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MICRO IRRIGATION WITH PHOTOVOLTAICS

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PREFACE

The adoption of photovoltaics in economic applications depends upon both the price of photovoltaics and the price and availability of alternative forms of energy. Within the developing nations today, there are vast areas which do not have access to centralized electrical power; these are areas away from the established grid and therefore not likely to be reached by the grid in the near future as well as areas whose aggregate demand is insufficiently great to justify grid extension on economic grounds. Many of these same area are difficult to supply with liquid fuels . Such high energy cost areas vary from nation to nation depending upon level of development and access to either domestic or foreign energy resources. Photovoltaic power systems offer modular electric power with minimum maintenance for many applications in such high cost energy areas within today's developing nations.

Douglas V. Smith in "Photovoltaic Power in Less Developed Countries", March 1977 analyzed a set of specific applications for the use of photovoltaic power in developing nations. The conclusions of this first study were that for many applications in irrigation and in village electrification there were potentially significant markets for photovoltaic power systems. In addition, irrigation in general appeared as a major potential market in which photovoltaics could compete effectively in many locations with both gasoline and diesel powered irrigation pumps. The initial work by Smith became the starting point for the analysis and proposals presented in this paper.

The development and analysis of the potential for photovoltaics in microscale pumping evolved from a set of concerns of the Photovoltaics project at the MIT Energy Laboratory. Our initial interest in further analysis of the potential for photovoltaics in developing nations centered on two areas, the first the identification of potential economically competitive markets for photovoltaic systems which would develop at prices higher than those anticipated in the United States or in other developed nations. The second was the estimation of potential market for photovoltaic power systems at any given price. The present paper represents a narrowing of both of these objectives to focus attention and analytic effort on one specific and highly attractive application -- micro-scale pumping -- which appears to accomplish a set of objectives of both the Department of Energy and the aid giving agencies simultaneously.

- It is an application with a potentially large market both through local sales and through both miltilateral and bilateral development assistance programs.
- It is an application that appears to be cost effective at values around 5 dollars per peak watt.
- It is an application which fits within current programs in increased food production and rural agricultural development of a number of the most active international funding agencies.
- It is an application which is directed at the smallest scale farming sector of the nations in which it would be applicable and, as a result,
- It is an application which is likely to have positive rather than negative impacts upon income distributions within these areas.

The paper which follows, therefore, strongly advocates a concept in both energy technology and development activities. It is written to receive wide audience and therefore is neither highly technical nor strongly market or marketing oriented. Versions of this effort by Smith and Allison are in circulation through the World Bank and through the other Aid giving agencies. In addition, a shorter version has been submitted for publication in Finance and Development.

The Photovoltaics Project of the MIT Energy Laboratory would like to acknowledge the interest and assistance provided by a number of individuals throughout both the International Division of the Department of Energy and the United States Agency for International Development. Of particular assistance, however, has been Dr. Allison of the World Bank who is the co author of this effort. In addition we acknowledge the assistance of the Photovoltaic Field Test and Applications project of the MIT Lincoln Laboratory who at present are beginning the detailed application testing required to confirm the performance characteristics of the micro pumps discussed in this paper.

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February 1, 1978

Micro-irrigation with Photovoltaics

Introduction:

The following report indentifies and analyzes one application of photovoltaics to irrigation water pumping: the case of the small farmer with 1-2 hectares of irrigable land and water available for pumping lift of under 5 meters. It is concluded that this situation is a common one in several parts of the world and that the development payoffs from meeting the needs of such farmers would be tremendous. Fractional horsepower photovoltaic pumps become economical for some widespread applications at array cost (in 1978 dollars) of around $5 per peak watt. The potential demand is enormous and if realized in part can make a significant contribution to generating solar cell sales leading to reduced costs for all. In addition such investments lead directly to increases in world food production and to improvements in the well-being of the small farmers in some of the poorest countries of the world.

This report complements an earlier report by Dr. Smith, "Photovoltaic Power in Less Developed Countries", 24 March 1977, which analyzed the economics of photovoltaics when compared with conventional motor pumps in the range above 5 KW. In that case breakeven costs are lower ($1.50 to $2 for irrigation pumping in Chad) because of the availability of a conventional alternative such as diesel pumps. For micro-irrigation there is no conventional alternative except use of human or animal labor.

Fifty million of the world's poorest farmers currently subsist on fewer than 50 million hectares of the world's best land (Table 1 and Map 1). This land is the rich alluvium of the broad valleys and deltas of the great rivers where over 250 million people now live: Nile and Euphrates, Indus and Ganges, Irrawaddy and Mekong. Over large portions of these areas, water is available from ground or surface sources for lifts of under five meters.

Since prehistoric times these lands have been centers of agricultural production, with rich soils, plentiful water supplies and long, warm cropping seasons. Population concentrations developed, but tropical parasites and diseases operated as controls on overcrowding. With the advent of public health programs and of better nutrition fostered by new crops and modern agricultural techniques, death rates dropped and populations started to increase. As a result average farm sizes are decreasing. Concerted efforts to increase food production have aimed at the larger farmers and have failed to halt declines in nutritional levels among the poorest and most numerous segments of the population.

Most of these areas experience extended dry seasons, during which the weather is warm but crop production impossible without irrigation. In drier regions, irrigation systems have been built and operated for thousands of years, but water in many of these is delivered at below surface levels and still has to be lifted onto the field. In other vast areas groundwater is available near the ground surface. In either case water lifting or pumping is needed and pumping requires power. Such power can allow a second crop to be grown (and the major crop to be protected from drought) and can result roughly in a doubling of production.

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Traditional means of lifting water the short distances required have relied on human or animal power. As farms have become smaller, draft animals for water lifting have become nearly unavailable to the small farmers because of the high costs of the necessary well and pumping mechanism, the animal feed or grazing space, and the animal itself. Use of human labor for water lifting is inefficient in terms of food energy needed for pumping and is considered unacceptable human drudgery by nations striving to improve living conditions for their entire population.

Large and medium farmers and large public projects have made effective use of electric or diesel pumps. As Figure 1 illustrates, however, the economics of using conventional 5 HP pumpsets become increasingly unfavorable as farm sizes decrease. (see also Tables 2 and 3.) Significantly smaller diesel engines are not manufactured, and electrification of the large numbers of small electric motors to reach millions of tiny plots would require massive and costly electric distribution systems.

The substantial economies of scale associated with manufacture, installation, and operation of diesel or electric pumps have led to numerous attempts to organize groups of farmers to cooperatively pump and distribute water, and to implement land consolidation programs. Many of these attempts have merely provided subsidized irrigation water to the larger farmers. Efforts to organize the large numbers (40-50 or more) of small farmers required to use a conventional pumpset effectively have floundered for institutional and social reasons and because of the inherent inefficiencies of a water distribution network that must cover scores of tiny plots from 0.1 to 0.5 hectares in size. In Bangladesh, the general rule is that the larger the pump the smaller the unit area

Figure 1

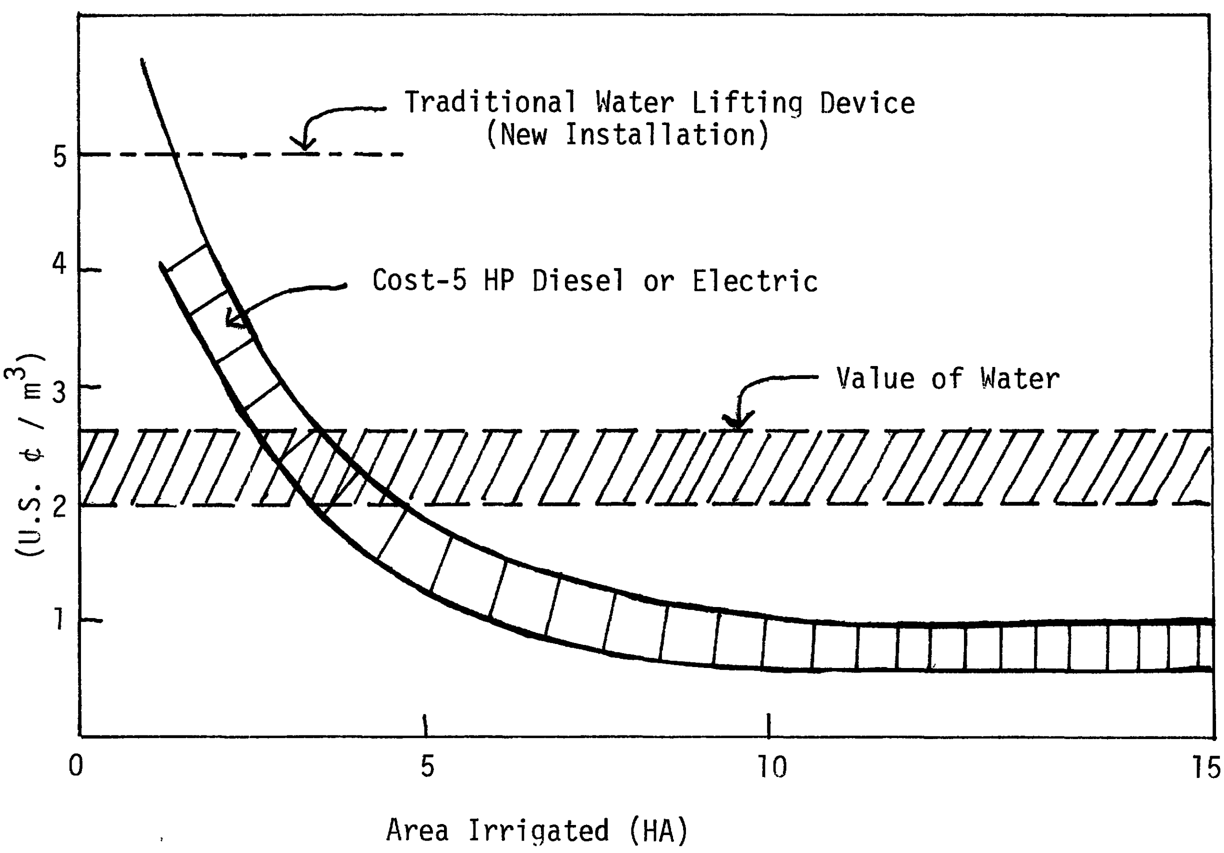

Traditional Water Lifting Device
(New Installation)
Cost-5 HP Diesel or Electric
Value of Water
(U.S. ¢ / m3)
5
4
3
2
1
0
5
10
15
Area Irrigated (HA)

Table 2

COST ANALYSIS

TYPICAL SMALL TUBEWELLS

DIESEL

Capital Costs 1/

Drilling (150 mm dia., 50 m deep)	250
Screen and Casing (PVC)	250
Gravel	25
Development and Testing	100
Pumpset (5 HP)	500
Miscellaneous and Other, including Pumphouse and Distribution System	775
Total	$1,900

Operational Characteristics

Area to be Irrigated (ha)	0.5	1	3	6
Water Required (m^3)	7,500	15,000	45,000	90,000
Hours of Operation Required	250	500	1,500	3,000
Fuel Used (litres) 2/	388	777	2,332	4,664
		- - - - - - - - -(US$)- - - - -		
Annual Costs				
Capital				
- Pumpset (12%)	88(10yrs)	110(7yrs)	138(5yrs)	208(3yrs)
- Remainder (20 yrs at 12%)	186	186	186	186
Fuel 3/	72	144	436	872
Spares and Repairs	40	47	60	73
Total	386	487	820	1,339
Unit Cost of Water (US ¢/m^3)	5.1	3.2	2.2	1.5

1/ Prices prevailing in India (U.P.), end 1977.
2/ At typical prevailing efficiency levels.
3/ At 18.5 cents/litre.

Source: S. V. Allison, World Bank

Table 3

COST ANALYSIS

TYPICAL SMALL TUBEWELLS

ELECTRIC

Capital Costs 1/

Drilling (150 mm. dia., 5 m deep)	250
Screen and Casing (PVC)	250
Gravel	25
Development and Testing	100
Pumpset (5 HP)	250
Miscellaneous and Other, including Pumphouse and Distribution System	775
Electrical Connection	300
Total	$1,950

Operational Characteristics

Area to be Irrigated (ha)	0.5	1	3	6
Water Required (m^3)	7,500	15,000	45,000	90,000
Hours of Operation Required	250	500	1,500	3,000
Energy Used (kwh) 2/	750	1,500	4,500	9,000
	-(US$)-			
Annual Costs				
Capital				
- Pumpset (12%)	44(10yrs)	55(7yrs)	69(5yrs)	104(3yrs)
- Remainder (20 yrs at 12%)	226	226	226	226
Electricity 3/	38	76	224	448
Spares and Repairs	25	30	45	60
Total	333	387	564	838
Unit Cost of Water (US¢/m^3	4.4	2.5	1.2	0.9

1/ Prices prevailing in India (U.P.), end 1977.
2/ At typical prevailing efficiency levels.
3/ At 5 ¢/kwh.

Source: S. V. Allison, World Bank

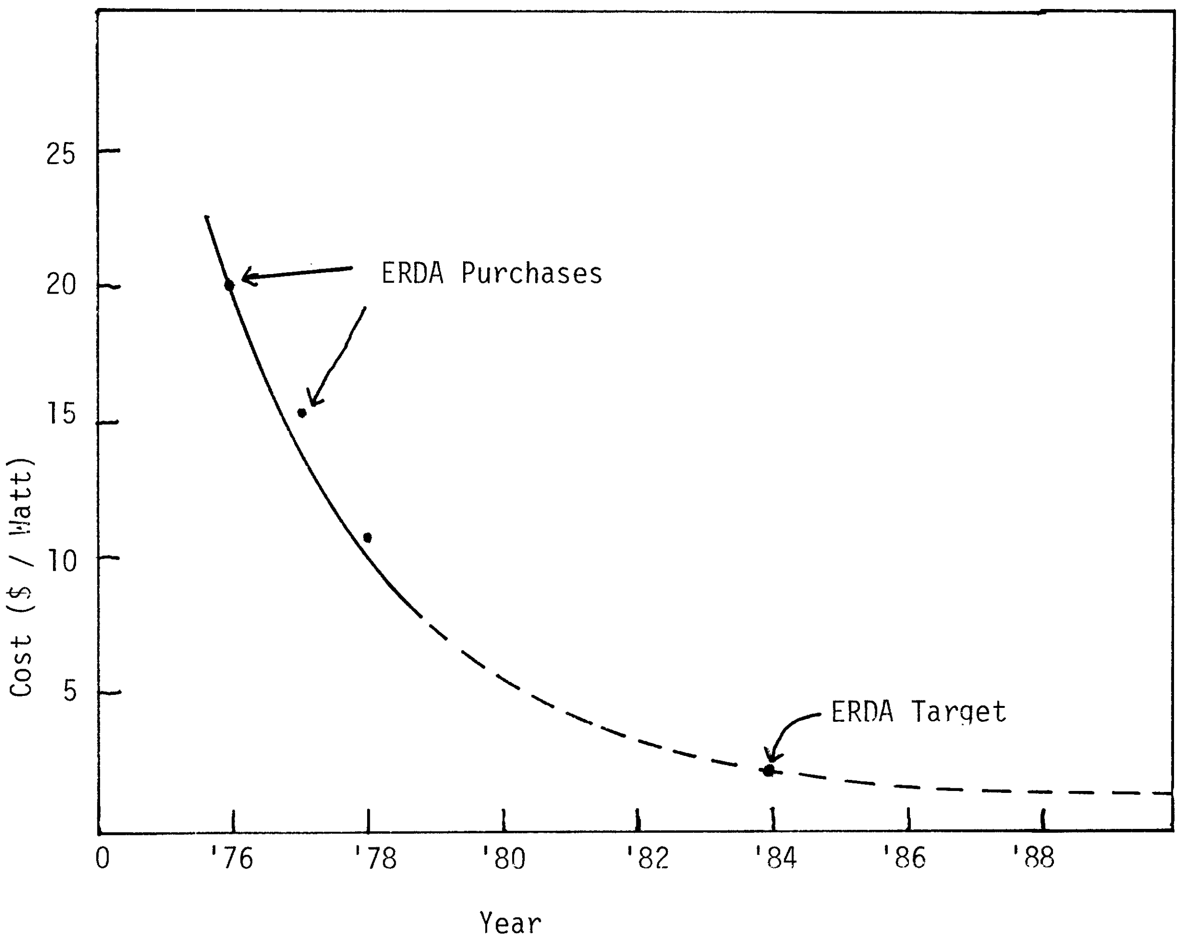
coverage. Thus a pump installation with a capacity one-fourth that of the typical installation covers 70 percent more area for each cubic meter per hour of capacity. The smaller units, however, are exceedingly expensive to operate.

The consequence of these factors is that the small farmer falls even farther behind the large farmer as mechanical pumping is introduced. There has not been developed to date a small mechanical pump that is appropriate to the small farmer's needs.

Small, photovoltaic powered pumping systems now appear to fill this void by providing the potential for cost effective application of this high technology system to one of the most severe development questions facing Third World Nations, the provision of irrigation water to small scale, marginal farmers.

The costs of such solar power cells are coming down dramatically, primarily as a result of research stimulated by the world energy crisis. Prices (in constant 1975 dollars) were over $150/watt for space applications before 1974 and $21/watt in early 1976 for terrestrial applications. Late 1977 prices are under $11/watt. These price declines, illustrated in Figure 2, have been a result of technology improvement, but most significantly of large procurements by the U.S. Department of Energy (46 kw in 1976, 130 kw in 1977, and 190 kw in early 1978). At this stage of their technological development, cost reductions are related to the number of units manufactured because of increased efficiencies in production brought about by larger scale manufacturing. Furthermore, solar arrays are modular and therefore unit costs are essentially independent of array size so that the array for the small pump costs the same on a unit basis as the array for the large pump.

Figure 2


25
20
15
10
5
Cost ($ / Watt)
ERDA Purchases
ERDA Target
0
'76
'78
'80
'82
'84
'86
'88
Year

The land areas with plentiful water supplies with which we are concerned -- the broad alluvial valleys and deltas of the great rivers with dense populations of small farmers -- can be characterized, in terms of parcel sizes, crops and source of water, as shown in Table 4, which illustrates the range of energy requirements for water lifting.

Table 4

Daily Energy and Peak Power Requirements for Micro-Pumping Installations

Plot Size (Hectares)	Surface Water 1/ Non-Rice Cereal	Surface Water 1/ Rice	Groundwater 2/ Non-Rice Cereal	Groundwater 2/ Rice
	(watt/hour/day) 3/			
0.25	80	160	240	480
0.50	160	320	480	960
0.75	240	480	720	1,440
1.00	320	640	960	1,920
	(peak watts) 4/			
0.25	16.7	33.3	50	100
0.50	33.3	66.7	100	200
0.75	50.0	100.0	150	300
1.00	66.7	133.3	200	400

1/ Lift 1.5 m.
2/ Lift 4.5 m.
3/ At 50% pumping system efficiency.
4/ At 4.8 watt-hours/peak watt/day.

An indication of the amount farmers can afford to pay for such solar pumps can be obtained by working backwards from the increased value of production due to irrigation. In rice growing areas production potential is increased by at least the equivalent of 2.5 tons per irrigated hectare. At 1980 prices, and net of out-of-pocket expenses, this represents a potential increment to income of about $250/ha/year. If credit facilities are made available, a farmer can afford to finance an investment in the vicinity of $1250 for each hectare owned and irrigated, assuming interest rate of 10 percent, unit life of 15 years, and 65 percent of incremental income to payoff loan.

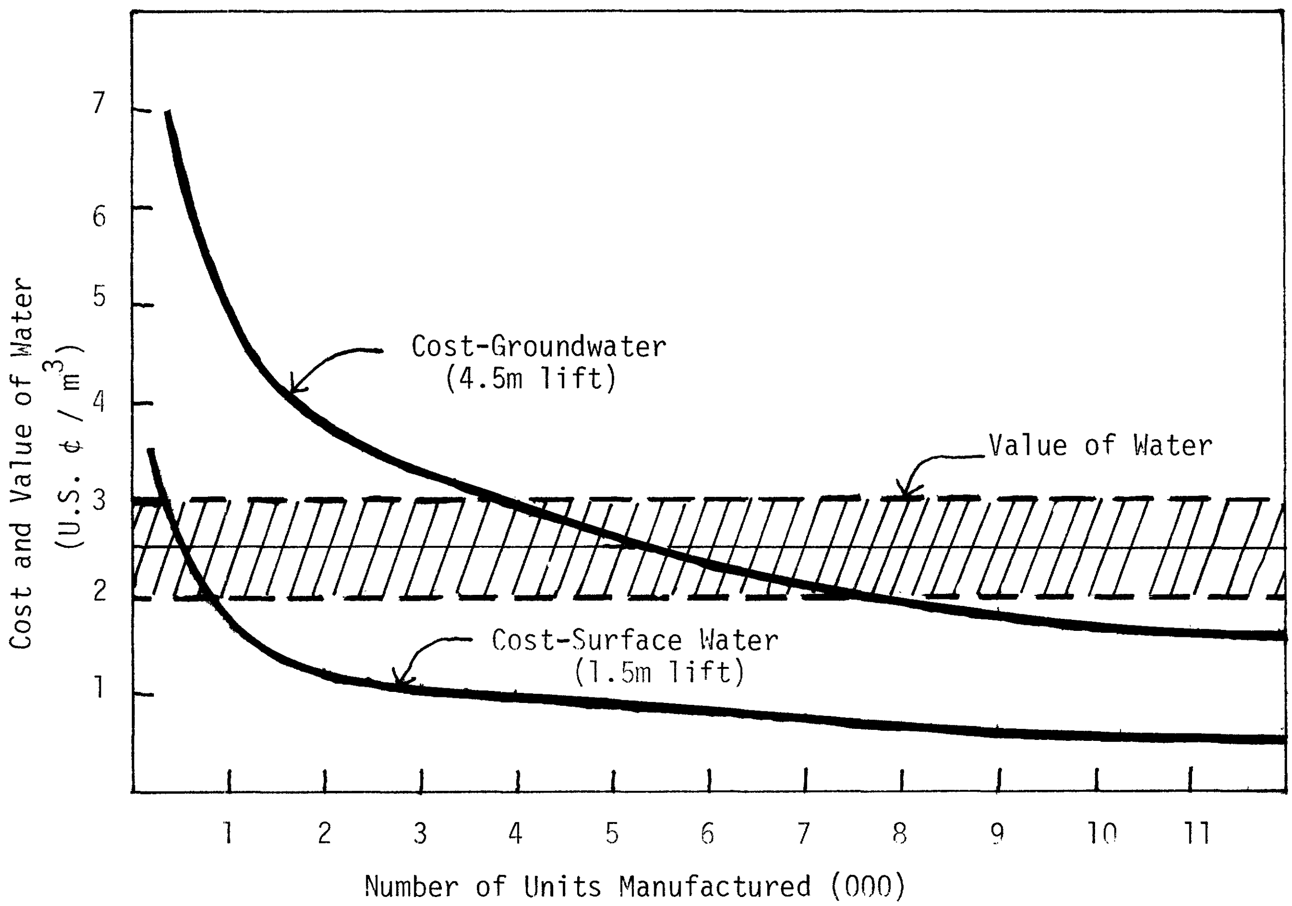
From Table 4 it can be seen that, for surface water irrigation of a second rice crop, peak power requirements are about 133 watts/hectare. Therefore the affordable unit costs of a pumping energy package will be in the vicinity of $8.60/watt. (Allowing $100 for the pumpset and other installation costs, $1150 is left for the energy package, $1150/133 = $8.64. If the pumpset cost $200, the affordable unit cost is $7.89 so this cost is rather insensitive to meter/pump/well costs.) Solar cells can be purchased now for $8/watt if 200 kw are ordered: 1500 units of 133 watts each. Solar pumping of irrigation water is thus economical today.

For groundwater irrigation of rice, with power requirements in the vicinity of 400 watts/hectare, and well, pumpset, and other costs of perhaps $150, $1100 is left for the energy source, indicating an affordable unit cost of about $1100/400 = $2.75/watt, which means that larger purchases are required to reduce unit costs to the affordable range. For non-rice crops, the lower water requirements mean that substantially larger areas are irrigable with each unit of energy available, and the indicated affordable costs are proportionately higher.

Similar calculations can provide indications of the value of each unit of water which can be compared to the cost of a unit of water pumped by various pumping devices as shown in Figure 1. If it required 10,000 m^3/ha of water delivered to the field to produce an additional 2.5 tons of rice, with a net value to the farmer of $250, then the value of the water to the farmer is about US¢2.5/m^3. (This is a number which recurs with considerable frequency over a wide range of cropping, water requirement, and marketing conditions.) On the cost side of the equation, it can easily be calculated that if enough standard pumping units (i.e. something over 2000) are produced to bring the unit cost of the power pack down to $2,400 or about $9.60/w for a unit of 250 w nominal peak capacity, and the ancillary facilities for a groundwater installation (well, pumpset, etc.) cost $175, the unit cost of water produced against a 1.5 m lift would be in the vicinity of about US 1.3¢ per m^3, while for water lifted from 4.5 m the corresponding cost would be 3.8¢ per m^3. If quantities manufactured are increased further, past 10,000 units, power pack costs will fall to about $1000, total installation costs to $1150, and the unit cost of producing water to 0.6 and 1.8¢ per m^3 for lifts of 1.5 m and 4.5 m respectively. Figure 3 illustrates this for one set of realistic assumptions regarding the effect of order size on price.

In addition to the apparent economic advantages of solar photovoltaic systems over other alternatives, these systems have a variety of other characteristics which make micro-irrigation in the Third World a particularly attractive proposition. Because land parcels are so small, strictly limited quantities of water are sufficient, and because of the low lifts, relatively limited quantities of energy will suffice to lift

Figure 3



Cost and Value of Water (U.S. ¢ / m3)
7
6
5
4
3
2
1
Cost-Groundwater (4.5m lift)
Value of Water
Cost-Surface Water (1.5m lift)
1
2
3
4
5
6
7
8
9
10
11
Number of Units Manufactured (000)

the water. Furthermore, plants only use water during the day-time, and then in direct proportion to the incoming solar radiation which in this case is also driving the pump. During the monsoon season, there are frequently clouds in the sky and a solar powered pump would perform with less output, but irrigation is seldom required in this season, unless there is an extended dry (and cloudless) spell. It is this unusual coincidence between the need for and availability of power which makes solar electric pumps peculiarly suitable for irrigation applications. When, to this high degree of compatibility with the environment, is added the minimal operation and maintenance requirements of the photovoltaic energy package, the modular nature of the system, and the opportunity for relatively low cost local manufacture, it becomes clear that this is a very special case of "appropriate" technology. These installations will be quiet and pollution free and have no recurrent fuel costs, near zero operating and maintenance costs, high reliability (no problem of electricical system power failures, load-shedding, or diesel fuel shortages), and offer protection against inflation and the political hazards of petroleum boycotts.

All this depends, of course, on resolution of the difficulty of financing capital investments (however well justified on economic grounds) for farmers currently operating at or below subsistence levels. They are limited at present to loans from moneylenders at exhorbitant rates of interest. It is evident that special financing arrangements need to be made to meet this situation, and a variety of alternative formulae are under consideration. The most promising of these involve relatively heavy subsidies for the first unit purchased by any farmer. All subsequent units would be priced at a premium, set at a level which would ensure that if many units are purchased by the larger farmers (the smallest farmers will need only one) there would be an effective transfer of resources in the desired direction.

The case for micro-irrigation financing mechanisms is a compelling one in a world facing critical problems of food supply, but to bring the prices of these units down to the required levels will take mass production on a worldwide scale and, imperatively, in the countries where prospects look most promising. To get sufficient political attention and provide the incentive for potential sponsors of such a program to act, introductory programs of significant size and with certain important attributes are required. They should serve certain fundamental policy objectives, holding the promise of contributing significantly to the resolution of one or more pressing national problems, avoid obvious disturbance to the environment or important vested interests, and if possible have some inherent glamour or excitement. A solar energy development program of appropriate dimensions, carefully packaged, would appear to meet these criteria.

An appropriate worldwide goal, based on the need to have a measurable effect on the world food problem, might be 10 million units in the field by the year 2000. To put this figure in perspective, it must be considered that, if there are 50 million farmers who need and could use such units beneficially in 1980, there will certainly be 100 million by the year 2000, while by 2000 the total population of the areas in question will have passed 500 million. The proposed target would thus reach only 10% of the potential farmer users. The production potential created would be in the order of 25 million tons (mt) of foodgrain annually, i.e., about 50% of the present production of the 50 million hectares involved.

By the turn of the century, the minimum food requirements of the 500 million people in these areas will be in the vicinity of 75 mt. With production having increased to the extent indicated by present trends to about 100 mt, and the additional 25 mt from this program, these areas would thus have a 50 mt surplus for export to urban areas and much of this should, because of the peculiar characteristics of the micro-irrigation package, be produced by the smaller farmers, whose economic position would be immensurably improved in the process. In addition, the substantial production increases would require proportionate increases in labour inputs, more important in terms of providing employment for the landless segments of the population.

The total capital investment requirements of a 20-year program of this magnitude would be in the vicinity of $3.5 billion 1/. Using IBRD traditional irrigation projects as a ruler, the capacity to produce this quantity of foodgrains has been estimated at about $9 billion.2/ The value of an additional 25 million tons of foodgrain production would be about $5 billion/year. The fuel saved, over the diesel power alternative, would amount to 800 million litres/year, alone worth over $1 billion.

To reach a target of 10 million solar powered pumping units in the field by the year 2000 would require a rapid acceleration from the present zero to over 1 million units manufactured and installed per year (Table 5).

Note: The estimates which follow are "order of magnitude".

1/ Total Bank/IDA lending for agriculture has recently passed $2 billion a year, and will probably total well over $60 billion for the period 1980-2000.

2/ These estimates are exclusive of supporting infrastructure and other services.

Table 5

INDICATIVE
PROGRAM NUMBERS AND COSTS

Year	Thousands of Standard Units Target	Cumulative	Effective Unit Cost of Array 1/ ($/watt)	Power Pack 2/	Unit Costs Well, Motor and Pump	Total	Cost ($million)
				- - - -	-(US$)- - -	- - -	
1978	0.5	0.5	16	4,000	200	4,200	2.1
1979	2.0	2.5	9	2,250	190	2,440	4.9
1980	22.5	25	6	1,500	180	1,680	37.8
1981	50	75	5	1,250	170	1,420	71.0
1982	80	155	3.4	850	160	1,010	80.8
1983	110	265	2.8	700	150	850	93.5
1984	145	310	2.2	550	145	695	100.8
1985	175	485	1.8	450	140	590	103.3
1986	240	725	1.5	375	135	510	122.4
1987	300	1,025	1.4	350	130	480	144.0
1988	400	1,425	1.3	325	125	450	180.0
1989	500	1,925	1.2	300	125	425	212.5
1990	600	2,525	1.1	275	120	395	237.0
1991	695	3,220	1.0	250	120	370	257.2
1992	780	4,000	0.9	225	115	340	265.2
1993	850	4,850	0.8	200	115	315	267.8
1994	880	5,730	0.72	180	110	290	255.2
1995	910	6,640	0.64	160	110	280	254.8
1996	940	7,580	0.58	145	105	250	235.0
1997	970	8,550	0.52	130	105	235	228.0
1998	990	9,540	0.46	115	100	215	212.9
1999	1,000	10,540	0.40	100	100	200	200.0
							= 3,556.2

1/ With frame, wiring and controls.
2/ Assuming 250 w peak.

To launch such a program it is clear that a first push of considerable magnitude will be required. For this purpose, a goal of 500 test and demonstration units in the field by the end of 1978 would seem minimal. Beyond this launch period, during which grant financing of US $3 to 4 million might be required, the program could be financed in the normal course of, and without significant changes in the scale or nature of, ongoing agricultural credit operations. Financing the establishment of local manufacturing facilities would also need emphasis.

The 500 test and demononstration units would be field by the end of 1978 in five counntries carefully selected on the basis of:

- importance of irrigation,
- availability of areas with suitable physical and socio-economic characteristics,
- presence of a suitable national, regional or international research institution to monitor and evaluate performance.

These countries would undertake to monitor program operations and impacts. In addition, they would identify private or public sector entities with the capacity to establish and manage manufacturing facilities for the units required in the second stage. Factory sites would have to be selected, feasibility studies of local production executed, licensing and technical agreements drafted, and at least preliminary arrangements made for financing. Concurrently, the detailed planning needed to establish networks of franchised servicing centers based on existing village workshops, and the training of local mechanics in service center operations, would be initiated. Then, immediately on successful conclusion of the first stage test and demonstration phase, financial arrangements could be concluded and the program could move smoothly into local production.