, like the larger static lift, the evenness of demand over the year and the greater importance of borehole cost which distinguish the water supply application and justify emphasising the salient points below in connection with village supplies:

o in contrast to irrigation, the water supply demand does not vary through the year, and this makes conditions in Bangladesh somewhat more favourable for water supply solar pumps than they are for irrigation solar pumps.

o boreholes are expensive to drill in Thailand and cheap in Bangladesh, which accounts for the difference in handpumped water costs between these countries. Handpumped water and low case diesel in Bangladesh are the cheapest of all the options examined (7.1 cents/m^3 and 6.4 cents/m^3 respectively) whereas the output cost of handpumped water in Thailand is among the most expensive of all the options examined. All handpumped water costs are very sensitive to the cost of labour and if only $0.5/day is charged to this task, the output cost of water increases by about 15 cents/m^3, with the result that the total cost of water is then as high as any other method.

o wind pumped water is generally competitive in comparison with low case diesel apart from Bangladesh where (on the basis of the data obtained for the study) the wind regime is not good enough for the method to be viable. It is about half the cost of handpumped water in Thailand, and the same cost in Kenya.

o wind pumped water in Thailand is under one third the cost of solar pumped water and in Kenya it is about 60% of the cost of solar. Wind pumps are particularly cheap in Thailand, although it is was not possible to check whether this was at the expense of reliability. However, it has to be remembered that solar is generally a more predictable source of power then wind, and that there are regions in Thailand where wind is not viable.

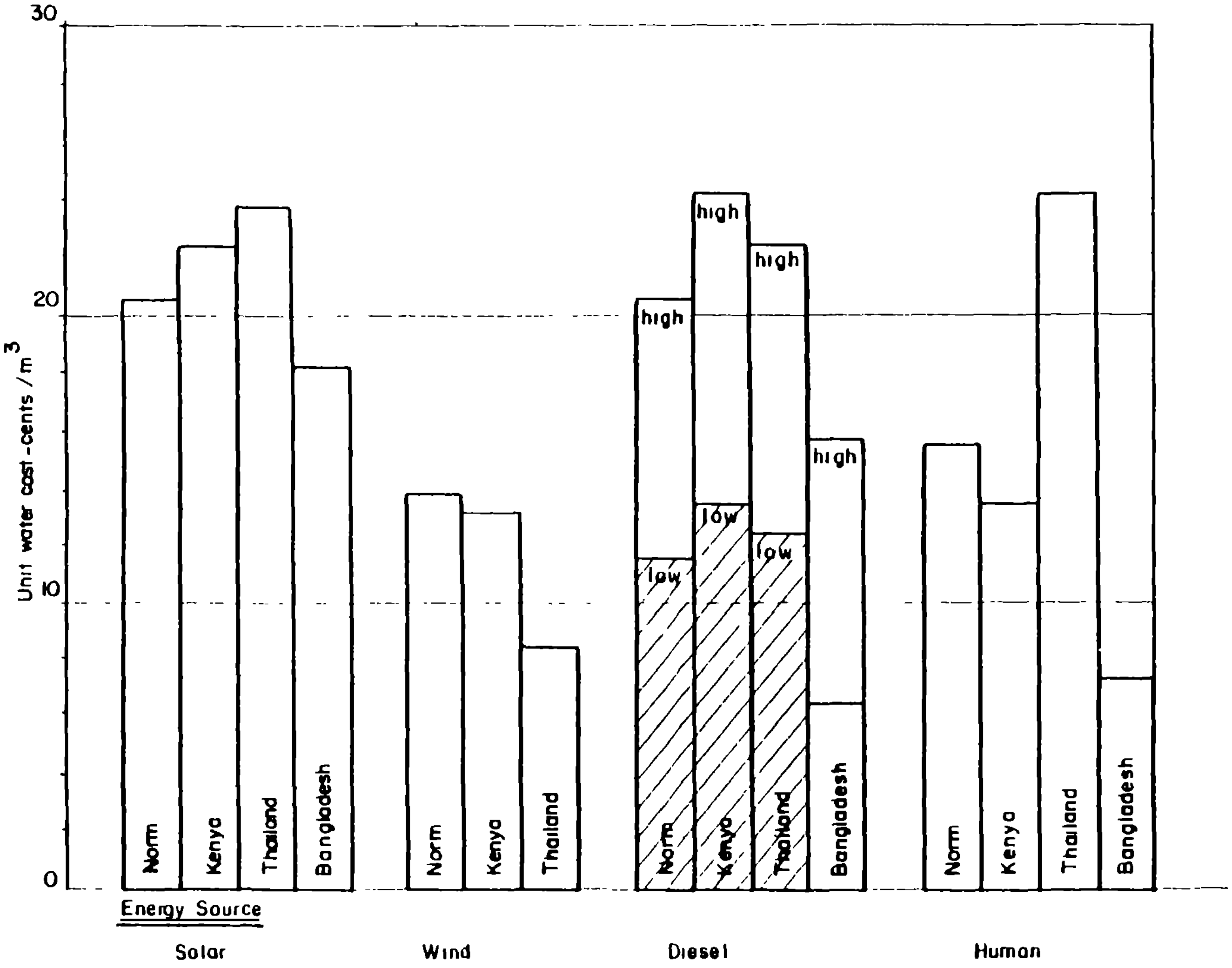


Figure 9.19 Histogram showing village water costs for alternative pumping methods
Village population 750, per capita consumption 40 litres/day, 20 metre lift

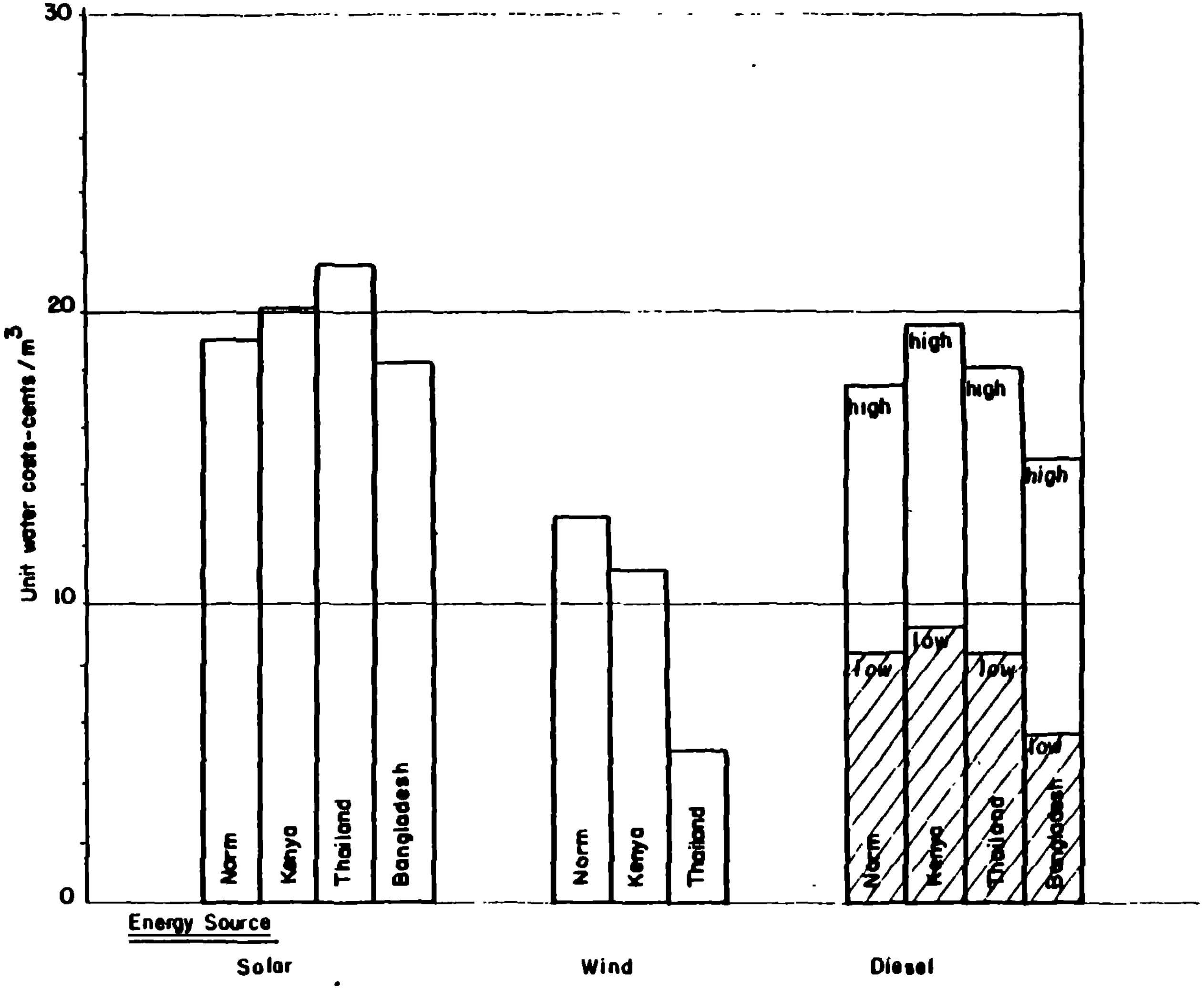


Figure 9.20 Histogram showing livestock water costs for alternative pumping methods 2000 head of cattle, consumption 40 litre/head/day, 20 metre lift

- diesel pumped water is cheaper is Bangladesh than Kenya mainly because engines are subsidised in the former country and taxed in the latter.

- solar pumped water is comparable with high case diesel in Kenya and Thailand. In very remote locations in these countries, where the real costs of diesel may approximate to the high case used in these studies, solar would be competitive, provided wind was not an option. In Bangladesh solar is around 2 cents/m^3 more expensive then high case diesel. The inherently better reliability of solar pumps may give them the edge over diesel, even at present prices.

- although the differences between solar irradiation in the least sunny months naturally affect the output costs, it is not the only factor as is evidenced by Thailand (with minimum monthly mean daily irradiation of 15.2MJ/m^2) being more expensive than Bangladesh (with 13.9 MJ/m^2). Costs of boreholes and tanks also influence the result.

In general the costs of water pumped for livestock follow the same trends as for village supply without piped distribution. However, because a greater daily volume is pumped the unit cost of water is 2 to 4 cents/m^3 less overall , and wind pumps increase their competitive edge slightly.

It should be noted that the exchange rates of the countries considered do not necessarily reflect the economic value of the currency in which their cost parameters were expressed. The facilities in the model for the calculation of local cost and use of the shadow exchange rate factor were not utilised in these initial studies and in further work costs should be shadow priced.

In summary, of the mechanised systems wind (where its use is practicable) pumps water for less than low case diesel or solar at present price levels. Solar falls between the low and high case diesel options but may be preferred if problems have been experienced over reliabilty and fuel supplies. The competitiveness of hand pumps depends very much on whether labour is 'free' or not. When solar pumps are available at target costs and efficiencies they will be cheaper than wind pumps and directly competitive with low case diesel and hand pumps. It should be stressed that conditions within these countries vary from one region to another and the characteristics of each need to be examined in more detail before an investment decision is made.

10. CONCLUSIONS AND RECOMMENDATIONS

This concluding Chapter to Part C of the Report is in three main sections: the first (10.1) summarises the conclusions from the economic evaluations reported in some detail in Chapters 8 and 9; the second (10.2) provides a general discussion and review of the context in which work has been carried out; while the third (10.3) gives some recommendations for future work.

It is difficult to encapsulate a multidimensional picture in a few words or graphs. It must be remembered that the graphs show the dependence of unit water cost on only one other variable at a time, with all the remaining technical and cost parameters being fixed. Care is therefore needed to appreciate the full implications of variations in the many parameters which contribute to the unit water cost.

10.1 Conclusions

10.1.1 Irrigation studies

Some of the key conclusions indicated by this study, on the basis of both the generalised base-line irrigation scenarios and the country-specific case studies, were:

o Solar pumping systems have an optimum capacity which depends on a number of factors including static head but for heads in the 2m to 7m range studied their output costs are lowest for irrigation areas of around 1 ha; the costs of water supplied by the smallest diesel pumps on the other hand decrease for areas up to around 4 hectares and are relatively constant thereafter. The presence of the minima in the unit cost curves is probably chiefly because of the effect of the fixed diameter pipes and fixed gradient open channels on the pumping head.

o The output costs of solar pumping systems used on a "stand-alone" basis are sensitive to the peak-demand factor, the size of pipes (or channels) used to convey the water to and in the field, and the field application efficiency. This is because any increase in water demand is reflected in the capacity of a solar pumping system and its capital cost, whereas with a diesel pump the increase in demand is reflected in higher fuel costs, the future effect of which on unit output water cost is discounted. Thus solar pumps are best used in situations offering little variation between the peak (design) demand requirement and the average annual requirement, where farming practices are good and water is carefully used.

Ways to deal with the peaking problem require more study - if the marginal value of human labour was low it might be possible to supplement the outputs of a solar pump at times of peak demand by the conjunctive use of handpumps.

o For static lifts greater than 2m solar pump system output costs are almost linearly related to pumping head: therefore as input costs come down, so the lift which can be pumped competitively increases. On the basis of 'Present' costs, solar pumping systems without storage and using either pipes or channels for distribution deliver water to the crop for around 10 cents/m^3 at 2m lift, but as the lift increases the systems with piped distribution become progressively more competitive than those with channels (because of the cost of pumping water lost by seepage). At 20m lift the delivered cost of water by a system with channel distribution is around 30 cents/m^3. Thus solar systems can just meet the general norm for economic cost of water delivered of 10 cents/m^3, at a 2m lift.

For the solar 'Target' case, channel distribution systems are cheaper than piped ones at 2m lift, the output costs being around 5 cents/m^3 and 9 cents/m^3 respectively: at 20m lift the positions have reversed and the output costs are 19 cents/m^3 and 18 cents/m^3. 'Target' case solar channel systems would be able to meet the global 10 cents/m^3 criterion for heads up to 9m.

For the 'Potential' case, solar channel systems deliver water more cheaply than piped systems over the range of lift from 2m to 20m, and could deliver water for costs within the economic norm of 10 cents/m^3 for heads up to around 14m.

- The storage of up to one days supply of water increases the output costs by around 3 to 7 cents/m^3, depending on head, and so solar pumping systems will find their first major applications where storage is not necessary. Lined and unlined channels were also investigated: their selection will depend on the relative costs in different countries. For the cases studied the output costs of systems with lined channels were marginally cheaper than unlined ones because of the savings in pump cost due to the smaller water loss.

- The high case diesel studied delivered water at a cost of cent or two less than the 'Present' case solar system with piped distribution at 2m lift: as the lift increased the difference grew to about 4 cents/m^3. At low heads these differences are hardly significant and would be reversed if the costs of attendance on the diesel engine were included. The 'Target' case solar systems delivered water throughout the range of lifts considered for costs around 5 cents/m^3 more than the low case diesel studied and up to 8 cents/m^3 less than the high case diesel, while for the 'Potential' case the costs were virtually identical with low case diesel. It is interesting to note that the relative competitiveness of solar (for the 'Target' and 'Potential' cases) and low case diesel does not alter with increase in lift over the range studied. It should not be assumed that because these relations were more or less linear from 2m to 20m lift, the relative cost will remain unchanged at much higher levels.

  Costs of attendance were not allocated to the diesel cases studied because the need for this in the irrigation context may differ widely from country to country, and in many locations the farmers themselves would carry out daily tasks. However, bearing in mind that properly costed attendance could normally be expected to add a few cents to the cost of water delivered and that most diesel engine systems will be operating under conditions which approximate more to the high case studied than the low, it may be concluded that within 5 years 'Target' case solar powered irrigation systems with channel distribution will be the economically preferred option in circumstances similar to the scenarios studied and will have a wide application.

- Windspeeds of around 2.5 m/s in the critical month represent an approximate breakeven requirement for windpumps compared with solar pumps. Windpumped water costs fall between the high and low case diesel values and are competitive with solar 'target' and animal power for lifts up to around 5m. Higher windspeeds will tend to favour windpumps as against solar pumps and vice-versa. Solar pumps are less sensitive to local site-specific variations than windpumps and are therefore more easily sized and sited.

- The relative cost effectiveness of handpumps depends on the static lift, the cost of boreholes and the value assigned to the time spent pumping.

  For the baseline case where operator cost was taken as $1 per day the output cost for a lift of 2m was around 12 cents/m^3 higher then any other system except solar with storage. Handpumps output costs do not become comparable with wind, low-case diesel and animal systems at 2m lift until the daily cost of the time falls to around $0.1 per day. At higher heads the position becomes even worse for handpumps: at a daily wage of \$1 per day the output cost is around 28 cents/m^3 and even if zero value is assigned to labour, an output cost of 15 cents/m^3 makes them uneconomic compared to wind, diesel, and animal pumps.

These results would suggest that even at low heads. the competitiveness of hand pumps may be marginal and will need to be carefully analysed, while at high heads they are simply uneconomic.

- Animal pumps appear a low cost option on the basis of the assumptions used: however, they are generally not used in the three countries selected for special study and in fact the trend has been for them to be replaced with engines in countries where they are used. These results would suggest that the role of animal power ought to be critically reassessed.

- Case studies based on data, collected specially from Bangladesh, Kenya and Thailand and using sample cropping patterns and their associated irrigation requirements showed Kenya had more favourable conditions for solar pumps because the region studied there has a more consistent irrigation water demand: the peak demand factor was much more favourable (at 1.76) than for Bangladesh (6.02).

  The unit water costs for the Kenyan conditions were about 8 cents/m^3 at a lift of 2m and nearly 16 cents/m^3 at a lift of 7m. Bangladesh has a lower average annual solar energy input than Kenya (15.7 MJ/m^2.d compared with 21.8 MJ/m^2.d) and this, coupled with the adverse peak monthly demand factor and the relatively lower costs of diesel, means that Bangladesh is not well suited to solar pumping for its rice based irrigation demand. In Thailand, the costs of solar pumped water (11 cents/m^3) are a little less than for high case diesel at 2m lift but at 7m lift have increased to about 22 cents/m^3, about 5 cents/m^3 more than high case diesel: as the costs of solar water pumps falls, they will progressively become competitive at higher heads and when they are at 50% of their current levels they will be competitive with low case diesel at 7m lift.

- The output water costs are critically dependent on the particular conditions for which solar pumps are being considered. For irrigation, the technical factors which have greatest effect are the area irrigated, the peak monthly demand factor, renewable energy available in critical month, subsystem efficiency, hydraulic efficiency of conveyance system, field application efficiency and static lift. Important cost parameters were capital costs of renewable energy systems, recurrent cost of diesels, wage cost of labour and discount rate. Component lives become of greater importance when they are less than the maximum values set for the baseline scenarios.

10.1.2 Rural water supply studies

Some of the key conclusions indicated by this study, on the basis of both the generalised base-line water supply scenarios and the country-specific case studies, were:

- At 20m lift (the baseline case) solar pumps can deliver water to a population of 750 people for around 22 cents/m^3 with piped distribution and 20 cents/m^3 with no distribution. These costs are well under the prices at which many people buy water from water sellers (which can be in excess of three dollars per cubic metre). Under the conditions of the base-line model solar pumps are more expensive than wind (at 14 cents/m^3)

and comparable with high case diesel pumps. The main factor against wind is that it has to blow consistently at more than around 2.5 m/s on average to pump economically and this can be severely limiting. After attendance costs are taken into account the real cost of diesel pumped water may well be more than solar, and the operational advantages of solar systems may well make them the most attractive option.

o At static lifts of around 20m handpumps produce water at a unit cost of 15 cents/m^3 comparable to windpumps provided they function reliably and that human energy requirements are regarded as being at no cost to those who use the water. However, even a low daily cost of US$0.25 assigned to human time, increases the cost of handpump water from around 15 cents/m^3 to about 23 cents/m^3 when it is as expensive as either high case diesel or solar pumped water.

Handpumped water is cheaper than low case diesel for heads less than about 15m. At greater heads the cost of handpumped water becomes progressively more expensive because the delivery drops and more boreholes are needed. Indeed, above 30m handpumps become less and less feasible due to the levels of physical exertion required. However, against this has to be set the dramatic effect of increase in human power input - an increase from 60W to 150W (possible for 2 minutes duration) reduces the output costs from 15 cents/m^3 to around 7 cents/m^3.

o When the installed capital cost of solar pumping systems falls to 'Target' levels (thought likely by 1987) solar pumps will provide water more cheaply than any other alternative studied for a lift of 20m, at an output cost of about 11 cents/m^3. Only handpumps deliver water more cheaply for lifts less than about 12m.

o In Bangladesh, for the baseline conditions, handpumps were the least cost option, in Kenya they were comparable to wind, but in Thailand the high cost of boreholes meant that handpumps were the most expensive option of all. It is important to note that this conclusion is head dependent.

o Windpumps come out generally as the least cost option by some margin under the conditions considered for livestock water supplies in Kenya and Thailand, but lack of wind appears to rule out windpumps in Bangladesh. Solar pumps, even at present prices, are competitive with the high-case diesel scenarios for both Kenya and Thailand and will become progressively more competitive as solar pumps move towards the target case expected within five years. Subsidised diesel is the most competitive option in Bangladesh.

o The total system head should be minimised for all pumping methods, low aspect storage tanks should be used and the pipe delivery system properly designed. With distribution systems the distribution pipe- work must be of adequate size and minimum length pipe runs should be used.

o The output water cost are critically dependent on the particular conditions for which solar pumps are being considered. For rural water supply the technical factors which have greatest effect on the cost of the mechanised systems are population served (particularly below around 500), renewable energy available in critical month, per capita consumption, and static lift. All input costs of course have a direct effect but particularly important were the capital costs of the renewable energy systems, the recurrent costs of the diesels and the discount rate. In the case of handpumps, population served, peaking factor, power input and static lift were important, while on the cost side the wage cost of labour would be predominant if included in the analysis. Component lives only become important when they are less than the maximum values set for the baseline scenarios.

10.1.3 Summary

This study has confirmed the importance of studying small pumping systems comparatively in the context in which it is proposed to use them. The costs and efficiencies of the different infrastructural elements make a significant difference to the output water costs and it is very misleading to quote output costs based on a consideration of the pumping system alone.

This study has shown that, even at 'present' photovoltaic array costs, solar pumps can lift water at a cost that is competitive with the primary alternatives - given suitable conditions such as a favourable solar irradiation regime, a steady demand for water all the year round and (for irrigation) low pumping heads (2m for baseline conditions).

It can reasonably be anticipated that for the target case as designs mature, production levels increase and array costs fall, solar pumps will become more widely applicable than at present: notably it will be possible to use them cost-effectively at higher pumping heads.

Within five years, relative costs should have changed to the extent that solar water pumps should always be among the serious options to be evaluated for small-scale applications. However, there will always be a continuing need to apply them under adequately favourable conditions, to size them properly and to operate them in an appropriate manner.

10.2 General Discussion

The study described in the previous two chapters is believed to be almost unique in having sought to establish the relative cost-effectiveness of a range of small-scale pumping technologies in the context of three selected countries as well as on a more generalised economic basis. Very little previous work of this kind has been reported and it is considered that it provides some of the best indications yet available of the technical and economic circumstances in which commonly used small-scale irrigation and water supply pumping systems - not only solar - are viable. Even so, it is important that this study should be regarded as pioneering and indicative, rather than definitive: there is a continuing need for more detailed assessments of this kind to proceed in parallel with the intensive technical developments currently in hand. Naturally the results presented depend on the performance and cost data assumptions incorporated into the model or input for the purpose of these analyses.

A special feature of this work was the use of purpose collected data and the care taken to model the irrigation and water supply systems in technical and economic detail. They are believed to be valid within the context of these assumptions used, but need to be interpreted with care for conditions outside these assumptions.

Therefore the conclusions outlined in Section 10.1 should be read and applied with the following important points in mind:

- The availability of authentic and reliable cost data for small-scale water lifting systems, both new and traditional, is extremely limited and therefore some uncertainty remains over many of the assumptions. It is hoped that publication of this Report will stimulate work to improve, refine and extend the data base. The recommendations that follow (section 10.3) suggest areas where further work is needed to improve the quality of these types of analysis.
- This work has presented the unit water output costs of the systems evaluated as the criterion for ranking and judging systems. It is the first criterion to be considered but for

systems with similar unit output costs other considerations such as affordability, the availability of funds to arrange credit, foreign currency requirements, maintenance and support service offered plus technical, social and operational considerations could effect the ranking.

- The numbers used for many parameters in this study represented individual "informed estimates"of a typical value selected within a range that occurs in practice. The one exception was with diesel systems where two groups of values representing the 'low' case (or best to be expected under good operating conditions) and the 'high' case (or realistic output under normal field conditions) were adopted, which in turn produced a range of unit output costs. Therefore, it is important that the results obtained from these analyses for different systems should be thought of as the likely "mid-range" values that would be obtained in practice, and not as precise values. Sensitivity analyses were completed for many of the other key parameters and the effects of changing input values on the output water costs were most interesting. In future work it would be desirable to define ranges for more of the parameters which cannot be expressed with precision.

- In many cases the differences in output costs between systems will be similar or smaller than the possible range of differences within individual system types, implying that a difference of a few cents/m^3 (say <3) between two options may not be significant, although differences greater than say 7 cents/m^3 almost certainly would be.

These economic evaluations have not studied the question of subsidies although the costs used for the country specific case studies included such elements. As is made clear in Chapter 1, the Consultants consider that the real costs and relative economics of the pumping alternatives have first to be demonstrated. In the light of the best factual data available the agencies responsible for the development of power sources for rural development have then to decide whether to let the market take its own course or whether, for policy reasons, they wish to subsidise a technology which is not yet economic in its own right. These decisions will be influenced to a considerable extent by whether conventional systems are being subsidised. If a policy of subsidy is agreed, decisions have then to be made on the appropriate method (eg, subsidy of first cost, or subsidised interest rate) and the sum it is appropriate to transfer from other sections of the economy to support them. Analyses can assist in showing the effect on unit water cost of changes to first cost or interest rate.

Such discussions will take place in the context of steadily improving prospects for solar water pumping and steadily worsening prospects for diesel engine pumps.

10.3 Recommendations

10.3.1 Introduction

It is considered that at the present stage of development of solar water pumps, techno-economic assessment of the kind reported here is at least as important as technical research and development, in that without it the fruits of technical work cannot be readily evaluated or applied and nor can future requirements be defined. Furthermore, the pointers from this kind of evaluation can be of considerable value in ensuring that further R&D to improve the technologies, plus actual procurement of developmental technology, proceeds in the most cost-effective and rational manner.

For small-scale applications of the type studied, the availability of the energy resource, the variability of end-use requirements and costs of renewable energy technologies are all region-specific, as is evidenced by the different results obtained for the circumstances prevailing in the selected "case-study" countries, Bangladesh, Kenya and Thailand. Thus care has to be taken in extrapolating the conclusions to other regions of the world. Indeed, for all major integrated rural development and agricultural projects in developing countries where small-scale energy technology might have a role there are strong grounds for organising techno-economic evaluations of this kind at an early stage, using technical and cost data applicable to the region concerned. The methodology developed for this study is believed to be generally applicable to a wide range of situations.

The work so far described on irrigation and rural water supplies provides an excellent starting point, but can usefully be extended to cover a wider range of scenarios and technologies. For this to be done, improvements in the models, and their methodology and presentation will need to be made. These recommendations therefore relate to three primary matters:

- Expansion and verification of the technical, operational, meteorological, hydrological, economic and financial data base, both for generalised and location specific analysis;
- Analyses on additional water lifting options and scenarios not so far considered;
- Further development of the mathematical models.

These three aspects are discussed below.

10.3.2 Expansion and verification of existing data base

The mathematical modeller is never satisfied with the adequacy of his data, but his natural desire to have more and better quality data has to be set against the cost of obtaining it and the consequences of using deficient data. The implications of erroneous data can be assessed through sensitivity analyses.

The general conditions under which solar pumps are likely first to become cost-effective in comparison with other systems have been identified in the work done for the study so far. The quest for more detailed information should be driven by the need to verify cost-effectiveness and economy in particular situations, otherwise data may be collected for which there is no real need. Further data therefore should be collected from countries and regions of countries where there is a particular need and serious plans for significant investment in the small scale irrigation and water supply aspects of rural development, with a view to determining the optimum systems that might be used and making appropriate recommendations which might then be verified through pilot demonstration projects.

In all such data collection exercises it will be important to obtain information on the range of values that the parameters are likely to take, so that ideally the statistics of variation can be calculated.

Particular attention should be paid to the collection of data on the following aspects.

- Resources and climate
    - solar regime (diurnal, monthly and annual statistics)
    - wind regime
    - hydrology (ground water and surface water resources, water quality, variation of depths with season and pumping rate)

- Application techniques and technical requirements
  - irrigation practices and consumptions
  - distribution and field efficiencies
  - storage requirements related to use of solar pump flows
  - range of crops which can be grown
  - potable water consumptions
  - typical ranges of hydraulic duties (flow and head) for irrigation
  - typical ranges of hydraulic duties for water supply
  - acceptable levels of reliability.

- Field Performance
  - performance envelopes of diesel, kerosene and gasoline engines, particularly at small end of range
  - operating lives under field conditions of all types of pump
  - operational and maintenance requirements for all types of pump used in rural development projects.

- Costs
  - water delivered by traditional method
  - diesel fuel
  - transport and installation on site
  - well/borehole construction
  - operation of all types of pump
  - maintenance of all types of pump.

- Economics
  - value of water for irrigation, village water supply and livestock
  - taxes, subsidies
  - shadow prices of all costs
  - opportunity cost of capital

This list reflects the ironic situation revealed by this Project that, whereas considerable independent data on the performance of solar water pumps now exists, there appears to be little data on the real performance of small engine driven pumps.

10.3.3 Additional water lifting options and application scenarios

The study reported herein necessarily started with the more common pumping systems used on their own primarily for water lifting duties for irrigation and village water supply. A number of additional aspects appear to warrant further study and these are outlined below: this would best be undertaken in two stages - preliminary assessment to identify the most promising developments, followed by more detailed assessment in the context of appropriate regions.

a) Single Water lifting options

The main single options on which it would be useful to make further studies include:

- solar pumps with battery storage;
- wind pumps in more detail, including lower cost cruder types;
- diesel pumps (in more detail);

- kerosene pumps (in more detail);
- gasoline pumps;
- natural gas fuelled pumps (both cylinder gas and piped gas);
- mains electrification (for a range of typical grid extension and electricity tariffs);
- biomass fuels (via alcohol and/or gasification of solid biomass with either i.c. engines or steam-pumps).

Some of these are already widely used or may be cheaper than the systems studied already.

b) Hybrid systems

The pumping systems so far considered were stand-alone systems which were required to meet the peak monthly water demand by themselves. This means that renewable energy pumps (i.e. solar and windpumps) have a high over-capacity for many months of the year in order to allow them to meet the demand for the critical month when energy availability is least in relation to demand. It is possible that certain hybrid systems may offer lower unit output costs than the individual component prime-movers operating in a stand-alone mode, but studies are needed to demonstrate this.

Hydrid systems which fall into this category and might offer advantages include

- solar/handpump;
- solar/gasoline engine pump;
- solar/kerosene engine pump;
- solar/windpump.

In the first three cases the solar pump would provide the base-load requirement and the peaks would be satisfied by the handpump or engines which would function on demand. This should significantly reduce the size requirement of the solar pump and more than compensate for the cost of the secondary pumping source. There may be situations where the combined wind and solar regime is more than twice as good as its individual energy resource components and could thereby produce a more cost-effective hybrid system than if one or other resource were to be relied on exclusively. In particular, windpumps are potentially a least cost option, but much uncertainty surrounds their storage requirements to cover calm periods; a solar pump in combination might more than pay for itself in reducing the storage and sizing requirement for the least windy month.

Most of these hybrid systems would require assessment in the context of specific countries or regions and they may well be attractive in some situations and not in others.

c) Application scenarios

Some of the aspects which are worthy of further investigation are:

Irrigation

- need for water storage with renewable energy systems in relation to operation and water management requirements and to cover against short term deficiencies;
- sub-optimisation of conveyance and distribution systems;

- relating system efficiency to static lift especially at lower lifts, and for situations with considerable drawdown;
- different cropping patterns and water requirements on overall economics;
- reliability and utilisation of system.
- different irrigation layouts and areas down to 0.5 ha;
- manual tracking of arrays;
- more realistic drawdown characteristics.

Water Supply

- influence of water storage on reliability of supply and costs including provision of some storage at each water point;
- sub-optimisation of distribution pipework;
- leakage in distribution pipework;
- reliability and utilisation of systems;
- relating system efficiency to static lift.
- diurnal variation of water level in storage tank;
- variation in water demand over the year;
- higher human energy inputs to handpumps for shorter durations
- different village shapes and distribution layouts

Cost and Economics

- shadow pricing on output costs;
- constraints on foreign exchange or balance of payments.
- more detailed and realistic treatment of recurrent costs, particular maintenance;
- opportunity cost of capital.

10.3.4 Further development of mathematical models

Technical

New or enhanced models will be needed to allow the additional studies outlined above to be carried out. For example, programs will be needed for the assessment of:

- hybrid systems;
- storage;
- change of system efficiency with head;
- sub-optimisation of conveyance and distribution systems.

Presentation

A major constraint with this kind of study is the time required for processing, interpretation and presentation of the large number of permutations of systems and scenarios, and the even larger number of output results. A significant further study would justify some refinement of the computer model to increase the variety of presentations that can be completed and printed out directly in an appropriate finished graphical or tabular form, thereby facilitating the implementation of extra analyses that appear justified in the light of results obtained from the planned schedule of runs.

PART D

Advancement of Application

PART D - ADVANCEMENT OF APPLICATION

11. STRATEGY

11.1 Introduction

In this brief Chapter, three interlinking subjects of some strategic importance are discussed: the need for a sound economic analysis to undergird all other activity; steps which should be taken to progress the application of solar pumps; and the continuing need for some international financial inputs. The remainder of Part D of the Report then goes on to discuss the value of field work and the content of a future field programmes, a summary of the work proposed for an international project in Phase II, the background to the prospective countries for Phase II and finally the importance of local manufacture. Some of the material in this Part of the Report has been drawn from work done for the Project, while the balance has been based on the thinking incorporated into a Proposal for Phase II submitted to the World Bank in January 1983. This Proposal is shown in Supporting Document 7.

11.2 The Primacy of an Economic Approach

The technology of solar water pumping is poised at a most interesting stage. The size of the PV pumping market and its rate of development depends upon the cost of the systems; yet that same cost is critically dependent on the number of units produced and sold. Although the overall future trend of PV array prices will be downward, it is likely that they will fluctuate in response to short term imbalances between supply and demand and the size of individual orders. The size of the PV market as a whole will be dependent to only a relatively minor extent on the water pumping application and this will further complicate the forecasts of growth of the pumping market. Marketing pressures will thus be very strong, and pumping systems may not always be chosen for situations for which they are well suited.

The Consultants consider it is vital that, for the long term good of technology, for the good of the country in which solar water pumps have a genuine potential use and, above all else, for the good of the prospective farmer or villager purchaser, the most careful economic analysis should be made of prospective applications so that, as far as possible, pumps are only bought for and used in those situations where they have a genuinely useful and economic role to fulfil. This Report contains one of the first serious studies on the comparative economics of solar and alternative pumps, and it is hoped that this will stimulate more work in this vital area. Although the economic evaluations will necessarily involve some market survey work to check on overall price levels for water and pumps, there is no point in undertaking elaborate market surveys until it is clear that the economics are becoming favourable from the point of view of the country as a whole. The whole question of fiscal policy and incentives can then be considered: however these two related (but distinct) matters must not be allowed to become confused; it is essential that a true economic picture first be obtained free from the distortions which the inclusion of subsidies (for example) would introduce.

Once having determined that, at the price levels for which solar pumps could be supplied or made locally, there were sound economic reasons for their use and that the number of applications was sufficiently great to justify the creation of the necessary repair facility (as a minimum) and possibly a local manufacturing base, the way would then be clear to consider the financial credit arrangements necessary to make capital intensive devices of this kind affordable by farmers and villagers. There are a variety of ways in which this could be done (e.g. subsidy to manufacturer, direct subsidy to the farmer, low interest rates on loans) but it is important to understand that such procedures simply represent an internal exchange of resources within the economy and do not effect the outcome of the economic analyses on which the decisions to invest should rest.

11.3 Steps Towards Application

The successful introduction of solar pumps to developing countries now depends on familiar principles of sound marketing: the right product in the right place at the right time at the right price.

The overall task remaining is to ensure that the market is developed in an appropriate manner, not only at the right time, but in a way that protects the interest of developing countries in general and the individual users in particular. It is in this area of market development and technology transfer that it is considered that further international support is required to ensure that maximum advantage is taken of the Project's achievements to date. It is the Consultants' view that the time is now right to demonstrate the appropriate use of solar pumps for irrigation and water supply to typical users in the countries which stand to benefit most from the technology; this demonstration would include full operational assessment of the pumps by users.

This overall task can be achieved in a number of steps which need to be progressed within the developing countries so that suitable solar pumps reach the people for whom they are intended. Although the governments of the developing countries will necessarily be involved to some degree in progressing this task, it should be clearly understood that it is neither necessary nor desirable for the government itself to be responsible for all the actions required.

The main steps are as follows:-

i) Demonstration of the capabilities of the pumping systems to technically qualified personnel and to farmers and villagers who represent typical users, building on the experience gained in Phase I and Phase II Preparation. This will also provide an opportunity to check on the actual performance and operation of the best pumps under field conditions, to verify their cost- competitiveness and to finalise aspects of system design.

ii) Detailed economic studies (on the lines of those reported in Part C of the Report) for the particular conditions in the region being considered. These should produce clear guidance on the situations in which solar pumps are most competitive and (hopefully) economic.

iii) If the prospects appear reasonable, these economic studies can then be followed up by market surveys of potential requirements for pumps, categorised into convenient groups of hydraulic duty (flow and head). These will produce demand-price relationships for different categories of pumps.

iv) Consideration of the prospects for the supply of pumping equipment to the market at the price levels indicated from the market surveys, and estimation of the cost levels at which it would be feasible to supply/produce a certain number of pumps. This will produce supply- cost relations for comparison with a market based demand - price relation, and so lead to the preparation of a business development plan involving either import, local assembly or manufacture. Such a plan would need to address the transfer of manufacturing technology.

v) Identification of local company(s) on which to base the repair, service, assembly and manufacture operation agreement, on scope of the operation and needs for links with foreign and local suppliers, staff, etc.

vi) Consideration of the needs for finance of firstly, the users to make purchase of pumps affordable and secondly, local companies which offer (say) a repair and maintenance service, before going into local manufacture.

vii) Selection of the best range of pumps for the local market, agreement on the best way to proceed as far a foreign supplier(s) are concerned, agreement an financial requirements, and the commencement of local operations.

The Consultants consider that the progressing of these steps requires a blend of continuing international aid (preferably through UNDP), local self-help and private business initiative. Although it is recognised that the perception of the extent to which the local government should become involved will vary from country to country, it is considered important that decisions are taken on technical and economic grounds as far as possible, and that any actions agreed on other grounds should be seen to be consistent with accepted rural development policies.

It is intended that at the end of the next 'international' Phase, appropriate pumping systems should be at a stage where they are immediately suitable for pilot scale assembly or manufacture in selected developing countries. No further international support for a global project should be necessary after the end of the next Phase. The market would then develop depending upon normal commercial prospects with aid assistance limited to specific projects, as for any other technology.

The activities required to fulfil these objectives are summarised in Chapter 13 and fully described in the Consultants' Proposal for Phase II (Supporting Document 7). Those that relate principally to the advancement of their application in the developing countries are described in the remaining chapters of this Part of the Report.

11.4 The Role of International Aid

The responsible advancement of solar pumps to mature development will be assisted greatly if some international funds can continue to support the work, through one more phase.

The main reasons for believing that international support is necessary for progressing the work can be summarised as follows:

- It is probably the only way to obtain independent performance data on the basis of international standards, publish it and so spur improvements to equipment.
- The momentum established by the first Phases of the Project needs to be maintained to ensure that systems continue to be improved to the benefit of the final users.
- The field demonstration aspect, which is a critical step in utilising renewable energy technologies, would be difficult to organise in widely different countries without international funds.
- Having been obtained as a result of international investment the knowledge gained can be made available to all.
- It ensures that the interests of the user remain paramount.
- The Governments of the developing countries have an important part to play in encouraging the responsible use of solar pumps and they in turn need the assurance that can be provided by an international project.
- Authoritative guidance in handbook format on the economic appraisal and system selection processes can be prepared to the benefit of all concerned.

- Training schemes can be more readily funded, allowing personnel from institutions in developed and developing countries to give and gain knowledge, as for monitoring and appraisal techniques to be demonstrated.

During such an international project the Consultants would circulate regular reports on progress to all organisations who were involved so that the benefit of lessons learnt in one location could be shared by others involved in the Project as quickly as possible.

The next chapter outlines the scope and purpose of the field programmes inherent in the advancement of the technology.

12 FIELD PROGRAMMES

12.1 Value of Work in Field

There are important gaps that remain to be filled in the abilities of developing countries to select from and adapt to their own needs technologies being developed by the industrialised countries. Field testing/demonstration is a critical step in moving renewable energy technologies from the laboratory into the hands of developing country users. Numerous testing and demonstration projects are now being conducted in developing countries, many of them with support from aid donors. However, these projects tend to be technology orientated rather than development orientated and often fail to recognise that testing economic, market and social viability is as important as demonstrating technical feasibility. Moreover, projects are frequently carried out on an ad hoc, uncoordinated basis, with insufficient provision for monitoring and evaluation and for the dissemination of results.

The work completed so far under Phase I and Phase II Preparation was largely concerned with refining the technology to a level where it could perform adequately in the field, ie, to establish technical feasibility and economic potential. This was achieved through a combination of laboratory and field testing, and analysis of the systems and components concerned. Under Phase II it is proposed to demonstrate and test under authentic field conditions selected commercial systems that have already performed well in the laboratory tests carried out under Phase II Preparation. In addition, the field programmes will establish the socio-economic requirements which are to be applied if solar pumping systems are to used successfully in irrigation and village water supply roles.

There is also a need to continue building up experience and knowledge of the technical performance and of the constraints regarding durability, reliability and life expectancy of systems. This requirement applies in particular to water supply systems operating through a higher head than those so far field tested in Phase I as irrigation pumps. It is important to be able to check the water supply application because it appears to be economically viable in a greater variety of situations than irrigation at 'Target' cost levels.

The field testing aspects of the proposed Phase II will be particularly important because there have been few serious attempts to monitor the performance of the 500 or so solar pumps in use in the world, except for the monitoring of systems in Mali, Philippines and Sudan, installed under Phase I of this Project, and a system in Egypt. The proposed Phase II field programme is likely to be the principal (if not the sole) source of reliable information on the true performance of present and future improved solar pumps under field conditions, and without it purchasers of commercial products will have little assurance that claims for cost-effectiveness are valid.

12.2 Lessons for Future Field Programmes

12.2.1 General

Before considering the content of the field programme proposed for Phase II, it will be helpful to outline the main lessons learnt from the conduct of field trials during Phase I and Phase II Preparation. Some of the material given below has been abstracted from chapter 9 of the Phase I Project Report (Ref. 9). It will be noted that many of the points made are essentially non-technical in nature: so often the achievement of technical objectives depends critically on the adoption of appropriate management and administration procedures. The Consultants took these points into account when framing their Proposal for Phase II.

12.2.2 Schedule for field programmes

The main aspects to be considered in relation to the schedule to be followed in organising and executing a field programme include:

- Adequate time should be made for reviewing possible sites for the systems to be field tested;
- The work should be planned to allow plenty of time for briefing and training of local staff on the field work;
- If the overall period for the trials is limited the start date needs to take account of the agricultural cycle;
- The content and timing of the programme needs to make realistic allowances for the time needed to clear systems through customs, arrange transport, install and then correct faults;
- The programme for measurements should make realistic allowance for difficulties of travel, climate, instrument failures, etc.
- If continuous measurements are to be made by the same individual, they should not be scheduled for more than two (or at most three) days a week;
- It may be helpful to start the programme with tests on the system(s) at a technical institution with the necessary resources in order to become familiar with observational routines. Problems will occur if new systems are put straight into the field;
- Following familiarisation at a technical institution, systems should be moved to the field for tests under proper working conditions: there should be agreement on this from the start;
- The schedule should allow for adequate time for visits to the manufacturers to inspect and witness tests on the equipment prior to shipment: on new systems, performance checks should be carried out at the Consultants' solar pump test or a similar facility;
- The programme needs to be planned sufficiently far ahead to give the local institution/ agency time to programme the budgets needed to meet locally incurred costs.

12.2.3 Technical

The main technical points to be borne in mind include:

- The need for high standards of observations should be stressed from the start, as well as the importance of calibrating all measuring instruments at regular intervals (not more than one month, preferably less);
- Although it is useful to collect cumulative data over a long period, continuous performance data should also be obtained on a regular basis (at least once per month) because this will provide the basis for understanding changes in system performance (good and bad);
- All the parameters to be measured in the field which are listed in the Phase I Project Report (Table 3) are needed if a fair picture of system performance is to be obtained and should not be reduced without good reason. The instruments listed in the Phase I Report all worked well, except for the multi-testers which were too sensitive and the energy meters which in some cases required repair after a short time of operation;
- The analysis of the data requires staff with a good technical and scientific background. It is particularly important that this work be done by staff from the participating institutions to give them training and an involvement in the work. It is also necessary to have this information as soon as possible on location so that any problems can be identified and settled quickly;
- In Phase I the instruments were bought in the UK and shipped out as one package. This was the best way to proceed then, but if the participating technical institutions have the capability, procurement and checking of instruments could be done locally in future;

- Proforma for recording observations should be issued and copies made immediately on return from the field, one to be kept at the technical institution and one to be returned to the Consultants;
- Adequate instrument spares should be available at the technical institution and it is helpful to have some duplication of the instruments on site;
- Systems to be tested in the field should not be new prototypes but have some record of reliable operation behind them.

12.2.4 Management

Aspects having a particular management importance include:

- Operational assessments need a different approach from technical evaluation and local staff should be involved who understand how to motivate and obtain genuine reactions from farmers and villagers;
- Where the progress of the work is dependent on a working collaboration between local organisations and the Consultants, it is very helpful to have a written statement of the objectives of the field programme and the responsibilities of both parties agreed before the field programmes start;
- Local funds for items like transport, materials and staff overtime will normally be needed and arrangements for the provision of these need to be agreed before the field programme starts - it is particularly important to reach agreement on transport requirements;
- Arrangements for the security of the equipment (especially in the field) and the scope and execution of insurance cover need to be set up;
- It is often necessary for more than one local organisation to be involved and in such cases clear agreement should be reached on management and operational responsibilities which the various organisations have accepted;
- The link between the local organisation(s) and the Consultants is very important and the Consultants will need to have a member of their staff on site to give advice, encouragement, assistance and training. It should be clear however that final responsibility lies with the participating institutions;
- Senior members of the Project Management team from both the funding agency and the Consultants need to make visits at regular intervals to maintain personal contact with the participating institution(s) and their representatives and review progress;
- Proper provision should be made for explaining the objectives of the field programme to the local institutions which will participate and for taking their views into account.

12.3 Scope and Purpose of the Field Programmes

Because of the context of this Report, the field programmes which it describes are inevitably associated with the proposed Phase II of the UNDP Project. However, the Consultants consider that the ideas outlined below have a wide and general application and may be used as the basis for other field programmes having similar objectives.

Three forms of field programme are outlines - full, limited, and monitoring and evaluation.

12.3.1 Full field programme

It should be noted that the field programme proposed for Phase II differs significantly from that carried out in Phase I. The Phase I field trials were carried out in order to obtain performance measurements of relatively unproven equipment under typical field conditions using the field as an outdoor laboratory. The Phase II field programme on the other hand is primarily intended to demonstrate that selected and reasonably proven systems actually do provide a cost-effective, reliable and appropriate means of pumping water in the field and to confirm the economic and social implications of introducing this technology as a component of rural development.

It is proposed that in countries where a full field programme is to be undertaken the trials should be executed in three distinct parts: technical evaluation, central demonstration, and operational assessment, and should involve two types of local organisation, technical institutions and assessment agencies. The three parts of the field programme are described first.

a) Technical evaluation

This first part would be based on the pumping systems chosen on the basis of the information collected during preparatory visits. This aspect of the work will be based at a "technical institution" (see 12.4) and its principal aims will be to:

- familiarise technical staff with the characteristics of solar pumping systems and the use of monitoring instruments, through systematic training programmes;
- measure continuous and daily performance data under controlled conditions at the technical institution on at least one of the pumping systems;
- collect continuous and daily data from typical sites in the field;
- check and analyse field data and report on performance to the Consultants;
- obtain information on reliability and durability.

The staff at the technical institution will also be able to undertake the following tasks:

- provide a reference point for advice;
- provide a maintenance and repair service;
- report to the Consultants on performance and reliability;
- provide training programmes for assessment agency staff and others:
- assist with installations of pumping systems at villages and farms.

The Consultants have consistently laid stress on the vital importance of collecting accurate and reliable data on the performance of systems in the field: indeed Phase I of the Project has been almost unique in this respect. It is considered that techniques similar to those used in Phase I for the collection of performance data continuously over a day should be used in Phase II, improved in the light of our earlier experience. The data to be collected comprises solar irradiance (global and in the plane of the array); temperature of the array; current, voltage and power output from array; speed of motor and pump (if possible); temperature of motor casing; flow delivered; pumped head; suction head and delivery head, and thus total static head; cumulative operating hours; wind speed, ambient temperature and humidity.

b) Central Demonstrations

Once staff at the technical institution are confident about the system(s) and have shown that they meet the performance specification, it is proposed that, as the second part of the full field programme, a demonstration programme be followed during which staff from the assessment agencies connected with the operational assessment part of the work be invited to witness and monitor the systems. Representative users (farmers and villagers) would then be asked to visit the institution to observe the systems prior to the start of the third part of the full field programme. Some basic training in how to operate and handle the systems and performance monitoring instruments would also be organised during the central demonstration part of the programme. Demonstrations at the location in the field would be organised during the third operational assessment part of the full field programme.

c) Operational Assessment

This third part would be carried out with the pumping systems installed at pre-selected sites at villages and farms. It is predominantly concerned with the user and has six main aspects, as follows:

- Methods of Application and Use: to gain first hand experience of the ways in which the output from small-scale solar pumping systems are used by farmers and villagers for a variety of agricultural and water supply uses under authentic operational conditions. Ideally two full annual cycles should be covered, but the duration of the field programme is governed by the finance available. The operational assessment should cover at least two growing seasons so that lessons learnt in the first can be applied to the second. This will help to determine optimum methods of use and to identify design constraints. One important area of investigation will be the way in which the low flows from solar pumps should best be stored and distributed for agricultural or water supply purposes.

- Economics: to gain information verified at first hand on the costs and benefits of PV systems when used for a variety of end uses over two annual cycles in representative countries and geographical regions. This will involve collecting and analysing a lot of information on agricultural production and costs and water supply practices and values, and will require considerable organisation.

- User Reaction: to obtain reactions of users to solar pumping technology and the ways in which the systems and methods of application should be amended to make them more acceptable.

- Performance and Reliability: to increase substantially the data base on system performance under field conditions initiated under Phase I and to study the behaviour of systems over a significantly longer period than was possible under Phase I. This will provide insight into longer-term performance reliability and durability and the necessary maintenance requirements. It is envisaged that two complete annual cycles will be experienced during the proposed field programme which should give a reasonable indication of the life that can be expected from various system components, and areas where improved reliability must be obtained. It will also show how seasonal changes in the solar regime and user requirements interact with the systems.

  Most of the performance testing will consist of the recording of cumulative input/output data on irradiation, flow and head plus recording of all significant events such as breakdowns, failures, repairs, and adjustments. In addition, occasional intensive tests will be carried out (as in Phase I) to monitor continuous performance in order to check on consistency of output and to indicate any reduction over a period of time. Systems will also occasionally be dismantled for detailed inspection to assess any deterioration or wear that may have occurred.

- Field Demonstrations: to provide a valuable demonstration role under comparable field conditions for other farms and villages in the region and so to extend the area of influence of the programme. It is envisaged that extension workers would wish to take full advantage of this opportunity.

- Sociological and Institutional Considerations: The widespread adoption of solar pumps by individual farmers for agricultural use or by small communities for water supply use could well have far reaching social implications. These would need to be understood before the technology is introduced commercially and should be taken into account when planning the way in which the technology is to be marketed. The existence of numbers of small solar pumps would also pose new operating, maintenance and repair requirement which would have training and institutional implications. Forward planning of management training requirements is therefore indicated.

12.3.2 Limited field programme

In countries where a limited field programme is to be undertaken, only the technical evaluation aspects of the full field programme as described above in 12.3.1 a) would apply. If subsequently agreed, the technical evaluation work could proceed to the central demonstration phase as described in 12.3.1 b).

12.3.3 Monitoring and evaluation programme

The monitoring and evaluation of existing solar pumping programmes will involve aspects of technical evaluation and operational assessment as described for the full field programmes. Its full scope would depend on the number and type of existing pumping systems available for monitoring under the Project and the interests of the technical institutions. Selected systems could also be used for central demonstrations, to which representatives of potential users from the surrounding region would be invited.

12.4 Institutional Requirements

From the above it will be appreciated that the different parts of the field programme would require the assistance of different types of collaborating institution or agency.

- o Technical evaluation will demand a high level of engineering capability and resourcefulness. Ideally, it should be carried out by a technical institution with a proven record in the solar pumping technology field and possessing scientific, engineering and technical support staffs and workshops. It should also have the interest and capability to provide technical support to local manufacturers. The staffs of the technical institutions should have an awareness of the applications of the technology and be able to explain the system to those with little technical background, demonstrate their use, and train others. These institutions will also be responsible for the central demonstrations.

- o Operational assessment will best be carried out in association with agencies experienced in evaluating agricultural techniques (particularly from the point of view of the farmer) and rural water services and possessing good extension services. The technical demands, insofar as they relate to solar pumping technology, will be relatively light. The agencies will need to handle maintenance and repair work of a simple type (with back up from the technical institution).

  The agency will need to have staff who are responsive to the concepts of introducing new technologies to aid rural development. It may also need to study any sociological implications of the introduction of solar pumps to farms and villages.

Depending on the size of country and locations of the sites for operational assessment, it is likely that only one technical institution need be involved. However, with the need to assess the operational use of pumps for both irrigation and water supply, it is likely that at least one agriculture oriented agency and one water supply orientated agency will be needed for the assessment work.

In countries where only the monitoring and evaluation of existing systems is to be carried out, the Consultants propose that a technical institution be the prime agency responsible for the field work, but other agencies involved in agriculture and rural water supply will need to be involved in the evaluation studies.

12.5 Reports on Performance and Reliability of Systems

During this period, the Consultants would inform the system suppliers/manufacturers of points in their design which lead to poor performance, limitations in application, operational difficulties, lack of reliability or other faults, so that the eventual agreement on technology transfer would be on the basis of a proved product with a wide market appeal. The opportunity would also be used to press the advantages of improvements in component performance revealed by the Consultants' earlier work and which might not have been taken up by the parent manufacturers. Finally specifications would be drawn up describing the performance requirements and design features of systems which satisfy the main hydraulic duties in a cost-effective manner.

13 INTERNATIONAL PROJECT FOR PHASE II

13.1 Impact of Project on Development of Solar Pumps

The reasons for proposing that the next phase of the Project should be funded internationally were outlined in Section 11.4. These views are given additional weight when it is appreciated that Phase I and Phase II Preparation of the Project have had a considerable impact on the development of solar water pumping technology over the past three to four years, and confirm that properly managed, international projects of this type can have considerable influence.

The main benefits of the Project can be summarised as follows:

- Before the Project started there was an almost total absence of evaluation activity by developing country governments or aid agencies purchasing solar pumps and a lack of self-critisism by suppliers. Now the need for initial appraisal of pump performance and the matching of pump to duty is widely accepted.
- There were no independent data on the performance and cost-effectiveness of pumping systems operating under realistic field conditions. The Project has published the first independent body of data.
- The Project has established standards for the field and laboratory evaluation of pump performance and presentation of data in terms of instantaneous and daily efficiencies and the Specific Capital Cost of systems, and put evaluation on a firm quantitative footing.
- Tests on component performance (done in the laboratory) have helped to identify the reasons for good and bad system performance, particularly for conditions away from the optimum point.
- The Project has highlighted the importance of a systems approach to design, and the need to match the characteristics of PV array, motor and pump. Mathematical models of PV and thermal pumping systems have been constructed and their potential use for design has been demonstrated. These will become available for use by third parties.
- The Project has pioneered the preparation of performance specifications for pumps in terms of a prescribed volume to be pumped each day under a specified solar day at design head. The specifications also define the performance required under a lower daily irradiance and at the limits of a prescribed range of head. Manufacturers have also been given target peak efficiencies for each main component and daily efficiencies for the overall system.
- As part of the performance specifications, a definition of a Standard Solar Day has been adopted and is likely to be taken up in this (or a closely related) form by the photovoltaic industry (Ref. 17).
- The design and manufacture of solar water pumping systems have generally improved: the best subsystem efficiencies are higher then in 1980 and with the gradual decrease of PV array prices the cost- effectiveness of systems has improved.
- Comparative economic analyses have been done which enable those wishing to evaluate alternative pumping strategies to identify the circumstances in which solar pumps are either economic or most cost-competitive. Economic models for small scale irrigation and water supply applications will become available for the evaluation of any particular situation.

- Under the stimulus of the Project, a test facility designed specially for solar pumps now exists and is available to any third party wishing to have an independent check made on pump performance under a very wide range of conditions.

- Information on solar pumping technology has been made freely available on a world wide basis, whereas without the Project it would have remained in a few privileged hands, even where it existed at all.

The Consultants consider the benefits obtained to date should be built on in Phase II, the objectives of which are outlined below.

13.2 Objectives of Phase II

The results and conclusions of the work to date, set in the context of the discussion in this Report, lead to the conclusion that one further international Phase of the Project should be undertaken, mainly devoted to a programme of field demonstrations, detailed economic analyses and the transfer of manufacturing technology. The essential difference between this field programme and the trials carried out in Phase I have been explained in Sections 12.1 and 12.3.1.

The basis of this belief is that firstly, there are circumstance in which solar pumps are already competitive with some alternative pumping techniques and will shortly be economic in their own right, and secondly,there are solar pumps good enough to warrant final evaluation in the field and demonstration of their capabilities to intending users.

The objectives of a Phase II of the Project to be funded from international sources can be summarised as follows:

- To confirm the technical, economic, financial and social conditions under which selected solar power pumping systems are able to provide a cost-effective, reliable and appropriate means of pumping water for agricultural and water supply purposes.

- To demonstrate by field trial and pilot use that selected solar powered pumping systems do provide a cost-effective, reliable and appropriate means of pumping water.

- To finalise the specifications of appropriate pumping systems taking account of the need for them to be suitable for operation, maintenance, repair, assembly and/or manufacture in the developing countries.

- To make background studies relating to the local assembly and/or manufacture on a pilot basis of suitable systems and for their distribution, manufacture and financing in appropriate developing countries.

- To prepare and issue technical and economic guidelines for purchasers and users on the selection, operation, monitoring and evaluation of solar water pumps.

It is intended that at the end of this Phase, appropriate pumping systems will be at the stage where they are immediately suitable for pilot scale assembly/manufacture in selected developing countries. No further international support for the global project should be necessary after the end of Phase II. The market will then develop depending on normal commercial prospects, with possible aid inputs limited to assistance for specific projects, as for any other pumping technology.

It is hoped that with the successful completion of Phase II in a few countries cooperating enthusiastically in the objectives of the programme, there will then be incentive for other countries to follow suit.

Since the previous Phases have been financed by the UNDP, it is presumed that Phase II will be considered for <u>similar</u> funding and for convenience Phase II has been linked with UNDP.

13.3 Summary of Principal Activities in Phase II

13.3.1. General

In the section below we list the main activities which we believe are needed to achieve the objectives set out in Section 13.2 above. It is worth making a few general points:

- These proposals are based on the Consultants' experience of Phase I and Phase II Preparation and seek to leave an adequate time for proper liaison with and within the countries participating in the field programme;
- It will be necessary for the Consultants to have a separate agreement with the prime managing institution in each country;
- It will be of great assistance to the UNDP Solar Pumping Project if arrangements for effective collaboration at working level can be reached with any field work being progressed in the participating countries under the UNDP Handpump Programme. The basic philosophy of field testing and the rural water supply objectives are both similar, and cost savings to both projects could accrue.
- It will be generally helpful if the solar pumping project can be seen to be a contributory activity to the UN International Drinking Water Supply and Sanitation Decade.

13.3.2 Summary of activities in Phase II

It is proposed that the general objectives outlined in Section 13.2 above should be achieved through the following principal activities.

Activity 1 Visits to each country participating in Phase II to reach detailed agreement on all aspects of the field programme (including choice of sites) and confirmation of the probable economic applications of solar water pumps, and size of the market.

Activity 2 Choice of pumping systems for sites selected in each country on basis of test data and design information obtained in Phase II Preparation and updated costs, and procurement of these for delivery to the Consultant's solar pump test facility. Instrumentation for monitoring all new and selected existing systems would also be selected and monitoring procedures formulated.

Activity 3 Inspection of each pumping system, check on performance of each category of pumping systems at the solar pump test facility and any necessary repairs or corrections, prior to despatch to participating countries. This work could include an evaluation of potential reliability and possibly some accelerated ageing test.

Activity 4 Conduct of field programme by local managing organisations in partnership with the Consultants to progress the following aspects:

- Visits to each participating country at time of arrival of systems to check all arrangements are in hand and to train staff at technical institutions.

- Technical evaluation of pumping systems at selected technical institutions.

- Demonstration of the systems at the technical institutions to farmers and/or villagers (with their participation as appropriate) and officials of agencies concerned with rural development, small scale agriculture and village water supplies, and possible local manufacturers.

- Operational assessment of pumping systems under authentic working conditions on small farms and in villages.

- Monitoring and evaluation of selected existing solar pumping programmes by other agencies wherever practicable, based on world-wide enquiries to catalogue solar pumps currently in use.

- Report on performance and reliability of pumps and discussion with manufacturers on any improvements needed.

Activity 5 Economic/financial analyses of the prospects for the systems on the basis of market surveys in each situation in each country, and discussions with government agencies about financial support for local manufacture and financing credit arrangements for purchase of pumps by users.

Activity 6 Preparation of a background report covering all issues related to the possible establishment of a local assembly/manufacturing industry for solar pumps. The report would include sections on market prospects, local resources, mechanisms for technology transfer, technical and financial aspects of pump manufacture and would conclude with a draft Plan of Action.

Activity 7 Preparation of technical and economic guidelines on selection and use of solar pumping systems. This guidance would be prepared in handbook form. Although no new knowledge would be required, the available material would need to be represented in a form designed to appeal to prospective purchasers and users who might have little previous acquaintance with solar pumps.

Activity 8 Workshops to be held as an informal means of discussing progress, evaluating results, demonstrating uses and maintenance procedures, and training.

Reports will be submitted to support recommendations for the purchase of equipment and detailed field programmes, to describe results obtained and inform on progress.

Although all of these reasons are important the immediate practical value of the technical and economic guidance makes it worthy of special reference. Solar pumping is a new technology, . equipment is being improved, the conditions under which it is viable are not always obvious and it is consequently very difficult for would-be purchasers to make informed decisions. Guidance is needed in handbook form on how to assess the technical and economic viability of solar pumps in their various applications so that policies and investment proposals can be properly evaluated. This guidance would be in two parts:

- technical guidance on selection of appropriate performance requirements, equipment procurement, use of model specifications, shipping and installation, evaluation and testing, operation and maintenance, storage and distribution of water etc.,

- economic guidance on methods of basic evaluation, comparison with alternative pumping techniques, selection of appropriate applications, effect of methods of financing, etc.

Although no new knowledge would be required, available material would need to be presented in a format designed to appeal to prospective purchasers and users who might have had little previous experience with this technology but who wished to work out for themselves whether it was worth purchasing solar pumps and, if so,the type which would be best for their application.

As part of the Consultant's management input, visits will be made to the participating countries throughout the field programme and in connection with the studies on economics, market, finance and local manufacture.

Each of the activities listed above is described in detail in Supporting Document 7.

13.3.3 Duration

The relationship between these activities is set out in the Fig 13.1. The activities are largely sequential in time and the overall duration will not depend to any great extent on the number of countries involved. It is estimated that, allowing for adequate consultation and familiarisation, the programme within each country should be for a minimum of 21 months (allowing a minimum of 18 months for operational evaluation). Six to nine months should be added to this for activities 1, 2, 7 and 8 to give an overall duration of 27 to 30 months.

13.3.4 Costs

The costs are dependent on the number of countries involved in Phase II and the number of systems to be installed and/or monitored in each country.

Within the geographical-political constraints of a UNDP project, it is considered that funds will be better spent by placing more systems in fewer countries, selected on the basis of suitability for solar applications, government support, technical support and capability for managing a field programme, rather than by spreading systems more thinly through a greater number of countries.

13.3.5 Workshops

Properly prepared and constituted workshops, organised regionally or on a global basis, are a valuable aid to the communication and sharing of ideas and conclusions and can also be used as a venue for demonstrating and training techniques. The location and timing of these events is obviously determined by the main programme but it is considered that there should be at least one global workshop in the middle and another at the end of the programme, with possibly additional regional workshops in-between.

13.4 Management of Phase II

13.4.1 General

The management of any international project whose objective is to make new technology available for the disadvantaged rural areas of the developing countries is always a difficult task. The paragraphs below discuss the issues which will need to be faced in relation to the field programmes within each of the participating countries.

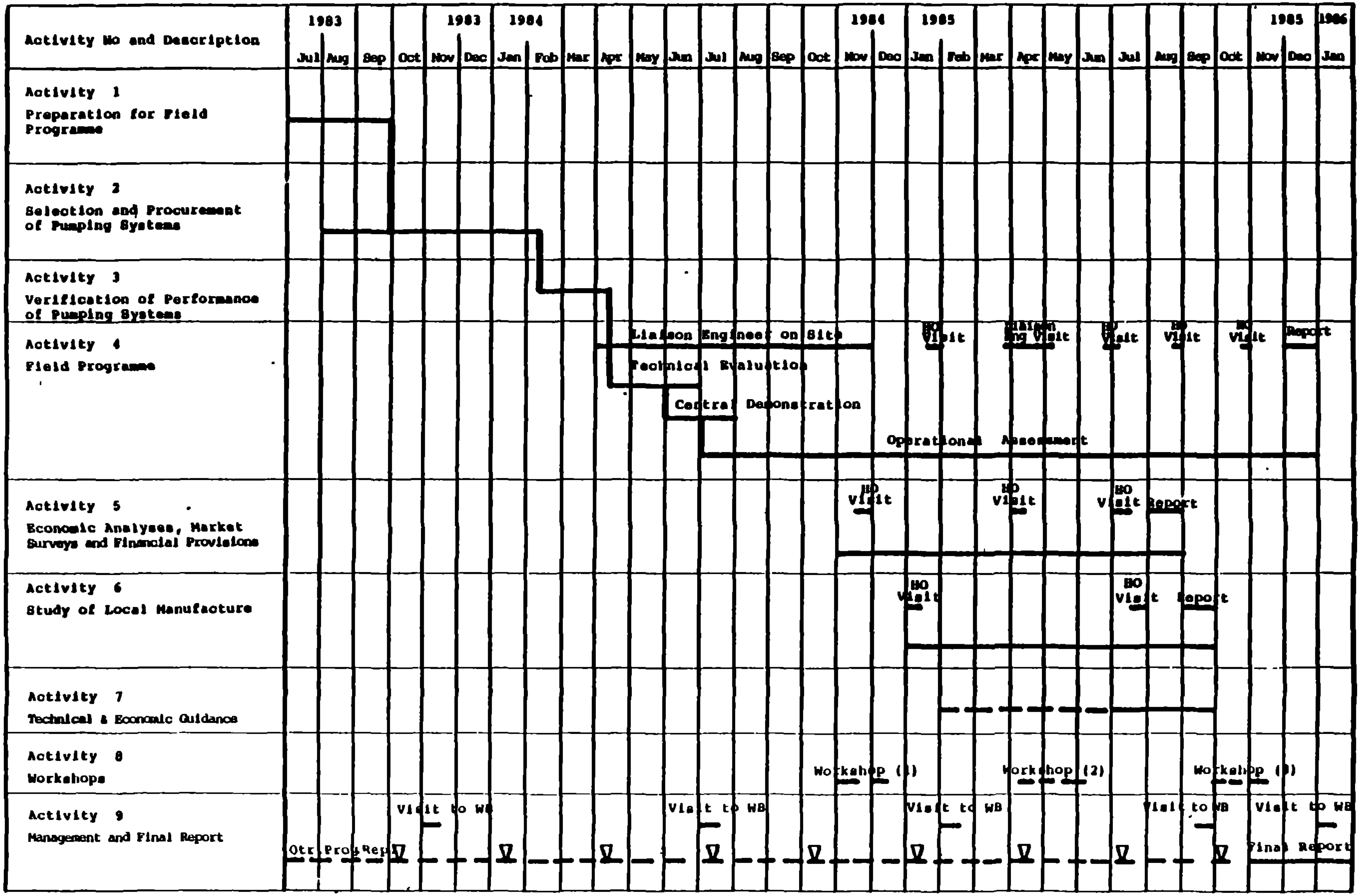


Figure 13.1 Development of Solar Powered Pumping Systems for Small Scale Irrigation and Rural Water Supplies - Activity Diagram for Phase II

13.4.2 Prime managing institution in participating country

The management of the work described above will be a delicate exercise. The ideal will be for one organisation (the prime managing institution) in the participating country to be responsible for managing all aspects of the work (recognising that it cannot do it all itself) while the various parts are executed through technical institutions and assessment agencies.

Agreement of objectives, programming and progressing the work, and communication will all be vital, and a way will need to be found (depending on the country) which does not absorb an undue proportion of time, effort and the budget. A task force approach could be appropriate, lead by a person of suitable calibre to give the Project authority and momentum. Lessons learnt from the way in which the UN Water Decade activities were organised would be taken into account.

To increase awareness of the host country's obligations and to improve liaison between the host country and the Consultant it is recommended that after the basic UNDP protocol has been signed by the host, a separate letter of understanding between the prime managing institution and the Consultant should be signed. It would be helpful if the UNDP protocol contained a reference to this letter of understanding. Such a statement of respective obligations can only assist progress in the field and help to underscore the vital importance of effective collaboration between the two parties.

13.4.3 Consultant representation in participating country

Experience in Phase I showed that the presence of an engineer from the Consultants was critical for progress and the provision of advice and encouragement; at the same time it was liable to be misunderstood as implying outside direction and interference. With so much work of importance proceeding in these countries it will be vital for the Consultant to keep in touch personally. Where possible, one solution would be to employ a suitable local independent Consultant as the representative of the main Consultant, with visits from time to time by the latter. For such a proposal to be effective, selected members of the staffs of the prime managing institution, technical institutions and local Consultants will have to be carefully trained, but this would all be part of the important process of technology transfer. The greater part of this training would obviously occur within the country but one or two key individuals could be considered for training outside the country.

The natural location for the Consultants' representative (whether expatriate or local) would be in the office of the prime managing institution. To save misunderstanding his title should be similar to "Liaison and Advisory Engineer". He would arrive shortly before the systems, assist in checking their condition, advise on their installation, brief staff and then institute training programmes. He would be available at all times to give advice on the field programmes and on monitoring procedures and system performance, but the executive control and management of the programme would remain the clear responsibility of the prime managing institution.

13.5 Training

The question of training for suitable technical staff from institutions in the developing countries has been mentioned several times in this Report. To emphasise the importance which the Consultants attach to this matter, the various strands of thought have been brought together in this brief section.

Training is required in a number of related areas:

- to explain the technical aspects of good system design and methods of appraising cost-effectiveness;

- to explain and demonstrate the techniques for monitoring performance in the field, the instruments needed and their calibration, and the analysis of the data;
- to explain the basis for evaluating the economics of solar pumping installations, in relation to solar regime, water requirements, peaking factors, head, value of water, and capital and recurrent costs;
- to explain the techniques of operational assessment;
- to review the factors involved in the successful transfer of manufacturing technology;
- to explain the basis of performance specifications and how they may be used to procure systems, including the use of the computers to run mathematical models to assess and/or optimise system designs.

Most training should be carried out on site, but it may be found helpful for some courses to be run in conjunction with demonstrations at the Consultants' solar pump test facility in the UK.

14 PROSPECTIVE COUNTRIES FOR PHASE II

14.1 Objectives of Study of Country Potential

One of the recommendations for future work made in the Phase I Project Report (Ref.9) was that additional countries should be considered for involvement in future field testing programmes, and that these should be able to satisfy a series of criteria, the most important being:

- The existence of important pumping needs for irrigation and water supply in rural areas that could be met competitively by solar powered pumping systems and which would require a range of pump output power suitable for solar systems.
- The presence of a suitable solar energy resource and the absence of any more readily exploitable alternatives.
- Government interest in solar pumping and a willingness and ability of host country institutions to provide the necessary technical and logistical support for the reliable field monitoring of the systems.

The objectives of the work reported in this Chapter were to assess a number of countries for their suitability for participation in the field programmes described in Chapter 12 carried out as part of the Phase II Project described in Chapter 13. Joint World Bank/Consultant missions to countries selected by UNDP and World Bank for these visits played a very important part in this appraisal.

14.2 Countries Considered

14 2.1 Short-listed countries

The following countries which were believed to offer good prospects for solar pumps were short-listed by the World Bank on the basis of available information on pumping requirements and solar regimes:

- Bangladesh
- Brazil
- Egypt
- Kenya
- Mexico
- Pakistan
- Sri Lanka
- Thailand

This selection was made prior to the UNDP/World Bank Workshop on "Solar Pumping in Developing Countries" which was held in Manila in June 1981 and each country was invited to send delegates to the workshop. Countries were requested to present information on their needs for water pumping and the potential for and their experience with solar pumps and other solar and renewable energy technologies. These are summarised in Ref. 8.

14.2.2 Phase I and additional countries

The Consultants included in their review the countries which had participated in the field trials in Phase I (Mali, Philippines and Sudan) and also suggested a number of additional countries which they believed might be considered for participation in Phase II (Botswana, China, India, Nigeria, Somalia, Zimbabwe).

14.3 Missions to Potential Countries

Each of the countries short listed by UNDP/World Bank was visited by a mission comprising a representative of the World Bank and a member of the Consultants' Project team (Table 14.1). The objectives of these missions were:

- To locate the principal sources of data on: solar energy, hydrology, village water consumptions, irrigation requirements and user practice.
- To form a view on the range of pumping requirements for irrigation and water supply, and the role that solar pumps might play in satisfying these needs.
- To explain the purpose of the Project to relevant departments and officials, and to determine their interest in participating in Phase II.
- To identify which organisations might host the trials and be responsible for logistical support.
- To explain technical and administrative support facilities needed for field trials, and possible sites for same.

In each case the mission was hosted by the local UNDP office in the country being visited. The UNDP office also arranged the initial meetings with relevant institutions and agencies. Following each mission, reports were submitted to the World Bank and abstracted information is given in Supporting Document 6. The progress made during each mission, and the quantity and quality of the data obtained varied considerably from country to country.

14.4 Assessment Criteria

The criteria used for assessing the prospective countries were as follows:

- The country's needs and interests: the extent of the requirement for small scale irrigation and/or water supply pumping, the potential demand for use of solar energy sources, and the interest in solar pumping expressed by the appropriate Government departments and implementing agencies.
- The technical conditions: the suitability of the solar irradiance regime, daily and seasonal water demand patterns, field application efficiencies, and average value and range of pumping heads.
- The economic conditions: the value of water when used for agricultural or water supply purposes, the cost of solar pumped water, the area distribution of small farms, the sizes of villages and the likelihood of solar pumps being economically viable on their own merits now and in the future.
- Competitive energy sources: availability and costs of conventional or other renewable sources of energy which may be more appropriate and cost-effective for powering small-scale water pumping systems than solar.
- Implementing agencies: the existence of local institutions capable of the technical and administrative support required for field testing. This involves installation, operation and monitoring of pumps, instrument calibration, analysis of results, demonstrations to farmers and villagers, operational evaluation and extension work.

Country	Dates of visit	Mission Team World Bank	Consultants
Bangladesh	14-23 March 1982	M A S Malik	D E Wright
Brazil	4-13 Oct 1982	R S Dosik	D E Wright
Egypt	10-25 April 1981	E M Mitwally	B McNelis K G Armstrong
Kenya	3-10 April 1981	E M Mitwally	W Armstrong
Mexico	14-24 November 1982	M A S Malik	B McNelis
Pakistan	11-17 June 1981	E M Mitwally	B McNelis
Sri Lanka	29 June - 7 July 1981	E M Mitwally (part)	P L Fraenkel B McNelis
Thailand	29 June - 3 July 1981	E M Mitwally (part)	D E Wright A Derrick (part)

Table 14.1 Missions to Prospective Phase II Countries

- Data quality: The range and quality of existing data on important physical parameters, eg, solar irradiance, climate, hydrology, hydrogeology, irrigation water requirements (net consumption variations over year) and water supply (per capita consumption).

- The scientific, technical and financial infrastructure: the existence of local organisations (eg universities, R & D agencies, manufacturers) with technological resources and staff with skills relevant to solar water pumping, and the interest of investiment agencies.

- Past experience: existence of testing and demonstration programmes in solar pumping and other renewable energy technologies.

There were substantial differences in the quantity and quality of data obtained and the usefulness of the discussions held during the missions. This has made it difficult to assess countries on a completely objective basis. Some examples of the difficulties faced are summarised below:

- UNDP country office interpretation of the missions' requirements: In some cases meetings were arranged only with organisations involved with renewable energy and it was difficult to establish working contacts with institutions concerned with agriculture and water supply in the limited time available for each visit.

- Government department providing liaison: In several cases a government agency had already been nominated as the collaborating institution. However, one of the purposes of the mission was to recommend which institution or agency was to be involved in the Project.

- Some countries believed that the need for solar water pumps was so widespread and apparent that there was no need for supporting data on water demand and needs, and solar and hydrological conditions.

- One country, in anticipation of Phase II being implemented, wanted the mission to devote the majority of the time available to selection of specific sites for field trials.

- A period of nearly two years has elapsed between the first mission and the overall review of the short listed countries and hence some of the information may no longer be valid.

14.5 Types of Involvement in Field Programme

It is considered that country involvement in Phase II should take three main forms, depending on the solar regime, the economic prospects for solar pumping, the size of the market and the levels of government interest and institutional support.

The three main types of involvement envisaged are:

- A full programme of field demonstrations, with thorough technical evaluation, central demonstrations and operational assessment.

- A limited field programme, concentrating on the technical evaluation of solar pumping systems. Central demonstrations would also be arranged.

- A comprehensive data gathering, monitoring and evaluation programme based on solar pumping systems and other pumping techniques already established in the country.

14.6 Assessment of Short-listed Countries

Utilising the data gathered by the missions, supplemented by information obtained from published reports and private sources, the short listed countries have been assessed on the basis of the criteria defined in Section 14.4. The Consultants' recommendations for the involvement of each country in the field programmes outlined in Section 14.5 above and described in Chapter 12 are summarised in Table 14.2.

An assessment summary of each of the short-listed countries including recommendations on their participation in the proposed Phase II field trials programme is given below.

- Bangladesh

There is a large demand for small water pumps and considerable investment in handpumps for irrigation and water supply. The potential for solar pumps may be limited because of the long wet season and somewhat inefficient and peaky water use. It would, however, be of benefit to have a direct comparison between hand and solar pumps for both applications. It is considered that, given the extensive development work in progress on handpumps, solar pumps should be technically evaluated alongside handpumps, and the potential for their use shall be investigated in more detail following central demonstrations.

- Brazil

The hydrological and solar conditions, and user requirements for irrigation and water supply in the north-east of the country are attractive for small scale solar pumps. There is a high level of interest from Government agencies, the country's technical and scientific resources are good, and local manufacture of photovoltaic pumps is commencing. There is good opportunity to compare solar pumps with diesel, mains electric and producer gas powered engine pumps. One possible difficulty is that the market may be closed to foreign suppliers. It is considered that technical evaluations and demonstrations followed by operational assessments of solar pumps should be implemented.

- Egypt

There are large numbers of low lift irrigation pumps used in the Nile Delta, and solar conditions are very attractive. The scope for solar pumps appears to be large, there is much Government interest, and systems are being installed under a number of international programmes. There is also potential for high lift solar pumps for water supply in desert areas and an installation of this type is already being monitored by the Project, with good data being collected. In view of the widespread international interest in Egypt it is considered that Phase II of the UNDP Project should monitor and evaluate the performance of systems supplied by others.

- Kenya

There is a demand for water and a good deal of official interest for water pumping by renewable energy resources, and solar conditions are good. The main potential is in the large arid areas that are sparsely populated. In these regions pumping heads are high and possibly outside the economic range of solar pumps. There are regions where water is available within a reasonable depth but more data is required before recommending a full field programme in Kenya. However, a number of photovoltaic pumps are being installed and could be usefully monitored. It is considered that solar pumps should be technically evaluated and the potential for their use suggested by the economic studies should be confirmed.

COUNTRY	GOVT. INTEREST	TECHNICAL CONDITIONS	ECONOMIC PROSPECTS FOR SOLAR PUMPS (2)	COMPETITIVENESS OF ALT. ENERGY SOURCES(3)	IMPLEMENTING AGENCIES	EXTENT OF PHYSICAL DATA	SCIENTIFIC TECHNICAL FINANCIAL RESOURCES	PREVIOUS EXPER. IN SOLAR PUMPING	ONGOING PROGS IN SOLAR PUMPING	RECOMMENDED ACTIVITY
BANGLADESH	••	•	•	••	•	•	•	•		Technical Evaluation
BRAZIL	•••	•••	••	••	•••	••	•••	••	•	Full Field Programme
EGYPT	••	•••	••	••	••	••	•••	••	•	Monitoring
KENYA	••	••	••	••	••	••	••	•	•	Technical Evaluation
MEXICO	•••	••	••	•••	•••	•	•••	••	•	Technical Evaluation
PAKISTAN	••	•••	••	••	••	••	•	••	••	Monitoring
SRI LANKA	•	•	•	••	•	•	•			
THAILAND	•••	•••	••	••	•••	•••	•••	•	•	Full Field Programme

NOTES

(1) Consultants' assessment - • fair
•• good
••• very good

(2) May apply to only one region within a country

(3) Rated from point of view of alternative to solar

Table 14.2 Assessment of Short-listed Countries

- **Mexico**

There is a strong government solar energy programme and considerable interest in solar pumping. Experience in the field is extensive and photovoltaic system manufacture is well advanced. Large areas of the country are arid and have good solar conditions although pumping heads are high. A large market for solar pumps is anticipated by local agencies, although one factor which may adversely affect the economic viability of solar pumps in Mexico is that the country is well endowed with its own oil reserves and the costs of engine pumps are low. It is considered that a programme for technical evaluation should be established under the Project and also that solar pumps which will be installed in Mexico under other programmes should be monitored by the UNDP Project. The potential market should be examined more closely.

- Pakistan

There is a large demand for water pumps and hydrological and solar conditions are attractive for solar pumps although some farming practices would need to be altered to match their outputs. In some areas replacement of Persian Wheels by solar pumps may already be close to being economically viable. There is already a high level of activity in demonstrating and evaluating small solar pumps with plans for their widespread introduction. In view of this, it is considered that Phase II of the UNDP Project should monitor and evaluate the performance of the existing and new solar pumps supplied by other agencies.

- Sri Lanka

A large potential for solar pumps has not been identified and generally solar pumping is not seen as a high priority by the government agencies concerned with energy, although there was interest from those responsible for water supply. Solar pumps for irrigation do not appear attractive compared to small kerosene pumps presently in use. On the basis of the information obtained it is not proposed that Sri Lanka should participate in Phase II.

- Thailand

There is a considerable government interest in rural development and the need for small scale pumps for irrigation and water supply is well appreciated. Hydrological and solar conditions are attractive, particularly in the north and north east and data on the solar regime is comprehensive. There is a broad experience in solar energy R & D, good scientific and technical resources and extension services, and under the stimulus of the Project some national agencies have procured pumps for installation in 1983 to the performance specifications prepared by the Consultants for use in Phase II Preparation. It is considered that solar pumps should be technically evaluated and demonstrated and operational assessment field trials undertaken. It will be important to define management responsibilities clearly.

14.7 Assessment of Phase I Countries

14.7.1 General

Mali, Philippines and the Sudan were selected by the UNDP for participation in the field trials organised in Phase I. A number of solar pumps were installed in each country in 1980 and performance data were collected. The field trials have continued through Phase II Preparation and each country has been visited twice by the Consultants (late 1981/early 1982 and early 1983). As explained earlier, a solar pump installed at Sadat City in Egypt by others was also monitored under Phase II Preparation and this site was visited twice.

The first four sections below give a resume of the position with regard to the trials in each country in early 1983, while the proposed involvement of the three original Phase I countries in the Phase II field programmes is outlined in Section 14.7.6.

14.7.2 Mali

Three photovoltaic pumps were installed in Mali during Phase I of the Project and, in addition, an existing photovoltaic pump, which had been installed by Mali Aqua Viva, was monitored. At the completion of Phase I in May 1981, the Photowatt pump at Korofina had failed and a replacement was awaited from the manufacturer. The SEI system was at the Laboratoire de l'Energie Solaire (LESO) and a test rig was under construction. The Pompes Guinard pump at Yangasso and the Briau pump at Babougou were operational but it was reported that these sites were too far from Bamako for the LESO to make monitoring visits unless transport could be provided.

Visits were made to Mali by the Consultants in February/March 1982 and February 1983. During the first visit performance measurements were made of the Briau and Pompes Guinard pumps and on the subsequent visit the Briau system was found to be still operating and in use, although no performance data had been collected. A second motor pump set of different design had been installed at Korofina by Photowatt in March 1982 but this also failed. However, the Korofina area is to be redeveloped and will no longer be a suitable location for a solar pump.

It is understood that no further visits to the Pompes Guinard system at Yangasso have been made since the Consultants' visit in March 1982, and the monitoring instruments have been returned to LESO as there appears to be little possibility of obtaining additional data. Some good data were obtained from the SEI system installed on a test rig at LESO before the motor pump unit failed and it has not been replaced.

14.7.3 Philippines

During Phase I some useful data were gathered from two of the four systems operating in the field by the then Centre for Non-conventional Energy Development, while the third system was hampered by a high suction head and the fourth suffered from persistent electronics problems. There was a major organisational change in late 1981/early 1982 which lead to the establishment of the Energy Research and Development Centre (ERDC) of the Philippines National Oil Company and a number of senior staff changes.

Coupled with problems over transport, these changes meant that plans for relocation of the three working systems could not be followed through and so little additional performance data was obtained.

Visits were made to Philippines by the Consultants in February 1982 and February 1983. After review of the situation with senior management and in view of the continued commitment of the staff directly involved and with full appreciation of the problems involved in obtaining field data, agreement has been reached in principle for relocation of systems for use in agricultural, water supply and training situations and the prospects are now good for obtaining performance data and operational assessment information. Climatic conditions and water demand patterns in parts of the Philippines are not ideal for solar pumps and so it is considered important to verify their potential on the basis of good data. Such activity will complement the ERDC's ongoing programmes for the demonstration of PV power for refrigeration, ice making and general village lighting.

14.7.4 Sudan

Four solar pumps were installed in the Sudan in Phase I in collaboration with the Energy Research Institute, Khartoum. Three photovaltic systems were installed at a farm in Butri and one thermal system was installed at the Energy Research Institute field test station at Soba. Visits were made to Sudan by the Consultants in October 1981 and February 1983.

Of the three photovoltaic systems one (supplied by Arco Solar) operated almost faultlessly until it was accidentally flooded, one (supplied by ITC/SolarCorp.) suffered from persistent binding problems because of tolerances were too small, while the third (Soterem) was never completed because of loss of and damage to components. Although the thermal system worked for short periods it could not be made to operate satisfactorily continuously because of a thermodynamic problem resulting from the high temperature of the ground water used as the condenser heat sink.

Some very good performance data were obtained during Phase I but since the departure of the Consultants' resident engineer no additional data have been collected except at the time of subsequent visits by the Consultants. The main reason for this lack of data collection was logistical. Recently the three photovoltaic system at Butri have been removed to the Soba field station where a lined open well is being constructed. In early February 1983 the well had been dug and was in the process of being brick lined. A surface water reservoir and overhead storage tank have also been constructed. When the construction work at Soba is completed the Energy Research Institute plan to install the Soterem system to pump water from the well to the surface reservoir and then to use the Arco Solar system to pump water from the surface reservoir to the overhead tank.

14.7.5 Egypt

During Phase II Preparation the opportunity arose to monitor a solar- powered irrigation scheme installed at the American University in Cairo (AUC) Desert Development Demonstration and Training Site at Sadat City. The system comprises an array of 96 ASI-16-2000 photovoltaic modules (3.3 kWp) and a deep well dc pumpset incorporating a progressing cavity pump delivering water through a head of 49 metres into a storage tank. A dc surface pumpset is used to pump the water from the storage tank through the drip irrigation scheme as required. Control logic and 24 kWhs of battery electrical storage is present.

The monitoring equipment was installed by the Consultants in October 1981 but a number of component failures mainly arising from vibration problems in the dc well pumpset and building work carried out on the pumphouse prevented the AUC commencing monitoring until August 1982. The system was also out of service during January 1983 as a result of a shaft failure in the well pumpset. However, useful data on the performance of this type of pumping system was obtained including the efficiency of progressing cavity pumps under field conditions and on control logic performance. The well motor/pump set was found to be 60% to 70% efficient, demonstrating the good potential of this type of pump. Monitoring is continuing.

The site was visited again by the Consultants in February 1983 when further monitoring and instrument calibrations were undertaken.

14.7.6 Involvement of Phase I countries in the Phase II field programmes

Despite a number of disappointments, difficulties over transport and provision of staff for work in the field, exacerbated by poor communications, it is concluded that the current interest of the participating institutions in Mali, Egypt, Sudan and Philippines in the Project and their determination to continue with evaluation of the technology means that contact between the Consultants and each participating institution in these three countries should continue in Phase II.

The Consultants propose that a field programme for each country should be prepared which incorporates a suitable combination of the different elements in the full field programme, the limited field programme and the monitoring and evaluation programme. As an absolute minimum, such a programme would include:

- the maintenance of written communications between the Consultants and each participating institution;
- visits by the Consultants to each country;
- relocation of reliable working pumping systems to sites where they will be actively used by farmers for irrigation, or villagers for water supply, or for the education/training of students or extension workers at appropriate colleges, or demonstration purposes at training centres;
- cumulative and some continuous performance measurements on systems provided by the Project or suitable system(s) supplied by other projects;
- if appropriate, relocation of monitoring instruments onto other working pumping systems which may be or already have been supplied under other projects;
- some operational assessment leading to improved understanding of the potential market for PV pumping systems in each of the Phase I countries.

Depending on circumstances, consideration would also be given to providing additional new PV pumping systems.

The application of these principles in each country will of course have to be agreed with each of the participating institutions.

14.8 Additional Countries

In the view of the Consultants there are also other countries which could be considered as potential participants in the Project and these are listed in Table 14.3.

There were no resources available within Phase II Preparation for the collection of information about them and the Consultants consider that before Phase II starts it would be reasonable to check on their level of interest in order to establish a 'reserve' list in case one of the short listed countries does not participate.

Country	Reasons for Interest
Botswana	- Large arid areas with water pumping required for village supply - Photovoltaic pumps installed - Institutions interested in and involved with solar pumps. - excellent solar regime
China	- Potential, given government support, could be enormous - UNDP solar and wind progress underway - All components manufactured in country (including PV cells) - excellent solar regime in certain provinces
India	- Immense potential market (solar & hydrological conditions very attractive) - Large government supported programmed within field - All components manufactured in country (including PV cells).
Nigeria	- Has expressed interest in joining Project - World Bank agricultural project already has solar and wind pumps
Somalia	- large number of small PV pumps installed and in regular use - good solar regime
Zimbabwe	- has expressed interest in joining project - very large rural water supply programme - good potential for solar pumps - strong government interest - solar pumps already installed

Table 14.3 Additional Countries Which Might be Considered for Phase II

15 LOCAL MANUFACTURE

15.1 Introduction

15.1.1 Background

As part of the Consultants' consideration of the advancement of the application of solar water pumping, a preliminary assessment was made of the broad and important subject of local manufacture and the technical, management and contractual conditions necessary for the successful transfer of the technology of manufacture from the developed to the developing world. As a subject, it did not flow specifically out of any one aspect of the work in Phase I or the other activities in Phase II Preparation but was recognised by the Consultants, with their general experience of the adoption of other appropriate technologies in the developing countries, as a topic of great importance which would benefit from preliminary study at this stage of the Project.

It was also recognised that the general credibility of the conclusions for the economic studies reported in Part C rested to some extent on successful local manufacture, in that in these studies an implicit assumption had been made that maintenance and repair could be carried out at modest prices and that replacement parts would be available when required.

15.1.2 Importance of Local Manufacture

Local manufacture is important for the following main reasons:

- when undertaken responsibly, the installed cost of locally manufactured solar pumping systems will be lower than that of imported equipment after taking account of reduction of shipping costs and import tariffs etc.
- for solar water pumps to be used widely with confidence in the developing countries, it is important that the skills and facilities for the maintenance and repair of the equipment should be available locally, and these are much easier to support if there is a local manufacturing base. Delays while spare parts are imported are not acceptable.
- it maximises the proportion of total cost incurred within the country, reduces the numbers of imported items and thus improves the balance of payments.
- any modifications required for the particular applications in the region or country concerned will be more readily made.

Other benefits which flow from local manufacture include the stimulation of related enterprises, the creation of jobs, the upgrading of technical and industrial skills and the development of greater self-reliance.

Since much of the present expertise lies within companies in the developed world, the realisation of these benefits depends on resolving the problems inherent in the complicated process of transferring the technology of manufacture.

15.1.3 Prior Conditions

Before any serious expenditure is incurred in transferring manufacturing technology by either the host country or the companies concerned, certain conditions must be met. These are:

- an economic case for the use of solar pumps must be already established through preliminary market surveys undertaken to confirm that pumps can be made locally for prices at which they are economically viable.
- the prices for which locally produced pumps were sold are less than the prices of imported items.
- the product is technically appropriate for the hydraulic duties of the main applications envisaged in the country concerned.
- finance can be provided at the appropriate time to make these capital intensive units affordable by the people who will benefit from using them.

The matters were referred to briefly in Chapter 11, are included among the activities recommended for Phase II (Chapter 13) and are discussed again later in this Chapter in the context of the responsibilities of the local company.

15.1.4 Objectives of the study

It was agreed that a brief desk study should be made of the technical, management and contractual questions which need to be resolved if solar water pumps are to be made in the developing countries and that this would provide a starting point for discussions in Phase II with manufacturers in the developed countries and companies in the developing countries keen to expand their businesses.

It was not possible to undertake case studies of specific systems with any developing country manufacturer, and this desirable aspect of the study will have to await Phase II of the Project.

Since only photovoltaic pumping systems are being produced commercially (in contrast to thermal systems), attention was naturally concentrated on this type.

As has been stressed above, investment in local manufacture should only be made after the preparation of acceptable estimates of the size of the local market and its sensitivity to the price of the product. The marketing aspect was not within the scope of this initial study however, which was directed to the feasibility of local manufacture per se.

A fuller discussion of the complex issues linked with the transfer of manufacturing technology will be found in Supporting Document 5. Section 15.2 considers the more technical aspects, while Section 15.3 discusses the management aspects of technology transfer.

15.2 Technical Aspects of Local Manufacture

15.2.1 Approach

In view of the relatively small resources which could be devoted to this preliminary study, it was agreed with the World Bank that progress would best be made through discussions with two European manufacturers of pumps and motors (forming part of solar systems) which also had experience of manufacture within the developing countries.

Accordingly, visits were arranged to two German firms Messrs. Klein, Schanzlin and Becker (KSB) and Pleuger, one of which (KSB) had provided equipment to the Consultant for Phase I and Phase II Preparation. Discussions ranged over each of the factors listed in 15.2.2 below and the problems faced in setting up and operating manufacturing plant in the developing countries.

Examples from the current product range of KSB and Pleuger were examined and certain features of these are quoted below to illustrate points in the argument and make the report more immediate. The suitability of some of these features for manufacture in the developing countries is then briefly discussed.

It must be emphasised that, while the Consultants believe that the two factories visited are typical of good modern manufacturing practice, neither the visit of the Consultants nor the examples quoted should be taken as recommendation of either of the Companies, or particular practices in relation to design, materials or methods of manufacture. Nor should it be thought that the appearance of a particular feature in a product built in Europe means that it is necessarily applicable to all pumps, or is appropriate for manufacture in the developing countries.

The point of this exercise was to see what two respected and competent manufacturers with extensive overseas experience actually did and what they thought was feasible in the developing countries.

15.2.2 Important technical factors

The study considered that the following technical factors were of particular relevance to the satisfactory transfer of manufacturing technology:

- design features
- materials (and local availability)
- manufacture and assembly procedures
- quality control

The significance of these factors in relation to local manufacture is discussed in turn for PV modules, support structures, motors, and pumps.

A further section discusses thermal systems.

15.2.3 PV Modules

General

The technology of the conversion of sunlight to electric power is developing very rapidly and new materials and production processes are under active development (see Section 5.3.3). The production of cells will continue to be a capital intensive high technology process involving few people. The Consultants consider that developing countries which have identified applications for PV power which could be economic within five years (say) should maintain a watching brief and a technical position from which progress can be evaluated and informed decisions made about the desirability of investment in local manufacture.

A decision to invest will of course, depend on the size of the market for photovoltaic power sources which, in addition to pumping will probably include other applications like communications to remote areas, small scale refrigeration for medical purposes and village lighting. Potential market applications should be confirmed through market surveys and if these are positive, consideration can be given to the relative costs of importing complete modules or the possibility of organising the facilities needed to import the cells and assemble them into modules. The scale of production at which this becomes a viable proposition depends on many factors eg size and growth of total market, costs of imported cells, labour costs, technical skills and infrastructure, and policy toward high technology and can only be determined on a case by case basis. Such plans should be based on commercial judgements rather than ones of technical or political prestige.

Design

Each module consists of a number of cells connected electrically and encapsulated in a transparent resin or laminate between a top sheet of glass and a bottom of either glass or, more usually, aluminium coated externally with plastic. The sheets, are sealed at the edges, the whole assembly being mounted within a metal frame (usually light alloy) to provide strength. Continued high performance depends on good electrical connections between the cells, the use of matched cells in the module, effective sealing of the edges of the sheet, and properly mounted electrical connection points at the back (or side) of the module.

Materials

For the great majority of countries the only items which will definitely have to be imported are the PV cells. It will be particular important for the importing country frequently to check the I-V characteristics of the cells, for the efficiency of the module depends critically on them being well matched and on each having a good 'Fill Factor'. India and Brazil have started to manufacture the cells themselves and some other countries are considering the assembly of modules from imported cells.

Manufacture and Assembly

It is vital to make good electrical connections between the cell, to exclude air from the layers between the sheets and the cells, and to seal the laminates properly at these edges. These tasks require care, extreme cleanliness and attention to detail. There is no reason why, after proper training, these tasks should not be done as well in the developing countries as in the developed ones.

15.2.4 Array support structure

Array structures can be very simple in the case of small mobile installation, but will tend to be large and complicated in the case of tracking systems. It should not be assumed that materials with a low risk of corrosion such as anodised higher alloy extrusions are necessarily more economic in life cycle terms than (say) rolled steel alloy sections which are cheaper and available in the local market, and different materials should be evaluated. Wood is an obvious candidate.

These should be no problem over the manufacture of support structures in the less developed countries, shipping costs will be saved and the end result should be considerably cheaper.

15.2.5 Motors

a) Design Points

Permanent magnet dc motors are normally used for driving the pumps in the range of systems sizes of interest to the Project. They are generally either surface mounted or submerged below the pump in a combined unit. In the former configuration the motor is necessarily air cooled and up till now, motors utilised in the latter configuration have also been air filled. If the external water pressure is high the design of the seals is critical and these are often rather complicated. AC motors are sometimes water filled to overcome this, a flexible bag in the base of the pump transferring the external pressure to the internal water and to reducing the differential pressure across the seals: this solution is obviously unsuitable for brushed dc motors, but might be applicable with brushless permanent magnet dc motors. Although ball bearings are in common use, they do pose sealing and lubrication problems and it would be worth looking into the manufacture of hydrodynamic bearings.

One of the design points which has been debated most strongly is whether it is better to use brushed or electronically commutated motors. It is considered that there is no intrinsic reason why electronically commutated motors should not prove reliable and be used successfully in the developing countries. The relative efficiencies of the two types of motor are difficult to predict and will depend on the quality of maintenance: brushes which are allowed to wear or are replaced out of alignment will cause low efficiencies, but the voltage drop across electronic switching devices may be higher than across well adjusted brushes.

b) Materials

A wide range of materials is used in some of the motors manufactured in the developed countries, but a developing country will obviously wish to minimise the value of materials imported.

There would seem little alternative to the import of the permanent magnet materials if the high efficiencies required of motors for cost-effective systems are to be met (whether the motors are brushed or brushless). The same will apply to copper wire (if not available indigenously) and also to the high quality insulation required.

Other items which may need to be imported in many cases include:

- armature stampings
- ball bearings
- mica insulation material
- specially extruded copper for commutator bars
- carbon brushes
- electronic components
- large and/or intricate injection moulded plastic parts

Mica will be available as a local resource in some countries and its preparation is labour intensive.

c) Manufacture and Assembly

The repair and rewinding of motors is almost a cottage industry in many developing countries and the assembly of complete units is not seen as a different problem.

Many of the operations used by European manufacturers are done by hand and are capable of being carried out effectively by local companies. Hand operations which stand out as being particularly suitable for labour intensive manufacture include:

- Assembling stator and rotor packs
- Filing the stator slots smooth (where liners are not used) to ensure no damage occurs to insulation of windings.
- Inserting windings .
- Forming electrical connections and making cable joints watertight.

European manufacturers buy in the armature stampings and the relative costs or import of local manufacture would have to be assessed for each individual case: manufacture to the tight tolerances required might prove difficult. (other techniques, like chemical etching, could be examined).

Unless a developing country already has the facilities to produce large and intricate injection moulded plastic parts, their use in solar water pumping systems will probably not be cost-effective. Where injection moulded components are vital (for dimensional reasons, or balance, or quality of material) they may have to be imported but for some parts not requiring tight tolerances, it might be possible to substitute moulded fibreglass and resin laid by hand on wooden formers.

Motors are the type of product in which the staged introduction of the assembly of sub units and then whole units, and the gradual substitution of imported by local manufactured parts is quite feasible. This is elaborated in Section 15.3.2.

15.2.6 Pumps

a) Design Points

The pumps of interest to the Project are mainly of the centrifugal type for low and medium heads and reciprocating piston pumps for high heads. Progressing cavity (or screw) pumps may also have applications.

Centrifugal pumps are already made in a number of developing countries and their manufacture in countries like India and Brazil is an industry of some national significance. Although hydraulic efficiencies may improve marginally in the future by production of smoother flow passages, by additional care over details of pipe and valve configurations and by the elimination of foot-valves, major advances in the hydraulic aspects of design are unlikely. A difficult point is the trade off between high efficiency and close tolerances and the ability to handle silt laden water and the consequential need for greater tolerances resulting in lower efficiencies.

Hydrodynamic bearings are sometimes used - although they rely on precise clearances the bearings can be moulded without the expensive equipment needed for ball bearings (for example).

Piston pumps, although simple in concept, may pose considerable problems in manufacture, because high efficiencies demand very close tolerances and smooth rubbing surfaces to minimise friction. Manufacturing techniques may be difficult to introduce and materials may need to be imported.

b) Materials

Some of the most interesting advances in pump design have been in the field of materials. The range of materials used at present by European manufacturers includes:

- castings of cast iron, bronze, or injection moulded plastic
- impellers made from bronze, cast iron, stainless steel, or injection moulded glass filled plastic (with bronze inserts to minimise wear on leading edges)
- journal bearings of chrome steel, bronze, gunmetal, carbon filled plastic (or resin) and fluted rubber
- thrust pads of plastic coated 'ferrobestos' or carbon filled plastic mouldings.
- honed brass cylinder liners for reciprocating pumps

There is no reason why the casings and impellers of centrifugal pumps should not be made in developing countries out of the traditional materials of cast iron and bronze in which they have centuries of experience. Bronze or gunmetal is the obvious material for journal bearings, provided they are adequately sized, although some countries might have difficulty with the supply of the copper tin or other alloys needed. The motor/pump assembly as a whole will need long-lasting thrust bearings and there may be advantages in importing proprietary 'ferrobestos' pads if this can be justified on economic life cycle terms. It may also be necessary to import shaft seals. There should be no problem over the use of hardened steel for the main shaft, although alloy steel might pose problems.

c) Manufacture and Assembly

Fortunately, the art of casting metal is an ancient one and foundries capable of producing complicated shapes are available virtually world wide. Thus there is no fundamental problem in casting radial or mixed flow impellers in bronze or pump bodies in cast iron in many developing countries. Sand casting gives a rough finish to the flow passages and with plentiful labour it could be economic to smooth and fettle these surfaces by hand and produce impellers with better hydraulic characteristics than those made in the developed countries.

Machining operations on shafts or plain bearings can be done locally at an early stage in the development of the facility.

In European manufacture the tube within which the motor/pump tubewell units are assembled is sometimes spun over at the ends and this must make dismantling for repairs very difficult. This practice should be avoided particularly for products destined for use in developing countries.

The assembly of centrifugal pumps and motor/pump units is not seen as a problem provided, of course, that quality has been maintained throughout (in particular the quality and balance of the rotating parts) and adequate training has been given.

The manufacture of reciprocating pumps may present problems. Honed brass cylinder liners need to be finished to very close tolerances, together with accurately ground valves and valve-seats and complicated transmission systems. In total, a pump of this type may well require more accurate machining and assembly work than centrifugal types.

15.2.7 Quality control

The maintenance of standards for quality of materials and dimensional tolerances is a crucial part of the manufacturing process and an important facet of this will be the authority accorded to those who carry out the inspections and their personal integrity. In general it may be necessary for the foreign supplier initially to provide the appropriate inspection gauges and test rigs to achieve these standards, and in all probability to second a technician (with quality veto authority) to oversee operations in the local company in the early years.

Typical operations to check on quality include:

- dimensional checks on all important components
- checks on material specifications
- tests on quality of insulation (of copper windings especially)
- tests on performance of imported components (eg PV cells)
- performance tests on assembled PV modules
- test on quality of corrosion resistant coating applied to magnetic parts
- dynamic balancing of all rotating parts
- testing high voltage breakdown resistance of electrical connections under hydrostatic pressure
- performance tests on selected motors and pumps
- performance tests on selected motor/pump units.

It is understood that in the well established factories in developing countries where there has been a planned programme of development with adequate time spent in training and building up the local operation, there is no problem about maintaining quality standards to full national (e.g. BSI, DIN) or international (ISO) requirements.

15.2.8 Thermal systems

Although the development of solar thermal powered pumping systems is not as advanced commercially as PV systems, this Report would not be complete without a brief reference to the problems of local manufacture of this type of system.

The concept of expansion engines has been around a long time and is familiar; however, the technology required to make them should not be underestimated. As indicated above, close tolerances and high surface finishes are required and the engineering skills needed to produce a thermal system are of the same high order as those needed to produce electric motors and pumps.

However, just as the skills required for the manufacture of motors and pumps are available in the more industrialised of the developing countries, so there is evidence of the presence of the skills needed for thermal systems. Indeed a number of thermal systems have been under development in India and elsewhere and all the components have been made locally.

15.3 Management Aspects of Technology Transfer

15.3.1 Introduction

This section focuses on a different set of questions of a management nature - those raised by the technical procedures associated with transferring a manufacturing capability to developing countries and the contractual and financial arrangements which would best provide the essential support to such transfers.

Technology transfer is a complex process. Relatively little practical experience has been obtained of the transfer of technology for the specific types of components required in solar pumping systems, and it seems certain that the transfer process will necessarily be gradual and require a good deal of flexibility.

In the sections below, the Report outlines some of the more important management aspects of transferring and establishing a capability to manufacture solar water pumping systems in developing countries.

The Report does not attempt to allocate responsibility for the various activities which are identified or proposed. Although governments will necessarily be involved in some of the decisions, no part of this section of the Report should be read as implying that government can or should attempt to do everything.

15.3.2 Phases in development of manufacturing facility

Based on the experience gained by a few firms based in the developed countries which have established successful manufacturing operations in the developing countries, it is possible to identify a number of distinct phases in the transfer of manufacturing technology:

i) The initial start up is often made via the establishment of repair shops to handle normal servicing, maintenance and repair operations on imported equipment;

ii) As the local company accumulate technical skills and know-how, the local fabrication of spare parts requiring frequent replacement may be undertaken either in house or by sub-contract. Quality control standards are established.

iii) In time, local spare parts supply is regularised and extended. Further training and investment in new capacity are part of a strategy which allows for an increasingly wide array of more complex replacement parts to be made by the firm or purchased from other local suppliers. As this progresses, strict attention to quality control has been maintained.

iv) In the next phase, the emphasis changes to the assembly of major components and then of complete products, with individual parts being procured partly by local manufacture and partly from the foreign supplier. As this stage develops, inspection and test procedures will need to be firmly established, with key test equipment probably coming from the foreign suppliers.

v) With further training and investment a planned programme is followed in which a greater proportion of the parts required for the complete product are made or purchased locally, until the local company is entirely responsible for manufacture, with only a few specialist items being imported.

Such programmes of manufacturing "localisation" by progressive "deletion" of the numbers of parts imported have been pursued by firms based in developing countries for a number of years. Though there will be a number of differences with regard to solar pumps, it is the Consultants' view that a similar strategy could be successfully followed for them as well. This is particularly true in relation to the electric motors and pumps. As noted in Section 15.2 the PV arrays could be assembled from imported cells.

15.3.3 Application to Particular Developing Countries

Although for convenience a complete developmental strategy is outlined above, it will be appreciated that every developing country is different and will wish to adapt the process of transfer to its individual circumstances.

The approach of different countries can be divided broadly into three. Firstly there are those with a reasonably developed and strong manufacturing base already which, although they might not make exactly the components required for solar water pumps, will not find it difficult to adjust their production to suit. Just as in Europe and North America, so in the developing country one of the component manufacturers will probably take the lead and buy in the other components needed for a complete system. Alternatively, if the general technological base is strong, it is also possible that a separate entity with a systems design capability could specify the designs required, procure the components, organise assembly and market the complete system in its own name.

Secondly there are countries with recently developed motor and/or pump industries, and a deliberate choice will need to be made about which of them should be the basis for manufacture and assembly of the complete systems. It is suggested that normally this should be the industry which is most advanced in the manufacture of its components: if the choice is not obvious it is suggested that the operation should be based on the entity making pumps. A considerable degree of technical support will be needed from outside the country and it will be essential for the local firm to have access to the knowledge which will enable it to appraise systems capability and to procure components which will provide the required performance.

Thirdly, there are countries which would virtually have to start from scratch. If the solar regime was exceptional and the applications were overwhelmingly suited to solar water pumps, the lack of an industrial base would be a problem which would have to be overcome by a combination of well managed inputs from the foreign supplier and by level entrepreneurial skills, backed by Government support. In such cases the choice of options is very limited and the local company would probably have to start by establishing a repair facility with a strong support of the foreign supplier. Initially there might be no local entity to which a foreign supply offering systems appraisal expertise could relate, and so a programme of workshop training would need to be organised in conjunction with local technical colleges and training institutions. At least one properly staffed and equipped repair workshop should be established before pumping systems are marketed in strength.

Given the very wide variety of developing countries in which solar pumps may be feasible, it is clearly difficult to forecast the time scale which would apply for local manufacture, for this will depend on the anticipated market and the basic scientific and engineering infrastructure existing in the country concerned. Assuming a steady (rather than explosive) growth in demand it would be unrealistic to expect the overall period to be satisfactorily accomplished in less than five years: at the other extreme, it should not take more than 10 - 15 years.

15.3.4 The importance of innovation and information

In this section a number of background issues to technology transfer are introduced.

a) A distinction between productive and innovative capacity

Technology transfer can be used by local companies to acquire not only the capacity to operate and maintain production systems but also (and more importantly) the ability to improve/adapt the manufacturing process and its products. The two types of capability are very different. Traditionally, developing countries have acquired only productive capacity from foreign suppliers of technology. A good deal of evidence exists which shows that firms which only acquire operating capacity tend to stagnate and remain technologically dependent (Refs 18 & 19). Productivity gains over time are small, considerable inefficiencies build up, and there is a general failure to develop or improve their products.

As a long term objective, it is important that local companies be encouraged to explore the possibilities of acquiring innovative as well as productive capabilities. The recipient firm should adopt a more positive approach towards identifying foreign suppliers willing to allow the recipient firm access to know-how and to provide training, and developing country governments and international agencies should be prepared to provide the type of incentives and technical support needed to make such a transfer project succeed. The attitude of the foreign supplier will be crucial to such success, and the local company will have to recognise that the foreign company also has legitimate interests.

b) The dissemination of international knowledge

The knowledge gained from projects of this type are in two main forms, firstly there is 'hard' know how which can be put in written or visual form; and secondly there is 'soft' knowledge whose essence lies in the understanding and experience gained of the way in which systems behave and of the methodologies evolved for studying comparative economics. Clearly it is easier to communicate the 'hard' knowledge than the 'soft' in the form of specifications, reports, handbooks and drawings but it is the 'soft' knowledge which is probably as important in developing the innovative capacities of recipient companies, and this is more readily transferred by person-to -person contacts through training courses and the like.

The knowledge gained in this Project is the intellectual property of the UNDP and in its 'hard' form is published for the benefit of all. Local companies keen to acquire an understanding of the technology are clearly eligible to receive the 'hard' form of information, but care will need to be exercised in defining the rights granted to recipients to exploit the 'soft' form of knowledge and the end users for whom the technology is intended to benefit. It may be helpful for the UNDP to consider its role in relation to the equitable distribution of its intellectual assets and the training courses which should be organised.

The development of the technology will not stop with this Report and it will also be necessary to find a way in which cooperation with the manufacturers of the present generation of systems (the foreign suppliers) can continue if the full benefit of future technical advances are to be realised.

c) Technology search and the need for an 'Informed Buyer' capability

In the field of solar pumping technology, potential local company assemblers or manufacturers are going to be faced with a variety of alternative sources of supply. There are obviously going to be some inherent difficulties for the local firm in selecting the most appropriate supplier or combination of suppliers. Experience from technology transfer in other sectors (Ref 20) suggests that it is crucial for potential buyers to undertake a comprehensive technology search which allows them to identify and evaluate as many different alternatives as possible. This is necessary to avoid the high opportunity costs that could be incurred if the best supplier is not identified.

This situation suggests that local company recipients must develop an "informed buyer" capability which will allow them both to specify their requirements and to evaluate the alternatives on offer. Necessarily this would require recipients to develop or have access to a certain degree of technical expertise in solar pumping technology and its appraisal even before the transfer process beings - an obvious area where some form of external assistance will be needed.

Clearly the costs of technology search are going to be high in the short run, but experience from other sectors suggests that the long term benefits would be considerable. This will be aided by the provision (in Phase II) of guidance in handbook form. An 'honest broker' service to supplement the guidance manual approach should be considered.

d) The local market

Implicit in the search for the right technology to transfer are the requirements of the local market: is no point in transferring the technology to manufacture solar water pumps if the product does not match the pumping needs of farmers and villagers where the pump could be used. The local firm will need to conduct its own market surveys to establish the hydraulic duties and design features required, the price people are prepared to pay for water for agricultural and domestic purposes, and the costs of water delivered by solar pumps under a range of conditions.

e) The functions of the local firm

Before discussing the various contractual mechanisms for technology transfer which can be employed, it will be useful to list for reference the range of responsibilities which a local firm would need to consider as part of its overall operation. These are not given in order of importance or in a time sequence for many are interdependent and need to be progressed together:

o market surveys of the hydraulic duties required, economic price levels for water, cost of water delivered, government polices on subsidies

- development of systems appraisal capability and the specification and selection of hardware to meet the technical and economic requirements of the market.
- assembly and manufacturing operation for motors and pumps including quality control, and acceptance tests. (Assembly of PV modules only if appropriate)
- marketing of pumping systems and organisation of servicing facilities
- planning of growth and development of the local firm and its relationship with foreign supplier.

A local firm would need to consider carefully what might be done for it under contract by other local entities, individuals or foreign experts but one over-riding priority is that there should be one person (or a small group) who has overall responsibility. Government assistance will probably be necessary but the firm should remain essentially independent with a strong market orientation.

15.3.5 Contractual mechanisms for technology transfer

The straightforward export of solar pumps from developed countries to the developing countries is not thought to be appropriate in the longer term and some form of association linking the foreign supplier in the developed country to the local firm has to be devised. The term "framework for partnership" is used to describe this linkage.

There are a variety of contractual-financial arrangements encompassed within a "framework for partnership" through which developing countries could acquire solar pumping technology and the following would seem to be worth exploring:

a) To invite a foreign supplier to establish a wholly owned subsidiary in the developing country.

b) To establish a joint venture between a foreign supplier and a local firm with suitable management, financial structure and outlook, where both share equity.

c) To have an independent local firm license the technology at arms length from a foreign supplier.

d) To have an independent local firm or government enterprise conclude technical services agreement with different foreign suppliers, the recipient to be highly selective and specific about the types of support it required.

e) A variant on (d) would be to have an independent local firm purchase equipment for repair, assembly and manufacture from foreign suppliers to allow development of local productive capacity in planned stages.

f) A final option would be for the host government to establish a national company charged with the responsibility for importing the technology on the best terms and offering assistance to local firms in setting up facilities.

The advantages and disadvantages of each of these mechanisms are discussed fully in Supporting Document 5, but it is considered that a joint venture mechanism should give both partners sufficient incentive to make a success of the venture (Refs 14 & 21).

A "Framework for Partnership" can incorporate many different permutations of the various mechanisms listed above. Precisely what these should be will depend on the objectives of the foreign supplier, the capabilities of the recipient and the size of the market. These may change as the local operation progresses through the phases outlined in Section 15.3.2. Whatever mechanism is established the full-hearted commitment of the parties is probably of greater importance than the precise terms. There are at least three areas where the depth of their commitment to each other will be crucial:

a) To ensure effective assimilation and long term viability, local participation in the transfer process and in subsequent manufacturing operations must be maximised. This means getting local engineers and technicians involved as early on in the transfer process as possible. (Ref 22).

b) Despite the stress which has been laid on the importance of participation by the local company, the full collaboration of the foreign supplier in the transfer process will be crucial. It will be necessary to ensure that the arrangements incorporated in the 'Framework of Partnership' are sufficiently attractive to the foreign supplier to persuade it to be a full and effective partner. These will have to include payment for services in international currency.

c) It is absolutely crucial for the production of reliable systems which possess the desired performance characteristics to ensure that effective quality control is maintained at all stages of technology transfer, and this aspect must feature in any transfer agreement.

It is important to stress the need for flexibility in setting up technology transfer arrangements. This flexibility should be manifested in two ways.

Firstly, it may well be necessary to change the type of agreement made between recipient and foreign supplier as the market expands and recipient capabilities develop. Secondly, flexibility must be manifested in the types of transfer agreements reached for different components of the system: the requirements for the import and assembly of PV modules will be different from those for motors and pumps.

Clearly, for some time to come there will be a major need for clear cut public sector support at the national and international level. Since the market is still relatively undeveloped in most countries, and because the technology is still new, government support for technology transfer will be essential.

For their part, recipient local firms will have to ensure that they are sufficiently aware of alternatives and sufficiently capable of evaluating alternative technology/supplier combinations.

Finally a strong effort must be made to involve users and operators of solar water pumping systems at the early stage in planning local production to ensure that their special perspectives are incorporated in the design of the final product (Ref 23).

15.4 Conclusions

This brief study was undertaken on the premise that the provision of local repair facilities and a manufacturing base to provide in depth resources are vital elements in the widespread adoption of small water pumping systems in the developing countries.

The main technical conclusions of the study are that:

o For some considerable time to come PV cells should be made in the developed countries, but consideration may be given to importing them and assembling modules in the developing country when the overall market is clear and cost savings will accrue.

- there is no reason why permanent magnet d.c. motors and centrifugal pumps of high efficiency should not be made in the developing countries.
- some items (eg magnetic materials) will need to be imported for a considerable period but these should not represent a large proportion of the total cost.
- full advantage should be taken of the craft skills of local workers and manufacturing processes should be adapted to these to achieve an optimum mix of costs of labour, plant, materials and overheads.
- the transfer of manufacturing technology should follow a planned programme which would normally include the stages of repair, local manufacture of frequently needed items, assembly of components (or sub-components), and then manufacture of most items required for complete motors and pumps.
- appropriate quality control standards must be established at the outset and strictly enforced. The necessary testing equipment to ensure that performance and quality is maintained may have to be provided by the foreign supplier.
- it is important that, from the outset, the local firm should aim at acquiring a capability to appraise and select appropriate pumping systems and also plan to develop an innovative as well as a productive capability.

It should be emphasised that, for a programme of technology transfer to succeed a number of non-technical conditions must also be satisfied. Among the most important of these are:

- full backing by developing country governments.
- equitable financial and contractual arrangements. There are a number of contractual mechanisms which may be used as the vehicle for transfer of manufacturing technology (and that may need to alter as the local entity develops its role) but on balance some type of joint venture arrangement which maintains the interest of both parties is preferred.
- full-hearted commitment by the foreign supplier and recognition that it is in its own interest to make technology transfer succeed.
- careful planning of the progress of transfer in clear stages, to allow the lessons from one stage to be drawn before embarking on the next.
- carefully thought out staff training programmes at all levels. This would include personnel from the local firm going to the foreign supplier and staff from it spending time in the developing country.
- maintenance of international interest in and support of the dissemination of the technology, particularly in relation to the distribution of knowledge for system appraisal and selection.

Support for these relatively optimistic views is to be found in countries like India and Brazil (for example) where motors and pumps to the highest quality standards are made and sold widely at home and abroad. It may be objected they are not typical developing countries, but the point is that manufacturing skills have been built up in them over the last two or three decades and what can be done in those countries can be done in many more.

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Kenya	Mr Peter V. Byrne (Capricorn Consultants Ltd., Nairobi)
Thailand	Dr. Subin Pinkayan (SEATEC Consulting Engineers, Bangkok)

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The Consultants established a purpose designed solar pump test facility for the measurment of the performance of the improved PV pumping systems. This facility contained a number of special features and the Consultants wish to thank firstly Professor Carlo Mustacchi, ADES, Rome for his help with the design, provision and commissioning of the hardware and software to monitor, log and analyse the performance parameters and secondly Dr. Leon Freris, Department of Electrical Engineering, Imperial College, London for his help with the design, construction and commissioning of the PV array output simulator.

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(ii) Bangladesh

Cropping pattern:	"Bangladesh Hand Tubewells Project - Staff Appraisal Report". World Bank Report No. 3280-BD, April 17 1981.
Solar Data	"Estimation of Solar Radiation from Sunshine Hours in Dacca, Bangladesh". A Hossain and E Haider, Renewable Energy Review Journal, Vol 3, No. 1 June 1981.
Wind Speed	Based on data for Calcutta from Renewable Sources of Energy, Vol III Wind Energy. Economic and Social Commission for Asia and the Pacific, United Nations 1981.

(iii) Thailand

Cropping Pattern:	"Thailand Irrigation Project XI" Staff Appraisal Report. World Bank Report No. 2622-TH. November 26 1979
Solar Data	"The Availability of Solar Energy in Thailand" R.B. Exell and K. Saniali. Research Report No. 63, AIT, Bangkok, Thailand (1976).
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2. Pump Performance

(i) Animal Pumps and Handpumps

"Energy Options for Low-Lift Irrigation Pumps in Developing Countries: The Case of Bangladesh and Egypt" D.R. Birch and J.R. Rydzewski. Institute of Irrigation Studies, University of Southampton, U.K, April 1980.

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(ii) Wind

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(iii) Kerosene Pumps

"Joint Evaluation of Wind Energy Utilization" Cross Cultural Consultancy, Intermediate Technology Power Ltd, Jan/Feb 1982.

(iv) Diesel

No referable sources for the performance of very small diesel engines have been located. The small amount of data has been obtained from anecdotal sources and is unverified.

3. **Cost Data**

"Energy Options for Low-Lift Irrigation Pumps in Developing Countries: The Case of Bangladesh and Egypt". D.R. Birch and J.R. Rydzewski. Institute of Irrigation Studies, University of Southampton, U.K, April 1980.

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"Photovoltaic Power Systems for Rural Areas of Developing Countries". L. Rosenblum, W.J. Bifano, G.F. Hein, and A.F. Ratajzak. NASA Technical Memorandum 79097, Feb. 1979.

"Shallow Wells" DHV Consulting Engineers, The Netherlands 1979.

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(Report of UNDP Seminar held in Malawi, December 1982). World Water. January 1983.

4. General Background

Considerable information on irrigation and water practice, costs of infrastructural works, pumps and fuel etc, was collected by the joint World Bank/Consultant Missions to the prospective Phase II countries (Bangladesh, Brazil, Egypt, Kenya, Mexico, Pakistan, Sri Lanka and Thailand). This information is lodged with the World Bank.

5. Project Questionnaires

Detailed questionnaires prepared especially for the economic studies provided information on water use and practice and associated costs in respect of Bangladesh, Kenya and Thailand. The information is abstracted in Supporting Document 2.

APPENDIX 1

Project Management Group
Management Advisory Group

PROJECT MANAGEMENT GROUP

Project Director	Sir Alan Muir Wood	Sir William Halcrow & Partners
Associate Project Director	P L Fraenkel	Intermediate Technology Power Ltd
Project Manager	D E Wright (Chairman)	Sir William Halcrow & Partners
Deputy Project Manager	M R Starr	Sir William Halcrow & Partners
Senior Solar Systems Engineer	B McNelis	Intermediate Technology Power Ltd
Solar Systems Engineer	A Derrick	Intermediate Technology Power Ltd
Solar Applications Engineer	J P Kenna	Intermediate Technology Power Ltd
Senior Test Supervisor	W B Gillett	Sir William Halcrow & Partners
Contracts Engineer	C C J Kropacsy	Sir William Halcrow & Partners
Solar Analyst and Test Engineer	F. Semmola	Sir William Halcrow & Partners
ITDG Executive Project Officer	M F Sinclair	Intermediate Technology Development Group Limited
Project Engineer	M B Aylward (Secretary)	Sir William Halcrow & Partners

MANAGEMENT ADVISORY GROUP

The Management Advisory Group consists of the Project Management Group and the specialist advisors to the Project:

Project Director	Sir Alan Muir Wood	Sir William Halcrow & Partners
Associate Project Director	P L Fraenkel	Intermediate Technology Power Ltd
Project Manager	D E Wright	Sir William Halcrow & Partners
Deputy Project Manager	M R Starr	Sir William Halcrow & Partners
Senior Solar Systems Engineer	B McNelis	Intermediate Technology Power Ltd
Solar Systems Engineer	A Derrick	Intermediate Technology Power Ltd
Solar Applications Engineer	J P Kenna	Intermediate Technology Power Ltd
Senior Mechanical Engineer	A W L Muir	Sir William Halcrow & Partners
Senior Electrical Engineer	W V Pereira	Sir William Halcrow & Partners
Senior Project Engineer	W B Gillett	Sir William Halcrow & Partners
Project Engineer	C C J Kropacsy	Sir William Halcrow & Partners
Project Engineer	M B Aylward	Sir William Halcrow & Partners
Solar Analyst and Test Engineer	F Semmola	Sir William Halcrow & Partners
Irrigation Advisor	P A Browne	Sir William Halcrow & Partners
Industrial Advisor	W Armstrong	Consultant
Solar Energy Advisor	Prof B J Brinkworth	University College, Cardiff
Mechanical Engineering Advisor	Prof P D Dunn	University of Reading
Photovoltaic Advisor	F C Treble	Consultant
Electric Motors Advisor	L L Freris	Imperial College, University of London
Pumps Advisor	D J Saunders	Consultant
Rural Water Supply Adviser	C C Kerr	Sir William Halcrow & Partners
Economics Advisor	K Marshall	Intermediate Techology Industrial Services
ITDG Management Advisor	D H Frost	Intermediate Technology Development Group Limited
ITDG Executive Project Officer	M F Sinclair	Intermediate Technology Development Group Limited

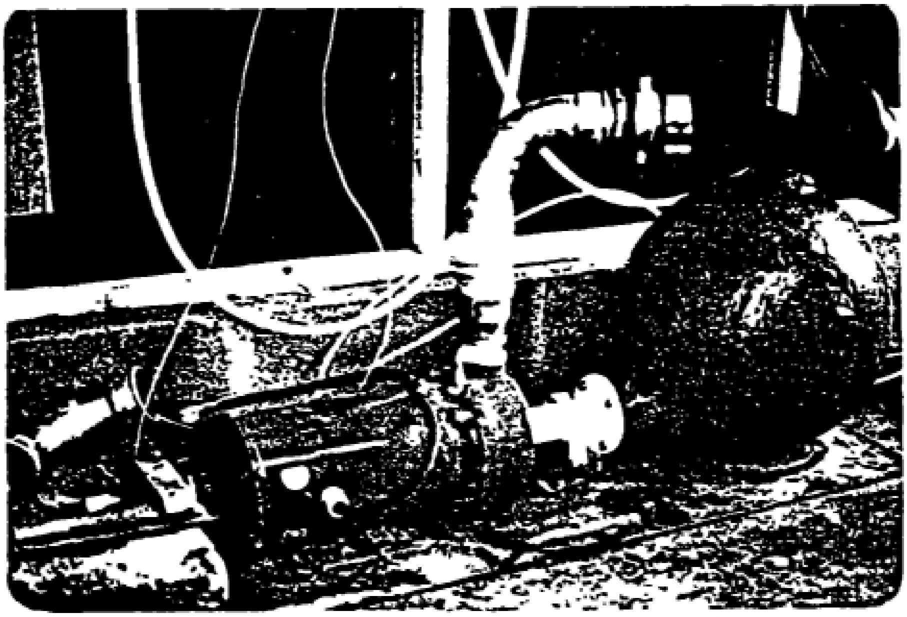
APPENDIX 2

Typical Test Report on
Solar Photovoltaic Pumping System

SIR WILLIAM HALCROW AND PARTNERS
in association with
INTERMEDIATE TECHNOLOGY POWER LTD

TEST REPORT ON SOLAR PHOTOVOLTAIC PUMPING SYSTEM

SUPPLIER:	HELIODINAMICA
CATEGORY:	B



1. SYSTEM DESCRIPTION

Supplier HELIODINAMICA Sa **Category** B

General Surface mounted lightweight unit on steel frame with carrying handles

PV array Heliodinamica HFP19B15 (882 Wp)
9 parallel strings of 5 modules in series (NOT SUPPLIED)

Motor/Pump Modified Honeywell permanent magnet d-c motor (SR 5316-2546) with direct drive to Jacuzzi centrifugal pump having plastic impeller, body and priming tank.

2. TEST RUNS

Static heads (simulator tests)	10, 8.5, 7, 6, 5 (m) (suction lift < 1m)
Static heads (sunshine tests)	none

Remarks Self priming tank has to be filled before use. Stainless steel strainer not supplied. Coarse basket filter used on inlet.

Motor tests Tested over full range.

3. COMMENTS ON INSTALLATION AND OPERATION

Supplier's instructions None supplied

Installation No problems found

Operation Difficult to fill priming tank and monitor water level Inspection/filling hole would be useful..

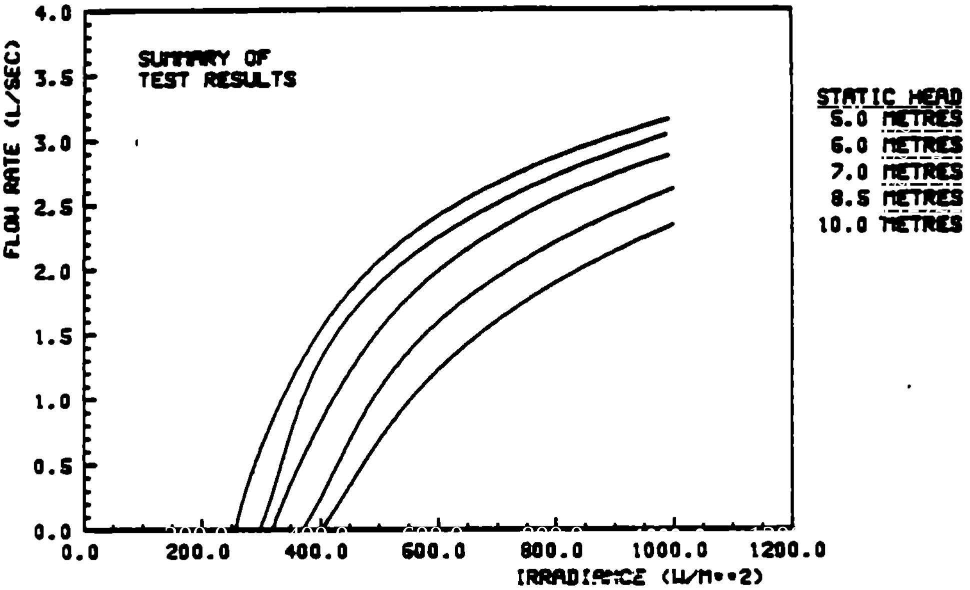
Durability, materials, wiring Good

Reliability, safety Appears to be good

Maintenance Routine motor brush and strainer checks

Suitability for local manufacture Appears generally suitable.

4A PERFORMANCE IN SIMULATOR TESTS



SUMMARY OF SIMULATOR TEST RESULTS

Static head m	Daily insolation kWh/m²	Daily Water Output m³/day			Daily system eff %	
		Required by Spec	Est. in Tender	From test results *	Required by Spec	From test results *
7	5	60	67	62.2	NS	1.5
5	5	NS	NG	76.7	1.1	1.3
10	5	NS	NG	40.3	1.1	1.4
7	4	43.5	NG	44.3	NS	1.3

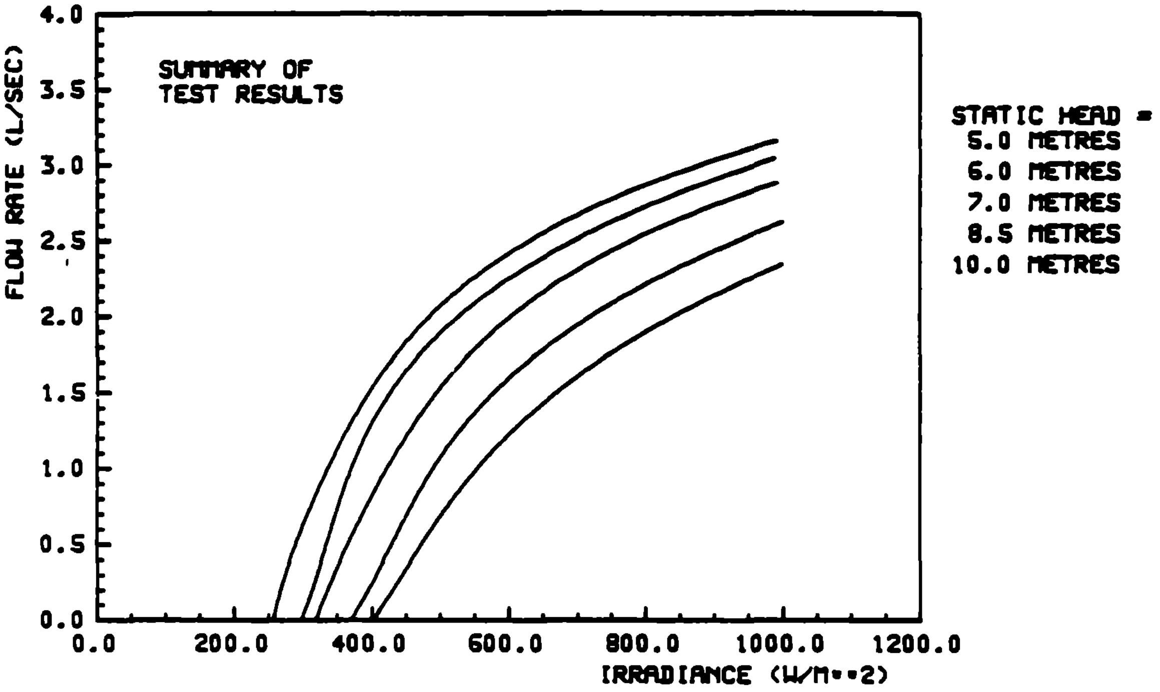
* for ambient temperature 30°C

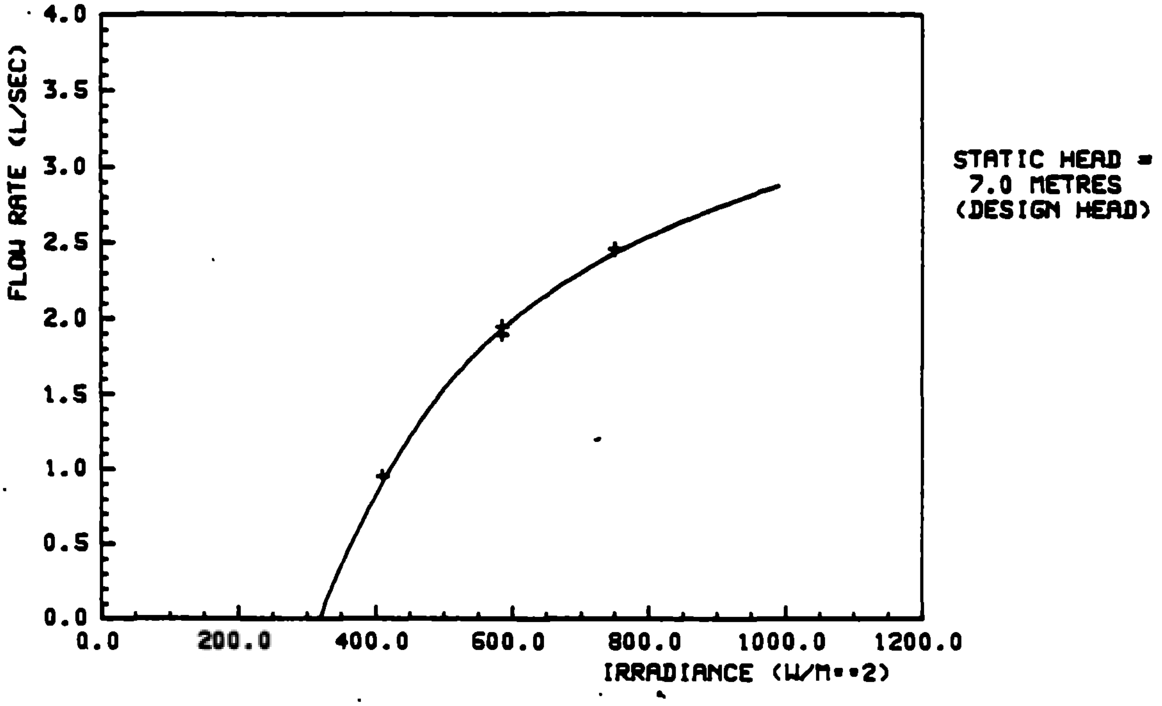
NS = Not specified NG = Not given in tender

NOTE

1. **System efficiency based on total solar energy received on gross area of array**
2. **Daily insolation is on horizontal plane. Irradiance on plane of array calculated for 20° tilt, fixed N-S orientation.**

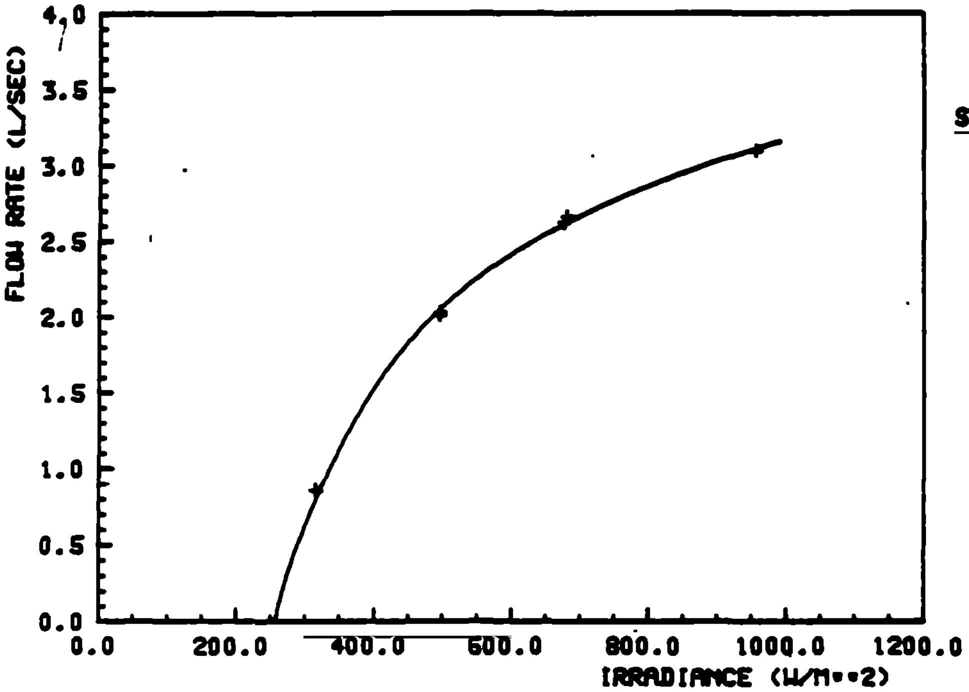
FIGURE



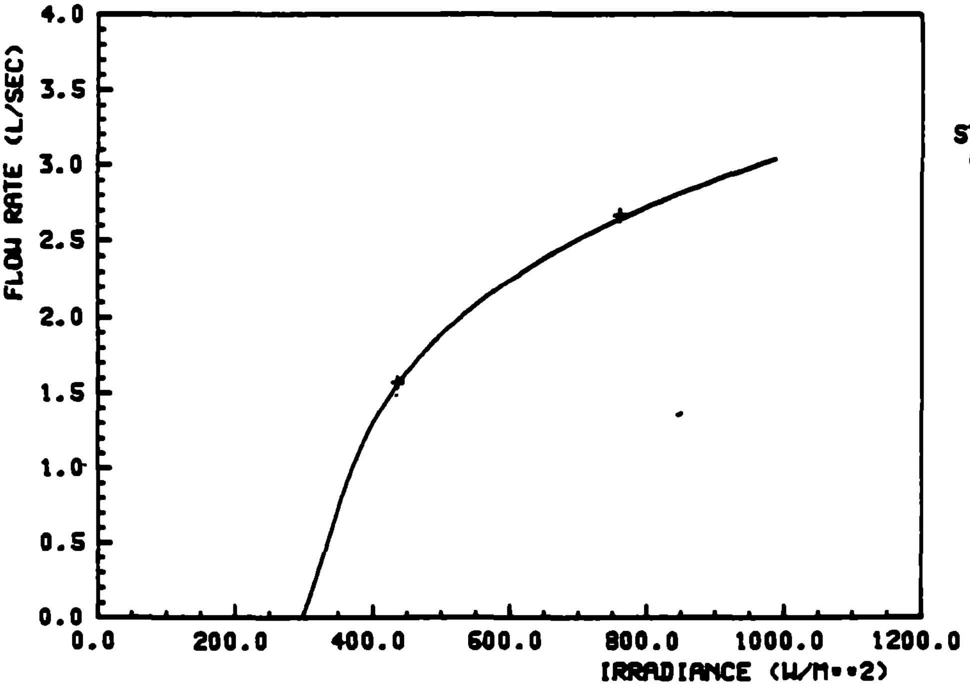


UNDP PROJECT GLO/80/003		DATE, 31/01/82
		SCALES AS SHOWN
CAT B	HELIODINAMICA SIMULATOR TEST	CHECKED BY,
		SIR WILLIAM HALCROW & PARTNERS/I.T.POWER

FIGURE



STATIC HEAD =
5.0 METRES



STATIC HEAD =
6.0 METRES

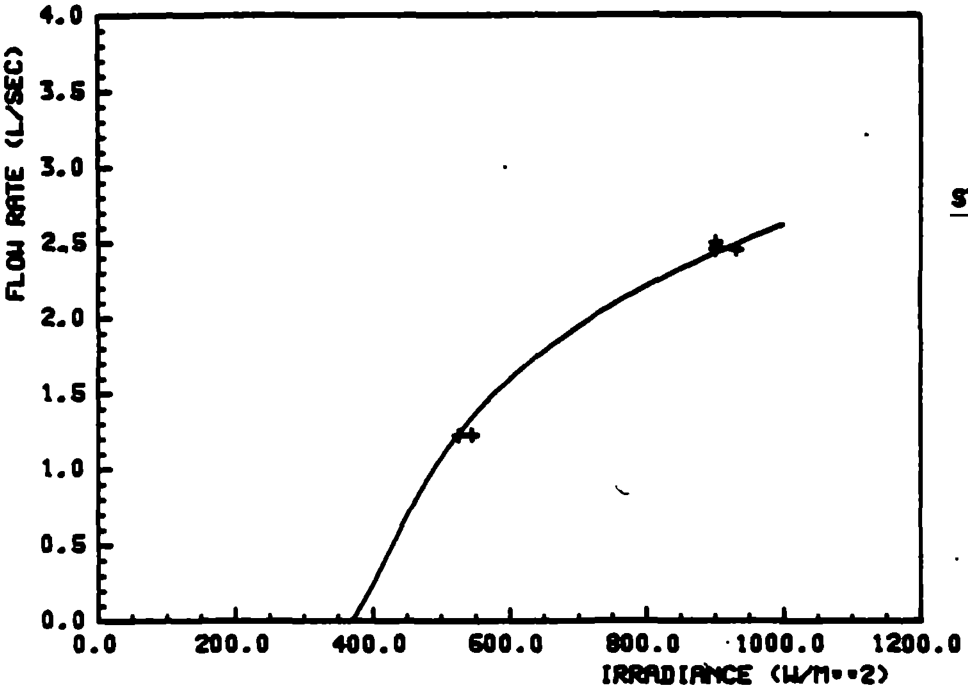
UNDP PROJECT GLO/80/003

CAT
B

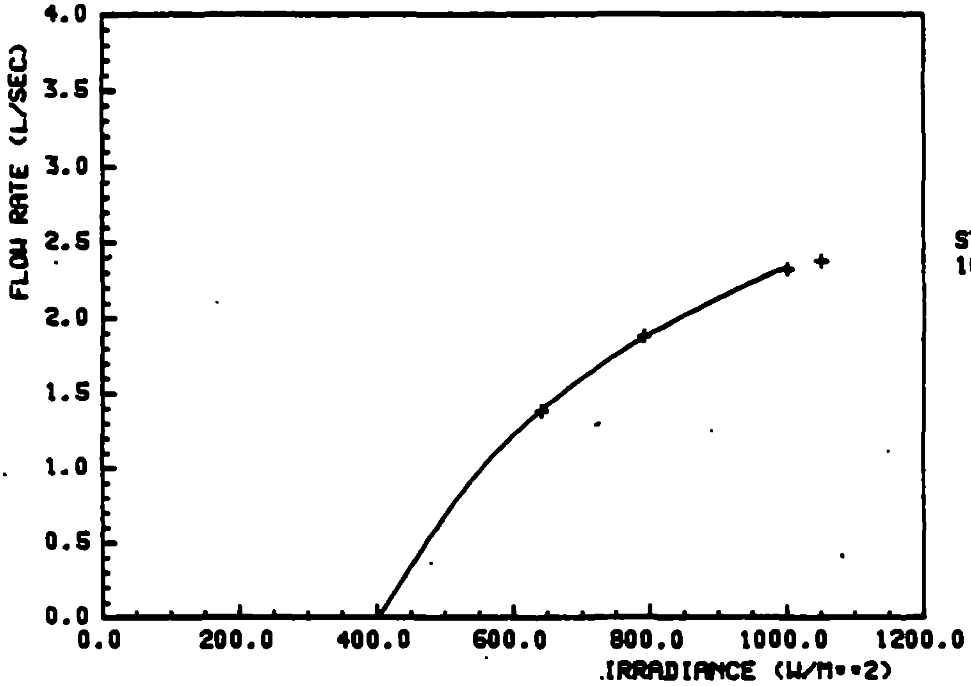
HELIODINAMICA
SIMULATOR TEST

DATE: 31/01/82
SCALES AS SHOWN
CHECKED BY:
SIR WILLIAM HALCROW
& PARTNERS/I.T.POWER

FIGURE



STATIC HEAD = 8.5 METRES



STATIC HEAD = 10.0 METRES

UNDP PROJECT GLO/80/003

DATE: 31/01/82

SCALES AS SHOWN

CHECKED BY:

CAT

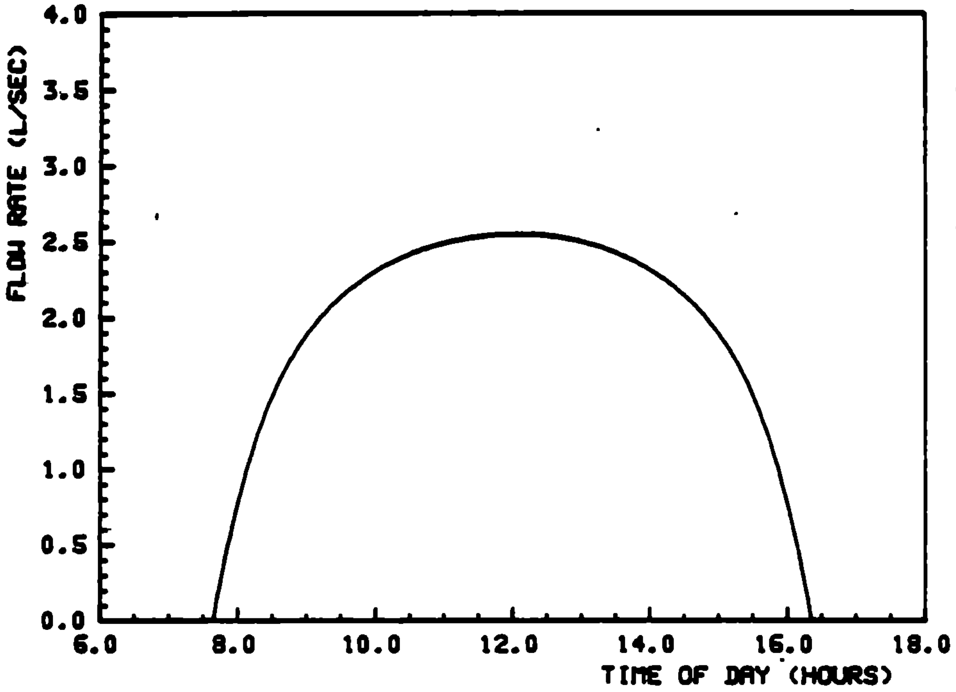
B

HELIODINAMICA

SIMULATOR TEST

SIR WILLIAM HALCROW
& PARTNERS/I.T.POWER

FIGURE

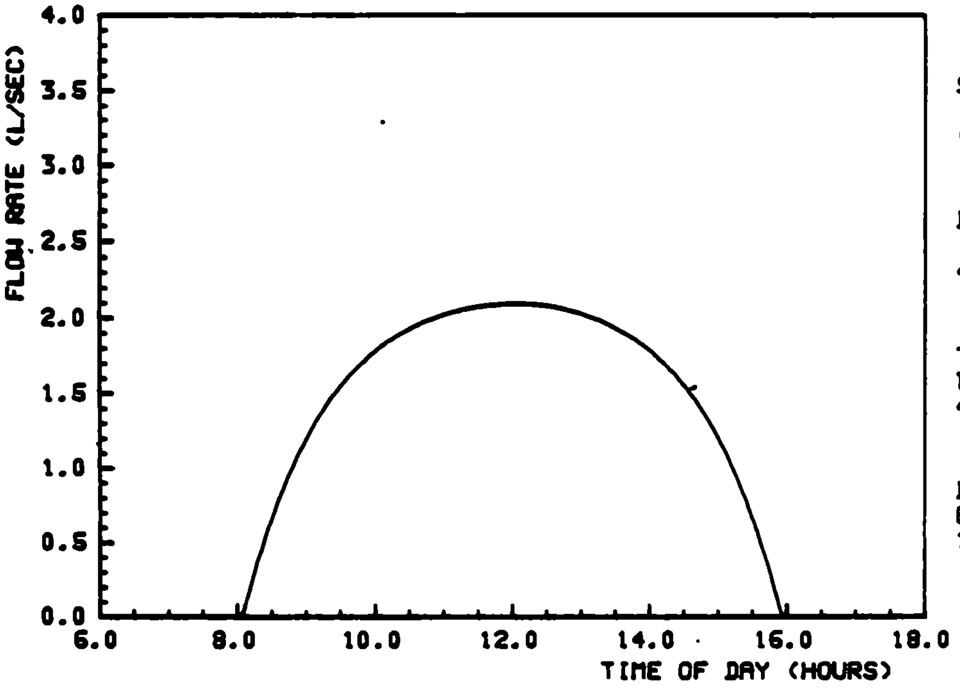


STATIC HEAD =
7.0 METRES
(DESIGN HEAD)

DAILY GLOBAL
INSOLATION =
5.00 KWH/M**2

TOTAL
PUMPED =
62.19 M**3

DAILY
EFFICIENCY =
1.51 %



STATIC HEAD =
7.0 METRES
(DESIGN HEAD)

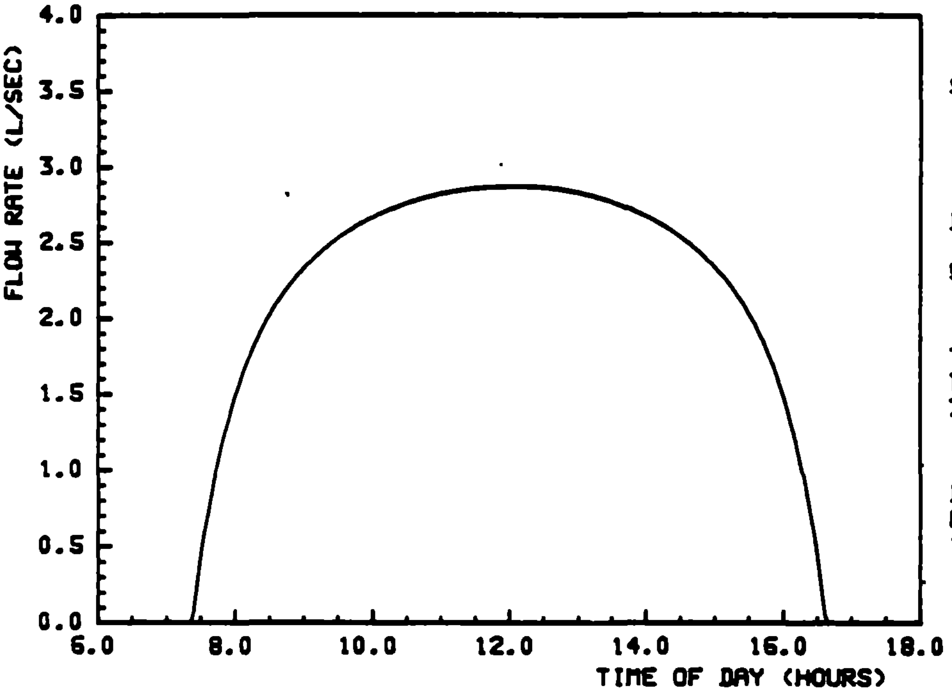
DAILY GLOBAL
INSOLATION =
4.00 KWH/M**2

TOTAL
PUMPED =
44.25 M**3

DAILY
EFFICIENCY =
1.26 %

UNDP PROJECT GLO/80/003		DATE: 31/01/82 SCALES AS SHOWN
CAT B	HELIODINAMICA SIMULATOR TEST	CHECKED BY: SIR WILLIAM HALCROW & PARTNERS/I.T. POWER

FIGURE

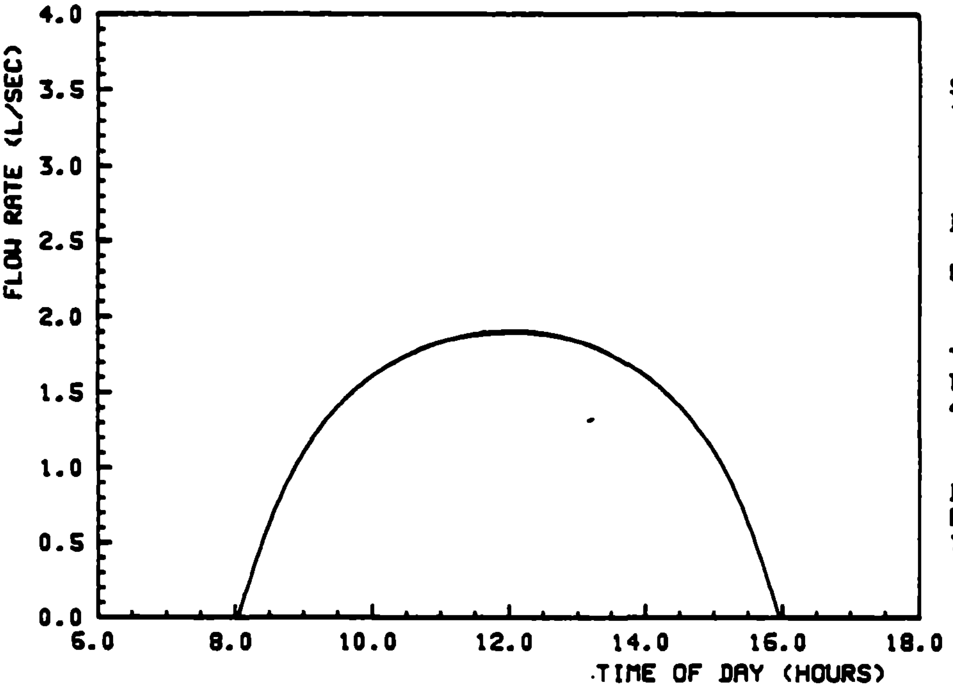


STATIC HEAD =
5.0 METRES

DAILY GLOBAL
INSOLATION =
5.00 KWH/M**2

TOTAL
PUMPED =
76.74 M**3

DAILY
EFFICIENCY =
1.33 %



STATIC HEAD =
10.0 METRES

DAILY GLOBAL
INSOLATION =
5.00 KWH/M**2

TOTAL
PUMPED =
40.30 M**3

DAILY
EFFICIENCY =
1.40 %

UNDP ~~PROJECT GLO/80/003~~

DATE, 31/01/82

SCALES AS SHOWN

CHECKED BY,

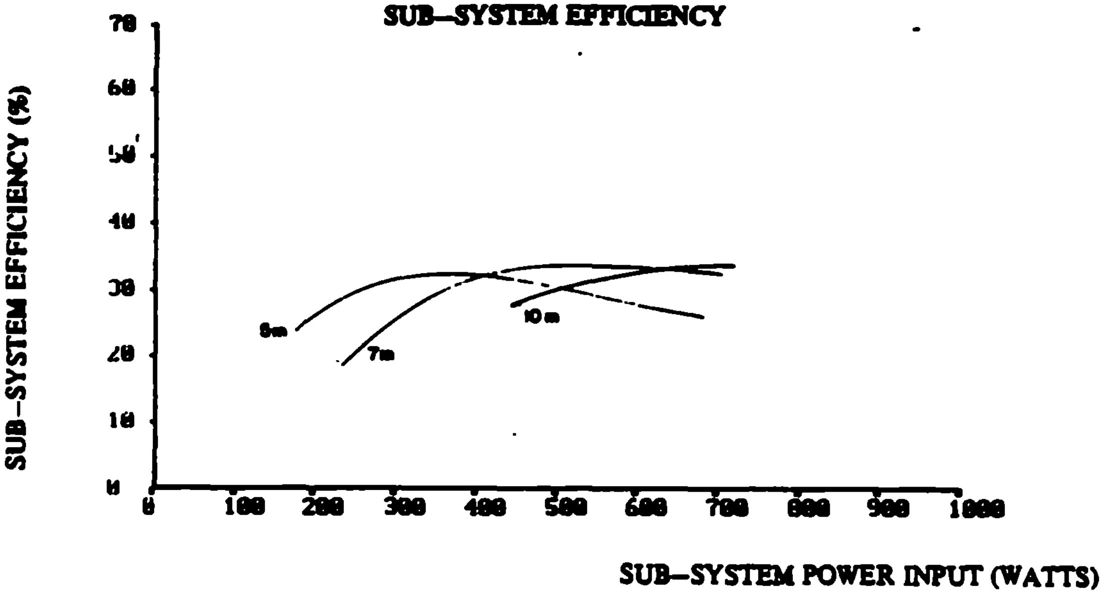
CAT
B

HELIODINAMICA
SIMULATOR TEST

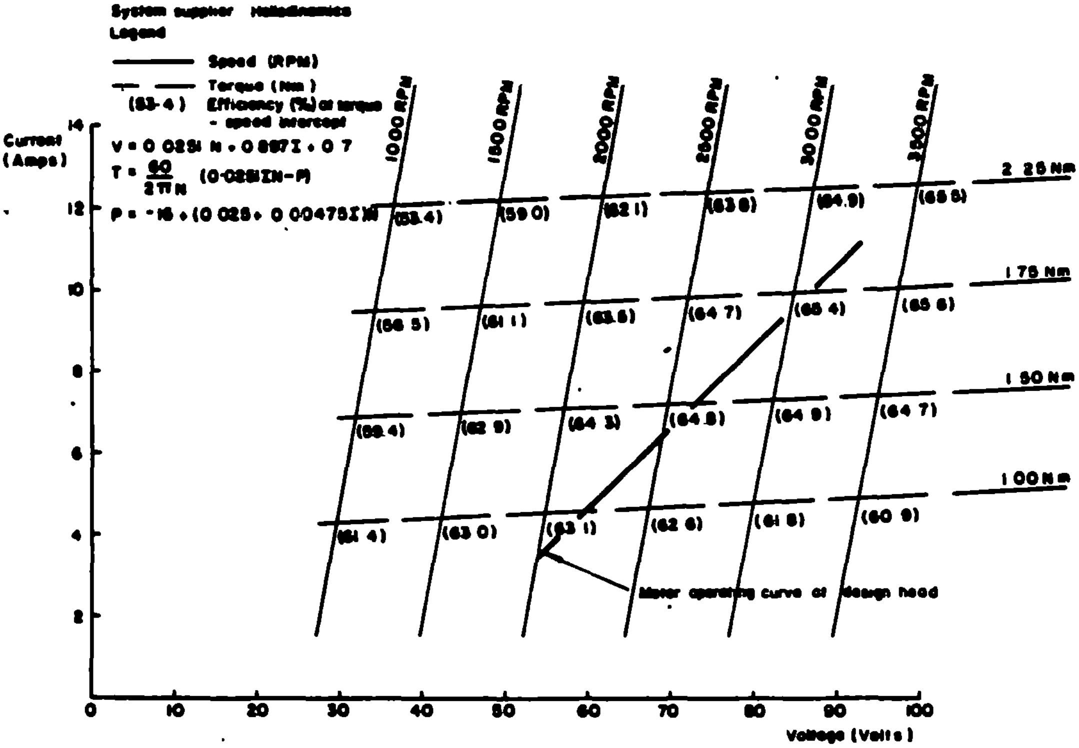
SIR WILLIAM HALCROW
& PARTNERS/I.T.POWER

5. SUB–SYSTEM AND MOTOR PERFORMANCE

SUB–SYSTEM EFFICIENCY



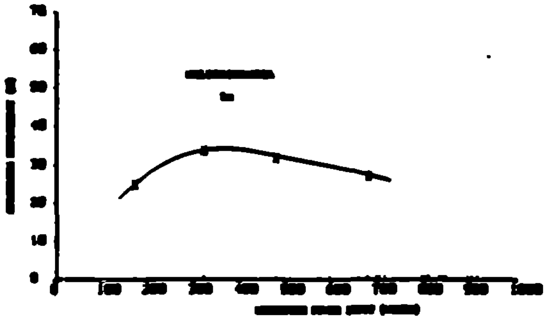
MOTOR CHARACTERISTICS

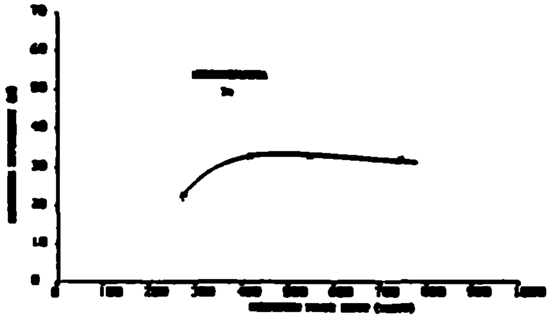


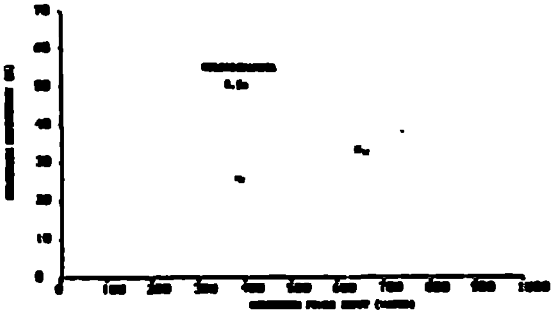
SYSTEM

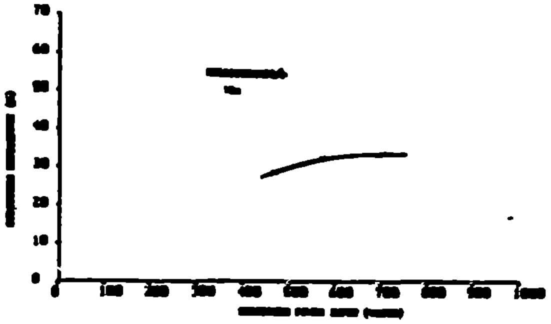
HELIODIN.

5A SUB-SYSTEM EFFICIENCY RESULTS









6. DISCUSSION OF RESULTS

Simulator tests System performance was slightly below the expectations of the manufacturer

Sunshine tests N/A

Sub-system performance Peak subsystem efficiency is fair at approx 33%

Motor performance Poor, with operating efficiencies of only 62-65%, contributing to the low subsystem efficiency.

Other comments Small piece of wood found in impeller after tests could have slightly reduced performance.

7. SPECIFIC CAPITAL COST

SCC = $C/\rho gVH$
C = (5 x 882) for array + 866 for balance of system
= \$ 5276
V = 62.2 m^3/day for 5 kWh/m^2 standard solar day
H = 7 m
SCC = 1.2 \$/kJ day

8. OVERALL CONCLUSIONS

This is a compact surface-mounted system with large self-priming chamber, obviating the need for non-return valves. The pump is constructed largely from plastics. Performance was good, meeting the specification in all respects. Subsystem efficiency was average with a peak of around 30% for all heads tested. Motor efficiency was poor, in the range 62-64%. The inferred peak pump efficiency is average about 47%. The projected SCC, already good at \$1.2/kJ.day could be further improved if a more efficient motor were used, requiring a small PV array. This system is an excellant example of a surface mounted solar pump, entirely made in a developing country.

Date of tests 24 NOV- 3 DEC 1982
Tested by ccJK/FS

Date of report 1 FEB 1983
Report checked by MRStarr

APPENDIX 3

Summary of Factors for Derivation of Cost Data

INTERNATIONAL			Capital Costs						Maintenance costs		
Component	Type	Dimensions of component Size	Fixed C_o \$	Fixed local cost factor Lc_o	Size related C_1 \$	Size related local cost factor Lc_1	Exponent at Size b	Differential Inflation i_c %	Costs M \$ per 1000 hrs	Local cost factor L_m	Differential inflation i_m %
Water Source	Well	m	0	0	3	1	1	0	0	0	0
	Borehole	m	40	1	50	1	1	0	0	0	0
	Riser pipe	m	0	0	25	1	1	0	0	0	0
Power Source	Solar	Wp(g)	0	0	16(h)	0.19	1	-0 07	6	1	0
	Wind	m^2 of rotor	0	0	260	0 7	1	0	6	1	0
	Diesel Engine	kW of shaft	1500	0 1	6 4	0	2	0	200(j)	0 5	0
	Animal	ox	0	0	250	1	1	0	0	0	0
	Human	people	0	0	0	0	0	0	0	0	0
Pump	PV	Wp hydraulic	530(i)	0	1.5	0	1	0	12	0 5	0
	Engine	Wp "	115	0	0 35	0	1	0	6	0 5	0
	Wind	Wp "	0	0	0 46	0 7	1	0	6	1.0	0
	Hand-well	Watts hydr.	0	0	6	1	1	0	50(a)	1	0
	Hand-7m tube	" "	0	0	6	1	1	0	50(a)	1	0
	Hand-20m tube	" "	0	0	8	1	1	0	50(a)	1	0
	Animal	" "	0	0	4	1	1	0	10(a)	1	0
Store-Irrigation	Concrete	m^3	35	0 75	15	0 75	1	0	0	0	0
Store-Village	Concrete	m^3	260	0 75	128	0.75	0 72	0	0	0	0
Channel	Concrete	m^2	100	1	2 0	1	1	0	15(a)	1	0
	Earth	m^2	50	1	0 1	1	1	0	50(a)	1	0
Conveyance Pipe	PVC 75mm	m	0	0	12	0 75	1	0	0	0	0
	PVC 50mm	m	0	0	4 0	0.75	1	0	0	0	0
	PVC 12mm	m	0	0	0 37	0 75	1	0	0	0	0
Furrow	Earth	m	0	0	0	0	0	0	0	0	0

Operating Costs

Type	Operating Cost C_f \$/MJ	Local Cost factor L_c	Fuel Differential inflation rate i_f%
Diesel (c)	0 01(k)	0	3 5
Animal(d)	0 25	1	0
Human (e)	0 926	1	0
Wind, Solar	0	0	0

(a) Annual maintenance costs
(b) see Section 7.6 3 for explanation of symbols
(c) 1 litre diesel = 38 MJ
(d) 1 animal day = 6.25 MJ
(e) 1 man hour = 1.08 MJ (working day = 5 hrs)
(f) Shadow exchange rate factor taken as unity
(g) Electrical output from array (includes installation and shipping)
(h) Includes \$ 6/Wp to cover delivery pipework, foundations, array support, shipping, transport and labour
(i) Includes dc motor
(j) For low case diesel, \$400 for high case diesel.
(k) for low case diesel, \$0 02/MJ for high case diesel.

Table A3.1 Summary of Factors for International Cost Data - Baseline Scenarios for Irrigation and Water Supply

COUNTRY: BANGLADESH			Capital Costs						Maintenance costs		
Component	Type	Dimensions of component Size	Fixed C_o $	Fixed local cost factor Lc_o	Size related C_1 $	Size related local cost factor Lc_1	Exponent at Size b	Differential Inflation I_c %	Costs M $ per 1000 hrs	Local cost factor L_m	Differential Inflation I_m %
Water Source	Well	m	0	0	2	1	1	0	0	0	0
	Borehole	m	33	1	8	1	1	0	0	0	0
	Riser pipe	m	0	0	4	1	1	0	0	0	0
Power Source	Solar	Wp(g)	0	0	16(h)	0 19	1	-0 07	6	1	0
	Wind	m^2 of rotor	1140	0 7	48	0 7	1	0	6	1	0
	Diesel Engine	kW of shaft	520	0 1	2 15	0	2	0	60(j)	0 5	0
	Animal	ox	0	0	125	1	1	0	0	0	0
	Human	people	0	0	0 9	0	0	0	0	0	0
Pump	PV	Wp hydraulic	138	0	0 42	0	1	0	7	0 5	0
	Engine	Wp "	69	0	0 21	0	1	0	3 5	0 5	0
	Wind	Wp "	318	0 7	0 06	0 7	1	0	3 5	1	0
	Hand-well	Watts hydr	0	0	6	1	1	0	0 57	1	0
	Hand-7m tube	" "	0	0	6	1	1	0	5 7	1	0
	Hand-20m tube	" "	0	0	8	1	1	0	5 7	1	0
	Animal	Wp hydraulic	0	0	4	1	1	0	0 5	1	0
Store	Concrete	m^3	35	0 75	15	0 75	0 72	0	0	0	0
Channel	Concrete	m^2	50	1	1 03	1	1	0	1 4	1	0
	Earth	m^3	25	1	0 06	1	1	0	2 8	1	0
Conveyance Pipe	PVC 75mm	m	0	0	3	0 75	1	0	0	0	0
	PVC 50mm	m	0	0	1 26	0 75	1	0	0	0	0
	PVC 12mm	m	0	0	0 25	0 75	1	0	0	0	0
Furrow	Earth	m	0	0	0	0	0	0	0	0	0

Operating Costs

Type	Operating Cost C_f $/MJ	Local Cost factor L_c	Fuel Differential Inflation rate I_f%
Diesel (c)	0 012(k)	0	3 5
Animal(d)	0 28	1	0
Human (e)	4 63	1	0

(a) Annual maintenance costs
(b) See Section 7.6 3 for explanation of symbols
(c) 1 litre diesel = 38 MJ
(d) 1 animal day = 6 25 MJ
(e) 1 man day = 1 08 MJ
(f) Shadow exchange rate factor taken as unity
(g) Electrical output from array (includes installation and shipping)
(h) Includes $6/Wp to cover delivery pipework, foundations, array support, shipping, transport and labour
(i) Includes dc motor
(j) For low case diesel, $120 for high case diesel
(k) For low case diesel, $0 024/MJ for high case diesel

Table A3.2 Summary of Factors for Cost Data for Bangladesh - Country Case Studies for Irrigation and Water Supply

COUNTRY: KENYA			Capital Costs						Maintenance costs		
Component	Type	Dimensions of component Size	Fixed C_o $	Fixed local cost factor Lc_o	Size related C_1 $	Size related local cost factor Lc_1	Exponent at Size b	Differential Inflation i_c %	Costs M $ per 1000 hrs	Local cost factor L_m	Differential inflation i_m %
Water Source	Well	m	0	0	3	1	1	0	0	0	0
	Borehole	m	50	1	33	1	1	0	0	0	0
	Riser pipe	m	0	0	25	1	1	0	0	0	0
Power Source	Solar	Wp (g)	0	0	16(h)	0.19	1	-0.07	6	1	0
	Wind	m^2 of rotor	1930	0.7	230	0.7	1	0	6	1	0
	Diesel Engine	kW of shaft	2310	0.1	9.55	0	2	0	265(j)	0.5	0
	Animal	ox	0	0	125	1	1	0	0	0	0
	Human	people	0	0	0	0	0	0	0	0	0
Pump	PV	Wp hydraulic	1400(i)	0	4	4	0	1	12	12	0
	Engine	Wp "	305	0	0.93	0	1	0	17	0.5	0
	Wind	Wp "	214	0.7	0.28	0.7	1	0	17	1.0	0
	Hand well	Watts hydr	0	0	6	1	1	0	0.57	1	0
	Hand-7m tube	" "	0	0	6	1	1	0	5.7	1	0
	Hand-20m tube	" "	0	0	8	1	1	0	5.7	1	0
	Animal	Wp hydraulic	0	0	4	1	1	0	2.5	1	0
Store	Concrete	m^3	35	0.75	15	0.75	1	0	0	0	0
Channel	Concrete	m^2	100	1	2.06	1	1	0	1.4	1	0
	Earth	m^2	50	1	0.12	1	1	0	2.8	1	0
Conveyance Pipe	PVC 75mm	m	0	0	25	0.75	1	0	0	0	0
	PVC 50mm	m	0	0	12.6	0.75	1	0	0	0	0
	PVC 25mm	m	0	0	2	0.75	1	0	0	0	0
Furrow	Earth	m	0	0	0	0	0	0	0	0	0

Operating Costs

Type	Operating Cost C_f $/MJ	Local Cost factor L_c	Fuel Differential Inflation rate i_f%
Diesel(c)	0.011(k)	0	3.5
Animal(d)	0.28	1	0
Human (e)	4.63	1	0

(a) Annual maintenance costs
(b) See Section 7.6.3 for explanation of symbols
(c) 1 litre diesel = 38 MJ
(d) 1 animal day = 6.25 MJ
(e) 1 man day = 1.08 MJ
(f) Shadow exchange rate factor taken as unity
(g) Electrical output from array (includes installation and shipping)
(h) Includes $6/Wp to cover delivery pipework, foundations, array support, shipping, transport and labour
(i) Includes dc motor
(j) For low case diesel, $530 for high case diesel
(k) For low case diesel, $0.022/MJ for high case diesel

Table A3.3 Summary of Factors for Cost Data for Kenya - Country Case Studies for Irrigation and Water Supply

COUNTRY: THAILAND			Capital Costs						Maintenance costs		
Component	Type	Dimensions of component Size	Fixed C_o $	Fixed local cost factor Lc_o	Size related C_l $	Size related local cost factor Lc_l	Exponent at Size b	Differential Inflation i_c %	Costs M $ per 1000 hrs	Local cost factor L_m	Differential inflation i_m %
Water Source	Well	m	0	0	6	1	1	0	0	0	0
	Borehole	m	34	1	120	1	1	0	0	0	0
	Riser pipe	m	0	0	25	1	1	0	0	0	0
Power Source	Solar	Wp (g)	0	0	16 (h)	0 19	1	-0 07	6	1	0
	Wind	m^2 of rotor	1884	0 7	112	0 7	1	0	6	1	0
	Diesel Engine	kW of shaft	1550	0 1	6 45	0	2	0	200(j)	0 5	0
	Animal	ox	0	0	175	1	1	0	0	0	0
	Human	people	0	0	0	0	0	0	0	0	0
Pump	PV	Wp hydraulic	945(i)	0	1 24	0	1	0	10	0 5	0
	Engine	Wp "	205	0	0 62	0	1	0	10	0 5	0
	Wind	Wp "	209	0 7	0 14	0 7	1	0	10	1	0
	Hand-well	Watts hydr	0	0	6	1	1	0	0 57	1	0
	Hand-7m tube	" "	0	0	6	1	1	0	5 7	1	0
	Hand-20m tube	" "	0	0	8	1	1	0	5 7	1	0
	Animal	Watts hydr.	0	0	4	1	1	0	1 5	1	0
Store	Concrete	m^3	35	0 75	15	0 75	1	0	0	0	0
Channel	Concrete	m^2	100	1	2 06	1	1	0	4 2	1	0
	Earth	m^2	50	1	0 12	1	1	0	8 4	1	0
Conveyance Pipe	PVC 3 75mm	m	0	0	16	0 75	1	0	0	0	0
	PVC 2 50mm	m	0	0	4	0 75	1	0	0	0	0
	PVC 12mm	m	0	0	2	0 75	1	0	0	0	0
Furrow	Earth	m	0	0	0	0	0	0	0	0	0

Operating Costs

Type	Operating Cost C_f $/MJ	Local Cost factor L_c	Fuel Differential inflation rate i_f%
Diesel (c)	0 011(k)	0	3 5
Animal(d)	0 52	1	0
Human (e)	13 88	1	0

(a) Annual maintenance costs
(b) See Section 7 6 3 for explanation of symbols
(c) 1 litre diesel = 38 MJ
(d) 1 animal day = 6 25 MJ
(e) 1 man day = 1.08 MJ
(f) Shadow exchange rate factor taken as unity
(g) Electrical output from array (includes installation and shipping)
(h) Includes $6/Wp to cover delivery pipework, foundations, array support, shipping, transport and labour
(i) Includes dc motor
(j) For low case diesel, $400 for high case diesel.
(k) For low case diesel, $0 022/MJ for high case diesel

Table A3.4 Summary of Factors for Cost Data for Thailand - Country Case Studies for Irrigation and Water Supply

APPENDIX 4

Glossary of Terms

GLOSSARY OF TERMS

Solar pumping covers a number of technologies, each with its own set of terms. For the convenience of readers and in particular to assist those who may be unfamiliar with solar terminology a glossary of the terms used in the Report which are specific to solar powered water pumping systems has been prepared.

Absorber

The absorber is that part of a solar collector which converts the incident solar radiation into heat and from which the heat is removed by the transfer fluid. If an absorbing liquid is used then this may constitute both the absorber and the heat transfer fluid.

Air Mass

The length of path through the Earth's atmosphere traversed by the direct solar beam, expressed a multiple of the path traversed to a point at sea level with the sun at zenith.

Angle of Incidence of Direct Solar Radiation

The angle of incidence of direct solar radiation is the angle between the direct solar radiation beam and the outward drawn normal from the plane of the solar collector or array.

Aperture Area

The aperture area of a solar collector is the opening or projected area of a collector through which the unconcentrated solar energy is admitted.

Array Efficiency, Overall

The electrical power output of an array at an instant divided by the total solar power incident upon the entire frontal area of the array.

Array, Solar

(See solar array)

Available Solar Energy

This is the solar irradiation incident on the PV array that can be used by the pumping subsystem. Values of solar irradiance below the critical radiation level do not contribute to the available solar energy.

Average Cell Efficiency (of a photovoltaic array)

The electrical power output of an array at an instant divided by the total solar power incident upon the entire frontal area of solar cells in the array.

Average Pumped Head

The average pumped head generated by a pumping system over a defined period of time is the total hydraulic energy delivered by the system in that time divided by the total weight of water pumped in that time. (The total hydraulic energy is the integration over time of the pumped power at an instant).

Capacity Factor

The ratio of windpump mean output power for a month to windpump rated power.

Collector

(See solar collector)

Component Lifetime

The actual number of years that the component functions taking into account the daily operating time.

Component Operating Hours

The number of hours that the component will function.

Concentration Ratio

The concentration ratio of a concentrating collector is the aperture area divided by the absorber area.

Concentrator

A concentrator is a system to increase intensity of solar radiation on a given area.

Concentrating Collector

A concentrating collector is a solar collector which uses reflectors, lenses or other optical elements to concentrate the solar energy incident on the aperture onto an absorber, the subtended surface area of which is smaller than the aperture area.

Continuous System Performance Data

Data obtained from a system under test when continuously monitored over a given time period and from which performance at any instance can be assessed.

Cumulative System Performance Data

Performance data integrated over a given time period (usually a day) obtained by taking integrated or cumulative readings of the system performance at the end of each time period.

Daily Cell Efficiency (of photovoltaic array)

The electrical energy output of a photovoltaic array divided by the solar energy incident upon the entire solar cell area of the array during a period of one day.

Daily Overall System Efficiency (of a solar pumping system)

The hydraulic energy delivered by the pump divided by the solar energy incident upon the entire frontal area (photovoltaic systems) or aperture area (thermal systems) of the solar array during a period of one day.

Daily Peaking Factor

The fraction of the total daily demand that is required in the peak hour for a village water supply system.

Diffuse Solar Irradiance

The radiant power from the sky (excluded by shading the power within the solid angle subtended by the sun's disk) incident upon unit surface area.

Direct Solar Irradiance

The radiant power from the sun within the solid angle subtended by the sun's disk incident upon unit surface area.

Distribution System

Moves water from the pump or a storage tank outlet to the user. Irrigation distribution systems consist of a conveyance component and a field application component. The former delivers the water from the pump (or store) to the field while the latter is used to apply water to the crops. Village water supply systems have a piped distribution subsystem which transfers water from the storage tank to the water points.

Energy Efficiency

The ratio of hydraulic energy output from the pump to energy input to the source of power (eg array). Losses are in the motor/pump and power source.

Evacuated Tube Solar Collector

An evacuated tube solar collector is a solar collector in which the absorber is positioned in one or more glass tubes and the heat loss from the absorber is suppressed by means of an evacuated layer between the absorber and the outer cover of the tube.

Flat-plate Solar Collector

A flat-plate collector is a solar collector whose aperture area is essentially identical to the area of the absorber surface, employs no concentration in which the absorbing surface is essentially planar.

Frensel Lens

A lens having the same optical profile as a conventional lens but in which the thickness is reduced by steps at intervals over the surface of the lens.

Global (Solar) Irradiance

The total solar radiant power incident upon unit area of a horizontal surface. Global Irradiance = Direct Irradiance (horizontal) + Diffuse Irradiance (horizontal).

Heliostat

An electromechanical device that automatically orientates a mirror so that direct radiation is reflected on a fixed position regardless of the position of the sun.

Hydraulic Power

(See Pumped Power)

Incidence Angle

(See Angle of Incidence)

Insolation

(See Solar Irradiation)

Instantaneous Overall System Efficiency (of a solar pumping system)

The hydraulic power output of the pump at any instant divided by the solar power incident on the entire frontal area of the array (flat-plate photovoltaic systems) or aperture area (concentrator and thermal systems) at the same instant when operating under quasi steady state conditions.

Instantaneous Cell Efficiency (of a photovoltaic array)

The electrical power output of a flat-plate solar array at any instance divided by the solar power incident on the total gross area of the array cells at the same instant when operating under quasi steady state conditions.

Instantaneous Subsystem Efficiency (of a solar pumping system)

The hydraulic power output of the pump at any instant divided by the electrical power delivered to the motor at the same instant and when operating under quasi steady state conditions.

Irradiance

The radiant power incident upon unit area of a surface (See also global irradiance, solar irradiance and total irradiance. In this report irradiance is solar irradiance).

Irradiation

The radiant energy received by unit area of a surface during a given time period. (The time integral of irradiance).

Local Apparent Time (LAT)

LAT is the system of astronomical time in which the sun always crosses the true N-S meridian at 12 noon. This system of time differs from local time according to longitude and time zone. The precise displacement also varies with the time of the year.

Maximum Power Point (of a photovoltaic module)

The power at the point on the current-voltage characteristic where the product of current and voltage is a maximum

Maximum Power Controller (MPC)

An electronic control device which continuously adjusts the voltage output of a photovoltaic array to an optimum value to maximise the array power output. Also referred to as a Maximum Power Point Tracker.

Mean Daily Input Energy Requirements

The mean daily load divided by the energy efficiency. (Hence the average daily energy required by the water supply system).

Mean Daily Load

The annual hydraulic energy output from the pump divided by the number of days in the year.

Mean Daily Operating Time

The number of operating hours per year divided by the number of days in the year.

Mean Daily Water Demand for a Period (month or year)

The water demand divided by the number of days in the period. The actual daily water demand may differ significantly from this parameter for applications with large variations in demand from month to month.

Module, Photovoltaic

(See Photovoltaic Module)

Module Area

The entire frontal area of the module including borders, frame and any protruding mounting lugs.

Monthly Demand Factor

The ratio of mean daily water demand for a month to the mean daily water demand for the year.

Over Capacity Ratio

(Only relevant for wind and solar power sources). The ratio of potential hydraulic output for the year to actual hydraulic output required over the year. The actual hydraulic output is lower than the potential output because systems have to be sized for the worst month conditions.

Oversizing Factor

It may be necessary to oversize the power source (relative to average conditions) even in the critical month because of year to year variations in the solar and wind energy for the critical month. The oversizing factor is the ratio of critical power source size to power source size to meet the critical month conditions.

Packing Factor (of a photovoltaic module)

Th entire frontal area of the solar cells in the module divided by the entire frontal area of the module.

Peak Monthly Demand Factor

The maximum value of the monthly demand factor. It is this factor that has a crucial effect on the size of renewable energy systems.

Peak Power (of photovoltaic module)

The power output of a photovoltaic module at a reference temperature under specified working conditions under a solar irradiance of 1000 watts per square metre with an air mass 1.5 spectrum.

Photovoltaic Array

A mechanically integrated assembly of modules (or panels) together with support structure (but exclusive of foundation, tracking, thermal control and other components), as required to form a dc power producing unit.

Photovoltaic Cell

(See solar cell)

Photovoltaic Module

The smallest complete environmentally protected assembly of interconnected solar cells.

Power Tower or Solar Tower

A tower placed so that the reflected direct radiation from heliostat mirrors can be focussed on a boiler or absorber mounted on top of it.

Pumped Head

The total energy added to the water by a pump per unit weight of water measured between the inlet and the outlet. It is equal to the difference between the sum of the velocity and pressure heads at the outlet and inlet.

Pumped Power

The pumped power of a pump is the product of mass flow rate, specific weight and pumped head at an instant. To obtain the input power to the pump it is necessary to divide by the efficiency of the pump.

Pumping System

In all cases this consists of a power source and a water pump.

Pyranometer

A radiometer normally used to measure global irradiance (or, with a shade ring or disc, diffuse irradiance) on a horizontal plane. It can also be used at an angle to measure the total irradiance on an inclined plane, which in this case includes an element due to radiation from the foreground.

Quasi-Steady State Condition

The condition of a system when all the variables affecting its performance are at or close to a steady state, such that small variations in these variables will not significantly affect its measured performance.

Rankine (Cycle) Engine

A heat engine working on the Rankine thermodynamic cycle.

Reflectance

The radiation reflected from a surface divided by the radiation incident on that surface.

Selective Surface (of an absorber)

An absorber is considered to be selective if it substantially absorbs all incident solar radiation whilst simultaneously exhibiting a low hemispherical remittance at longer wavelengths.

Solar Elevation

The angle between the direct solar beam and the horizontal. (Air mass is the cosecant of Solar Elevation).

Solar Array

A number of individual solar collection devices (thermal or photovoltaic) arranged in a suitable manner to collect solar energy.

Solar Azimuth

The angle between the local meridian and the direction of the sun measured in a horizontal plane.

Solar Cell

Also known as a photovoltaic cell. A semiconductor device which can convert radiation directly into an electrical current. The basic photovoltaic device which generates electricity when exposed to sunlight.

Solar Collector (Thermal)

A solar-thermal collector is a device which absorbs solar radiation, concerts it into heat and passes this heat on to a circulating heat transfer fluid.

Solar Concentrator

(See Concentrator)

Solar Radiation

Radiation emitted by the sun in the form of electomagnetic waves or particles.

Solar Irradiance

The radiant solar power incident upon unit area of a surface at an instant. (See total irradiance and global irradiance).

Solar Irradiation (Insolation)

The time integral of solar irradiance

Solar Pond

An artificially enclosed body of water containing a stratified solution which absorbs and stores solar radiation as heat.

Solar Sensor (measuring instrument)

A photovoltaic device adapted for the measurement of solar irradiance.

Solar Thermodynamic Process (or Solar-Thermal Process)

A process in which solar energy is converted and utilised as heat.

Specific Capital Cost (of a solar pumping system)

The capital cost of a system (operating under reference conditions) per useful energy output over a standard solar day.

Single Axis Sun Tracking System

A mechanism for maintaining the plane of a solar array or other object in the general direction of the sun perpendicular to the direct solar beam by means of adjusting the array about one axis only.

Static Head (of a solar pumping system)

The difference in elevation between the water level at rest in the well, borehole or surface water source and the level of the ground adjacent to the tank or inlet to the distribution system.

Stirling Engine

A heat engine working on the Stirling thermodynamic cycle.

System Efficiency

The product of volumetric efficiency and energy efficiency

Threshold Radiation Level

The value of solar irradiance at which a solar pump either commences or ceases to operate. The two values may be different.

Total Pumped Head

The total head generated by the pump. It is the summation of the static head, the store height, the head loss in the distribution system and (if applicable) the drawdown in the well or borehole.

Two-Axis Sun Tracking System

A mechanism for maintaining the plane of a solar array or other object perpendicular to the direct solar beam by means of adjustment in two axes so that it tracks the apparent motion of the sun.

Total (Solar) Irradiance

The total solar radiant power incident upon unit area of an inclined surface.

Volumetric Efficiency

The ratio of water delivered to the user to the water delivered by the pump. Losses are in the storage and distribution subsystem.

Water Application Time

The time taken to delivery the daily demand for systems with storage. This parameter determines the water supply flow rate and hence distribution size (or head loss).

Water Source Flow Rate

The rate of removal of water from the well or borehole. This parameter determines the drawdown and for systems with no storage determines the size or head loss in the distribution system.

Water Supply Flow Rate

This is the water flow rate in the distribution system. It may differ from the water source flow rate for systems with storage.

Water System

The whole system from the water source to the point at which water is delivered to the user. System losses generally mean that a quantity of water greater than that demanded must be removed from the water source. The water supply system includes a pumping system and a distribution subsystem.

Windpump Rated Power

The windpump output power at which increases in windspeed cause no further increases in power output.

APPENDIX 5

Supporting Documents

SUPPORTING DOCUMENTS

As explained in Section 3.3, annotated reports on the main constituent activities of the Project are available for reference from either the World Bank or the Consultants. For the guidance of the specialist who may wish to consult this material, a brief summary of the contents of each 'Supporting Document' is given below.

1 Performance Tests on Improved Photovolatic Pumping Systems:

This Document presents the results of the tests on 12 solar pumping systems and draws conclusions about the choice of pumping systems for the field programme to be organised under Phase II. It describes the procedures used by the Consultants for procuring the systems and subsystems through international tender for performance testing. The tender called for the supply of three categories of pumping systems, each category being based on the hydraulic requirements for irrigation or water supply duties. The performance tests were carried out at a specially constructed solar pump test facility.

2 Economic Evaluation of Solar Water Pumps

This Document describes a study in which the economics of solar pumps were compared with wind, diesel, animal and human powered pumps for agricultural and water supply applications. The costs in the baseline models represented international norms, while case studies were completed with data from Kenya, Bangladesh and Thailand.

3 Potential for Improvement of Photovolatic Pumping Systems

This Document presents a study of ways in which the cost- effectiveness of PV Pumping Systems may be improved by further development of their components. Such ideas could be a stimulus to the commercial development of the next generation of equipment.

4 Review of Solar Thermodynamic Pumping Systems

This Document presents a review of the present state of development of solar thermodynamic pumping systems. After evaluating developments worldwide, basic studies were made of a number of system options. The report offers some predictions about the future of this type of pumping technology.

5 Manufacture of Solar Water Pumps in the Less Developed Countries

This Document summarises a brief desk study of the problems of transferring manufacturing technology to companies in the developing world. Technical, management and contractual aspects are discussed.

6 Potential for Field Programmes in Selected Countries

This Document summarises the conclusions resulting from visits made to eight countries to explore the possibilities for their involvement in Phase II of the Project. Discussions were held with senior staff in Government and in the departments or agencies concerned with energy, agriculture, water supply and industry.

7 Proposal for Phase II of the Project

This Document reviews the progress made in Phase II Preparation, outlines the objectives of the next Phase and describes the activities required to achieve them, principally field programmes in a number of developing countries. The continuing role of international aid is discussed.

8 Program Users' Guides

During the Project a number of computer-based mathematical models have been constructed to facilitate system design studies. Three models have proved particularly useful:

- on PV pumping systems
- on thermal pumping systems
- on the economics of PV and other pumping systems used for agricultural and water supply purposes.

It is envisaged that the computer programs which incorporate these mathematical models will be available for general use under arrangements to be agreed by the UNDP and World Bank. Document 8 contains the Program Users' Guide for each model.