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Rural Water Supply in Developing Countries

...dings of a workshop on
... held in Zomba, Malawi,
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Rural Water Supply in Developing Countries

Proceedings of a workshop on training held in Zomba, Malawi, 5–12 August 1980

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An Assessment of Water-Pumping Technologies Using Locally Available Energy Resources, Botswana

R. Carothers[1]

Problems with Respect to Water Supply

Botswana is a dry, semi-arid country with little or no surface water throughout most of the year. Rainfall is erratic and although a number of rainwater catchment dams have been constructed, about 75 percent of the people and livestock depend on groundwater as a source of water supply. In some areas water is close enough to the surface to allow for the construction of shallow wells, but in most cases the drilling of boreholes is required. In the eastern part of the country it is possible to find water at depths of 25 m or less, but the national average is 100 m and increasing as new boreholes are drilled. Because of the depths of the boreholes and the demands placed on them, power sources superior to hand pumps often become necessary for withdrawing water from wells.

The original pumping systems installed throughout Botswana used reciprocating pumps driven by diesel engines. In the days before high fuel costs these could supply water reasonably cheaply, but they suffered from maintenance problems. The saline nature and high grit content of the water in many boreholes caused excessive wearing of pump seals. Because of a shortage of trained maintenance crews, repairs could take up to several months. Also, the diesel power plants have been the source of a variety of faults in the past. Recently, government and many private borehole operators began using mono pumps. These can supply water from deep boreholes with less pump-related maintenance problems. As a result, the government prefers to continue using mono pumps.

The rising price of petroleum-based fuels has added a new economic element to the problems facing water supply systems. During 1979 the price of diesel fuel in Botswana doubled and further increases are expected during 1980. A directive from the president's office has recently involved government ministries in the search for suitable wind pumps that could be used both for government and private borehole operations.

During a survey carried out in 53 neighbouring villages, the Rural Industries Innovation Centre (RIIC), which is located at Kanye in the southern part of Botswana, found that problems related to water supply were by far the main concern of village dwellers. The search for suitable water-pumping technologies led the RIIC to investigate the possibility of using local energy resources including biogas, solar radiation, and wind energy. Because of previous pump-related maintenance problems, it was proposed that new systems be designed to operate using the mono pump.

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Windmills for pumping water were a possibility, but it was not known how suitable these would be under Botswana's windy climatic conditions. A limitation of commercial windmills was that they would be unable to operate the mono pumps. Perhaps other options would offer greater benefits. Cow dung, in plentiful supply in the cattle fields, could be fermented in biogas plants to produce a substitute for diesel fuel. Advances were being made in technologies for harnessing solar radiation and it could be that these would work well under Botswana's clear, sunny skies. To compare these different methods, the RIIC decided to undertake a program of testing wind, biogas, and solar pumping techniques. The intention was to study each alternative to determine what difficulties, including maintenance problems, might arise and to determine, in economic terms, which option could provide water at the lowest cost. To carry out the economic comparisons it was necessary to refer all costs to a unit pumping capacity that was the same for each pumping technique. In this report all costs have been referred to a unit pumping capacity of 1 kW-h/day. In terms of the amount of water pumped per day, 1 kW-h/day is equivalent to pumping 36 m^3 from a depth of 10 m; 18 m^3 from 20 m depth; 7.2 m^3 from 50 m depth; and 3.6 m^3 from a depth of 100 m.

An Assessment of Alternative Pumping Techniques

As a means for comparison, an attempt was made to determine the present-day value of all costs for a standard diesel engine on a per unit pumping capacity basis. It is worth noting that the analyses for the diesel engine and other options are specific to costs occurring in Botswana at the present time.

The Diesel Engine

A study carried out on behalf of the Government of Botswana (Department of Water Affairs 1975) produced a cost breakdown for the installation and operation of a diesel engine over a 20 year period. An updated summary of this study is given in Table 1. These results are, if anything, overly optimistic in favour of the diesel engine, particularly in the assumption of a 20 year operating life.

Biogas/Diesel Pumping

Although the maintenance problems associated with diesel engines would still remain, it is possible to develop an alternative energy source, using locally available resources, to fuel existing diesel engines. At the RIIC, biogas digesters have been constructed in which a mixture of 60 percent methane and 40 percent carbon dioxide (biogas) is produced through the anaerobic fermentation of cow dung and water. This biogas can be fed into a diesel engine after only minor modifications to the engine and will replace 85 percent of the diesel fuel. There are, however, technical problems associated with supplying sufficient biogas for the engine throughout the year. The rate of gas production decreases during the colder winter months. To supply sufficient biogas to replace 85 percent of the diesel fuel during this period, the biogas digesters must be made considerably larger than those supplying gas during the warmer months of the year. This requires higher investment costs. It is this "worst case" that has been used in the economic analysis shown in Table 2. The economic outlook improves, however, if the biogas plant provides 85 percent of the fuel for 8 months and 42.5 percent of the fuel for 4 months. Although fuel costs increase, they are offset by reduced investment and as a result the costs per kilowatt hour per day pumping capacity decrease.

There are other economic factors that favour the use of a biogas/diesel pumping system. The 85 percent saving in fuel equates to a similar saving in foreign expenditures, whereas the cost of establishing the biogas digesters involves mainly labour and, therefore, contributes positively to the national economy. Another advantage of the biogas/diesel pumping option is that it can be designed to supply

Table 1. Operating costs for a diesel engine (based on 1980 rates).

Technical data	
Engine	ST 1 (4.5 kW (6 hp))
Borehole depth	115 m
Demand	600 head of cattle
Annual hours of operation	3036
Years of operation	20
Fuel consumption (litres/year)	3656
Cost data	
Engine	P1460 (P1.00 = U.S.$1.27)
Fuel	P0.42/litre (middle rate for stationary engine, January 1980)
Energy delivered per day	21.6 kW-h (assuming 8 h of operating time per day and pump/transmission efficiency of 60%)
Operating costs	
Engine	P1460
Fuel	P13418
Repair and maintenance scheme (Department of Water Affairs 1975)	P6582
Spare parts	P616
Overhaul	P877
Total	P22953
Cost per kW-h/day pumping capacity	
Based on 1980 diesel prices	P1063
Allowing for 5% per year inflation in the price of diesel fuel	P1522

fuel for larger diesel engines which are required when pumping water from very deep boreholes.

Solar Pumping

In considering the use of solar radiation as an energy source for pumping water, it is necessary to determine the amount of solar energy available and to evaluate the technologies that could be used to capture this energy.

Botswana is fortunate in having abundant solar radiation, being situated within one of the world's few areas that receives more than 3200 h of sunshine annually. In addition, the intensity of the radiation is high, ranging from 0.7 kW/m^2 in winter to 1.2 kW/m^2 in summer (the mean level of solar radiation throughout the year is approximately 5.4 kW-h/m^2/day). It is interesting to note that at this rate the solar energy falling on 4 m^2 would be equivalent to that delivered (during 8 h of operation) by the 4.5 kW (6 hp) diesel engine discussed earlier. Unfortunately, the technologies for capturing this energy are expensive and are generally felt to be uneconomic at present for pumping water. Nevertheless, research aimed at developing solar pumping equipment is continuing. A photovoltaic panel that converts solar radiation into electrical energy which is then used to power an electric motor and pump is one type of pump being considered. Another possibility involves the vaporization of a heavy organic liquid which causes the transfer of a liquid mass in a rocking-beam arrangement. Both of these pumps, however, require further development to reduce their cost of operation.

Wind Pumps

As in the case of solar pumping, consideration of wind pumps as a means of providing water requires a knowledge of both the energy available and the performance characteristics of the wind pumps being considered. In practice, there

Table 2. Operating costs of a biogas/diesel pumping station (based on 1980 rates).

Technical data (for engine, borehole, and other data see Table 1)	
Biogas plant (summarized from McGarry 1980)	
Gas yield/kg dung	0.050 m^3/kg
Gas production rate (winter, 17°C)	10% of digester volume per day
Gas production rate (summer, 27°C)	30% of digester volume per day
Consumption rate of biogas by engine	0.9 m^3/kW-h
Diesel equivalence of biogas	1 m^3 of biogas = 0.25 litres of diesel fuel
Operating costs	
Case 1. Biogas plant providing 85% of fuel throughout the year	
Engine	P1460
Fuel	P2013
Repair and maintenance (Department of Water Affairs 1975)	P6582
Spare parts	P616
Overhaul	P877
Total	P11548
Cost per kW-h/day pumping capacity	P535
Cost for biogas plant per kW-h/day of delivered energy	P650
Total operating costs per kW-h/day pumping capacity	P1185
Case 2. Biogas plant providing 85% of fuel for 8 months and 42.5% of fuel for 4 months. (The engine and maintenance data are the same as case 1, except fuel prices increased to P3891.)	
Total	P13426
Cost per kW-h/day pumping capacity	P622
Cost for biogas plant per kW-h/day of delivered energy	P430
Total operating costs per kW-h/day pumping capacity	P1052
Cost per kW-h/day pumping capacity	
Assuming 85% of fuel replaced by biogas throughout the year	
Based on 1980 diesel prices	P1174
Allowing for 5% inflation in real terms for diesel fuel	P1242
Assuming 85% of fuel replaced by biogas through 8 months and 42.5% replaced through 4 months	
Based on 1980 diesel prices	P1040
Allowing for 5% inflation in real terms for diesel fuel	P1171

are complexities in evaluating both of these parameters.

Wind Monitoring

The energy available from the wind depends on the cube of the wind speed , i.e., doubling the wind speed means that the available energy increases by a factor of eight (2^3). As a result, equipment capable of measuring only average wind speed over a given time interval, when used to predict available wind energy, can introduce large errors. In response to this, equipment has been developed to measure and record instantaneous wind speed, thus providing a frequency distribution of the wind speed and allowing a more accurate prediction of the energy available to be made.

The Filippini Rotor and Mono Pump System

The mono pump presents some serious technical difficulties when operated by wind. Its high starting torque and high operating speed (revolutions per minute) require that the transmission of the wind pump be specially designed to overcome these problems.

A three-stage transmission was used to achieve the high pump speed required and a clutch mechanism was designed to overcome the starting problems. This system also allowed for easy hand operation of the pump if there were prolonged periods with no wind or if the wind rotor required repairs.

The choice of the Filippini rotor (Fig. 1) as a means of driving the mono pump also solved one additional problem. The mono pump requires a rotary drive, whereas most conventional (horizontal-axis) wind rotors operate reciprocating pumps. The vertical-axis feature of the Filippini rotor allowed for the coupling of the rotor and pump with a straightforward V-belt drive system.

It can be shown that the efficiency of a wind-pump system decreases for wind speeds above the minimum level required for the wind pump to operate. By selecting a pumping rate per rotor revolution that corresponds with wind speeds that provide maximum energy, maximum efficiency of the system will be achieved. This is illustrated in Table 3.

The optimization of the Filippini wind pump has been made easier because the clutch mechanism allows the unit to start at the minimum operating wind speed. Wind pumps that do not have a clutch will usually require a wind speed higher than the minimum operating wind speed before they will actually start. If these speeds are significantly different, then allowances for this need to be made in predicting the amount of water that will be delivered in a particular wind regime.

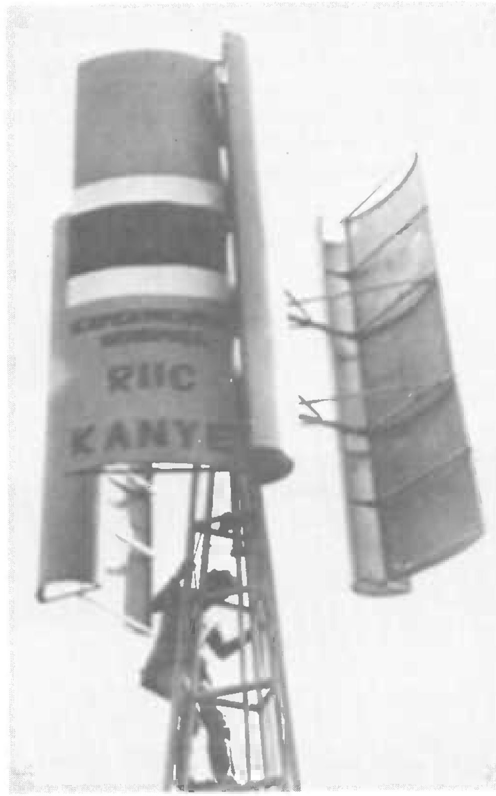

Fig. 1. Filippini rotor at the Ramonedi site.

Although the Filippini rotor has been successfully matched with a mono pump, it must still be classified as an experimental wind pump. Further work to develop a high-wind protection system for the rotor and to refine the clutch mechanism will be necessary before production can begin.

The Experimental Horizontal-Axis Rotor

The horizontal-axis wind pump that was originally designed by the Intermediate Technology Development Group (ITDG) of the United Kingdom is currently being field tested in several countries. Figure 2 shows one version of the unit that is already in commercial production in Kenya. The ITDG design used in Kenya is well made but expensive when compared with other locally manufactured wind pumps and imported

Table 3. Operating costs of Filippini rotor/mono pump system.

Technical data	
Filippini/mono pump system optimum efficiency	11%
Energy delivered per day (winter, starting/min. running wind speed = 15 km/h)	1.6 kW-h/day
Energy delivered per day (winter, starting/min. running wind speed = 20 km/h)	2.5 kW-h/day
Available energy per m^2 of sweep area	3.59 kW-h/m^2/day
Sweep area	11.7 m^2
Cost data	
Rotor and tower (cost estimate based on prototype)	P1500
Operating costs	
Wind rotor and tower	P1500
Spare parts	P252
Total	P1752
Cost per kW-h/day pumping capacity	
With starting/min. running wind speed = 15 km/h	P1095
With starting/min. running wind speed = 20 km/h	P701

Fig. 2. Intermediate Technology Development Group rotor as produced in Kenya.

commercial models. Part of the high costs is attributable to moulded fiberglass blades, which are specific to the Kenyan rotor.

The ITDG design, as built in Botswana, incorporates all-metal blades, as in the original concept. However, because the transmission was intended to drive reciprocating pumps, major modifications are required to run the rotary-drive mono pump. Efforts are under way to obtain a suitable right-angle drive gearbox that will be able to handle the torque loads.

As with the Filippini rotor, a clutch will be necessary in the transmission to overcome starting problems. The inclusion of a clutch will have additional advantages in reducing construction costs. With a clutch, the rotor will be able to start without a load and as a result will require only six blades. The 24 blades of the normal rotor are needed only in starting. A rotor with fewer blades will run faster, thereby requiring less step-up in the transmission to meet the high pump speed (revolutions per minute) requirement, and will normally operate with a greater overall efficiency. The rotor in its present stage is shown in Fig. 3.

Fig. 3. Intermediate Technology Development Group rotor as produced in Botswana.

Because the ITDG rotor in Botswana has not yet been connected to a pump, data on the performance and costs per kilowatt hour per day pumping capacity are not available.

Commercial Windmills

The manufacturers of commercial windmills do not specify the performance of their windmills over a range of operating wind speeds. It is not possible, therefore, to accurately predict the energy delivered under actual wind conditions. It is, however, possible to predict the output under idealized conditions, where all of the available energy occurs at the minimum operating (maximum efficiency) wind speed for the windmill. On this basis, the costs per kilowatt hour per day pumping capacity have been estimated for a Climax and Southern Cross wind pump (Table 4). Thus, under idealized wind conditions it is possible to compare one windmill against another, but it is not realistic to compare the windmills against other pumping options. Better data will become available as the Government of Botswana monitoring program continues to develop.

Summary

In comparing power sources (in economic terms) that make use of locally available energy resources, with the existing diesel engine, it appears that both the biogas and wind-pumping options are practical alternatives. The use of biogas as a supplementary fuel becomes particularly attractive due to the probability of further increases in the price of diesel fuel. The use of wind as a power source for pumping water seems to be the best economic choice even now, provided that the wind pumps are properly matched with local wind regimes. Solar pumps would be impractical at the present time, but would become the least expensive option in the future if the price of photovoltaic equipment continues to drop as predicted.

There are other economic factors to consider. The biogas and wind systems will involve local costs (if the wind pumps are produced locally), which will contribute to the domestic economy. The use of biogas or wind for pumping, on the other hand, requires a higher initial investment than that required to use the diesel engine. Where capital funds are in short supply, therefore, the diesel engine as a power source could be the most economic short-term choice.

When comparing the alternatives, the diesel engine and the biogas option are the most similar. Both can be operated at any time by the user and neither require large storage facilities nor backup systems. They can also meet large pumping demands when these occur. Both of these systems, however, have the maintenance problems associated with the use of the diesel engine. The biogas system, although providing considerable fuel savings, also introduces the need to operate the biogas digester and requires the collection of dung.

Table 4. Operating costs of commercial windmills under idealized wind conditions.

Southern Cross – Seneschal, 7.5 m diameter	
Technical data	
Southern Cross windmill overall efficiency (inaccuracies arise because testing procedures are not specified in manufacturers published data)	15 – 31% ?
Energy delivery per day	24.6 – 49.1 kW-h/day
Available energy per m^2 of sweep area	3.59 kW-h/m^2/day
Sweep area	45.6 m^2
Cost data	
Windmill rotor and tower	P5700
Operating costs	
Windmill rotor and tower	P5700
Repair/maintenance scheme (Department of Water Affairs 1975)	P2870
Total	P8570
Cost per kW-h/day pumping capacity under idealized wind conditions	P175 – P348
Climax No. 12, 3.7 m diameter	
Technical data	
Climax windmill overall efficiency (inaccuracies arise because testing procedures are not specified in manufacturers published data)	8 – 17% ?
Energy delivery per day	3.2 – 6.4 kW-h/day
Available energy per m^2 of sweep area	3.59 kW-h/m^2/day
Sweep area	10.5 m^2
Cost data	
Windmill rotor and tower	P1640
Operating costs	
Windmill rotor and tower	P1640
Repair/maintenance scheme (estimated)	P700
Total	P2340
Cost per kW-h/day pumping capacity under idealized wind conditions	P366 – P731
Cost per kW-h/day pumping capacity under idealized wind conditions	
Southern Cross – Seneschal	P175 – P348
Climax No. 12	P366 – P731
Filippini rotor	P380

Note: The values in this table should be taken as approximate.

Wind pumps can deliver in the range of 1–20 kW-h/day of useful energy, which would be equivalent to pumping 3.6–72 m^3 of water from a depth of 100 m each day. This would make them useful to supply small to medium water demands. In general, they require less frequent and less sophisticated maintenance. Wind pumps, however, require larger storage facilities or backup systems (manual operation in the case of the Filippini wind pump) to allow for extended calm periods. Locally produced wind pumps can be matched more effectively to domestic wind regimes and preferred pumps. Also, the decision to produce wind pumps locally boosts the level of expertise within the country that can be applied to future maintenance needs and in training others in the selection and use of wind-pumping systems.

Implications for Training

As imported energy costs continue to rise, it seems inevitable that Botswana will turn more toward locally available energy resources for the pumping of water. It will be necessary to maintain an up-to-date assessment of the available energy resources and the technologies that may be used to apply these to pumping water. There will also be a need for field personnel to carry out basic energy assessments for individuals or groups, and to recommend the most appropriate pumping systems. Additional skilled and semi-skilled manpower will be required to design, manufacture, and maintain biogas or wind-powered pumping systems.

In Botswana, progress toward meeting some training needs has been made, as new windmills are being manufactured at Kanye and Gabane, with work also starting in Serowe. Biogas pumping systems have also been developed and tested at the RIIC site in Kanye. The Government of Botswana evaluation program of commercial windmills will be a means whereby the skills necessary to assess the wind energy resources available could be developed. This program, along with the tests of experimental wind pumps and biogas systems, could be used to develop future training materials and programs. These could then be used to equip extension staff with the knowledge and support materials necessary to play an essential role in advising local groups or individuals as to the most suitable pumping system for their needs.

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