Climatic Change and Paleoceanography

All the examples I have used here have been derived from core-top data, and in my interpretation I have used the present ocean surface climate and observations of living planktonic foraminifera. In the case of the gyre northeast of Iceland, the core-top data have suggested a slightly more southerly average position for the time interval represented by the core tops.

To examine earlier climatic change, one must consider the changes in species composition downcore. No direct observations of surface drift and surface temperature are available for these times. One must instead proceed by assuming a changed surface climatology for the ocean and work out how this would alter the species composition of the plankton. Through an iterative process, one then compares the predicted micropaleontological composition with that observed in the cores. The assumptions are then modified until reasonable agreement is reached. A number of possible surface climatologies should be used in order to explore how sensitively the inferred distribution depends on the assumptions.

As long as one is still dealing with present-day species, their ecological characteristics can be determined from the living plankton. If one goes further back and observes now extinct species, assumptions about their ecological characteristics must also be made. At some stage, one will reach a point where the lack of data no longer justifies a sophisticated analysis and one must then rely on simpler interpretations based on classifications of the fossils into rough climatic zones. The examples I have explored, however, suggest that the analysis of drift trajectories can lead to improvements in our knowledge of the ocean surface climate of the Quaternary.

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Economics of Wind Energy Use for Irrigation in India

Wind energy could be economically competitive for irrigation from open wells on small farms.

Sharat K. Tewari

Although the technology of wind energy conversion is basically simple and is thus likely to be acceptable in rural areas of India, little attention has been paid to improving windmill design or reducing the costs of manufacturing them. Since there are inherent advantages in utilizing wind energy there should be no difficulty, at least in principle, in considering it along the same lines as rural electrification. The viability of rural electrification projects is determined in terms of cost-effectiveness over an extended period of time and not by the initial costs alone. Moreover, provisions exist for differential interest rates with regard to loans for selected areas of socioeconomic development. The availability of such loans would cushion the influence of the high initial costs of installing windmills.

I propose here that the development of groundwater-dependent irrigational facilities (*1*) for small and marginal farmers, with landholdings of less than 1 or 2 hectares, is a priority task. There are probably more than 50 million such farmers in India (*2*). Most of these farmers are unwilling to use diesel and electrical water pumps because of the high costs of purchasing them and the nonavailability of maintenance services and spare parts in villages. Furthermore, electricity is available in only 32 percent of the approximately one-half million villages in India. Since many farmers could not af-

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ford diesel or electric pumps which initially cost less than most windmills now available, they would not be able to afford a windmill either—even a low-cost one. This focuses the need for governmental assistance, and a case could be made for such support if the economics of wind energy could be shown to be reasonably attractive.

Summary. The production of energy from windmills designed specifically to operate in the low wind velocities that usually prevail in India during the main irrigation season is estimated to be reasonably economical for irrigating small farms from open wells. The economics would improve if irrigation was practiced all year round, even in the hot summer season. The calculations made here are expected to be valid for the windier 10 percent of the locations identified from available wind speed records. Other, windier locations are expected to be identified when more wind speed data are collected in the future. Governmental policies along lines similar to those for rural electrification may be needed to support research and development efforts to optimize the designs of windmills and to promote their use in rural areas.

Availability of Wind Energy

Data collected at more than 200 meteorological stations in India indicate that wind speeds at nearly 10 percent of the stations have averaged more than 13 kilometers per hour on an annual basis, and that there are as many inland windy locations as coastal ones. These data do not give a true picture of wind speeds, however, because meteorological stations are not always situated in open surroundings. By rule of thumb, in locations where annual average wind speed is found to be 13 km/hour, the rated wind speed for energy maxima could be nearly twice as high. But this would not ensure regular energy availability from day to day or even on a weekly basis and for irrigation purposes allowances would have to be made for some form of water storage. Since a ground-level water reservoir would occupy about 5 to 6 percent of the precious farmland (*3*), a better solution would be to compromise on energy maxima and choose a lower rated wind speed.

The availability of wind energy may vary from season to season, particularly in inland locations (except in the eastern region) (Table 1). In general, wind speeds during the main irrigation season (November to February) are lower by a factor of 2 or more compared to the summer and early monsoon months of May, June, and July. Higher wind speeds are, in fact, required for irrigation during May, June, and July because of the receding water table and excessive losses of water through transpiration and evaporation.

Let us consider a location such as Bangalore where the mean annual wind speed is 13 km/hour but the average wind speed during the Rabi season (November to February) is only about 8 to 9 km/hour. Is it possible to utilize such low wind velocities? The answer is "Yes." The cut-in speed (the threshold wind speed) of the old windmill WP-2 developed at the National Aeronautical Laboratory (NAL), Bangalore (*4*), is 8 km/hour and this windmill could deliver 50 to 60 watts in a wind speed of 10 km/hour.

Through an appropriate aerodynamic and mechanical design, low wind speeds can be used for water pumping from shallow wells. However, the disk area must be increased with the lower power densities being associated with lower wind velocities. The NAL sail windmill (Fig. 1) has a disk diameter of 10 meters and is capable of irrigating about 1 ha of land in low wind conditions. The threshold wind speed is as low as 6 km/hour. This windmill is expected to have an output of 100 watts when the wind speed is 10 km/hour. In Bangalore, where the annual average wind velocity is 13 km/hour, such wind speeds are likely to occur daily for about 10 hours on the average.

Windmills that are 10 m in diameter and that are installed at an average interval of 100 m (in all directions) would not interfere with one another because they hardly extract 15 to 20 percent of the energy available and this would get replenished within a distance of ten times the diameter of the disk.

Crop Sequencing

Because of inadequate irrigational and other facilities only a fraction of the gross cultivated area in India is sown more than once annually. In principle, however, relay cropping can be practiced all year around. If sufficient water is available from canals and tanks, even three crops of rice can be raised in the hot weather regions of peninsular India. However, groundwater recharge is relatively poor in the 70 percent of the country that has a hard rocky subsurface structure.

To assess the economics of wind energy utilization on small farms, one must also consider the use of open dug wells for irrigation. Deeper tube wells are un-

Table 1. Monthly average wind speeds in kilometers per hour (*24*).

Area	January	February	March	April	May	June	July	August	September	October	November	December	Annual average
						Coastal areas							
Southern tip (Cape Comorin)	21.8	19.4	15.1	12.7	19.0	18.7	18.6	19.7	18.3	13.9	16.1	19.5	17.7
West coast (Okha)	17.4	17.1	18.0	19.8	22.8	22.8	24.3	22.1	15.9	11.7	15.4	17.5	18.7
East coast (Puri)	11.9	15.9	20.5	24.0	26.2	23.3	23.3	19.7	15.9	12.3	10.2	10.5	17.8
						Inland locations							
Eastern region (Calcutta)	4.1	5.1	8.4	13.0	16.2	12.4	11.5	10.0	8.4	5.0	3.9	3.5	8.5
Northern region (Mukteshwar)	11.0	12.3	12.9	14.9	16.7	15.4	12.1	10.1	10.0	10.2	10.3	10.5	12.2
Central region (Indore)	9.9	10.8	13.0	15.5	24.4	27.0	26.2	21.7	18.5	9.8	7.5	7.1	15.9
Western region (Phalodi)	10.0	8.8	12.9	14.1	20.7	25.6	23.6	19.4	16.6	11.6	11.8	8.3	15.3
Southern region (Coimbatore)	10.3	10.7	12.0	14.7	23.0	32.6	31.0	30.8	20.2	16.3	9.5	10.1	18.9

economical for small farmers unless there are water-sharing schemes, but such schemes are not always successful because of certain social factors. There are more than 5 million open wells in the country, and about one-half of these have been motorized; water-lifting in the remaining wells is achieved with bullock power. Open wells can be easily constructed on small farms where groundwater is available.

The yield of water from nonmotorized open dug wells in several parts of the country is believed to be 0.6 to 1.0 hectare-meter (6000 to 10,000 cubic meters); twice as much water can be obtained from these wells when they are motorized (*5*). This shows that bullock-powered lifts can not fully utilize the water available from such wells. In this article I use the upper figure of a total of 20,000 m^3 of water, uniformly available all year round.

There are two reasons why I consider the irrigation of rice fields here, even though only a fraction of a 1-ha holding can be irrigated from one windmill installed on the side of an open well. The first reason is that rice has the advantage of requiring standing water, about 40 to 100 millimeters in depth, all the time after it has been transplanted. By a suitable adjustment of this water level, one can cushion the effect of nonavailability of wind energy for 3 to 4 days at a stretch. This arrangement simply amounts to using the rice field itself as the water storage facility. The second reason stems from the data that are available on the areas under cultivation with various crops. Rice accounts for 40 percent of the total cultivated area, wheat accounts for another 15 percent, and other cereals, pulses, vegetables, sugarcane, and other crops account for the remaining cultivated area.

In an experiment in western India (*6*), maize was sown in the last week of June and harvested at the end of September (100 days). Potatoes were sown on the same land in the first week of October and harvested in the third week of December (80 days). Wheat was then sown at the end of December and harvested in the third week of April (115 days). Lastly, green gram (mung bean) was sown in the third week of April and harvested at the end of June (70 days). This experiment illustrates the potential of relay cropping when water is available.

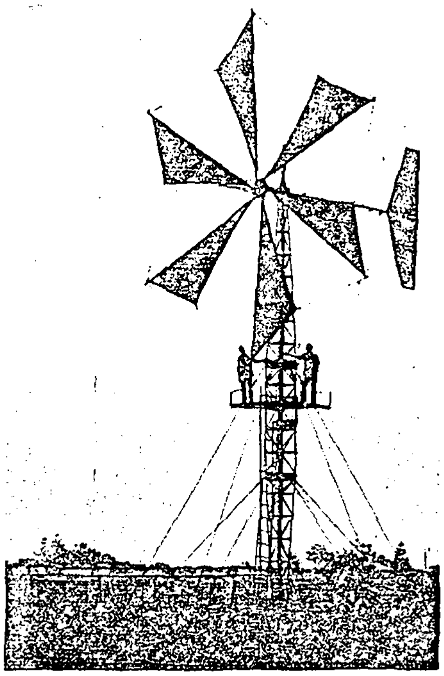

Fig. 1. The prototype of the 10-m sail windmill installed at the NAL campus, Bangalore, India. The tower height is 12 m. The rotary pump can be seen under the platform. This windmill is expected to irrigate 1 ha of wheat grown in an area with wind velocities averaging 10 km/hr for about 10 hours per day.

Energy Matching

Depending on the amount of water drawn and the head over which it is lifted, one can calculate the energy requirements for irrigation. If one assumes a constant efficiency of the devices, the energy required is simply a product of these two factors. But both water requirements and the head are found to vary from one region to another and also from season to season.

In Table 2, seasonal water requirements for crops other than rice are shown for tropical and subtropical parts of the country. Rice can be grown all year round only in the tropical zone. In order to obtain a comparative assessment of irrigation for rice and other crops, I have eliminated subtropical areas from this analysis. In any case, open wells are more extensive in the central, western, and southern parts of the country. The water requirements for crops grown in the hot season in these areas is about 50 percent higher than for crops grown during the Rabi and Kharif seasons (see Table 2). In addition, during the hot season, the water table recedes, especially just before the onset of the monsoon (May and June). A variation in depth by a factor of 2 is quite common in shallow wells where the water table averages about 7 to 10 m (*7*). A change in depth by a factor of 2 amounts to a change in energy requirement also by a factor of 2, if one assumes that the same quantity of water is drawn. But water requirements also increase by 50 percent during the hot season. Thus for a particular area the total energy requirement could increase by a factor of 3 during the hot season.

The wind speed data for Bangalore show that the monthly averages during the Rabi season are 8, 8, 9, and 7 km per hour. For the hot season (March to June) these are 9, 9, 13, and 23 km per hour. As a first approximation, wind energy availability in each of these months can be calculated on a relative basis as a cube of the average monthly speeds. Almost seven times as much energy is thus available in the hot season as in the Rabi season. This is much more than the estimated threefold increase in the demand for energy during this season. However, a windmill designed to operate in low wind speeds would give poor efficiencies in high wind regimes and the sails might even have to be furled in really high wind speeds (say, 36 km/hour), thus the matching may turn out to be closer than this. Calculated in the same manner, the energy availability during the Kharif season is higher by a factor of 12 with respect to wind energy available during the Rabi season. But much of this energy would go unutilized because of the availability

Table 2. Water requirements (in millimeters) for field crops (other than rice) at 70 percent field irrigation efficiency. [Data from (*10*)]

Zone and climate	Season Kharif (July to October)	Rabi (November to February)	Hot season (March to June)
North zone (subtropical); cool temperature and semiarid	150 to 350	125 to 250	300 to 400
Eastern zone (subtropical)			
Hot and humid	500 to 600	400 to 500	800 to 900
Hot, subhumid, and humid	450 to 550	400 to 500	600 to 700
South zone (tropical); hot, subhumid, and humid areas	450 to 550	500 to 600	650 to 710
Central and western zone (tropical)			
Hot and semiarid areas	660 to 700	600 to 700	900 to 1000
Hot and arid areas	900 to 1000	800 to 900	1200 to 1400

of water from direct rainfall. Some irrigation would still be useful however, because of the higher demand for water and poor predictability of rainfall at the critical periods of crop growth. Thus the same amount of energy input may be required during this season as during the Rabi season. Owing to the high wind speeds available during the Kharif, the windmill would be required to operate intermittently for a much lower total duration than during the Rabi season. Sail windmills are particularly appropriate for such a mode of utilization: the sails can be furled during rains or when water is not required, and this means a longer life for the sails and less wear of other parts.

Baseline Parameters

In assessing the relative economics of wind energy in irrigation, one must also consider alternative resources. However, my purpose in this study is to assess wind energy, and for this a comparison with conventional alternatives should suffice. Thus I will include only the conventional alternatives of bullock-powered water-lifts, diesel engines, and electrical pump sets.

For the purpose of comparison one needs a common basis of useful energy output per season or per day (on the average) for irrigating under a certain set of conditions. This requires that one establishes such parameters as seasonal water requirements under different cropping sequences and the depth of water table.

During the Rabi season the water requirement for rice is estimated to be around 1500 mm (*8*), and for other crops in the tropical zone, about 600 to 700 mm (Table 2). In hot weather, the water requirement for rice increases to 2000 to 2500 mm and for other crops to 900 to 1000 mm. On a rough basis one may assume water requirements for rice and other crops in the ratio of 2.2:1. If one takes the limitation on water availability from open dug wells to be 20,000 m^3 per year, it would be possible to irrigate a maximum area of 0.44 ha under rice and about 1 ha under other crops. Because of the higher water requirements during summer the coverage would be lower than these figures. In cases where farm sizes are smaller than 1 ha, the energy requirement would be proportionately lower and I consider this aspect to be included in my analysis.

The average daily water requirement for 0.44 ha under rice during the Rabi season amounts to 55 m^3 per day. If this is pumped over a total head of 6.67 m, the useful daily energy output is equivalent to 1 kilowatt-hour. Even though the head for water pumping might differ from this assumed value, the energy requirements could be easily converted proportionately. The energy requirement for a crop grown during the hot season would amount to 3 kWh per day and for a crop grown during Kharif season, another 1 kWh per day on the average. Thus the total requirement would be about 600 kWh annually.

Irrigation all year round, especially during summer, would not be practical in most parts of the country. It would be more realistic to study an alternative possibility in which irrigation was carried out in the Rabi and Kharif seasons only. The energy needs would then amount to about two-fifths of the 600 kWh, that is, 240 kWh.

Installed Capacities and Costs

Although human labor is utilized to some extent in water-lifting through counterpoise lift, Archimedes' screw, or swing basket, for example, the energy output is somewhat limited—no more than about 0.2 kWh per man per day. Moreover, these means of water-lifting are generally used when there is a low head (0.5 to 1.0 m) as in lift irrigation from canals and, in rare cases, from wells for irrigating very small areas (much less than 1 ha). In any event, the labor for this is usually obtained free from members of the farming household, so I will not consider the economics of this alternative.

Bullock-powered water-lifts such as Persian wheels and self-emptying buckets are used in irrigation to a significant extent in India. More than 40 percent of the water lifted in 1971 for irrigation came from such devices (*9*). I have found an equivalent energy output of 1.8 to 2.0 kWh in a few spot surveys with respect to self-emptying bucket lifts operating on open wells (water table about 7 m deep) with two pairs of bullocks and one man for controlling them. The bullock pairs were used intermittently for a total of about 12 hours every day. It should therefore be possible to obtain 1 kWh on the average from one pair of bullocks. This observation is in agreement with the information available in the literature (*10*).

A pair of bullocks may cost anywhere between $120 and $350 (*11*). Let us assume an average value of $235. The average working life of bullocks is usually under 10 years, and we may further assume that it costs 60¢ per day to feed a pair of bullocks. These figures are not intended to be accurate; it is somewhat difficult to

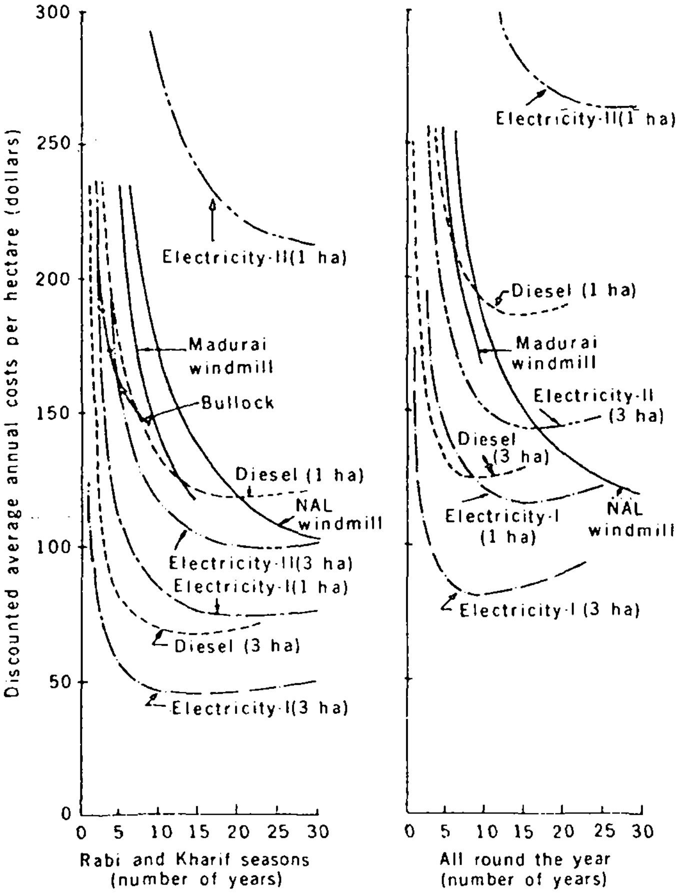

Fig. 2. Discounted average annual costs for irrigating 1 ha (under wheat or equivalent water-consuming crops) from open wells with an average depth of 6.67 m for the water table. Windmills would prove to be economical if they were designed to operate effectively at low wind speeds, and especially if they were utilized all year round.

obtain truly representative figures. For example, bullocks can be reared on the farm and fed on crop residues and locally grown pulses. Cost estimations in such cases can only be approximate at best.

A pair of bullocks producing an equivalent of 1 kWh per day would probably suffice during the Rabi and Kharif seasons, but would not permit irrigation of the same area in summer when the energy requirement would be 3 kWh per day. The availability of two extra pairs of bullocks during this season would be unlikely, particularly since temperatures during the day in central India during May and June often exceed 40°C, which is uncomfortable both for the bullocks and the human operator. This restricts water-lifting to the early hours of morning and late evenings. Thus it is appropriate to consider the use of bullock-powered lifts for irrigation in the Rabi and Kharif seasons only. Revelle (*12*) estimated for 1970–1971 that 4.8 to 7.2 billion hours of bullock time was spent in water-lifting. This could have irrigated about 5 to 7.5 million hectares per season. For the same year, the total area irrigated by means of groundwater was 10 million hectares, and of this, 40 percent, that is, 4 million hectares, was irrigated with the use of bullock-powered water-lifts. If one divides the previous value by this figure, the number of seasons in which bullock power was utilized amounts to 1.25 to 1.87. Therefore, even two seasons of irrigation is a somewhat optimistic estimate with respect to bullock-powered water-lifts.

The manner in which bullock powered water-lifts are used in irrigating one part of a field at a time is instructive in considering the utilization of wind energy for the same purpose. Under this practice, a field is divided into several parts and each part is irrigated in turn. In this manner a desired frequency of irrigation is obtained for those crops requiring water on certain critical days only. For example, the critical days for wheat are days 25, 55, 75, 95, and 110 after sowing (*13*). If a 1-ha field is divided into five parts, and 3 days are allotted for irrigating each of these parts, then it is possible to irrigate each of these parts on the critical days mentioned above. This amounts to a maximum staggering in sowing and harvesting dates by 12 days. But this is not expected to cause any significant difference in production, as shown by some field experiments (*14*). A similar approach can be adopted with other crops. Rice fields can be irrigated in the same manner because the field itself can be used to store water.

A large number of windmills are available commercially, but few, if any, of them are capable of producing significant output at low wind speeds of about 10 km/hour. Sherman's Madurai windmill (*15*), adapted in India from the well-known Cretan sail windmills, was designed to operate in low wind velocities. It has a 10-m-diameter sail rotor coupled with a variable stroke reciprocating pump. Sherman claimed an efficiency of 8.6 percent at the rated wind speed of 8 km/hour (*16*). If we accept this claim, the Madurai windmill was capable of delivering about 80 watts in a wind speed of 10 km/hour or about 0.8 kWh/day as a minimum guaranteed average daily output in the Rabi season. This windmill had eight canvas sails supported on bamboo spars, and these two items cost about $98.8 out of the total windmill cost of $647 (*11*). If used all year round, the sails and bamboo would probably have to be replaced every 2 years. This period could be doubled if the windmill were operated for the Rabi and Kharif seasons only. Wood beams and poles, at a total cost of $55.3, would have to be replaced every 5 and 10 years, respectively. The life of the windmill would probably be 10 to 15 years.

Another windmill, a little more than 10 m in diameter, has recently been set up near Sholapur by Smith (*17*). This has a maximum of 12 triangular sails supported on bamboo spars. A chain pump is coupled with the rotor shaft. Sufficient performance data, particularly at low wind speeds, are not yet available for this windmill. From experience with the prototype construction Smith mentions an upper limit of $1600 as the reproducible cost of the windmill, which is a metal construction except for the sails and spars which are made from canvas and bamboo.

The 10-m NAL windmill (Fig. 1), which has a six-sail rotor, is also adapted from the Cretan windmills and is similar to the nearly 8-m windmill of Windworks (*18*). The NAL windmill has been coupled with a swinging vane rotary vane pump in order to obtain high performance at low wind speeds. The pump does not load the windmill at start-up and allows the windmill to operate at wind velocities as low as 6 km/hour. The power transmission has been designed to minimize frictional losses. Tests with this windmill indicate that its output is likely to be about 1 kWh per day during January and February. Costs of reproducing the windmill are estimated to be $1180 if it is manufactured in batches of about 100 units. The six sails, costing a total of $47, may have to be replaced every 2 years if used all year round (as in the Madurai windmill), otherwise every 4 years. The pump, costing $95, may similarly have to be replaced every 5 or 10 years, respectively. The life of the basic structure may be around 25 to 30 years. It is designed in a manner to eliminate maintenance almost completely, except for an occasional, perhaps biannual, inspection and greasing.

The average cost of taking electrical lines to a village in India is estimated to be around $8800. The principal justification for providing a village with electricity is that the villagers need energy for their irrigation pumps. In fact, 80 percent of the electricity consumed in rural sectors is used for irrigation pump sets (*19*). The cost of electrification in terms of each pump set energized is, very approximately, $590 to $1765 per pump (*20*). I have assumed an average value of $1175 per pump in this analysis. The cost of the pump set would be extra, say another $353. For delivering a useful output of 1 kWh per day, the average load factor for such a pump set would be approximately 1 hour every day. Unfortunately, a poor utilization factor of this order is found for small farms all over the country (*21*). On large farms, however, and in cases where the wells are large enough to irrigate more than 1 ha, the load factor is higher. In some parts of the country the average area that can be irrigated is larger by a factor of 3; for example, in Punjab the area irrigated per open well is 4.3 ha compared to 1.10, 1.30, and 1.75 ha in Maharashtra, Tamil Nadu, and Uttar Pradesh, respectively (*10*). These areas could be increased through water-sharing arrangements among several small-size farms. Such arrangements are usually made for large tube wells (public or private) which can easily irrigate more than 15 ha. I have included the possibility of water from one open well being shared among three farms, each 1 ha in size. In this arrangement the capital cost and the maintenance expenses are distributed over 3 ha. In the case of electrical pumps as well as power lines, I have assumed maintenance costs of 3 and 4 percent for irrigating 1 and 3 ha, respectively, during Rabi and Kharif seasons only. For irrigation during the summer as well, these figures are higher, 4 and 5 percent, respectively. I have assumed the energy cost per kilowatt-hour electric input to be 2.94¢. I have assumed that this cost will increase by 5 percent per year.

A typical diesel-powered pump set in the range of 3 to 5 horsepower operates at an overall efficiency of approximately 15 percent (30 percent engine efficiency, 50 percent pump efficiency). It consumes about 0.65 liter of oil in delivering pumping work equivalent to 1 kWh. Such a pump set would cost about $530. I have assumed a maintenance expenditure of 5 and 7 percent for diesel pumps used during Rabi and Kharif seasons for irrigating 1 and 3 ha, respectively; these expenditures would increase to 7 and 11 percent, respectively, if the pumps were used in the summer as well. The price of light diesel oil increased during the 1960 to 1973 period (before the oil crisis) at an annual rate of 4.2 percent. I have assumed a 5 percent annual rate of increase in future oil prices.

Present Values

The capital costs of windmills are high compared to bullocks, diesel pump sets, and electrical pumps. But the cost of electrification per pump set is even higher. The rural electrification authorities provide loans for power projects; in some of the backward areas these loans can be repaid over a period of up to 30 years in some instances. I have considered this time factor in my analysis. Also, the interest rates on electrification loans vary from 4¼ to 11 percent. Under minimum needs programs, such as that for providing drinking water in villages, the rate is usually 6 to 7½ percent (*22*). I have considered a 7 percent interest rate in this analysis.

By taking recurring charges into consideration, discounted present values of cash outflow may be determined. A consideration of present values is justified because policy planners may wish to assess the cost-effectiveness of various water pumps. Pumps that involve lower present values for the same effectiveness may be preferred. Average annual costs may be calculated from the computed present values. This provides additional information regarding the optimum lifetime of the devices.

The present values and associated average annual costs may be calculated by taking into account the rate of interest on loans, the price hike in fuels, and inflation in the prices of raw material (*23*). The 5 percent increase that I have assumed for fuel oil also applies to feed for bullocks and to electricity; I assumed a 3 percent rate of inflation to account for increases in the cost of maintenance services, spare parts, and raw materials. However, I have not considered salvage values, which no doubt would be higher for windmills than for diesel and electric pumps, because of their relatively larger structural parts.

As shown in Fig. 2, the annual cost estimated in this manner is rather high for the Madurai windmill. The NAL sail windmill could prove attractive, especially for all-year-round irrigation, if it was considered over a period of 30 years. This windmill is inferior only to electrical pumps, if one excludes electrification costs (Electricity-I in Fig. 2); it would also be inferior to these pumps if they were used to irrigate 3 ha. However, the irrigation of 3 ha with one electric pump requires that water-sharing arrangements be made among the farmers. Such arrangements are usually fraught with problems, as gauged from the fact that many small farmers have not opted for electrical pumps even when electricity has been available in the village. The choice of a windmill suitable for irrigating 1 ha would be particularly attractive if energy costs increased at a rate higher than the 5 percent assumed here. Similarly, a higher rate of inflation (from the 3 percent assumed here) would also favor windmills compared to diesel engines which may have a lifetime of only 15 to 20 years. The cost of energy derived from bullock power appears to be somewhat high, but the conclusion would have been entirely different if I had assumed the feed to be wholly available within the farm and the bullocks to be raised within the farm itself. Inclusion of the cost of electrification (Electricity-II in Fig. 2) in the manner discussed earlier would render electrical pumps somewhat expensive.

These data indicate that windmills designed to operate in low wind speeds would provide an economical means of irrigating small farms from open wells. Widespread use of such windmills, however, might require government assistance in the form of a credit at low rates of interest. The economics can be expected to improve further if efforts are channeled into optimizing the design of windmills for operating in low wind speeds.

References and Notes

1. About 50 million hectares out of a total of 160 million hectares of gross cultivated area are provided with irrigational facilities from dams, tanks, and wells. The irrigation from wells amounts to one-third of the total irrigated area. It is estimated that about 60 percent of the exploitable groundwater recharge is being utilized, which leaves a sizable margin for future developments.
2. According to the *Agricultural Census Report* (Government of India, New Delhi, 1975) about 50 percent (35.7 million) of the holdings belong to marginal farmers (farm size less than 1 ha) and another 20 percent (13.4 million) belong to small farmers (farm size 1 to 2 ha). Combined, these two categories account for 20 percent of the total cultivated area.
3. A rice crop is usually irrigated once every 6 days. In order to irrigate 1 ha, about 750 m^3 of water would have to be stored, which would require 500 m^2 of base area for a 1.5-m-high ground-level reservoir. This base area would be 5 percent of the total farm size. Similarly, for irrigating a wheat crop every 21 days, the storage would cover 6 percent of the farm area.
4. Windmill WP-2, developed in the period 1960 to 1964, has 12 sheet metal vanes arranged on a 4.9-m rotor on a ring assembly. This is coupled with a fixed stroke, single-acting reciprocating pump. The basic concept of this windmill is similar to the well-known water pumps of the Comet, Aeromotor, and Southern Cross type. It is estimated that the WP-2 windmill would cost about $1200 if produced in batches of 100 units. Windmills of this type can be manufactured in India without any of the parts having to be imported.
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23. The present values of cash outflow over a period of n years may be calculated from

$$PV_n = I_o + C_f\left(\frac{x_{1n} - 1}{x_1 - 1}\right) + C_m\left(\frac{x_{2n} - 1}{x_2 - 1}\right)$$

where I_o is the initial investment, C_f represents annual fuel and electricity costs, and C_m is the annual maintenance charges and cost of replacement of sails and other material.

$$x_1 = \frac{1 + r_1}{1 + r}$$

and

$$x_2 = \frac{1 + r_2}{1 + r}$$

where r is the annual rate of interest for the loans, r_1 is the annual price hike with respect to fuels and energy, and r_2 is the rate of inflation. The average annual charge may be calculated from

$$a_n = PV_n \frac{1 - D}{1 - D^{n+1}}$$

where

$$D = \frac{1}{1 + r}$$

24. Data from *Climatological Tables of Observatories in India 1931-1960* (Publ. No. DGO 84/1200, India Meteorological Department, New Delhi).