archive

THE ECONOMICS OF WATER LIFTING FOR SMALL SCALE IRRIGATION IN THE THIRD WORLD: TRADITIONAL AND PHOTOVOLTAIC TECHNOLOGIES

RICHARD D. TABORS

MIT ENERGY LABORATORY WORKING PAPER #MIT-EL-78-015

August 1978

Presented at:

International Conference: Energy and Community Development - Athens, Greece - July 11, 1978

SUMMARY

Towards the Solar Era: The New Economics of
Water Lifting for Irrigation in the Third World

Richard D. Tabors

The Energy Laboratory

Massachusetts Institute of Technology

The traditional and conventional methods of water lifting for irrigation in the developing nations of the world have been adapted for medium and large scale farmers, those with irrigated holdings in excess of 2 hectares. It has been these farmers who have been able to take the fullest advantage of the benefits of new seed varieties in wheat and rice combined with fertilizer and water, the ingredients of the green revolution. This paper summarizes the experience to date in the development of water pumping systems for primarily the deltaic areas of the third world, those areas in which irrigation water is available at depths between 1.5 and 4.5 meters. The areas discussed cover 50 million hectares of the earth's surface and contain roughly 250 million people. This area includes the basins of the Nile, Euphrates, Indus, Ganges, Irrawaddy, and Mekong Rivers.

The value of water for irrigation has been estimated in the range of 2 to 3 U.S. cents per cubic meter. This paper analyses the cost of provision of water by traditional - human and animal - power, by conventional systems - diesel, gasoline, and electric - and by renewable resource systems, in particular photovoltaic powered systems. It has been shown that the means of lifting water available to farmers with land of one hectare of less provide water at costs in excess of its value. Investigations of the Shadoof systems of North Africa and Asia show costs of water as high as 7¢/m^3. The investigation of animal power used to operate a Persian wheel showed highly variable results dependent upon the feed required by the animal. For environments in which the animal must be stall fed

from crops grown on the irrigated land it was shown that water costs were 4¢/m^3 while for animals which could be freely grazed this cost could be reduced to under 1¢/m^3. It was pointed out that for the smallest of farmers land was never available for free grazing and the land required for the animals to walk while pumping was not marginal to the overall irrigated area.

Four pumping systems were investigated using conventional power systems, two diesel, one gasoline, and one electric. In each instance, because of the availability of pumping systems in relatively fixed sizes, these systems were not available in economic cost ranges for small farmers. The cost per m^3 for irrigation of 1 hectare were: diesel, Chad, 3,5¢; gasoline, Chad, 4.0¢; diesel, India, 3.5¢; electric, India, 3¢. In each of these instances the cost of provision of water using conventional systems supplying small scale farmers was greater than the economic value of the water supplied.

The final water pumping system investigated was one utilizing a high technology power system, photovoltaic cells combined with efficient electric motor and pump systems. In this analysis it was shown that at today's cell prices such systems would provide water at a cost of 2.8¢/m^3 for lifts of 1.5m and at 5.4¢/m^3 for lifting heads of 4.5m. It was shown that for production within the United States it is likely that prices for photovoltaic power systems will be reduced from their present cost of $10 to $11/watt peak to values in the range of $24/watt peak by 1982. In the analysis we have looked at the cost of irrigation water with photovoltaic power system costs of $4/peak watt. In this case for a lift of 1.5m water costs are 1.2¢/m^3 and 2.3¢/m^3 for lifts of 4.5m.

It is concluded that additional information is required to analyze more fully the potential for photovoltaic powered micro irrigation systems in the third world. Significant in the analyses must be more detailed analysis of the price of photovoltaic modules delivered and installed in such small scale systems, the efficiencies available in the pumping systems and the availability of credit and institutional structures within the rural areas to guarantee that small farmers will be able to take full advantage of such systems when and where they are proved economically viable.

The economic development of rural communities in most developing nations is heavily dependent upon increased agricultural productivity. For rural populations, particularly at the margin, to survive and indeed to increase their economic position requires increased return from small as well as large land holdings. This paper focuses attention on the economics of irrigation of small farms (.5 to 2 hectares) in developing countries. It analyses the experience of the "green revolution" reaching small farmers, the economics of both traditional and conventional pumping systems for small farms and finally analyses the competitive advantage of micro scale photovoltaic (solar cell) powered irrigation systems.

The development of new varieties of wheat and rice was hailed as the turning point in agricultural development and income distribution for the nations of the third world. While the benefits of the "green revolution" have been enjoyed by medium and large scale farmers, the small, frequently marginal, farmer has been unable to take advantage of the benefits of new varieties largely because irrigation water has either been unavailable or too expensive.

Evidence of the constraint to increased production (and potential income) caused by lack of water has been seen in virtually all regions which have a predominance of small farm holdings. Thus, while the wheat growing Punjab of Pakistan and India benefitted dramatically[1], the small farm, predominantly rice growing, deltaic areas such as the Ganges (Bangladesh) or Mekong (Vietnam) have not seen the same level of benefit from improved varieties. Nonavailability of reliable water supply in dry seasons which allows for multiple cropping of land has played a major role in differentiating between large and small farm benefits.

Both Bangladesh (formerly East Pakistan) and Vietnam have been the site of detailed analyses of the benefits of irrigation. The work of J.W. Thomas and others in analysis of the Rural Works program of East Pakistan pointed to requirements for cooperatives for sharing of water from moderate (1 to 2 cusec) pumping systems among groups of small farmers[2]. Though this offered communal/cooperative structures within rural communities it was found that the pumps themselves tended to be monopolized by the larger farmers and that the hectares irrigated decreased as the number of farmers within a pump group increased.

There has been considerable recent work, not formally published to date, attempting to estimate the value of irrigation water in a range of environments. As will be discussed later, Smith and Allison have used a value for small farms in deltaic areas equivalent to an increase in yield of 2.5 metric tons of cereal per irrigated hectares[3]. The work of a number of researchers at the International Food Policy Research Institute has indicated benefit values in the range of 1.4 tons per hectare[4]. Econometric analysis by Alan Strout of MIT has shown values of from 1.4 to 3.0 metric tones per ha[5]. Samsom in his work on Vietnam has shown output to double with the motor pump. In general all of these values roughly translate to a value for irrigation water in the range of U.S. $.02 to .03 per m^3 of water pumped.[6]

Evidence from Vietnam as reported in the work Sansom, Economics of Insurgency again indicates that smaller farms, those at a mean of 1.2 ha. are not able to take advantage of the motor pump technology while larger farmers (mean 2.5 ha.) are.[7] The work of Sansom is significant in this analysis for two reasons. The first is that the motor pump technology employed for water lifting was indigenously developed; it was an inexpensive low technology development and was readily available in the local market yet was not economic for the smallest of land holders. The second point of importance is that the motor pump entered the economy of rural Vietnam at an unprecedented rate. Sansom reports of districts whose farm adoption of motor pumps increased from zero to 50% in less than four years[8]. One concludes from these experiences that the provision of irrigation water brings a rapid economic

Figure 1

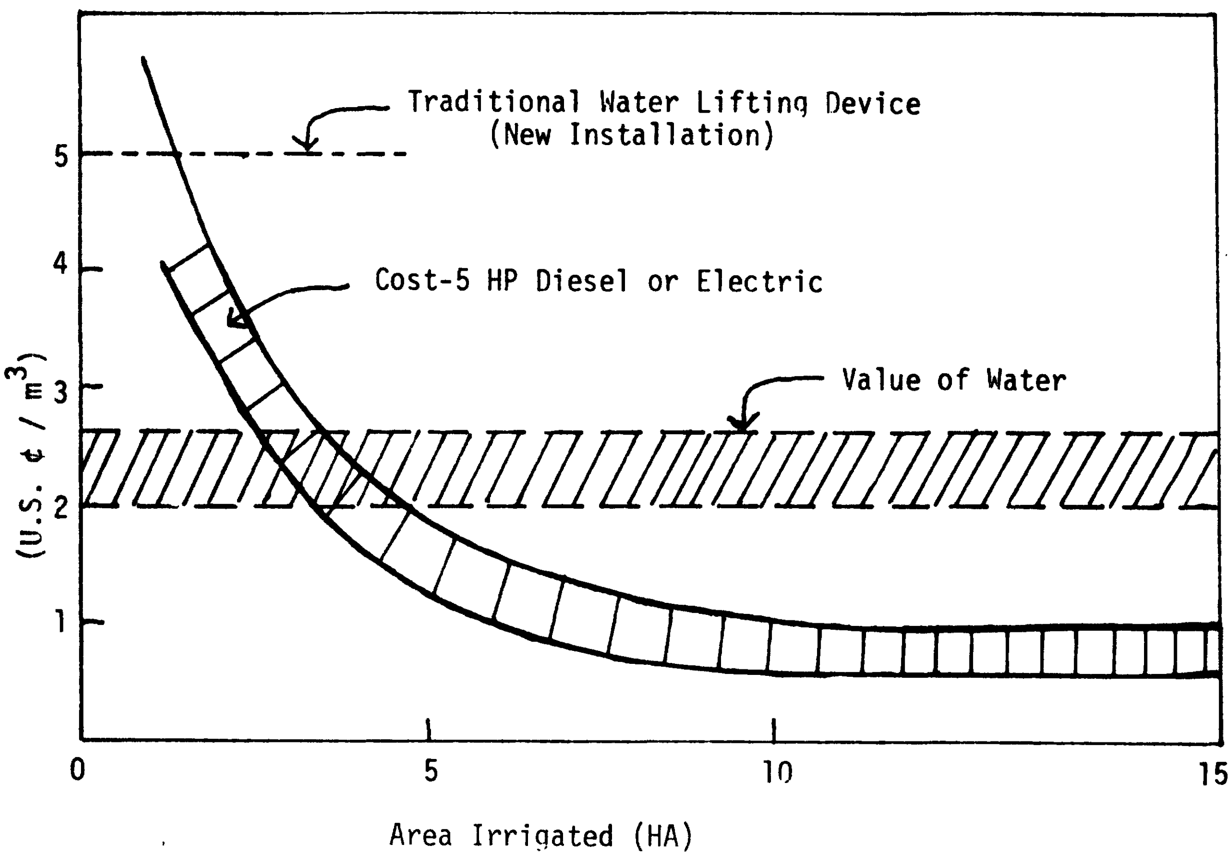
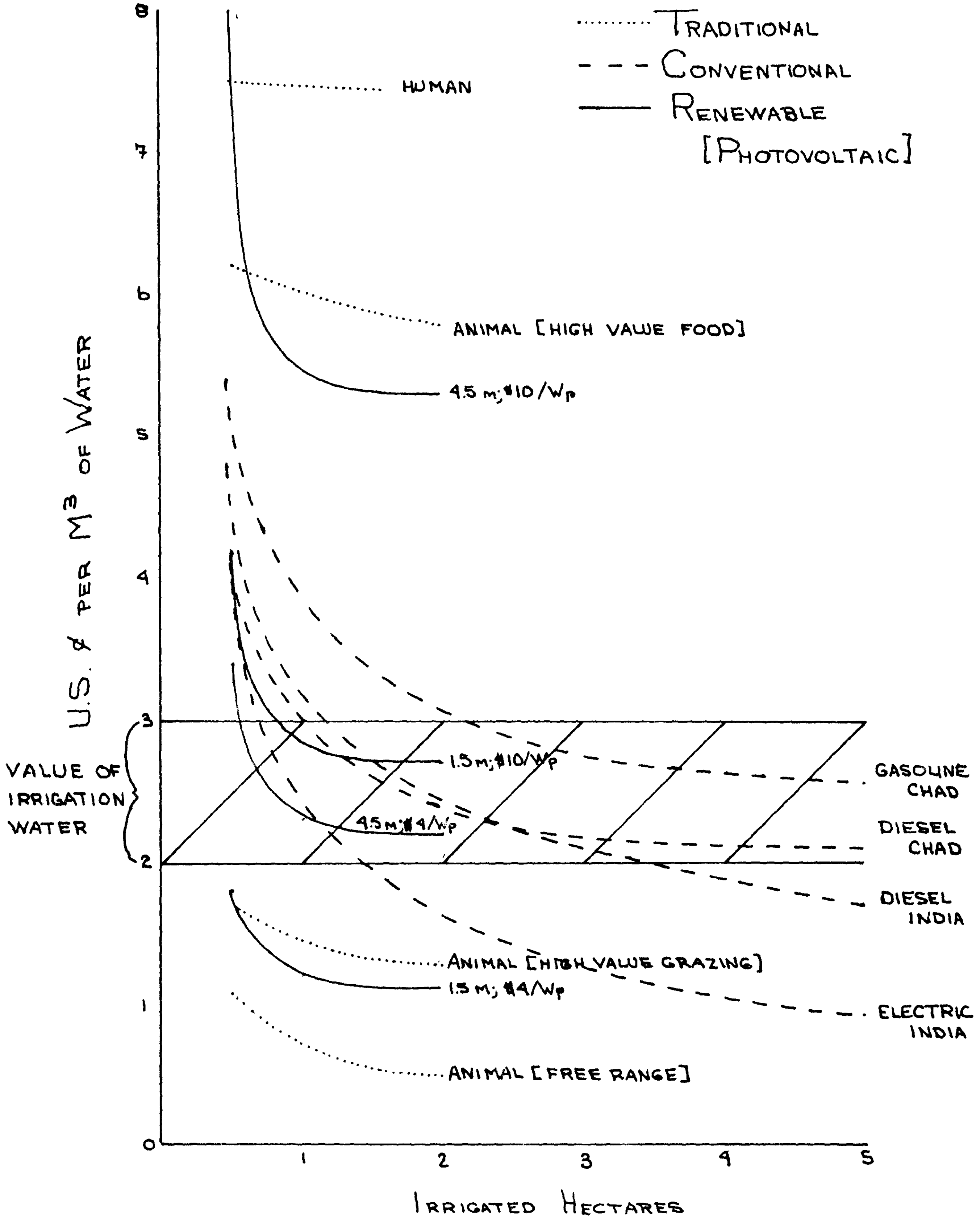

Traditional Water Lifting Device
(New Installation)
Cost-5 HP Diesel or Electric
Value of Water
(U.S. ¢ / m3)
5
4
3
2
1
0
5
10
15
Area Irrigated (HA)

FIGURE 2

VALUE AND COST OF IRRIGATION WATER



benefit which is quickly recognized by the traditional farmer.

The information from pumping of water in the Punjab, in Bangladesh and in the Mekong points to two significant conclusions. The first that provision of reliable supplies of water brings economic benefit and the second that these benefits do not accrue to farmers below a specific threshold. The remainder of this paper focuses attention on provision of water to small farms, (.5 to 2 hectares) specifically in water lifting environments which require minimal amounts of energy, i.e., those areas requiring water lifts in the range of 1.5 to 4.5 meters. Figure 1 shows graphically the areas of the world in which this water regime exits, primarily the large alluvial deltas of Asia, North Africa and Arabia. These regions account for 50 million hectares of land and a population of over 250 million.

Traditional methods of water lifting over relatively low heads have utilized both human and animal power[9]. Figure 2, which summarizes the economics of all water lifting systems discussed shows the cost of water lifting using human power with a relatively efficient system, the Shadoof of much of Africa and Asia. While detailed economic analyses were not carried out for a range of human powered irrigation systems, man in general is not an economic machine in such tasks as water lifting where his food requirements nearly equal the incremental production from the water pumped. The Shadoof has been used as an example of a relatively efficient system still costing roughly 7.5¢/M^3 of water.

Irrigation water from animal power is available over a range of costs primarily as a function of the cost of food for the animal. As shown on Figure 2, these values vary widely. The analysis presented is for a camel operating a Persion Wheel in Chad. The results are, within the errors of estimation, similar to those available for other animals such as bullocks operating similar lift persian wheels in south and southeast Asia. In general, if it is necessary to feed the animal from forage crops grown on the irrigated land, the cost of irrigation water is between 5.5¢

and 6.5¢/M^3. If animals can be fed on crops grown or harvested from non-irrigated lands the cost may be reduced dramatically to 1.5 to 1.7¢/M^3 and further reduced to .6 to 1¢/M^3 when animals can be left to forage for themselves. For the majority of the deltaic areas under analysis in this study availability of land for forage is limited, particularly for the smallest of farmers, as a result as farm size decreases the cost of maintaining (feeding) work animals increases effectively removing draft animals from consideration on farms of one hectare or less.

Conventional small, on-site irrigation pumping schemes range in size from roughly .5 cubic feet per second (cusec) to 2 cusec systems. For the deltaic areas, such pumping systems are either pumped wells (tube wells) or low lift systems. Figure 2 again summarizes water costs from four pumping systems, two in Chad and two in India[10]. The pumping systems analyzed for Chad represent conventional gasoline and diesel systems utilizing .5 cusec pumps with available power packs of 7.75hp. Pumping systems of this magnitude are available utilizing gasoline power. The diesel system was assembled on paper for the purpose of this analysis. As can be seen, the fixed capital portion of the investment in conventional pumping systems makes them only marginally economic at farm sizes of 2 hectares and uneconomic on farms below 1 to 1.5 hectares.

Two points should be made concerning the conventional pumping systems for Chad included in Figure 2. The first of these is that both the gasoline and the diesel systems are not specifically designed for low water head operation and as a result are overpowered for the required task. These are, however, the pump and motor combinations generally used in both USAID and IBRD low lift pumping programs throughout most of South and Southeast Asia. The second point is that the pumping systems studied were based upon U.S. prices and equipment. Work done by META Systems also attempted to estimate capital costs of lowspeed diesel systems constructed in Pakistan and India. The impact of assuming low-speed diesel engine sets was an overall cost reduction of roughly 40%.[11] The shape of the curve remains the same, however. The META report also suggests the use of "sewage" pumps as having a high potential for application in low head water lifting. These pumps have never been used for irrigation and therefore their economic performance is highly uncertain. The preliminary analyses cited showed costs of low-speed diesels with "sewage" pumps to be roughly one-third those of conventional diesel systems[12]. If this is the case such systems would be economically attractive to farmers of one or fewer hectares.

Two curves for the cost of water have been shown for pumping experiences in India. These figures, reported in Smith and Allison, are for pump sets (pump and motor) of 5hp and are assumed to be operating on wells of 5m depth[13]. As was the case with the analyses for Chad, the curves show a range of uneconomic operation at farm sizes less than 1.5 to 2 hectares. As can be seen from Figure 2, the least expensive of the alternatives investigated was that for electric pumping in India. The environment within which such electric pumping can occur is extremely limited. Few rural areas in the third world receive gridded electrical power or are likely to do so in the near future. In addition, the authors have calculated the cost of the electrical pumping scheme assuming a flat cost of electrical power at the rate of $.05/kwh, a level requiring government subsidy. Small-scale irrigation power requirements do not justify the extension of distribution systems given both the seasonal natuare of and the low level of rural demand. It is significant to note, however, that electrical pumping systems appear to be the most economic of the set of conventional alternatives for the size of the system studied.

Given current traditional and conventional methods of water pumping for irrigation as shown in Figure 2, there are no economically viable alternatives open to the smallest of farmers, those farming in the range of one hectare of land. The section which follows discusses the potential availability of irrigation water to small farms utilizing photovoltaic (solar cell) powered pumping systems to supply water over low lift regimes. The systems considered were for 1.5 and 4.5 meters, a pumping environments common within most deltaic areas. While photovoltaic electric generation systems require a relatively high technology production process, their modularity and lack of moving parts makes them an ideal power source in geographically isolated applications. These characteritics make photovoltaic pumping systems, even at today's relatively high prices, an economically attractive investment for small-scale farmers.

Before beginning a more complete discussion of the potential economic benefits to development of photovoltaic powered irrigation systems it is important to mention briefly the history and projected path of cost decline in solar cell modules. Figure 3 presents the historical and projected cost decline curve for photovoltaic modules manufactured in the United States in part with the active involvement of the government. It does not, however, include direct subsidization of the manufacturing process. The current price of photovoltaic modules in 1975 dollars is roughly $11 per peak watt.[14] The work of the Jet Propulsion Laboratories of the California Institute of Technology has shown a clear pathway for manufacturing of modules in the range of $2 to $3/Wp given current technology. The governmental goals supported by research at JPL indicates that prices in the range of $2/Wp can be reached by 1982. These estimates for cost reduction for photovoltaic modules become significant in the analysis of the potential for such systems in developing country irrigation applications for two reasons; the first associated with the market for photovoltaic systems for U.S. manufacturers and the second for the potential economics in the developing nations themselves.

There have been shown to be only limited markets for photovoltaic power systems within the United States of other nations with well-developed electric power grids.[15] As a result if there is to be a decrease in module costs as a function of increased

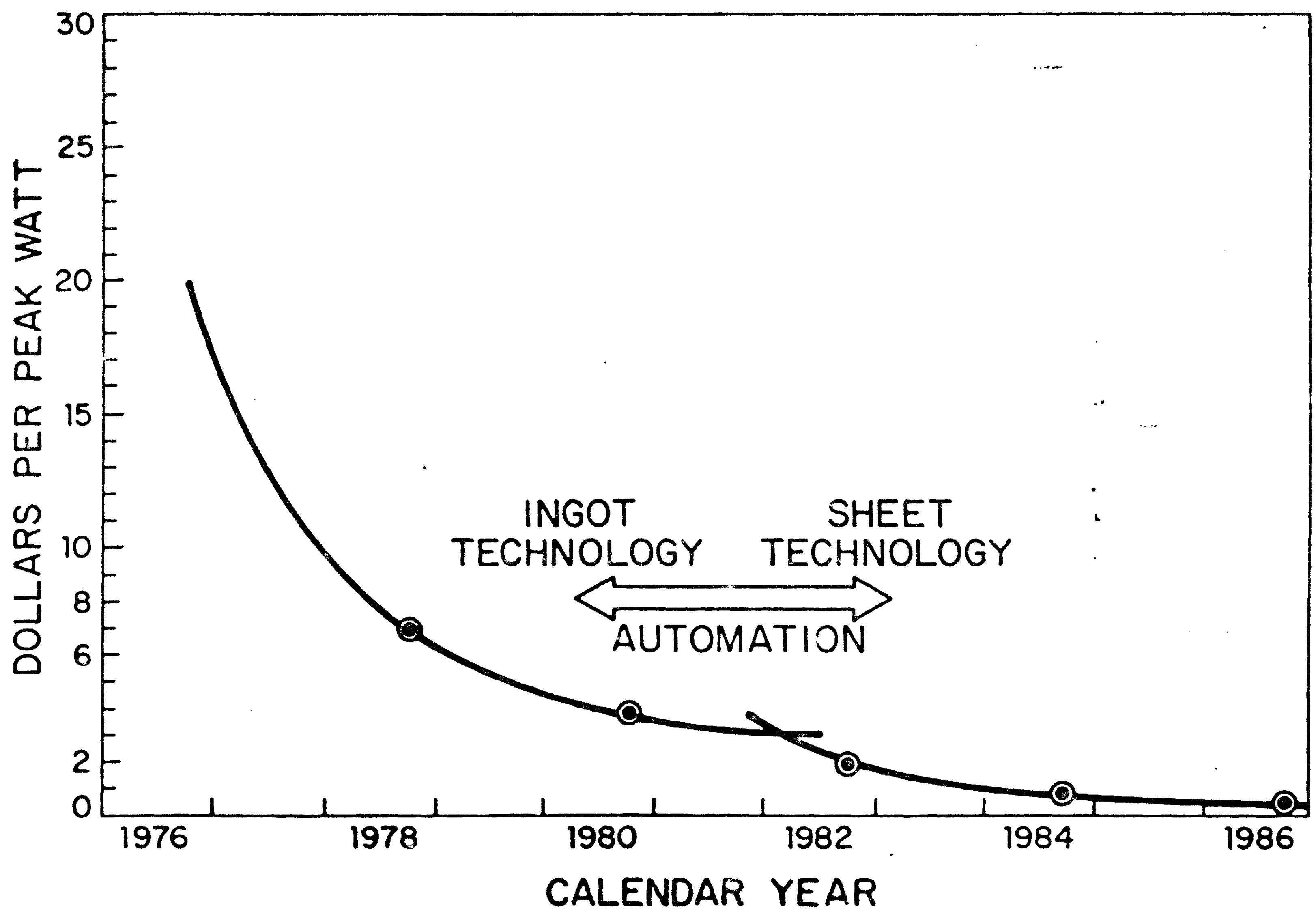


FIGURE 3

TERRESTRIAL SOLAR ARRAY PRICE HISTORY/GOALS volume as well as a function of technological progress, the increase in volume must, in all liklihood, come from markets outside of the United States. The irrigation market discussed in this paper represents an application which shows a major potential for sales in a true market environment.

The economic benefits which can be seen in the potential development of photovoltaic irrigation systems appear to be great even at prices of modules available today. The lower module costs anticipated by U.S. manufacturers in the near future will make these systems all the more economic to their adopters. As was discussed earlier in this paper the approximate value of water for irrigation purposes is between two and three cents, U.S., per m^3 of water provided. Given the value of water to a farmer it is possible to calculate the amount that farmer would be able to pay for water. When this calculation, as was done by Smith and Allison, is carried out for the 1.5 and the 4.5 meter lifting regimes, given the assumptions in Table 1, it can be seen that the value of the photovoltaic modules for a 1.5 meter lift is between \$8.60/Wp (given a non-module rest-of-system cost of \$100) and \$7.90/Wp (given a \$200 non-module rest-of-systen cost). The comparable values for lifts of 4.5 m with \$150 and \$300 non-module (pump, casing, and well) costs would imply values for the modules between a high of \$2.75 and a lower value of \$1.40/Wp.

To calculate cost of water for small-scale farmers comparable to that presented in the previous discussions and in Figure 1, this paper departs somewhat from the previous work of Smith and Allison and looks at a 1.5m lift system employing 200 Wp of photovoltaic power equipment, somewhat larger than that actually required. It has been assumed that the 4.5 meter lift system will require 400 Wp of photovoltaic power equipment. Such sizes allow for the consideration of 200 Wp modules for the hypothesized microscale pumping systems. Given that photovoltaic modules are available att \$10/Wp (as they are at present available between \$10 and \$11/Wp for

TABLE I

PERFORMANCE ASSUMPTIONS: PHOTOVOLTAIC POWERED MICRO SCALE PUMPING SYSTEMS

Area Irrigated	1 hectare
Pumping Regimes (Power in Peak Watts)*	1.5 M Lift 133.3 4.5 M Lift 400.
Crop	Rice
Crop Water Requirements	10,000 M^3/ha
Incremental Crop Production	2.5 Tons
Value of Incremental Crop	$250**
System Life	15 Years
Interest Rate	10%
Pumping System Efficiency	50%
Pump plus well costs	$100-$200

* Given 4.8 watt-hours/peak watt/irrigation day

** It is assumed that 65% of the incremental income is available to pay off the loan.

SOURCE: Adapted from Smith and Allison, Micro Irrigation with Photovoltaics, MIT Energy Laboratory Report, MIT-EL-78-006, Cambridge, MA, April 1978.

large purchases in the United States), the cost of the water pumped would be between 2.7 and 2.9 cents U.S. per M^3 for the 1.5m lift and between 5.4 and 5.6 cents U.S. for the 4.5m lift. (See Table 2). Calculations for values of Dollars U.S. of 4.00/Wp would yield costs per M^3 of 1.2 cents for lifts of 1.5m and 2.3 cents for lifts of 4.5m. These values contain a set of assumptions concerning the production package for pumping systems, i.e. that a module of 200 Wp would be a useable size. Clearly for the lowest lift this size of one-third larger than is required and as a result were the systems perfectly modular it would be possible to reduce the cost of water by one-third for this lifting environment. For the deeper lift, 4.5m, this is not, however, the case.

There are a series of questions of sensitivity of the results reported in this analysis to information not available at the time of this writing. Table 2 summarizes both the base case values in cents/m^3 and the sensitivity analyses discussed below. The economic value of the micro-scale pumping systems is highly dependent upon the cost of the modules. As was shown, at values of Dollars U.S. 4.00/Wp the 1.5m lift is more than economic for farms of 1 hectare and the 4.5 lift requirements are at least marginally economic. The anticipation of the U.S. govenmental program is that these system costs will be achieved during the next two to three years.

As was shown the system costs themselves are not highly sensitive to the cost of the non-module components such as well casings and pumps. This is true because these non-module components make up a relatively small proportion of the total cost. It appears unlikely that these costs would dominate in the decision to buy or not to buy a pumping system, though it is possible that were pumps not available at these cost levels and efficiencies, these components could bear a more major portion of total cost.

The area of sensitivity most crucial from the viewpoint of the analysis

TABLE II: VALUE OF WATER PER CUBIC METER PUMPED WITH A PHOTOVOLTAIC POWERED MICRO SCALE IRRIGATION SYSTEM

	Lift(M)	Wp	$/Wp	Non-Module Costs	Total Cost	Annualized Cost	¢/M^3
Ia	1.5	200	10	100	2100	279.1	2.8
Ib	1.5	200	10	200	2200	289.2	2.9
Ic	1.5	200	4	100	900	118.3	1.2
Id	1.5	200	4	200	1000	131.5	1.3
IIa	4.5	400	10	150	4150	545.6	5.4
IIb	4.5	400	10	300	4300	565.3	5.7
IIc	4.5	400	4	150	1750	230.0	2.3
IId	4.5	400	4	300	1900	249.8	2.5
Sensitivity of Results assuming pumping efficiency of 25% rather than 50%							
IIIa	1.5	400	4	100	1700	223.5	2.2
IIIb	4.5	800	4	150	3350	440.4	4.4

* For financial and system assumptions not included in this table, see Table 1

carried out in this paper is the assumption of total pumping system efficiency of 50%. Considerable research is required to either discover existinq pumping systems which will deliver efficiencies on the order of 50% ot to develop systems with these characteristics. The significance of this cannot be overstated as is shown in Table 2 where it can be seen that if efficiencies of the pumping systems were only 25% the required cost would effectively be doubled given the small proportion of the total cost which can be accounted for by the cost of the non-module portions of the total irrigation system.

The final point of sensitivity analysis is that concerning farms of less than one hectare in total size. It is difficult to argue for perfect modularity in the development of photovoltaic powered irrigation systems. If there were no economies of scale in production, the it would be possible to have a nearly flat curve for pumping systems presented in Figure 2. We have assumed, as was assumed with the other systems presented, that there are some economies in production and as a result that the prices would increase as the farm size decreased to 1/2 ha. The curve presents a median value. It is unlikely that the cost to the farmer of 1/2 ha. would be the same as to the farmer of one hectare, i.e., that there are no scale economies. It is equally unlikely that given the basic modularity of the photovoltaic power system that there would not be systems available smaller than 200 Wp. Figure 2 presents a cost per M^3 of water to the farmer of 1/2 ha. equal to 1.5 times that to the farmer of 1 ha.

In summary, it can be seen that the technology of photovoltaic powered, micro-scale irrigation systems may offer a highly economic source of water to farmers with extremely small plots of land, those less than 2 ha. These systems have not been fully tested and as a result there are at present three major areas of uncertainty which must be resolved to their effective entry into the market. Most significant of the uncertainties is in terms of the cost of the photovoltaic modules themselves though as was discussed it is likely that future anticipated cost reductions by U.S. manufacturers will more than accomplish the reductions required for entry into this market. The second uncertainty is more critical in that there is required additional testing and research on the levels of pumping system efficiency available. This analysis has assumed 50%, a value that may be optimistic. The third level of uncertainty relates to the institutional structure within which such a development will be introduced. The systems themselves will be capital intensive but requiring virtually no operating and maintenance costs. For the systems to enter the market it will be necessary that there be available an active and well developed rural credit system and a willingness on the part of lending institutions to finance such systems. For the lender to be an active participant in the expansion of the use of photovoltaic powered micro scale irrigation systems these systems must leave the laboratories and be tested and demonstrated on agricultural experiment stations and on model farms in the deltaic regions. The competitive advantage of such systems shown in Figure 2 requires proof in the market.

FOOTNOTES

1. For a more complete discussion of the impact of the Green Revolution on farming in the Punjab region of Pakistan see: C.H. Gotsch, "Technological Change and Private Investment in Agriculture: A Case Study of the Pakistan Punjab" (PhD Dissertation, Harvard University, 1966).

2. For East Pakistan, see contribution by J.W. Thomas in G. Papanek, editor, Development Policy II; The Pakistan Experience, (Cambridge: Harvard University Press, 1971).

For Vietnam, see R.L. Sansom, Economics of Insurgency in the Mekong Delta of Vietnam, (Cambridge: Massachusetts Institute of Technology Press, 1970), see in particular Chapters 7 and 8.

3. D.V. Smith and S.V. Allison, Micro Irrigation With Photovoltaics, (Massachusetts Institute of Technology Energy Laboratory Report - MIT-EL-78-006, April 1978).

4. Personal communications with Dr. James Gavan, International Food Policy Research Institute, Washington, D.C., May 1978.

5. Alan Strout, Projecting Agricultural Crop Supply From Cross-Country Data, Mimeo, Massachusetts Institute of Technology, June 1978.

6. Sansom, op. cit., Chapter 8.

7. Sansom, op. cit., p.173, p.174.

8. Sansom, op. cit., p.169.

9. The analyses for human, animal, and conventional water lifting systems have been adapted from work by Tabors in Meta Systems, Inc, Analysis of "Revelle" Polders Development Scheme and Design for a Long Range Lake Chad Basin Study, Working Draft Report, Cambridge, Massachusetts, 1974, pp.52-109. Values

reported are in United States Dollars. Those from META Systems are 1973/74, those for India for 1975.

10. Calculations for Chad are from META Systems, op. cit. Those for India are from Smith and Allison, op. cit., pp.10-11.

11. Meta Systems, op. cit., pp.75-81.

12. Ibid.

13. Smith and Allison, op. cit.

14. A peak watt is the potential energy which can be generated from a photovoltaic device at 1 atmosphere at 12 noon given a cloudless sky. The analysis which follows assumes that in much of the areas requiring irrigation one peak watt (Wp) will generate 4.5 watt hours per day.

15. See P. Carpenter and G. Taylor, An Economic Analysis of Grid-Connected Residential Solar Photovoltaic Power Systems, (Cambridge, Massachusetts: Massachusetts Institute of Technology Energy Laboratory Technical Report - MIT-EL-78-007, May 1978).