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The Potential for Groundwater Exploitation by Solar-Powered Pumps in Pakistan

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SUMMARY

This paper reports on the preliminary field testing of small-scale solar-powered irrigation pumps in Pakistan, and seeks to establish how far the cost of these devices would need to fall before they could be expected to become attractive to farmers presently using other forms of irrigation. The data available at present are insufficient to support firm conclusions, but it does appear that relatively modest reductions in price might be sufficient to persuade Persian wheel users to adopt the new technology. In the case of deep tubewells, rather larger reductions seem likely to be required. The question of who would be able to enjoy access to solar pumps is also explored. Here it appears that, whilst more landholders will be able to benefit than is the case with other modern forms of irrigation, those with less than 2 ha remain likely to be excluded.

INTRODUCTION

The cost of photovoltaic cells, which convert solar insolation into electricity, has fallen very rapidly in recent years; and a point is now being approached where solar energy may be able to compete effectively with existing energy sources in certain areas.[5,6] Potential is greatest where temperatures are high and cloud cover low. Of the many applications of the new technology which may prove possible, the lifting of relatively small amounts of water for irrigation and other purposes is generally regarded as the most promising.

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For a number of reasons, Pakistan appears to offer a particularly favourable environment in which to explore the feasibility of solar pumping. Insolation is high and rainfall low, and over extensive areas of the country regularly recharged aquifers are available within a few feet of the surface. In addition, there are a large number of small farms, most of which lack adequate access to modern forms of irrigation.

Taking these factors into account, and encouraged by a preliminary report prepared by Stephen Allison of Solar Electric International (SEI), the Agricultural Development Bank of Pakistan (ADBP) decided in 1981 to embark upon a programme of field tests designed to determine the performance of prototype pumping systems under farm conditions.[3] (At the same time, a small but more controlled experimental testing programme was set up by the Pakistan Agricultural Research Council (PARC).) The pump sets were supplied by Intermediate Technology Industrial Services (ITIS).

This paper, a shortened version of a report commissioned by ITIS, is based upon a trip which the author made to Pakistan in February 1982, at the end of the first year of the programme, and has two main objectives.[7] The first is to compare the existing solar pumping system, and others now following in its wake, with other forms of irrigation presently in use; and the second is to assess its likely impact upon the different classes of which rural society is made up. It builds upon a foundation provided by a technical report prepared on the same visit and on earlier assessments by Abernethey[1] and Pallett.[8-10]

The central issues are addressed in the third and fourth sections below, but a start is made with two brief exercises designed to set the context for the discussion which follows. The first is an attempt to convey something of the diversity of physical conditions, agricultural practices and social relations which Pakistan exhibits; whilst the second takes the form of an account of the development and distribution of the established systems of irrigation which solar pumping will either have to compete with, or in some way to complement, if it is successfully to establish itself.

AGRICULTURE AND AGRARIAN RELATIONS

The greater part of Pakistan's land area is barren and largely uninhabited. Nearly all of the country's agricultural activity, and the bulk of its population, are concentrated in the Indus basin which includes the

Peshawar valleys of the North West Frontier Province (NWFP), most of the province of the Punjab, and a part of the Sind. In terms of its agriculture and social relations, the basin may be subdivided into two smaller units. The first, and less important, are the *barani* (rainfed) areas; these are defined broadly by the 1250 mm (50 inch) isohyet, within which rainfall is generally sufficient to support cultivation without recourse to irrigation. They stretch across the north of the Punjab and a small part of NWFP, and correspond approximately to the administrative districts of Lahore and Rawalpindi (the area immediately surrounding Islamabad in Fig. 1). These are the oldest settled and most heavily populated parts of the country; farm sizes accordingly are well below the national average, and only small amounts of land are available for cultivation under tenancy arrangements.

The canal-irrigated areas to the south, comprising the remainder of the Punjab, and the greater part of the Sind, are characterised by much lower densities of population, the concentration of land ownership into a smaller number of hands, and a high incidence of tenancy. Detailed district level data on the distribution of land holdings and the extent of tenancy are not available, but the fact that such a large percentage of the land under cultivation nationally falls within these areas means that the countrywide figures presented in Table 1 give a fairly accurate impression of the situation here at least.

'Effective landholding' expresses ownership and operation of land in combination. Thus the upper limit of the 'small' farm category might comprise either a household which owned 2 ha of land, or one which held 4 ha in tenancy, on the assumption of a 50–50 sharing arrangement; and so forth. The figure of 2 ha as the minimum necessary for adequate subsistence is an approximate average based upon conditions in the canal area. More than half of all farms fall within this category, suggesting that most rural households are forced to take land in tenancy where this is available, and to seek alternative sources of income where it is not. In this case they enter into competition with the landless, who comprised more than 10% of the national labour force in 1961, and have almost certainly grown in relative importance since.

The 'medium' or subsistence band is defined in relation to the average area of 5 ha which can be ploughed by one pair of bullocks. With two pairs of bullocks being taken as the maximum which one household could operate itself, this gives an upper limit of 10 ha. Just over a third of all farms fall within this category.

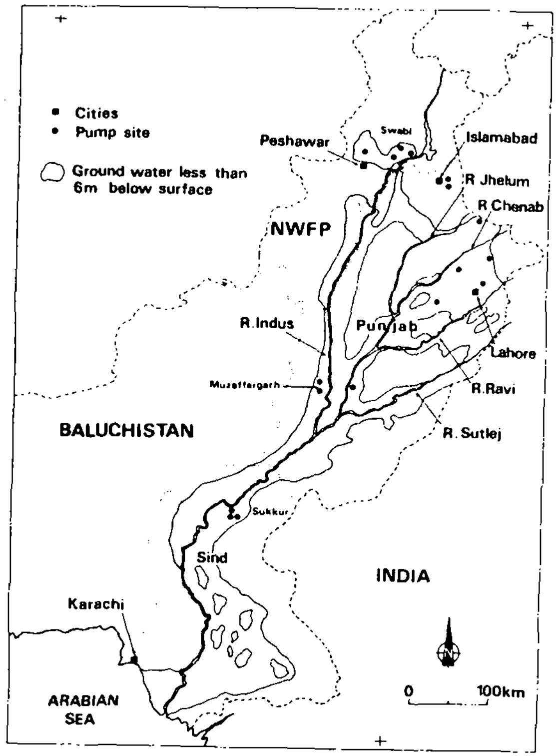

Fig. 1. Location of the solar pumps in Pakistan

'Large' farms, in excess of 10 ha, are taken as those which could not be operated on the basis of family labour alone (at least under circumstances where oxen must be used for ploughing); and where clear potential exists to obtain a surplus over and above domestic subsistence requirements. Only 3% of all farms fall within this category, but they account for 19% of the total land cultivated. Figures from 1960 indicate that a further

TABLE 1
Distribution of Land Ownership in Pakistan

Farm category	*Effective landholding (ha)*	*% of farms*
Small (below subsistence)	0–2·5	58
Medium (subsistence)	2·5–10	39
Large (surplus)	> 10	3

Source: Alavi,[2] pp. 192–3.

49% of the farm area was tenant-operated, suggesting that something approaching 70% of the total farm area was in the possession of either large farmers or non-cultivating land owners. This highly uneven distribution of landholdings has important implications in terms of access to the benefits arising from the various forms of irrigation discussed below.

PRESENT FORMS OF IRRIGATION

Canals provide by far the greatest amount of water at present, and account for about 75% of the total area irrigated. But in spite of their overall importance, they have only made a relatively modest contribution to the spread of high-yielding varieties (HYVs). This is so for two major reasons: firstly, because of the unpredictability of water supply which canals provide in many areas; and secondly, because of the shortage of water available from this source during the *rabi* (winter) season, when wheat, the major HYV crop, is grown.

The critical factor, as far as HYVs are concerned, has been the introduction, from the 1950s onwards, of deep tubewell (DTW) irrigation, which offers a far more controllable, and hence reliable, source of water. By the end of the 1970s, these accounted for about 20% of the area under irrigation. Initial developments were confined largely to the public sector, with large electrically operated tubewells being installed in areas of the Punjab and Sind where increasing soil salinity was leading to a reduction in the area available for cultivation. More recently, however, the emphasis has switched to smaller, privately owned tubewells, the most common of which are of 28 litres/s capacity. About 20% of these are electrically operated; whilst the remainder rely on diesel power, and about 95% are located within the Punjab. Within the province, most wells have been installed in the canal colony region, with the districts of Jhang, Gujranwala, Sialkot and Multan taking the largest share; but the richer old settlement district of Lahore also has suitable groundwater conditions, and has also figured prominently.

With the extensive adoption of deep tubewells, the traditional Persian wheel technology (which is ox-driven in most instances, but relies on camels in the more arid areas) has tended to be displaced. This is reflected in the decline in the amount of land irrigated by well from 5% in 1971–72 to only 2% in 1978–79. But in areas where there are fewer tubewells, the Persian wheel continues to be used. By far the most important of these is Muzaffargarth in the southern part of the Punjab. This will be of significance later since it is thought likely that the new solar irrigation technologies will initially prove most successful in areas where traditional methods continue to be used.

The uneven geographical spread of canals in the period up to the 1950s led to considerable variations in the types of cultivation which could be practised in different places, and the introduction of tubewells has served to make these more pronounced. But apart from increasing the gap between regions, the new irrigation technology, and the HYV package which it makes possible, have also served to deepen inequalities within them. Precise data are again difficult to obtain, but the indications are that as many as 90% of all tubewells are located on the land of large farmers with 10 ha or more. This does not mean the others have been totally excluded; there are perhaps seven farms which purchase tubewell water for every one that has its own tubewell, and most of these would fall within the subsistence categories; but most purchasers have access only at a higher cost per unit of water than deep tubewell owners, and are far less able to obtain water in the quantities required, and at the most appropriate times.

Superimposed upon this, and serving to widen inequalities further, have been the effects of the rapid introduction of tractors, and, in particular, the tendency for tenants to be evicted. As a result, the small farmers, at least bypassed and at worst adversely affected by developments in irrigation, therefore find their livelihoods directly threatened. Many have already become landless, and many more will join their ranks if present trends continue.

Part of the problem has been the unavailability of 'divisible' technologies suitable for use on small landholdings. However, the proponents of solar irrigation systems have argued that their low command areas and zero energy costs might provide a base from which small farmers could begin to resist the pressures which have recently been brought to bear against them. Whether this will prove to be the case, and whether the various systems will be able to compete effectively against other irrigation methods are matters which will be explored in some detail a little later. But first of all, it is important to say a little more about solar technology itself, and the way in which it is currently being tested.

SOLAR IRRIGATION

The technology

The pumpsets tested in the programme were all purchased from SEI by ITIS and have three principal components. 'The first is the solar array, consisting of 7 panels each to 0·3 m² in area, mounted in sets of 4 and 3 respectively, upon two lightweight wheeled frames. The second is the maximum power controller, which takes in the roughly constant d.c. voltage and varying current that is generated by the panels, and adjusts these continuously to match the pump load in such a way as to maximise the power utilisation. The third is the submersible pump and motor, suspended in the well from a spherical polystyrene float. The solar array uses silicone cells and is designed to generate 250 W in standard bright conditions. The pump is a vertical-axis single-stage centrifugal unit, close-coupled to a brushless d.c. motor, whose nominal operating point is 300 rpm at 60 V. The pump is manufactured by KSB of Germany; it is not a standard design, but has been adapted by the manufacturers for this specific application under low heads'.[1]

Pumpsets of this kind can currently be obtained in small numbers for about $6200, and were the only ones being tested in Pakistan at the time of the author's visit. Since then, however, three additional systems have been proposed as alternatives to that presently in use, and subjected to some preliminary field trials. These operate on the same principle as the present system (which will henceforth be known as 'A'). They are however, both more powerful (with 8, 12 and 16 panels respectively), and said to be more efficient, with peak watt capacities of 260, 390 and 520. They will subsequently be referred to as systems 'B', 'C' and 'D'.

The price at which B, C and D can be made available in the event of a sizeable order has proved the subject of some controversy. The manufacturer claims that it will be possible to market them at $3500, $4500 and $5500, but others regard these figures as unrealistically low. To be on the safe side, alternative systems have therefore been costed at the rather higher, and generally more acceptable level of $15 per peak watt, giving a price of $3900 for system B, $5850 for system C, and $7800 for system D.

Field trials

The location of the 14 type A SEI pumps used for testing is shown in Fig. 1. Ten of these were visited and in each instance farmers' records of solar pump use were examined, and interviews carried out to check these, and to determine in more detail how the new system had been used. Information was also collected about other methods of irrigation used prior to the introduction of solar pumping or in conjunction with it.

Whilst it has proved possible to base at least part of those aspects of the analysis which deal with alternatives to solar irrigation on the primary data, the information gathered from test sites on solar system A has proved difficult to apply directly. This is so for a variety of reasons, ranging from the location of the pumps in quite unsuitable places, to the failure of farmers to keep adequate records.

In view of these difficulties, it has been necessary to make a large number of assumptions regarding the performance of solar systems. Whilst it is unlikely that few, if any, of these will prove wildly inaccurate, it is important to bear in mind that many parameters will need to be modified as better information becomes available, and that all of the figures presented subsequently should be reported and used with caution. This is particularly important in the case of data presented in relation to systems B, C and D.

Assumptions and procedures

The first main assumption is that the various solar systems will be used as an exclusive means of irrigation. This departs from reality in that most, if not all adopters of the new systems, appear likely to use them jointly with water from canal and/or other sources; but it is an essential device if solar is to be compared with other forms of irrigation. The next step is then to

determine the amount of water which the various solar systems could lift at different times of the year, and to go on from there to see what area of different crops they could actually be used to irrigate. System A, about which most information is available, will be investigated first.

The best way to have measured the system's capacity would have been to have attached flow meters to the irrigation devices, but these were not available, and an alternative method of calculation has therefore been devised, which builds upon procedures developed by Pallett.[10] This involves:

(a) calculating the amount of effective insolation available on an average day in each month, in kWh/m^2, from radiation data collected at a Research Institute in Multan (which is at the centre of the region where solar systems are most likely to prove viable);
(b) estimating the efficiency of the solar system on the basis of field and experimental station data;
(c) calculating the volume of water which could be lifted each month at a head of 4 m (the minimum level specified by ADBP) on the assumption that all effective insolation would actually be utilised for pumping;
(d) allowing for 40% of water loss in the form of water seepage and deep percolation;
(e) devising a cropping system where as much of the water available as possible is used, but where the crop water requirement in any particular month (after allowing for evaporation and effective rainfall) does not exceed the amount of water available.

The outcome of these calculations is summarised in Table 2 which shows that system A should be capable of irrigating about 1·08 ha of berseem, wheat, potatoes and sugar in the *rabi* (winter) season; and 0·47 ha of sugar, cotton and fodder in *kharif* (summer).

The next step was then to establish an index facilitating the comparison of system A with systems B, C and D, about which rather less was known. This was calculated on the basis of the peak flow of water obtained from different systems under test conditions at a standard lift of 4 m. The results of this calculation are summarised in Table 3. It should be noted in passing that there is no direct correspondence between peak watt capacity (which has been used to determine price) and the actual amount of water lifted, indicating that the systems perform with varying degrees of efficiency. System B (with 8 panels) performs best, followed by system C

TABLE 2
Crop Water Requirements and Sun Pump Capacity at 4 m Pumping Lift in $m^3 \times 10^2$

Rabi *Crops*	*Area (ha)*	*Oct.*	*Nov.*	*Dec.*	*Jan.*	*Feb.*	*Mar.*	*Total*
Berseem	0·27	2·16	2·09	1·82	1·75	2·29	3·97	14·08
Wheat	0·27	1·82	1·21	0·94	1·75	2·69	2·69	11·10
Potatoes	0·27	—	—	0·74	0·94	1·41		3·09
Sugar (perennial)	0·27	2·16	1·21	—	·	—	0·81	4·18
Total requirement[a]	1·08	6·13	4·51	3·50	4·45	6·40	7·48	32·45
Water available at field[b]		8·14	7·73	7·48	6·83	6·41	7·48	44·07
Water available at pump		13·56	12·89	12·46	11·39	10·69	12·46	73·45
Water surplus to requirements		2·01	3·22	3·98	2·38	0·01	—	11·60
Kharif *Crops*	*Area*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept*	*Total*
Fodder	0·10	0·27	0·74	1·09	0·79	0·79	0·42	4·08
Cotton	0·10	—	0·42	1·36	1·72	1·38	0·99	5·87
Sugar	0·27	4·45	5·79	5·79	4·71	4·71	3·50	28·95
Total requirement	0·47	4·72	6·95	8·24	7·22	6·88	4·89	38·90
Water available at field[b]		8·24	9·42	8·87	7·22	8·26	7·87	49·88
Water available at pump		13·73	15·70	14·78	12·04	13·76	18·12	83·13
Water surplus to requirements		3·52	2·47	0·63	—	1·38	2·98	10·98

[a] Crop water requirement calculated using evaporation-effective rainfall data.
[b] Assumed 40% is lost by seepage and deep percolation.
Note: Totals may not add up exactly due to rounding.

TABLE 3
Comparative Indices of Solar Pumping Performance

	System			
	A	*B*	*C*	*D*
Peak watt capacity	250	260	390	520
Peak flow (litres/s at 4 m lift)	1·65	3·00	4·00	4·80
Index figure[a]	1	1·82	2·42	2·91

[a] Expressed as multiple of peak flow of System A.

(with 12 panels) and system D (with 16 panels). The original 7-panel system A comes quite a long way behind.

To the extent that relative peak flows diverge from relative total flows over extended periods of time, the indices given in Table 3 will need to be adjusted; but in the absence of any actual recordings of the latter there is no alternative at present to using the former as a basis for calculation.

With these indices established, further calculations can be carried out to establish the amount of water which could be lifted in a year, the amount which could be available at the field, the amount actually utilised, and the area irrigated in different seasons in the case of systems B, C and D. The relevant results are presented in the upper part of Table 4.

Having dealt with the question of the performance of different solar systems the next problem to arise concerns which of the existing types of irrigation they should be compared with, and how this comparison could be effected.

There would be little point in comparing the cost of solar with canal irrigation since the latter is necessary if aquifers are to be maintained at a level which makes solar irrigation possible; and it is, in any case, cheaper when available than solar could ever be in the foreseeable future. Given present levels of subsidisation the same applies to water from electric tubewells, which on average can be pumped at a cost which is only about 60% of that incurred with diesel fuelled systems.

There does, however, seem to be a good chance that solar pumping can shortly begin to displace the traditional Persian wheel, where irrigation costs are much higher; and at a rather lower price level, it might also start to attract farmers who currently purchase water from diesel-operated deep tubewells, although consideration of scale and convenience make it unlikely to appeal to many deep tubewell owners. Data have therefore

TABLE 4
Comparison of Performance of Solar and Other Irrigation Systems

(1) *Method of irrigation*	(2) *Lift in metres*	(3) *Amount lifted in year* ($m^3 \times 10^3$)	(4) *Water to field* ((3) × 60%)	(5) *Water used*	(6) *Area irrigated (ha)* Rabi	Kharif	*Average*	(7) *As multiple of system A*
A. Present solar system	4	157[a]	94	71	1·09	0·47	0·78	1
B. New SEI solar system (8 modules)	4	286[a]	171	129	1·98	0·85	1·41	1·82
C. New SEI solar system (12 modules)	4	380[a]	227	172	2·63	1·13	1·88	2·42
D. New SEI solar system (16 modules)	4	457[a]	274	207	3·16	1·36	2·26	2·91
E. Persian wheel with two oxen	4	130[b]	78	78	1·19	0·51	0·85	1·10
F. 28 litre/s diesel tubewell (16 hp)	20	3013[c]	1808	1808	27·63	11·85	19·79	25·46

[a] Theoretical figure based on the assumption that all available effective radiation will be used for pumping.
[b] Figure based on our own recordings and interviews which suggested that Persian wheels would on average lift 2·5 litres s × 4 m and be used for 8 hours a day and 180 days a year.
[c] Derived from Chaudhary.[4]

been collected on the amounts of water typically lifted in a year by ox-driven Persian wheels and by a 28 litre/s diesel DTW, as well as upon the costs involved; and performance figures have been incorporated in the lower part of Table 4, and used as a basis for assessing the power of the systems by comparison with solar pumping. (It should be noted here that all water available at the field is assumed to be used, since operators, by contrast with those of solar pumps, can exercise control over when DTWs are used and when they are not.)

The first set of calculations is then completed by examination of the likely effects of different levels of subsidy which the ADBP is contemplating as a means of encouraging the early adoption of solar pumping. The minimum level being considered at present is $1500 per set, and the higher figures of $2400 and $3000 were also mentioned in discussions with Bank officials.

Using these figures, calculations have been made, against different assumptions, to assess the reductions which would be required from present solar price levels before they could start to become economically viable as alternatives to these two types of irrigation. To do this, farms equal in size to the *rabi* command systems A–D, at a head of 4 m have been assumed (1·09, 1·98, 2·63 and 3·16 ha, respectively).

Comparing solar costs with the Persian wheel and purchased diesel tubewell water

Space is insufficient to give detailed explanations of the assumptions and methods used in arriving at the results presented in this section. In outline, it has been assumed that the solar system will last for 15 years, and that once the initial fixed capital investment has been made, the only additional expenditure required will take the form of a sum set aside annually for repair and maintenance. With the Persian wheel, a larger number of factors must be taken into account: the initial outlay on materials and on oxen, and their 'scrap values'; annual repair and maintenance costs; the opportunity cost of the land on which the oxen are grazed (adjusted downwards by 20% to allow for the average amount of time which animals spend on work other than irrigation); and the opportunity cost of supervisory labour time. Similar allowances are made in the case of the DTWs for initial expenditure, scrap values, repair and maintenance, operator's wages and fuel. A 12% discount rate is used throughout.

TABLE 5

A Comparison between Present Prices of Different Solar Pumping Systems, and the Levels to which Prices Would Need to Fall in Order to Compete with Existing Forms of Irrigation ($)

	System			
	A	*B*	*C*	*D*
Present price	6 200	3 900	5 850	7 800
Price at which system becomes competitive with:				
(a) Persian wheels due for replacement	1 709	3 422	4 575	5 490
	(72 %)	(12 %)	(22 %)	(30 %)
(b) Persian wheels recently replaced	999	2 130	2 857	3 423
	(84 %)	(45 %)	(55 %)	(56 %)
(c) Purchased DTW water	1 327	2 727	3 651	4 378
	(79 %)	(30 %)	(38 %)	(44 %)

(Figures in brackets express the difference between present prices and those which would be required as a percentage of the former, thus also giving the rate of subsidy which would currently be necessary to persuade existing irrigation to switch to solar systems.)

The results of the comparison between the costs of irrigation by Persian wheel and the four alternative solar systems are presented in Table 5.

Part (a) of the table shows the price at which solar systems need to be made available in order to become attractive to a Persian wheel owner at the point at which both equipment and oxen would need to be replaced. Given an assumed equipment life of 30 years, and an assumed oxen working life of 10 years, the first of these two assumptions would only apply to one thirtieth, and the second to one tenth of all irrigators in year one of any scheme. Part (b) of the table presents a situation where both equipment and oxen have just been replaced, and where both are assumed (somewhat artificially) to have no resale value. These figures thus show the level at which all Persian wheel irrigators would be encouraged at once to switch immediately to solar. With the passage of time, increasing numbers of irrigators would arrive at the point where they would wish to adopt a solar system at the higher price levels. The results arising from this exercise may be summarised as follows:

(1) none of the systems are yet cheap enough to compete with the Persian wheel under the most favourable conditions where fixed capital items (equipment and oxen) would have to have been replaced immediately;

system A, which has already been subjected to a year of field testing, would not appear attractive to present Persian wheel users even if the highest level of subsidisation considered by the ADBP ($3000) were to be made available;

(3) where Persian wheel fixed capital items were due for replacement, then the minimum level of subsidisation ($1500) would be sufficient to make system B and system C attractive; system D could compete at the second level of subsidisation ($2400);

(4) where fixed capital items had been replaced, system B could be made attractive at the second level of subsidisation, but even the highest subsidies failed to bring C or D within the acceptable range;

(5) all of these results are calculated at a 12 % level of discount; the effect of adopting a 20 % level would be to raise the subsidies required by a modest factor in all instances.

The overall conclusion to be derived from this exercise is therefore that systems B and C appear likely to attract a small proportion of present Persian wheel users immediately, and a growing number as time elapses and existing fixed capital is used up, with a relatively modest reduction in the price levels which have been used here. It should, however, be remembered that no allowance has been made here for the fact that solar systems are imported at a cost for the foreign exchange budget of the country, whereas Persian wheels are locally manufactured and repaired.

The comparison between the Persian wheel and the solar pumping systems was relatively straightforward, since in all instances the head over which water is being lifted is much the same, and at the smaller end of the solar scale at least, discharge volumes and areas irrigated are of the same order of magnitude. The comparison between solar systems and diesel deep tubewells is more complicated for a number of reasons. In the first place, although it is a relatively simple matter to compare costs per unit of water pumped, this does not allow for the fact that the low discharge from a large number of solar installations may, in some cases, require much more labour on the part of fieldmen than in the case of the deep tubewell. Secondly, differences in discharge might lead to differences in the extent of water transmission losses in the case of the two systems (although what solar systems lose by virtue of the time which they take to transmit water a fixed distance, may to some extent be counteracted by the greater distances which deep tubewell water has on average to travel). Thirdly, in instances where tubewell water purchasers wished to switch to solar pumping but did not already have an open well, then the additional cost of making a boring and installing a well screen would need to be taken into account.

These difficulties, each of which could substantially alter the point at which solar pumping systems could become attractive, cannot be adequately dealt with here. The results presented in the lower part of Table 5 should therefore be treated with caution.

A further problem of interpretation concerns the very large difference in scale between the diesel tubewell, which at the 28 litres/s level used here can irrigate about 20 ha, and even the most powerful solar system considered (system D), which will only cover 2·5 ha. The convenience and economy to a large landowner of being able to rely upon one device as opposed to five or six, with all of the extra labour which this would entail, means that solar prices would need to fall very much further than calculations carried out on the simple basis of the cost of water at the well, and equal transmission losses from all irrigation systems, might suggest.

Nevertheless, the comparison is worth making since, for every deep tubewell owner there are perhaps seven purchasers of deep tubewell water, and for them the cost of water to the owner should define the minimum price at which they will be able to purchase (the maximum being defined as the cost of irrigating the area in question by Persian wheel). In the absence of reliable data, it seems reasonable to assume that the larger landowner will be able to obtain deep tubewell water at something close to its cost price (because if he were asked to pay much more than this he would simply obtain a deep tubewell himself), whilst the smaller landowner will have to pay something approaching the Persian wheel cost. As the price of solar pumping falls through the relatively narrow band separating Persian and deep tubewell costs, it may therefore be assumed to become progressively more attractive to larger farmers.

Proceeding on this basis, Table 5 suggests that further reductions in solar prices will be required beyond the level where they can compete with the Persian wheel, before they will be able to appeal to purchasers of diesel DTW water. In more detail it appears that:

(1) system A is less attractive than in relation to the Persian wheel;
(2) systems B and C would require high levels of subsidisation in order to compete here;

(3) system D could not be made attractive even at the higher subsidy level contemplated by ADBP.

All of this, however, assumes that (*inter alia*) diesel prices will remain constant in real terms. But if, as seems likely, oil prices were to increase, then these conclusions would have to be modified accordingly.

Access to the benefits of solar irrigation

From the economics of solar, we turn finally to the question of who is likely to benefit if prices fall to the levels at which adoption begins to make financial sense.

System A—the one currently being tested—has been promoted at least partly in terms of its suitability for small farmers. In one sense this is not an unreasonable claim, since the technology does appear to lend itself to ownership and operation on farms which are at least smaller than those presently equipped with modern irrigation (a conclusion which stands even if one assumes the displacement of system A by system B). But by the same token, simple interpolation from the figures presented in Table 1 (above) suggests, in fact, that more than 50% of all farms would be of insufficient size to justify the adoption of system B; and this takes no account of land fragmentation.

There are additional reasons for assuming the exclusion of the smallest. Owing to the inadequacy of the data available, no consideration has been given to the likely influence of tenancy on adoption behaviour. Since a high proportion of small farms are at least in part dependent upon land which is not owned, and since insecurity of tenure must inevitably exercise an influence upon the decision of whether to adopt a new technology or not, it is difficult to avoid the conclusion that many small farmers who are not already excluded on other grounds, will be unable to take the risk of adoption.

Finally, here, in carrying out cost calculations, it has been assumed that farmers who previously used the Persian wheel would be able to give up their oxen when they switched to solar. This overlooks the fact that small farmers also use their oxen for ploughing and for transport, and means that in instances where tractors or other oxen are not readily available for hire, the solar pumping system could therefore be considerably less attractive than the earlier discussion suggested.

A further factor to be taken into account is the stated intention of the ADBP of promoting only systems with a capacity to discharge 4 litres/s at a head of 4 m. This would have the effect of excluding those farms suited to system B; and of leaving only those with large enough contiguous areas of land to justify the adoption of systems C and D.

The question of credit must also be considered, since few farmers will be able to adopt without it. The ADBP proposes, after subsidies, a 10% down payment, a one year grace period, and then seven annual repayments. Allowing for the 11% rate of interest which ADBP charges, this would mean repayments of about $300 per year at the price levels anticipated. This, in itself, should not create insuperable difficulties but raises the question of who will have access to any credit which is available.

The record of the Bank to date indicates a very strong tendency for loans to be concentrated in the hands of those with five or more hectares of land. It is, however, argued that this reflected a situation where available technologies (notably tractors and tubewells) were inappropriate to the needs of small farmers; and that the new small farmer credit programme has already begun to redress this imbalance. The most recent statistics do indeed indicate a very substantial shift away from lending to large landholders, but the main beneficiaries have been farms falling within the two to five hectares category, with only an insignificant percentage going to the under two hectares group who comprise the bulk of the rural population. So even where there is a demand from small farmers, and a capacity to repay—a question which cannot be adequately investigated until much more is known about the cropping patterns which will be adopted with solar pumping systems—then the indications are that they will still generally be excluded.

This is not an argument for opposing a solar programme, from which many relatively small farmers can benefit; but it does point to the need for specific measures to ensure that the smallest farmers are not excluded. These might include:

(1) devising smaller capacity systems than those presently anticipated so that farms which would otherwise be too small can participate;
(2) recognising that many of the smallest farmers would not have open wells and would therefore need help in sinking borings for solar pump use; this would entail attaching at least a lower priority to the objective of displacing the Persian wheel;
(3) offering higher subsidies for smaller systems, and building in safeguards against their resale with profit to larger landowners;
(4) earmarking the greater part of the loans to be made available for landholders with less than two hectares.

CONCLUSIONS

On the basis of information currently available about the price and performance of different solar pumping options, it would be premature to make any hard and fast statements about their likely future viability.

It does, however, seem likely that relatively modest reductions in price (or modest increases in levels of subsidisation) would enable the more efficient solar pumping systems to start displacing the Persian wheel in areas where no other form of lift irrigation is currently available.

Where other forms of lift irrigation (most notably, diesel deep tubewells) are available, then the magnitude of the solar price reduction required before adoption could be expected to take place on a substantial scale would need to be considerably larger.

As things stand, if solar pumping technology does become established, then it is likely to benefit the smaller farmers who have thus far only been able to participate marginally in the benefits of the Green Revolution. But without some rethinking of current strategy, the smallest farmers will continue to be excluded and may indeed indirectly suffer a further deterioration in their living standards.

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Investment in Capacity to Supply Water for Irrigated Agriculture from Underground Water Storage

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SUMMARY

This article develops the concept of groundwater-supply-capacity (GSC). The concept is straightforward in the case of large public tubewells with defined command areas but more difficult where private pumps are used. It is argued that level of GSC is fundamental to economic analysis of groundwater options, and that the relationship with agricultural benefits needs explicit treatment. Comparison of the performance of groundwater irrigation developments requires an adjustment for the level of water supply.

The level of GSC serving an area of land determines the amount and frequency of irrigation, and thus the crops and yields that are possible. If supply-capacity is sufficient, groundwater can be tapped on demand to provide the ideal water-supply for agriculture. Yet the unit area cost of groundwater irrigation is closely related to the level of GSC, and in a capital-short developing economy there is a resource allocation trade-off between high levels of capacity or larger areas irrigated at lower levels of supply-capacity. For efficient development of groundwater resources, reasonable solutions have to be found to the interaction between the economics of the crop-water response, the physical and organisational efficiency of water distribution, and the cost-mix alternatives, all of which are functions of the level of GSC.

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