USING RENEWABLE ENERGY TECHNOLOGIES FOR

SMALL-SCALE IRRIGATION IN KENYA :

The Problems and Prospects for the Use of Wind and Solar Energy Technologies for Agricultural Development

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Abstract

The need to increase the area of agriculturally productive land in Kenya and the fact that large-scale irrigation has been an expensive option for doing so has led planners to explore alternative means of providing water for the smallholder agricultural sector. It is generally believed that small-scale or micro-irrigation schemes hold some potential in this respect, but the costs and problems of using conventional pumping technologies sometimes make these approaches prohibitive.

This study reviews the potential uses of wind and solar energy-based water pumping technologies for small-scale irrigation in Kenya. These technologies are dependent on the availability of an adequate wind regime or solar radiation and on the smallholder's access to ground or surface water resources. Financially, they are often characterized by high first costs and by low recurrent costs. Major constraints to the use of windmills and photovoltaic-powered pumps in Kenya are identified in this study, and possible policy options to affect their use are explored.

Windmills and solar pumps appear to be financially competetive with and technically comparable (or superior) to diesel pumping technologies under certain conditions of operating load and insolation or wind regime. This is particularly true for low-head applications and where diesel is costly or unavailable. The major constraint to their use is their high capital cost, even though in the long run they may be cheaper to operate than conventional pumping technologies. It is unclear, however, whether or not small-scale pumped irrigation schemes can be cost effective, regardless of the pumping technology that is used.

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USING RENEWABLE ENERGY TECHNOLOGIES FOR SMALL-SCALE IRRIGATION IN KENYA

I. INTRODUCTION

This is the second of two papers that discuss the possible uses of renewable energy technologies in Kenya, and that more specifically focus on the possible applications of these technologies for small-scale irrigation. The first paper broadly described some of the experiences planners have had with renewable energy technologies in developing economies and suggested that there may be some potential for using these technologies in Kenya by relying on the private sector's investment resources.(1)

Perhaps the most significant lesson that has been learned so far has been that the successful employment of these technologies in developing economies is dependent on their ability to provide energy for meeting individual end-uses, rather than on the willingness of the consumer to adapt end-uses so that they would be able to meet the capacities of sometimes sophisticated technologies. Individual investment decisions favor renewable energy technologies when they can be guaranteed to provide for highly-valued end-uses, especially when conventional energy conversion and utilization technologies are unavailable, unreliable, or are technically inappropriate. Further, it is apparent that public policy options which might affect individual investment decisions should be determined on the basis of the potential developmental impacts of renewable energy technologies, rather than on their energy substitution potential in the aggregate.

The decision to focus on small-scale irrigation technologies (which developed out of the first paper) was arrived at by considering several points : an assured supply of water for rural agriculture, which small-scale irrigation technologies could provide, would likely be very highly-valued; the positive developmental impacts of increasing the area of agriculturally productive land in Kenya by using small-scale irrigation technologies could be significant; and finally, renewable energy technologies for small-scale irrigation are already either manufactured or are otherwise commercially available in Kenya. It was concluded that a study of the potential for renewable energy based small-scale irrigation schemes vis-a-vis conventional irrigation technologies in Kenya would be both timely and appropriate. Specifically, such a study would :

-- assess the potential of locally manufactured and/or commercially available wind and photovoltaic-powered water pumping technologies for small-scale irrigation in Kenya;(2)

-- assess these technologies with respect to conventional small-scale irrigation options; and would

-- identify possible policy approaches, where appropriate, for alleviating constraints and for developing opportunities, for stimulating consumer demand, and for promoting the consequent industrial production of renewable energy technologies in Kenya.

This paper will assess several sets of issues :

1. Irrigation and Kenyan Agriculture. Land constraints to agricultural development. Existing irrigated areas. Irrigation potential in Kenya with respect to other approaches for increasing agricultural productivity through land-use intensification and by increasing the area of land under production. Availability of groundwater and water from riverine and lacustrine systems.

2. Energy Availability. What is the availability of wind and solar energy resources in Kenya. What seasonal fluctuations in insolation and in the wind regime could be expected.

3. The State of Technology Development. What wind and photovoltaic-powered water pumping technologies are available on the Kenyan market. What are their reported performance characteristics, maintenance demands, levels of current production, and how are they being marketted.

4. Irrigation Demand Requirements and Supply Options. How much water could be provided by solar and wind-powered water pumping technologies to meet theoretical irrigation requirements under several different agro-climatic conditions, and under reasonable assumptions of energy availability, and of renewable energy technology utilization.

5. Financial Analyses. Estimated net present and average annualized costs of technologies or technology combinations under realistic assumptions of installation, operation, maintenance, repair, and replacement costs over a project's life. Sensitivity of these costs to the cost of more (or less) frequent replacements of worn out parts, to changes in component costs, etc.

6. Constraints, Opportunities, and Policy Options for Future Development. Factors limiting the use of renewable energy technologies. Risks associated with the introduction of irrigation as an agricultural technology. Social and economic appropriateness of water pumping in rural areas. Labor issues. Financial constraints. Development assistance for renewables. Possible public sector interventions to alleviate constraints to renewable energy technology utilization for small-scale irrigation.

It became clear very early in this analysis that three closely related questions needed to be addressed to arrive at a pragmatic assessment of the potential role of renewable energy technologies for small-scale irrigation in Kenya :

-- Firstly, what has been the record of irrigation projects generally in Kenya?

-- Secondly, what has been the record of small-scale or micro-irrigation projects vis-a-vis large-scale irrigation projects?

-- Thirdly, what has been the record of renewable energy technologies which have been used for small-scale irrigation?

While these questions imply that this study has been broad in scope, in fact, a comprehensive effort has neither been possible nor necessarily desirable. Instead, we have attempted to make some observations about the last of these questions, and then we have incorporated these findings into a wider discussion of the potential for small-scale irrigation in Kenya. There is the necessary caveat that, regardless of the generalizations and conclusions arrived at here, they should not be applied too broadly. There is no "norm" of experience with renewable energy technologies, primarily because there is no "norm" of social, economic, physical, or other site-specific conditions which will consistently result in the same outcome. Further, the technologies themselves have a limited track record. Life cycle cost estimates, for instance, have been based on theoretical (albeit realistic) performance characteristics. In fact, there is no way of knowing whether a windmill or a solar pump will have to be replaced in 5 years or in 50 years, simply because the specific technologies on the Kenyan market have not been around that long. The intention here is to present a pragmatic view toward renewable energy technologies for small-scale irrigation by suggesting issues which might be considered by potential institutional or individual investors.

II. IRRIGATION AND AGRICULTURE IN KENYA

Until the early 1970s, the Kenyan agricultural sector experienced particularly high rates of growth and was characterized by the development of a strong smallholder base, supported by a well-developed commercial and institutional infrastructure. The challenges of continued strong agricultural development have become increasingly difficult to address because of drought-related reductions in food production between 1979 and 1981 and because of the pressures a rapidly growing population is placing on the available agricultural land of good quality.

Of Kenya's 569,000 square kilometer area, it has been estimated that

> ". . . only about seven percent can be described as good agricultural land in the sense that it has adequate and reliable rainfall and good soils and is not steeply sloping. A further four and a half percent is suited for crop production but is in the areas where in some years, rainfall will prove inadequate and crop failures may ensue. From an agricultural point of view, the remaining land, in the absence of irrigation or water conservation, is suited only to stock raising at various levels of intensity, depending mainly on rainfall and soil type."(3)

Geographic patterns of rainfall probability and of land-use potential are shown graphically in Figures 1 and 2 of the Technical Appendix. Settlement patterns have, not surprisingly, followed these patterns of agro-ecological potential. Nearly 40 percent of Kenya's population occupies less than 5 percent of its land area.(4)

In view of these constraints, targetted growth rates in the agricultural sector, suggested in the Fifth Development Plan (1984 to

1988) seem daunting indeed. The Plan targets agricultural production to grow at an annual rate of 4.5 percent through 1987, rising to 5 percent in 1988. Two-thirds of this growth is expected to come through higher agricultural yields, resulting from the intensification of existing land-use patterns. The other one-third is expected to come from increasing the area of land under production, primarily by developing grazing lands where rainfall -- and the potential crop yield -- is lower than in areas that are already under cultivation.(5)

There are several possible approaches for intensifying the pattern of land-use in Kenya, for instance, by bringing about shifts in cropping patterns, by adopting improved agricultural technologies and husbandry practices, and by redistributing large landholdings. None of these approaches are particularly straightforward. The shifting of cropping patterns, for instance, to favor the cultivation of highly-valued export crops is constrained by production quotas established by commodity agreements such as the International Coffee Agreement. Conversely, the need to maintain cash crop exports for the most part prevents the shifting of cropping patterns to favor food production. Increasing production by using improved technologies (including irrigation) may be theoretically possible, but it is unclear whether it would be economically justifiable. By redistributing large landholdings, production could be increased by taking advantage of the fact that small farms have higher employment and higher output per hectare than large farms on land of comparable quality.(6) Action has already been taken to formalize the subdivision of large group-owned farms. However, land redistribution by itself would be unable to provide the necessary increases in agricultural employment and production to meet year 2000 demands.

Approaches for increasing the area of agricultural land under production include the clearing of forested lands to allow for cultivation, increasing the use of marginal lands under dry-land farming, and reclaiming fertile land by draining valley bottoms. The first two approaches could have serious long-term environmental impacts. Forested lands are highly-valued for catchment and habitat protection and for rural wood production. Marginal lands are, to some extent, already utilized to their capacity by traditional pastoralists. Of the possible approaches addressed thus far, the drainage of valley bottoms may show the most promise, as it has been estimated that there are up to a million hectares of drainage-impeded lands of high to medium agricultural potential.(7) There has been little experience with drainage projects in Kenya, and so it is difficult to say whether this approach has as much potential as it appears.

Within this framework of possible options for increasing agricultural productivity, more experience has been accumulated with irrigation programs in Kenya than with any other approach. Around 9,900 hectares are irrigated through 7 large-scale schemes managed by the National Irrigation Board, and another 2,850 hectares are irrigated through various programs of the Ministry of Agriculture and Livestock Development (including the Small-Scale Irrigation Development Program). Finally, over 20,000 hectares are privately irrigated through commercial and traditional schemes. See Table 1. The total area of irrigated agricultural land, 344.4 square kilometers, is only .06 percent of Kenya's total land area, and just 13 percent of the total area of cultivated land.(8) To some extent, it is understandable that irrigation has been a low developmental priority because, until recently, the dual constraints on agricultural productivity of erratic rainfall patterns and the limited availability of high potential agricultural land were not especially clear.

Public sector-financed large-scale irrigation schemes in Kenya have been characterized by their high costs and their low returns. Of the schemes managed by the National Irrigation Board, only one, the Mwea Scheme, is self-supporting. Other schemes such as the Bura project have been enormously expensive because of major infrastructure requirements. Recent cost estimates of the Bura Scheme have lowered the estimated economic rate of return to 9 percent, and have thus raised serious questions about its economic viability. Even though Bura is going to be limited to 4,000 hectares instead of its originally planned 6,700 hectares, it will still impose a major burden on public sector finances. Estimates of the investment costs required for the development of future large-scale schemes range from around K.Pounds 4,400 per hectare to K.Pounds 9,400 per hectare.(9)

Because of the limited availability of public sector resources, it is clear that if irrigation is to be carried out on any signficant scale in Kenya, investment costs will have to be lowered substantially, or output per hectare will have to be raised considerably. The current Development Plan emphasizes the need for low-cost approaches to irrigation and suggests that "preference should be given to (the) rehabilitation of existing schemes and to the encouragement of small-scale projects where water is available through gravity flow." It is interesting to note that the Development Plan estimates the cost of 10 potential minor irrigation projects covering 17,400 hectares to be aqround K.Pounds 6 million -- or only K.Pounds 345 per hectare.(10) If indeed these estimates are an accurate reflection of required investment financing, they represent a significant cost breakthrough in irrigation project design.

The shift in emphasis toward smaller scale activities in order to lower cost generally implies that the area irrigated from a single source (a feeder canal, for instance) would be relatively small compared to large-scale schemes. For instance, a number of small-scale irrigation projects on the lower Tana range in size from 40 to 100 hectares, while large-scale schemes like Mwea irrigate in excess of 5,700 hectares. It is also argued that, in addition to irrigating a relatively small area from a single source, the size of individual smallholdings should also be reduced in small-scale schemes. Large-scale schemes are subdivided into holdings that average around 1.6 hectares, but these are often larger than a single family can manage to cultivate without mechanization. By reducing the size of the irrigated smallholding, labor constraints would not be as serious an issue. In areas where the availability of land of good quality is a limiting factor, decreasing the size of the smallholding would allow for the settlement of a larger number of farming families within a scheme. Although this last point would be significant, even for smaller schemes such as those on the lower Tana, it would not be as important an issue with micro-irrigation schemes where very small holdings of between .5 and 5 hectares are irrigated from a single source.

It would be useful at this point to emphasize that renewable energy technologies are, for the most part, capable of irrigating only very small areas of under 5 hectares. While conventional irrigation technologies can pump a large amount of water from a single source, and can thus irrigate a large area, renewable energy technologies do not have this capacity, and consequently do not allow for much flexibility in choosing the size of the area to be irrigated. The real limiting factor is the size of the pump : if a larger area is to be irrigated, additional units will have to be installed. This point will be expanded upon in a later discussion of command area calculations, but for the moment, it should be kept in mind that the nature of the technologies involved will limit this discussion to micro-irrigation schemes. Further, although the infrastructure and investment requirements for large-scale and micro-irrigation schemes are very different, repeated references will be made to large-scale schemes simply because they provide a useful point of departure in this discussion. See Table 2.

Although the Kenyan experience with large-scale irrigation schemes has been somewhat limited, experience with traditional and small-scale irrigation schemes has perhaps been even more so. It is generally believed that between 500 and 1000 hectares are still irrigated by traditional irrigation schemes in various parts of the country. (Admittedly, the word "traditional" is often misused, but it is used here to refer to schemes that were originally developed non-commercially, using indigenous rural technologies, and without public sector intervention.) Perhaps the oldest of these schemes were built in the area south of Lake Baringo. These were primarily gravity-fed systems where diversion canals were built upstream and led to a system of furrows and channels which were used to distribute irrigation water among smallholders. Other similar schemes have been constructed in the Kerio Valley and on the Tana River. There are reports that traditional irrigation schemes had functioned for many years in the Mt.Kenya area, but pressures for agricultural land resulted in the deterioration of the channels and the system has long-since fallen into disuse.

Some of these schemes evolved into major projects as developmental priorities on cash crop production emerged. The Perkerra Irrigation Scheme, begun in the early 1950s, was partly the result of the Colonial Administration's need to utilize surplus labor in the Marigat region that had been generated by the "repatriation" of Kikuyu, Meru, and Embu peoples during the Emergency. It was actually only the latest incarnation in a series of irrigation schemes, the earliest of which had been developed and maintained by the Njemps people in the late 1800s. Even earlier forms of this scheme may have been in operation before then, but there is little information available about the period prior to 1900. The Njemps managed to divert the Perkerra River onto flat and uncultivated lands by constructing small dykes and canals. Although seasonal floods often seriously damaged these irrigation canals and required their reconstruction, early European explorers in the region reported the existence of a stable and successful system of irrigation. The stability of the system was shaken by the incursions of settlers whose livestock greatly contributed to overgrazing and caused the resultant serious erosion of the catchment area. A major flood in 1918 altered the river's course, and a succession of the Colonial Administration's attempts to repair the damaged dykes failed. Even today, after repeated injections of capital, one observer has noted that the Perkerra Scheme has

> ". . . become a mature dwarf, confirmed in its independence, kept alive by its richer sister (Mwea), and sustained in its search for economic vitality by the hope that a near-miracle would overcome its structural impediments."(11)

Other interesting points to note about the Perkerra Scheme include the fact that its mixed crop of chillies and onions yields the highest gross reported returns per hectare of any of the National Irrigation Board's schemes -- K.Pounds 810 per hectare (1981/82) -- and that of the 2,800 irrigated hectares that were originally envisaged in the early 1950s,(12) only 210 hectares were cropped in the 1981/82 season.(13)

On the Tana River, a very complex rural agricultural economy developed among the Pokomo around traditional irrigation schemes, and still functions to varying degrees. It is characterized by a very complex farm management system which emphasizes low levels of technology and high biological flexibility. A study supported by the National Christian Council of Kenya (NCCK) found that over 32 different varieties of paddy have been planted in areas of different agro-ecological potential in response to climatic risk. As long as the system was maintained, fluctuations in yield were minimized. However, the pressure to expand beyond their subsistence economy has rapidly eroded the Pokomo's traditional agricultural competence and has exposed the increasingly cash and production-oriented economy to varying degrees of ecological risk.(14)

In a number of instances, early settlers took advantage of some of the existing traditional irrigation schemes by augmenting, improving, and expanding upon them to increase their own crop production. Schemes that were developed by the settlers include the Yatta Furrow in Machakos District, and Njoro Kubwa in Taveta District. Improvements to the Yatta Furrow were completed by the Colonial Administration in 1959 at a cost of Br.Pounds 324,982. The 37-mile long furrow was intended to irrigate around 750 hectares,(15) but now it only irrigates around two-thirds of that area. The current Development Plan notes that the government intends to enlarge both the Yatta Furrow and Njoro Kubwa.

In the mid-1960s, a number of church and development organizations initiated several small-scale projects to irrigate arid and semi-arid areas. The intention was often to provide an alternative to the raising of livestock by traditional pastoralists. The development of irrigated agricultural schemes in these areas has been very risky because it has involved promoting the transition from pastoralism to a completely unfamiliar economy. In any case, the effect of these projects on agricultural production has been minimal and they have required continued financial assistance. These projects were developed primarily along the Turkwell River, along the Ewaso Ngiro River, and in some parts of the Kerio Valley.

Within the Ministry of Agriculture and Livestock Development, responsibility for the development of small-scale irrigation schemes has rested since the late 1970s with the Small-Scale Irrigation Development Project of the Irrigation and Drainage Branch. Other small-scale efforts have been spearheaded by regional drainage basin development authorities and by District Development Committees. Because of the different administrative entities involved, and because of development objectives which may be at cross purposes, it has sometimes been difficult to coordinate local efforts in an effective and practical way. Nonetheless, there exists, at least in theory, an administrative framework for initiating and carrying out small-scale irrigation activities.

Regardless of the extent to which irrigation activities have been undertaken in Kenya, there is little argument that only a fraction of the country's irrigation potential has been realized. Many estimates of the land area which is potentially irrigable usually mention a figure of around 200,000 hectares. Recent estimates have been as high as 540,000 hectares, including 200,000 hectares in the Lake Basin catchment, 200,000 hectares in the Tana River catchment, 70,000 hectares in the Rift Valley catchment, 40,000 hectares in the Athi River catchment, and 30,000 hectares in the Ewaso Ngiro catchment.(16) These estimates were arrived at primarily by considering the extent and distribution of Kenya's riverine systems. Major perennial rivers traverse nearly 2,250 kilometers and drain around 214,000 square kilometers of river basin catchments. An additional 860 kilometers of rivers flow seasonally. Major surface water resources are listed in Table 3.

Especially in arid and semi-arid areas, seasonally flowing rivers such as the Turkwell can provide an important source of groundwater because underground rivers continue to flow the year around. These aquifers lie at reasonably shallow depths of 3 to 5 meters and low-head pumping systems could easily be used to irrigate small plots. At the same time, the digging of shallow wells along river banks can be tricky. Water quality may be poor, as studies of subsurface aquifers along the Tana River have indicated. High sediment levels could also be a problem, as they tend to wear out a pump fairly quickly. The instability of river bank sediments would require that well-linings be adequate to prevent excessive sedimentation. Finally, where these rivers seasonally flood their banks, pumps would have to be protected, either by making them portable, or by building protective structures around them.

In addition to these underground rivers, there are indications that there are other significant groundwater resources in Kenya. Three groundwater characteristics will determine whether or not these resources can be exploited : the depth of the aquifer, the potential borehole yield, and the quality of the water in terms of the amount and type of dissolved solids. Preliminary assessments of these groundwater characteristics have yielded a tremendous amount of information. The National Master Water Plan of 1977 summarized the results of an analysis of around 4,000 boreholes distributed througnout the country and provided a preliminary picture of Kenya's groundwater characteristics.(17) Greatly simplified maps which summarize average groundwater depth and potential borehole yields are shown in Figures 3 and 4 of the Technical Appendix to this paper.

Most of the available groundwater in Kenya lies at substantial depths. In only a few areas does the water table rest closer than 15 meters to the surface. These areas are primarily in a 50 mile wide strip on both sides of Lake Turkana, in a small triangular area bordering Uganda south of Mt.Elgon and north of Lake Victoria, in the vicinity of Lake Naivasha, and in the eastern watershed of Mt.Kenya between Embu and Meru. Groundwater lies between 15 and 55 meters in much of the western half of the country, with the exception of the Rift Valley where, with most of the eastern half of the country, the water table is deeper than 55 meters below the surface.

Borehole yields and water quality also vary considerably from one part of the country to another. Very generally, it could be said that the deeper the water table, the lower the yield. Higher yields are found in the immediate vicinity of Lake Victoria, around Lake Naivasha, and in a strip between Taveta and the coast on Kenya's southeastern border with Tanzania. Even in the lowest yielding areas, a borehole could yield as much as 80 to 90 cubic meters of water per day, which would be sufficient for some agricultural or domestic uses. Because this water often lies at significant depths, it could be very costly to use it, regardless of the type of pumping technology which is used. Groundwater quality is closely correlated with the availability of fresh surface water. In areas of high rainfall, for instance in the Highlands and along the coast, the quality of the water is quite good. In some of the more arid regions, groundwater is characterized by high levels of dissolved solids.

There are obvious risks in having made these generalizations. The 1977 National Master Water Plan presented averaged data for each major drainage basin. The depths of the water table, the potential borehole yields, and water quality will vary greatly within each drainage basin and are greatly dependent on the geological history of the area in question. The point is simply that if the investment capital is available, these groundwater resources could possibly be used for irrigation in areas where rainfall is inadequate or uncertain. There are plans to update and refine the information summarized in the 1977 Master Plan which was really only the first phase in an effort to assess Kenya's groundwater resources.

In addition to groundwater and riverine water resources, nearly 10,000 square kilometers of Kenya's surface area are covered with lakes, listed in Table 3. Around 95 percent of this area is accounted for by Lake Turkana and by a part of Lake Victoria. The quality of Lake Victoria water is quite good and is suitable for irrigation purposes, but only with the exception of Lake Naivasha, the rest of the lakes are either too saline or alkaline to be used for irrigation. With over 67,000 square kilometers of surface area, the possible uses of the water in Lake Victoria should not be underestimated. If a 1,000 hectare plot were irrigated with 80 cubic meters of water per hectare per day, it would take over 2,300 years to lower the level of Lake Victoria by 1 meter. At the same time, because of the number of countries with competing claims on Lake Victoria's water, such a scheme would be politically ill-advised at best.

III. PATTERNS OF RENEWABLE ENERGY AVAILABILITY

Like any other energy-dependent technologies, water pumps must have an adequate and assured supply of energy before they can be operated. This analysis assesses water pumps which function using two renewable energy sources : wind and solar radiation. However, before their performance characteristics can be assessed, it is essential to establish the patterns of renewable energy availability in Kenya. While shortages of fossil fuels such as diesel and petrol can be a serious constraint to conventionally-pumped irrigation projects, the same point about energy availability can be said about renewable energy technology-oriented water projects. This perhaps seems to be an obvious point, but it has occasionally been missed by overenthusiastic development planners who have invested huge sums of money on renewable energy technologies, only to find that the planned installation site was cloudier than they had originally remembered or that the wind really wasn't quite as strong as they had thought.

We intend here to present some of the available data about Kenya's geographically varying wind regimes and levels of insolation. This data however, provides only a broad picture and is necessarily incomplete. A wind regime can be highly variable over an area of just a few square kilometers and will be influenced by physical obstructions and the local topography. The amount of utilizable solar radiation will be dependent partly on whether or not there are any local obstructions such as trees or buildings, or whether the planned site is in a valley or on a hillside where the number of daylight hours may have been shortened by shadowing effects.

In a sense, these considerations emphasize that renewable energy technologies are extremely site-dependent for their energy sources. While human intervention can bring supplies of diesel or petrol, there are few things people are able to do to increase the availability of sunlight, or the windspeed. These constraints, once there, cannot be removed or impacted upon. Rather, if renewable energy inputs are inadequate, the pumping unit will have to be moved to an appropriate site; obviously, it is better to have identified these constraints prior to the installation of the pumping unit. The data summarized here provide only the first order of information needed regarding energy availability and would have to be verified or expanded upon for each site under consideration. In order to assess the performance characteristics of solar pumps and windmills in several parts of the country, we have determined the wind speed and insolation for three locations with differing agro-ecological potentials. This information is included in Table 4 of the Technical Appendix.

A. The Distribution of Solar Radiation

Obasi and Rao provide a comprehensive assessment of the distribution of solar radiation in Kenya.(18) Their study analyzed data provided by the East African Meteorological Department (EAMD) which was collected over a period of between five and eighteen years. Although the EAMD ceased to function after the breakup of the East African Community, their earlier reports provide a valuable source of information about climatological patterns in Kenya.(19)

Obasi and Rao reviewed solar radiation data that had been collected at or estimated for 52 stations in Kenya. Most of these stations were equipped with Eppley or Kipp pyranometers or with Gunn Bellani radiation integrators. At 7 stations with no recording equipment, a series of regression equations using data from nearby stations was used to estimate insolation. These equations are of the form :

$$Q = Q_a\ [x + y(n/N)]$$

where Q and Q_a denote the daily insolation at the earth's surface and at the top of the atmosphere respectively, x and y are regression constants, and n/N is the ratio of measured to possible duration of sunshine. Their assessment provided insolation data in Langleys per day; we have converted their data to kilowatt-hours per square meter per day (kWh/m^2 day).(20) This convention is somewhat more useful in our analysis because it will allow us to more easily determine the power output of photovoltaic-powered pumps.

Maximum and minimum periods of solar radiation, averaged over the country, are in January and July, respectively. The spatial distribution patterns of insolation for these months are shown in Figures 7 and 8 in the Technical Appendix, and have been averaged over the year in Figure 6. About half of the country receives over 5.8 kWh/m^2 day, averaged over the year. For the country as a whole the average is closer to 5.5 kWh/m^2 day. Highest average levels of around 7 kWh/m^2 day of insolation are reported between Kapenguria and Lodwar, centered in Lokori and along the northern shore of Lake Victoria between Kisumu and the Ugandan border. Lowest average levels of insolation of around 5.1 kWh/m^2 day are reported for the northwest around Moyale, along the coast around Mombassa, and along the Tanzanian border between Lake Magadi and Taveta.

Seasonal variations in insolation are minimal in some areas and are significant in others. In the Lake basin area, for instance, insolation over the year fluctuates by less than 5 percent. However, in northeastern Kenya, radiation values in July are nearly 35 percent lower than they are in January. Changing insolation values largely reflect the extent of the cloud cover which accompanies the usually regular cycle of the long and short rains. Other changes are observed because of the earth's different axial configurations with respect to the sun in July and January.

The extent to which solar radiation can be converted to useful energy units is dependent on the conversion efficiency of the interceptor. For photovoltaic cells, efficiencies of around 10 percent are common.(21) A square meter of solar cells with an efficiency of 10 percent, for instance, would convert incoming radiation of 5.5 kWh/m^2 day into 550 watt hours of electricity.

B. Characteristics of the Wind Regime

Perhaps the most thorough assessment of the wind energy sector that has been completed to date is that of van Lierop and van Veldhuizen,(22) and will be referred to repeatedly in this analysis. Their study greatly expanded on the earlier work of Chipeta,(23) ILACO,(24) and van Vilsteren(25) and provides a critical analysis of much of the wind energy data that had been compiled but that had not been adequately or consistently processed for estimating wind energy potential. Much of their data had been collected by the EAMD, the current Meteorological Department of the Ministry of Transport and Communications, and by other organizations such as the WMO/UNDP Hydrometeorological Survey, the FAO, and by the German Special Energy Program (SEP). Their study identified around 125 different wind monitoring stations in Kenya. See Figure 5 and Table 5. However, it was found that there was little consistency in the pattern of data collection and in the degree to which the data was processed, and that many of the monitoring stations were non-functioning or were poorly-sited.

It would be useful to elaborate on a number of conventions that are commonly employed in discussions of wind energy.(26) Among these are the Power Coefficient (C_p) which is the ratio of actual power output (P_a) to the theoretical power of the wind (P_t) :

$$C_p = P_a/P_t$$

The Power Coefficient has a theoretical maximum of around .59, called the Betz Maximum, but under most load conditions and depending on the efficiency of the drive mechanism and the transmission, the C_p is usually around .4 or less. The C_p will vary with windspeed, and is usually highest at the so-called "design windspeed" and decreases at higher windspeeds. The "cut-in windspeed" is the speed at which there is enough torque so that water can be pumped and is usually between 2.4 and 3 meters per sec. The "rated windspeed" is the speed at which the windmill has reached its peak power output. Most windmills are designed to turn out of high winds to avoid structural damage. This is called the "furling windspeed."

The theoretical power of the wind (P_t) is proportional to the cube of the wind velocity (V), to the density of the air (p), and to the "swept area" (A) through which wind is passing. It is represented by the relationship :

$$P_t = 1/2\ pV^3A$$

The swept area, A, is equivalent to the area through which the windmill's rotor passes. The density of the air, p, is dependent on the temperature and on the barometric pressure.

To determine the expected windmill power output, given a particular wind regime, we can multiply the theoretical power of the wind, P_t, by the Power Coefficient, C_p, and by the length of time the wind is blowing and for which windspeeds have been measured (based on cumulative frequency distributions for measured windspeed intervals).

Using information from a variety of sources, van Lierop and van Veldhuizen have estimated the average windspeeds for 26 locations where adequate information about the local wind regime was available. This data is present in Table 6. This information has been converted into values of P_t for $A=1m^2$ and are given in Table 7.

Generally, a number of characteristics of Kenya's wind regime seem evident. The highest measured windspeeds are recorded in the northwest in Turkana District. Other particularly windy areas are reported along the coastal strip and in the vicinity of Lake Victoria. Average windspeeds vary throughout the year, but generally are lower during the long rains, and are higher in the months preceding both rainy periods (February and March, September and October). Diurnal patterns are also highly variable, but generally winds are highest in the mid-afternoon, and lowest in the mornings and at night. Exceptions include the Tana River region, where windspeeds are higher in the mornings, and the Turkana region, where very high winds occur at night. Average windspeeds are as high as 5 meters per second in some areas (around 11 miles per hour).

Even though average daily windspeeds may appear to be too low to be useful, because of daily variations in the wind regime, there could well be sufficient wind during part of the day to pump an adequate amount of water. When evaluating a site for its wind energy potential, records of the local windspeed should be checked if they are available. A selected list of some of the wind monitoring stations in Kenya is given in Table 5 of the Technical Appendix. Perhaps even more so than for solar pumps, it is essential that reasonable assessments of site-specific energy availability are made for windmills. It is much easier to move a solar pump, for instance, if there is inadequate insolation than it is to move a windmill where the wind regime is inadequate. Wind regimes vary greatly from site to site, and because the power output of a windmill is directly proportional to the cube of the wind velocity, proper site selection is essential in order to utilize the maximum amount of wind available. Where windspeed monitoring records are unavailable, rural farmers often can provide a wealth of meteorological information.

IV. RENEWABLE ENERGY TECHNOLOGICAL OPTIONS

If there were no limits to the availability of capital, one could purchase nearly any type of renewable energy technology available on international markets and import it into Kenya. Obviously, this latitude of choice would make any reasonable assessment of different technologies for small-scale irrigation fairly difficult. We have instead limited our discussion to technologies which are easily available on the Kenyan market, albeit "easily" is as subjective a term as any. For the most part, we will review a selection of technologies which are manufactured here by a variety of commercial and non-commercial bodies, or that are available through local distributors who market imported technologies. This last criteria will exclude technologies which are occasionally brought into the country by licensed import agents who have no established mechanism for assuring a guaranteed supply of spares or interest in providing maintenance.

Most unfortunately, there are a number of examples in Kenya of imported renewable energy technologies which have been brought into the country with no thought given to subsequent maintenance demands or to the fact that there are limited technical and financial resources available to keep these devices working. In some cases, equivalent locally manufactured technologies have been available, thus reducing problems associated with finding adequate spares and qualified maintenance personnel. One of the arguments in favor of renewable energy technologies is that their maintenance demands are low, and their record in Kenya seems to bear this out. However, if a technology is imported without any means of maintaining it, and if it breaks down, it becomes virtually useless. There are many examples of windmills, for instance, which were imported into Kenya by local distributors who have since gone out of business. There has been no easy way to maintain these machines, and many of them are now non-functioning. Other sometimes-unproven technologies have been imported into Kenya by bilateral aid agencies under the guise of "commodity assistance." When there are no provisions for technical support, these types of activities more closely resemble the "dumping" of technologies on developing country markets in order to assist industrialized economies. These rather transparent efforts should be greatly discouraged. Resources did not allow for a thorough review of these technologies and of their maintenance records, but anecdotal evidence has suggested their record has been poor indeed.

We will review in this section, the technologies which meet the criteria discussed above, i.e. renewable energy-powered small-scale irrigation technologies which are manufactured in Kenya, or which are imported by a local distributor. The assessment will include a review of each technology, their reported performance characteristics, and their maintenance records. Cost sensitivity, the structure of import tariffs, export promotion and compensation, and other financial issues will be covered in subsequent sections. We will also discuss the commercial histories of the manufacturing and marketting companies involved, and the markets which have been addressed thus far. Not surprisingly, successful companies have one common feature : their success has been dependent on the energy and enterprise of individual entrepreneurs who have been willing to assume considerable risks both in the manufacture and marketting of these new technologies.

A. Photovoltaic-Powered Water Pumping Technologies

Although the technologies employed in solar photovoltaic pumps are relatively sophisticated, the principle behind their operation is straightforward. Solar photovoltaic pumps have two primary components : a pump is powered by electricity which is generated by photovoltaic cells. (These pumps should not be confused with other solar pumps which use process heat, provided by solar-thermal flat-plate collectors, to heat an expansion fluid which operates a reciprocating engine.) The straightforward design of this system led early experimenters to take off-the-shelf electric pumps and hook them up to photovoltaic panels. These pumping systems were marketted in the early 1970s, but a number of serious problems were encountered. Most electric pumps are powered by an Alternating Current (A.C.), while photovoltaics produce Direct Current (D.C.). In order to convert D.C. into A.C., an A.C. inverter must be added to the system; depending on its efficiency, the inverter may cause substantial efficiency and line losses. Another problem was that the electric current which photovoltaics produce will not be constant, and will fluctuate depending on the amount of sunlight that is available. Most pumps were not designed to handle substantial fluctuations in the inverted A.C frequency. Pumps had short life expectancies and were easily damaged as a result. Finally, most electric pumps do not have to be tremendously efficient because it is assumed that if electricity is available from a grid, it will not be a limiting factor. Photovoltaics however produce relatively small amounts of electricity at a very high cost. More photovoltaic panels would have to be added to make up for significant efficiency losses, and this made the cost of PV-powered pumping systems very prohibitive.

In order to overcome these problems, a research effort was mounted in the mid-1970s with the aim of developing electric pumps specifically for use with photovoltaic cells. Most photovoltaic manufacturing companies now sell matched PV-powered pumping systems, although their performance characteristics and costs vary greatly. From the start, a number of development agencies were greatly interested in the potential of these pumps for applications in rural areas. The result of this interest was the commissioning of a series of studies to test and evaluate different pumping systems under laboratory and field conditions. Financed by the World Bank and the UNDP, a final report was issued by the company of Sir William Halcrow and Partners in June of 1983 which provided a pragmatic view of the different economic and technical parameters of a variety of PV-powered pumping systems.(27) If anything, this report encouraged photovoltaic companies to more actively promote sales of solar pumps in developing countries. It gave solar pumps a new credibility which they had lacked because of the failures of earlier badly designed systems.

Nonetheless, one of the real drawbacks to the Halcrow report was that it presented a static picture of the industry. Photovoltaics are a rapidly changing technology. The costs of photovoltaic cells, for instance, have gone down dramatically -- although not as dramatically as predicted in some studies. Early optimistic estimates indicated that photovoltaics would cost as little as US $2.50 per peak watt)(28) by 1984, and US $.40 by 1990, down from around US $30 in 1976.(29) Under even the best of assumptions, photovoltaics currently cost between US $5 and $10 per peak watt on the American market. The Sacramento (California) Municipal Utility District, which is installing a 100MW photovoltaic-powered electricity generating facility, will be purchasing PV cells at a record low cost of US $5.14 per peak watt.(30) Current cost estimates for PV cells on the Kenyan market range from US $7 to US $11 per peak watt (not including import duty and sales tax of 45 percent and 17 percent respectively). The impact of falling photovoltaic prices on total pumping system cost will be discussed in a subsequent section

Beyond the cost issue, the Halcrow report failed to address several innovative changes in the design of a number of pumpsets. In order to get away from the need for an A.C. inverter, a number of companies have introduced D.C.-powered pumps, which, without the inverter, are somewhat more efficient than A.C.-powered pumps. These companies have suffered somewhat from their late entry into the market, because the timing of the Halcrow report prevented the new pumps from being tested to the same extent as earlier pumps. Indeed, one company (which only produces A.C.-powered pumps) noted in a recent report that A.C. pumps are "far better tested than the recently introduced D.C. submersible pumps, which are still in the experimental stage and have essentially no operating record."(31) This last point is however patently untrue. In East Africa alone, D.C.-powered photovoltaic pumps have accumulated an operating record of perhaps as many as 50,000 hours since 1980. In comparison, it would be optimistic to suggest that A.C.-powered photovoltaic pumps in East Africa have a cumulative operating record of much more than 10,000 hours.

1. D.C.-Powered Photovoltaic Pumps : the SEI 300M

The D.C.-powered photovoltaic pump which is currently being actively marketted in Kenya is manufactured by Solar Electric International (of London, Malta, and Nairobi). Called the SEI 300M Portable Sun Pump, it is being marketted as a complete system and is powered by 8 photovoltaic panels which are manufactured by ARCO Solar (of Chatsworth, CA., USA). They are able to produce a peak power output of 300 watts. The pumping system is being marketted in East Africa by the local distributor for ARCO Solar products (Animatics, Ltd.) which has an office in Nairobi. Technical support, installation, and pump maintenance can be provided by SEI which also has an office in Nairobi. There are around 10 of these pumps installed in Kenya, and another 30 or so that have been installed in Eastern Africa (in Somalia, Zanzibar, Sudan, Djibouti, and Tanzania).

The ARCO Solar photovoltaic cells themselves are circular, flat, single crystal cells which operate at a conversion efficiency of roughly 12 percent (although this will vary by a few percentage points depending on the quality of the light and the ambient temperature). The individual cells are mounted on a white surface, 35 cells to a module, and are protected by a front surface of tempered glass. The exposed white surface between each cell reflects light, which is refracted by the front surface, and is then utilized by adjacent cells. This feature reportedly increases module output by around 5 percent. The panels meet or exceed performance specifications established by the United States Department of Energy (Jet Propulsion Laboratory Test Exposure Program 5260-S, Block IV), and are expected to have a useful life of around 20 years. The panels are warranteed for 5 years in the event power output should fall significantly below specifications due to defects in materials or workmanship. The modules are mounted in two sub-arrays on portable mounts which can be wheeled about. The exposed module surface area covers around 3 square meters, and by turning the array twice a day, around 95 percent of the available solar radiation can be tapped. A recently introduced alternative mounting structure positions the modules on an aluminum frame with a trapezoidally-shaped supporting structure. The support structure is designed to be manually tilted to one of three positions, depending on the altitude of the sun during the day. This mounting scheme was developed especially for low-latitude locations, such as in Kenya. Regular required maintenance involves cleaning the modules' surface so they are free of dirt and can operate at peak efficiency.

The pumping unit is a centrifugal pump which is operated by a 60 volt brushless motor. The pump has a minimum of moving parts and is submersible. For operation, it is hooked up to the photovoltaic array and is lowered to float upon the water's surface, either in a shallow well, an irrigation canal, or a river. Depending on the water source and on the design of the system, the water is pumped through a 2-inch plastic output pipe. The pump and its workings are fairly wide in diameter, and are not designed to fit down wells with narrow openings. Regular required maintenance involves occasionally cleaning the pump's intake screen of debris. In this analysis, the pump is expected to have a useful life of around 5 years, which is not uncharacteristic of centrifugal pumps. The impact of changing this assumption on annualized cost estimates is discussed in a subsequent section. Centrifugal pumps are most efficient for lifting water from low heads. The SEI 300M is designed to lift water from a depth (total dynamic head) of between 3 and 7 meters. The pump's performance characteristics are summarized in Figure 9 of the Technical Appendix.(32) At a head of 5 meters, and with an insolation of 7 kWh/m^2 day, the pump will lift around 70 m^3 of water. Under the same conditions of insolation, the pump will lift 90 m^3 at a head of 3 meters. The pump is warranteed by SEI for one year in the event of failure because of defects in parts or workmanship.

With every subsequent conversion to another form of energy in the system, there are efficiency losses which, for the entire pumping system, are quite substantial. Assuming an insolation of 6 kW/m^2, and at a head of 5 meters, the pump will deliver around 2.5 liters per second. This represents an effective delivered power output of 122.6 watts.(33) With an interceptor area of 3 square meters, and with an insolation of of 6 kW/m^2, total incoming power is equal to 18,000 watts. This gives a total system conversion efficiency of 0.68 percent.

Although no thorough exercise has been carried out to determine this pumping system's overall performance and maintenance record, numerous site visits indicated that there have been very few technical problems with them. Like any pump, it has to be attended to from time to time and can't be ignored, for instance, if the well is pumped dry. The part of the pump which is most likely to be damaged by water-borne sediments is the impeller which is a plastic fan-like part which performs the central water lifting function, and which can be cheaply replaced. The pumping unit is sealed, which is both an advantage and a disadvantage. The primary advantage is that it prevents the pump from being disassembled out of curiosity. At the same time, maintenance such as the replacement of the impeller must be carried out by SEI, or by someone trained by them. When compared with other conventional types of pumping systems which can often be repaired by a village fundi, the Sun Pump is at something of a disadvantage. This disadvantage is mostly offset by the fact that maintenance demands are very low.

In some of the pumps installed in Kenya, a few problems have been encountered with the electrical systems. The modules are electrically interconnected by cables which are joined in junction boxes on the back of each panel. These boxes have occasionally loosened from their supports and would be something of a hazard if tampered with. The main electrical cable is quite heavy, and is connected to the pumping unit with standard electrical connections. When the pump has to be removed from a shallow well, it can be lifted by a lifting cable attached to it for that purpose. Because of the larger size of the electrical cable, there is a tendency to lift the pump with it, instead of with the lifting cable. This invariably loosens some of the electrical connections to the pumping units. None of these problems are especially serious, as they can be fixed by anyone with even a basic knowledge of electronics. However, they could be quite simply attended to by some very basic design changes.

The SEI 300M was developed after field experience had been gained with its predecessor, the SEI 250M. The SEI 250M was powered by 7 PV panels instead of with 8. Efficiency improvements in the SEI 300M pumpset and declining PV costs have allowed for the production of an improved pumping system at a lower cost. Most of SEI's pumps in Kenya are of the 250M variety, but the recent introduction of the 300M in 1982 indicates that the technology is an evolving one, subject to refinements in engineering as more field experience is gained.

2. A.C.-Powered Photovoltaic Pumps : the Grundfos SP4-8/35-5

Although the majority of the solar pumps which have been installed in Kenya are of the D.C. centrifugal type, there are a number of A.C.-powered vertical turbine solar pumps which have been installed as well. The number of these pumps, as well as their performance characteristics and origin of manufacture are uncertain, primarily because most of them have been imported directly by development agencies under "commodity assistance" programs or by aid organizations that have circumvented the usual routine of importation through local distributors. In some cases, these pumps have been purchased sight-unseen by procurement officers who have been ignorant of the fact that solar pumps especially must be chosen after having considered site conditions such as insolation and total dynamic head. It would be somewhat like randomly buying 6 pairs of shoes of different sizes on the off-chance that one pair might fit. Based on the information we have been able to gather, there are around 8 of these pumps in Kenya, manufactured by ARCO Solar, Grundfos, and Genau, and powered primarily by ARCO Solar and Solarex photovoltaic panels.

For the sake of comparison, it would be useful to include an analysis of an A.C.-powered photovoltaic pumping system in this study. Solarex and Grundfos are both locally represented (by Advanced Communications and by Davis and Shirtliff respectively) but have sold only a few matched systems in East Africa. It is very likely that, since the publication of the Halcrow report, which reviewed both technologies, both parent companies will be interested in attempting to increase their share of a somewhat limited market in developing countries.

Grundfos solar pumps have been widely promoted by Solarex, which manufactures semicrystalline photovoltaic cells at a unique "Solar Breeder" facility in Rockville, MD, USA.(34) Grundfos manufactures a variety of solar and conventional pumping technologies and has never specifically promoted the sale of their solar pumps matched with any particular brand of photovoltaics. SEI's marketting strategy of selling their Sun Pump as a packaged system that comes complete with ARCO Solar panels is probably more pragmatic than Grundfos'. By selling a packaged and fully-matched system, the potential investor has fewer decisions to make about the product that may be purchased. In Kenya, this marketting strategy has been wise, as the choice of photovoltaics and the appropriate mounting equipment that is available on the market may not be especially clear. The potential investor is interested in the cost and viability of the pumping *system*, and is less interested in the performance characteristics of the power supply by itself.(35) At the same time, SEI could probably increase its profit margins by relying on an alternative and less expensive supplier of photovoltaic cells. During the early days of the industry, ARCO Solar was the recognized leader in terms of the quality of their product. Now, however, virtually all manufacturers of photovoltaic cells produce modules which meet the same reliability and performance specifications established by the United States Department of Energy.

The marketting strategies of both ARCO Solar and Solarex reflect precisely the fact that these companies are primarily manufacturers of photovoltaic cells, and not of solar pumps. They see solar pumping as a means of selling more photovoltaic modules. For instance, while the local ARCO Solar distributor markets SEI pumping units, it has also marketted ARCO Solar, Grundfos, and Tri-Solar pumps. Although it could be argued that each of these companies manufacture pumps which are suitable for different pumping requirements, this is not always the case. For instance, locally marketted Tri-Solar centrifugal suction pumps which were recently installed in Somalia are very similar to, but less efficient (and thus require a greater number of panels to pump the same amount of water from the same depth) than the SEI pump.

In any case, SEI and Grundfos manufacture pumps which, in terms of their performance characteristics, are basically non-competing technologies. All of Grundfos' solar pumps are vertical turbine pumps which are only appropriate for drawing water from deeper than five meters. There would be some overlap with SEI in the 5 to 7 meter range, but even here, SEI has an advantage in that it produces a more efficient pumping system. Because Solarex has widely promoted Grundfos pumps, in this analysis, we will assess a Grundfos pump matched with Solarex photovoltaic panels. Solarex's experience with water pumping in developing countries has included the installation of several facilities in Egypt (a 21.6 kW system) and in West Africa. Recently, Solarex prepared a proposal to supply pumps for a U.S.AID-sponsored solar pumping project in Mali. The analysis here is taken from information provided in that proposal regarding the installation of a Grundfos SP4-8/35-5 solar pump in the village of Bema.(36)

The Grundfos SP4-3/35-5 is powered by 35 Solarex photovoltaic panels which produce a peak power output of 1400 watts at 122.5 volts. The photovoltaic panels themselves are composed of 40 square semicrystalline cells connected in series and protected and mounted much like ARCO Solar cells. They have roughly the same conversion efficiency of around 12 percent, and meet or exceed the same performance specifications established by the U.S. Department of Energy. The panels are connected in series in 5 sub-arrays with 7 modules in each sub-array. The panels are expected to have a useful life of around 20 years, and Solarex provides a 5-year warranty identical to the ARCO Solar warranty. The sub-arrays are designed to be permanently mounted at a fixed angle (equal to the local latitude). This feature reduces the amount of utilizable solar radiation somewhat, especially at low latitudes, because the tilt of the panels cannot be easily changed to take maximum advantage of the sun's position at different times of the day. The total module surface covers an area of around 16.5 square meters. Array power is controlled either manually or by an automatic shutoff switch which is triggered when the water level gets too low. The D.C. current is converted to 3-phase A.C. by an inverter with a 95 percent conversion efficiency. Output varies in frequency from 6 to 60 Hz.

The pumping unit is an eight-stage vertical turbine pump constructed out of stainless steel. It is cylindrical in shape and is a little over 2 feet in length. It can be suspended in a borehole by a cable, but the mouth of the borehole must be at least 4 inches in diameter for the pump to clear it properly. The turbine rotors must be submerged for the pump to effectively operate. Water is discharged from a 2 inch plastic pipe. Grundfos estimates the life of the pump to be around 20 years, but in this analysis, we have chosen to use a more conservative estimate of 10 years. This is primarily because the efficiency of these pumps is dependent on the close fitting of the impeller blades against the pump housing; most of the operating parts are inaccessible and difficult to inspect, and low efficiencies are common in this type of pump after a period of hard use. Maintenance may be required to regularly clean the intake screen of debris. Vertical turbine pumps are designed to lift water from moderate depths, although specially designed pumps can lift water from as deep as 350 meters. The Grundfos SP4-8/35-5 has a design head of 22 meters, and has an operating range that enables it to lift water from a depth of between 15 and 35 meters. (Other Grundfos solar pumps have design heads of 6.5, 8, 14, 50, and 100 meters.) The performance characteristics of the Grundfos SP4-8/35-5 are summarized in Figure 10 of the Technical Appendix. At a head of 25 meters, and with an insolation of 7 kWh/m^2 day, the pump will lift around 47 m^3 of water. Under the same conditions of insolation, the pump will lift around 59 m^3 at a head of 15 meters. It is unclear from the manufacturer's information whether or not the pumping system is warranteed, but it very likely carries a standard 1-year warranty from defects in materials or workmanship

The efficiency of the total pumping system, pumping at a head of 25 meters, is just half that of the SEI 300M pumping at a head of 5 meters. Assuming an insolation of 6 kW/m^2 (on a day with 8 hours of sunshine), output is 5 m^3 per hour, or about 1.4 liters per second. This represents an effective delivered power output of 340.6 watts. With an interceptor area of 16.5 square meters, total incoming power is 98.8 kW. This gives a total system conversion efficiency of 0.34 percent. Such low conversion efficiencies make the pumping of water with this system extremely expensive.

Although not clearly a technical issue, a recurrent problem with various solar pumping installations in Kenya has been that of security from theft and vandalism. An accurately thrown stone can easily disable a pumping system by breaking one of the solar panels. Where the solar panels are left unprotected and in the open, and where the pump is used without supervision, vandalism can be a problem. In Mandera District, a pump purchased by the National Christian Council of Kenya (NCCK) worked quite well as long as several expatriate mission workers saw to it that it was adequately protected and maintained. After their departure, one of the panels was broken, but has since been repaired. Subsequent vandalism has made the system non-functioning, and a substantial investment has been made useless. In at least 2 other cases, entire units were stolen outright, but were recovered after the suspicious appearance of a "Local Distributor for ARCO Solar Panels" in the area. While one of the advantages of the SEI 300M is its portability, its susceptibility to theft is something of a disadvantage. The permanent mountings of the Grundfos system make it less vulnerable to outright theft, but vandalism can still be a problem. Consideration should perhaps be given to the development of a protective screen for photovoltaic panels which would deflect rocks while not seriously reducing the system's efficiency. Alternatively, a fence could be constructed to secure the pumping unit.

3. Summary

The photovoltaic-powered water pumps which are commercially available in Kenya generally operate at very low overall system conversion efficiencies, but are viable and reasonably reliable technologies for pumping water from varying depths. The SEI 300M has a number of technical advantages over other pumps because it is designed for low-head applications, easily portable, simple to operate, relatively maintenance-free, and is technically straightforward. Its technical disadvantages include that its portability makes it subject to theft, it is unsuitable for deeper applications, and that specialized maintenance, though seldom required, may be difficult to obtain. Other solar pumping technologies have the technical advantages of being able to pump from deeper heads and of being fairly reliable systems as well. Their technical disadvantages include that they operate at very low system efficiencies, that they require a large number of permanently mounted PV modules, and that, like the SEI pumps, specialized maintenance, though seldom required, may be difficult to obtain.

B. Wind-Powered Water Pumping Technologies

Unlike solar pumps, windmills have been around for thousands of years. There is evidence that the Egyptians used windmills as early as 3600 B.C. for water pumping and for grinding grain. The early Persians ground grain with vertical axis machines, and Europeans imported the technology from the East and probably introduced the first horizontal axis machines to Europe in the twelfth century. In the United States. windmills were popularly used in the Midwest for pumping water during the early 1900s.(37)

Windmills were first introduced to Kenya by European settlers around the turn of the century. These were mostly imported machines, primarily Dempsters, Climaxes, and Southern Crosses. It has been estimated that by the early 1960s, as many as 100 windmills had been imported into Kenya, but that perhaps a third of them are still operating.(38) The current importation of windmills has been discouraged because of restrictive import duties and because spares and proper maintenance are difficult to come by. Despite this last point, a number of aid agencies have continued to finance the importation of foreign-made machines, primarily Dempsters, Aeromotors, and Bowjohns. There is simply not the technical know-how available to properly install and maintain these machines, and their future importation should be greatly discouraged.

There are several types of windmills which are manufactured and are commercially available in Kenya. The most common type uses the power of the wind to turn a horizontally rotating crankshaft. A section of the shaft is offset from the horizontal axis, and is connected to a vertical shaft in such a way that the rotational energy of the crankshaft is converted into a vertical stroke. The vertical stroke of the machine is commonly used to operate a reciprocating pump which rests in the well or borehole. This characteristic requires that the windmill is constructed directly over the borehole. The rotor and transmission on most machines are designed as a unit which can freely turn in the wind, to take maximal advantage of changing wind directions. Where the wind blows in the same direction most of the time, a number of machines have been constructed which use a fixed-head design. Variations on this basic design have been constructed to operate posho mills or to turn electricity generators.

Earlier reports have discussed the wide variety of wind energy activities in Kenya. Perhaps the most thorough of these was by van Lierop and van Veldhuizen, referred to earlier.(39) They analyzed 7 major windmill programs and 10 minor programs and concluded that only a few projects held good potential for the long term. Most of the efforts they reviewed have been discontinued, with a few important exceptions. While van Lierop and van Veldhuizen's review was fairly extensive, we have chosen instead to focus on 3 specific manufacturing initiatives : Bobs Harries Engineering, Ltd. (of Thika), Kenya Industrial Estates (based in Nairobi), and the non-commercial windmill construction efforts at the Redd Barna-Homa Hills Centre in Nyanza Province.

These activities are representative of 3 different approaches toward technology-transfer aimed at bringing about the industrial production of new technologies in a developing economy. Bobs Harries Engineering, Ltd. is an example of a successful North-South linkage between a private sector entrepreneur and an appropriate technology engineering firm that together developed a commercially-viable windmill technology. Kenya Industrial Estates is a public sector organization which attempted to promote the private sector manufacture of windmills by providing technical and financial resources. Lastly, the Homa Hills Centre is a multi-sectoral rural development effort which has developed a viable windmill technology as part of its vocational training program. We have excluded a number of other efforts for the sake of brevity (e.g. the windmill efforts at the University of Nairobi and the commercial efforts of Pwani Fabricators of Mombassa), but these projects should not be discounted as a result.

1. Bobs Harries Engineering, Ltd. : The Kijito Windmill

When one visits the Bobs Harries Engineering, Ltd. (BHEL) workshops on the Karamaini Estate outside of Thika, one becomes very aware of the levels of skill, entrepreneurial talent, and capital that are required to undertake the commercial manufacture of a new technology, particularly in a developing economy where the markets for the new technology may be obscure or poorly defined. BHEL is a case study in technology transfer that involved their adaptation of a windmill design that had been designed by a "Northern" engineering firm for manufacture and use in Kenya. Among commercial producers of renewable energy technologies in developing economies, BHEL is perhaps the best known, both because of its own record, and in part because of its close association with the Intermediate Technology Development Group (ITDG) -- the British-based organization which specializes in adapting tools, machines, and methods of production to the needs of developing countries and that was founded by the late E.F.Schumacher.(40)

The Harries family has been a pioneering one in every sense since they arrived in Thika in 1904. Currently, they farm a large coffee estate, but also produce macadamia nuts (which they introduced into Kenya), lychees, and a variety of horticultural products. The farm workshop was originally used to repair farm equipment and was also used to assemble and market diesel pumpsets. With rises in petroleum prices in the 1970s, the Managing Director of the farm, Mr.Mike Harries, saw the development of a viable windmill technology in Kenya as an alternative to conventional pumping technologies, especially in view of the fact that windmills were not particularly new to Kenya. He investigated the potential for windmill manufacture by first buying some abandoned imported machines to determine if they could be reconditioned or duplicated more cheaply than it would cost to import a new machine.

At the same time, ITDG was exploring the possibility of supporting the development of windmill technologies for water pumping in developing countries. ITDG's early involvement with windmills developed out of request in 1975 for technical assistance to evaluate the performance of, and to suggest improvements in 19 "Cretan Sail" low-technology windmills that had been constructed by missionaries on the banks of the Omo River in Southern Ethiopia.(41) These windmills were being used for irrigating small plots of land, and were relatively low-powered devices, drawing water from a head of 10 or 15 meters. They were constructed using basic metalworking tools : an electric arc welder, a wood lathe, an electric drill, some handtools, and a plumber's pipe-thread cutters. One of the conclusions from ITDG's experience with this activity was that a more sophisticated technology would be more cost-effective than these low-technology cloth sail machines because they required constant supervision so that sails could be added or removed as the windspeed changed. The development of a more sophisticated "intermediate" technology would require a better equipped workshop; but low cost, ease of manufacture, and low maintenance demands would still be essential prerequisites for the development of the windmill they had in mind.

ITDG began the development and testing of a prototype they thought would meet these prerequisites. With funding provided by the UK-based charity Christian Aid, they began a program to disseminate the technology, first to see if local manufacture in developing countries was possible, and then to field-test locally-manufactured windmills. Shortly thereafter, Mike Harries approached ITDG about possible collaboration with BHEL, and in 1977, along with 5 other groups in developing countries, BHEL was given the plans for ITDG's "intermediate technology" windmill.

In early discussions with ITDG, it was evident that if this windmill were to be successfully introduced to the Kenyan market, it would have to be able to compete in the same market for high-technology imported machines which were capable of high-head and low-volume operation. This requirement made what was originally anticipated to be a relatively simple exercise in technology dissemination much more complex : the machine had to be capable of handling heavy loads; it had to be less expensive than imported machines, yet just as durable; BHEL would have to provide rapid and reliable after-sales service and maintenance; and because of this last requirement, maintenance demands would have to be kept low. In the end, it was decided that ITDG's "intermediate technology" approach would have to be abandoned for the time being, and that if high-quality low-cost windmills were to be made available for smallholders in the future, the market for high technology and heavy-duty machines would have to be penetrated first.

Having made that decision, BHEL embarked on the construction of their first prototype machine, which was completed in January of 1979. An intensive testing program followed, and numerous modifications were made to the original prototype before it was introduced as the "Kijito" windmill at the Kenya Industrial Trade Fair in April of 1979.(42) The first commercial model (and second prototype) with a 24-foot diameter rotor, was purchased and installed in June of 1979 on Ol Pejeta Ranch in Nanyuki to pump water for livestock from a 100-meter borehole. Despite the fact that the machine's transmission failed after only 3 days of operation, BHEL persisted and completely redesigned the transmission by incorporating different bearings; a strengthened chassis and rocker tube; and a new rotor hub construction.

Because of the expense involved, it became clear that if BHEL was going to remain in the windmill business, it would not be able to finance the redesign of its product without selling windmills in the process, nor would it be able to finance pilot projects or demonstrations.(43) In this last respect, private windmill purchases have acted as project demonstrations, with BHEL guaranteeing maintenance in case of malfunctions. Although the early failures of the Kijito gave the windmills something of a bad name, BHEL's marketting decision to completely assume the consumer's risk in these early stages of technical development helped, at some expense, to develop its reputation for being able to provide solid field support and maintenance. Many of the older machines have since been refitted with improved transmissions. The essential reduction in the consumer's perception of risk has helped to greatly strengthen BHEL's market position.

ITDG has continued to provide inputs into BHEL's efforts. They provided assistance to prepare an economic study of Kijito windmills and of ITDG's collaboration with BHEL for the 1981 United Nations Conference on New and Renewable Sources of Energy.(44) An accountant hired by Intermediate Technology Industrial Services (ITIS), an ITDG affiliate, prepared a financial report of the company in order for it to qualify for a much needed bank loan in 1981. ITIS also carried out a market study of Kijito windmills the following year, and supported several monitoring efforts to evaluate their performance. With assistance from the British Overseas Development Authority (ODA), ITDG hired a bearings expert and a mechanical engineer to assist in the redesign of the transmission and has sponsored the full-time services of an engineer for 2 years to assist in the further development of the Kijito line of windmills.

Because of Kenya's often low windspeeds, and because of the need for sufficient water pumping power, the earliest Kijitos used a large 24-foot diameter rotor. The stresses on these machines were substantial, and a great deal of effort was spent in trying to redesign the transmission and supporting superstructure so that it would be able to handle the stresses. Finally, however, it was decided to stop production of the 24-foot Kijito in 1982 and to continue producing smaller machines while improving upon the design of the large machine. BHEL is very near the point of being able to confidently begin production of the 24-foot model again using the improved design. Currently, it is marketting its regular models with 16 and 20-foot diameter rotors, as well as two smaller versions with 8 and 12-foot diameter rotors. These smaller models were recently introduced as BHEL's "Wananchi" models, and have been designed with the requirements and the budget of the smallholder in mind. Although technically they resemble the larger models, their smaller size reduces the need for them to be as heavy-duty. Consequently, they are much cheaper, yet are reportedly as reliable. The Wananchi models come closest to meeting the criteria established by ITDG during the earlier period of its collaboration with BHEL when it was hoping to develop a low-lift high-volume windmill as durable as a commercially available one, but cheap enough and simple enough to be sold and manufactured in developing countries. By gaining experience with its larger windmills, and "building down," BHEL seems to have successfully made the transition from being a manufacturer of a high-technology windmill to being a manufacturer of mixed high and intermediate technology machines.

A number of technical characteristics and design modifications of the BHEL machines are worth mentioning. See Figure 15. :

-- The machines are usually mounted on a standard 3-legged, 10 meter high tower which, during installation, is hinged on 2 legs to a concrete base. This allows the machine to be assembled while the tower is resting on its side. When assembly is complete, the machine can be winched into an upright position. This also makes major repairs somewhat simpler to perform, if they become necessary. Most of the towers are made of tubular steel, but in coastal areas where corrosion may be a problem, they are made of braced angle iron and are galvanized.

-- Although all the steel which is used in the machines has been imported, the bearings are the only components of the windmill which are actually manufactured outside of Kenya. BHEL manufactures pump cylinders for low-head (up to 10 meter) applications, but imported pumps are used for deeper boreholes.

-- The rotor blades were originally made of fiberglass, but costs have been cut down by making them out of steel. Blades can be added or removed, depending on power requirements and on the wind regime.

-- BHEL has been doing some experimental work with remote pumping windmills where hydraulic pressure generated by the windmill is used to pump water from a remote well. This technology can be used where winds are high, for instance, on the top of a hill, and where water must be pumped from a well at the bottom of the hill. Remote pumping systems have been installed at two sites, but BHEL does not anticipate that the demand for this type of technology will be very great.

-- The overall design is continually being improved upon. Parts of the transmission, for instance, which were originally constructed of arc-welded steel tubes have been replaced with gas-cut steel plates. Bearing housings have also been greatly simplified. The transmission has been made adjustable so that it can operate with an 8, 10, or 12-inch stroke. In a few cases where the windspeeds have been very low, the water pumping load has been counterbalanced by adding weights to the rocker arm of the transmission in order to increase the pumping efficiency. Although this is not a standard feature of the design, BHEL has accumulated enough experience to be able to make the modification where it is necessary.

In short, the willingness to experiment and make changes to its design has meant that BHEL has been able to continue to improve and to make technical innovations to their windmills.

Regular maintenance requirements are low. The bearings need to be greased once a year. (BHEL suggests twice a year to their customers, in case they might forget.) Especially in coastal areas, the machine should be painted every couple of years. In a number of cases, BHEL has provided training so that the machines could be properly maintained in remote locations. The Norwegian aid agency, NORAD, financed the purchase of a Kijito for installation on Rusinga Island on Lake Victoria. After recurrent maintenance and operational problems, two people from Rusinga were brought to Thika for training, and they now see to it that the machine remains operational. Future training will be provided for 8 people from Lamu and from the Mtwapa Settlement Scheme where the German aid agency, the GTZ, has installed 4 machines. While the availability of training is obviously dependent on access to financial resources, BHEL has demonstrated that the design and the technology of its windmills are easily understood and could be incorporated into the rural *fundi*'s wealth of technical knowledge.

Depending on site-specific conditions such as the wind regime, the depth of the water table, and local water requirements, the pumping capacity of the Kijito windmill is determined by matching the required power output with the size of the rotor. At a head of 15 meters, and with an average windspeed of 3.5 meters per second (not uncommon in Kenya), the 8 and 12-foot models will pump around 15 m^3 and 40 m^3 of water per day, respectively. At a head of 30 meters, and with the same windspeed conditions, the 16 and 20-foot models will pump around 65 m^3 and 100 m^3 of water per day, respectively. At a head of 40 meters, and under the same conditions of windspeed, the 24-foot machine will pump around 145 m^3 per day. The performance characteristics of BHEL's windmills are shown in Figure 16. This chart should only be used to arrive at a very rough approximation of water output.(45) As Gingold has noted,(46) because the overall efficiency of a windmill varies with windspeed, estimates of a windmill's performance are likely to be optimistic, "and at best, inaccurate." He goes on to suggest that predictions of a windmill's output are probably correct to within 30 percent.

It would be useful to compare the output of the Kijito windmills with the output of the photovoltaic-powered pumps we have already discussed. If we reduce the pumping head of the 8 and 12-foot models to 5 meters, to compare with the output of an SEI 300M solar pump, they will pump around 42 m^3 and 100 m^3 of water per day, respectively, at an average windspeed of 3.5 meters per second. At this head, an SEI 300M will pump around 58 m^3 of water per day, with an insolation of 6 kWh/m^2 day. If we reduce the pumping head ot the 16 and 20-foot machines to 25 meters in order to compare their output with the output of a Grundfos SP4-8/35-5 solar pump, we find that under the same conditions of windspeed, they will pump around 76 m^3 and 137 m^3 of water per day. A Grundfos SP4-8/35-5 will pump around 40 m^3 of water per day at a head of 25 meters, and with an insolation of 6 kWh/m^2 day. It would perhaps be unwise to draw any conclusions from this comparison primarily because of variability in the wind regime, in the insolation, in end-use demands, and in the availability of capital.

BHEL anticipates that the markets for its Wananchi windmills are potentially very large, but the problems involved with penetrating this market are completely different from the problems involved with introducing the earlier Kijito. The costs of the earlier machines put them out of the reach of the rural smallholder; the largest group of customers were cattle ranchers, aid agencies, and charitable organizations. Certainly, this group is less risk averse than the rural smallholder, and is familiar with technical innovations like windmills. It could safely be said that anyone who was seriously interested in buying a windmill in Kenya would know about BHEL, but this group is only a small fraction of the potential market. Targetting the Wananchi models for introduction on a large-scale, beyond this first group of customers, will take a major effort -- through advertising, extension, education, and demonstration projects. It is unlikely that BHEL will be able to develop this market on its own, and the fact that the markets for larger machines are potentially more lucrative would be a major argument against a decision by BHEL to commit its financial resources to doing so. Other problems associated with the introduction of small-scale irrigation technologies are discussed in a subsequent section of this paper.

BHEL is a very unique example of a collaboration between a "Northern" research and engineering group and a developing country entrepreneur. Its management has made a number of very sound and timely marketting decisions and has made innovative changes in the machine's design to lower production costs and to increase pumping efficiency. Financially, its position is somewhat more secure than it was a few years ago, and the number of windmills sold has grown at an annual rate of around 20 percent since 1980. Since 1979, BHEL has sold and installed 73 windmills, 15 of which were exported. These machines and their locations are listed in Table 8.

2. Kenya Industrial Estates : the 12PU500 Windmill

Kenya Industrial Estates (KIE) is a parastatal organization that was established to promote industrial development in Kenya by providing entrepreneurs with the financial and technical resources necessary to start small and medium-sized manufacturing enterprises. Its windmill activities date back to late 1978 when KIE first involved itself in a windmill project which had been initiated in 1976 by the United Nations Industrial Development Organization (UNIDO) with UNDP funding. The earlier effort was in large part inspired by a windmill project that was being carried out by a Catholic missionary, Father Tielen, in Mbita in Nyanza Province. The UNIDO project had the full support of the Provincial administration in Kisumu, and early and very preliminary surveys of the lake region had indicated that the wind potential was very good.(47) Subsequent and more extensive efforts to evaluate the existing wind data confirmed these earlier conclusions,(48) and a project was begun to explore the possibilities of locally manufacturing windmills. Four prototypes (called the SK75-1, 75-2, 75-3, and 75-4) were developed by 3 UNIDO experts, a Dutch volunteer, and a UN Volunteer. For a number of reasons, none of them terribly clear, the prototypes were considered unsuitable for local production and were abandoned. (Perhaps not surprisingly, work on new prototypes was usually initiated whenever a new expert or volunteer arrived on the scene. There was very little continuity in the design process, and the project suffered greatly from it.)(49)

Production work initially began in various workshops, but was shifted to the KIE Technical Services Center in Kisumu when KIE first became involved with the project in December of 1978. Six months later, a final UNIDO expert arrived to work on the project, and he initiated production work on the 12PU500 windmill. This machine was among the first wind technologies that had been designed specifically as a low-cost machine that was intended to be adopted for production in developing countries. The 12PU500 had been designed in the Netherlands by the Working Group on Development Technology (WOT) of Twente University. It had been introduced with some success in the Ghazipur region of Uttar Pradesh in India, and was being produced there at a cost of around KSh 19,000 each (at 1980 exchange rates).(50)

A crucial mistake at this early stage was the assumption that the 12PU500 was a mature and fully-tested technology. It was not. In fact, only 8 machines had been installed in Ghazipur when the 12PU500 was adopted by the KIE for production. In many ways, the history of subsequent mechanical and production problems with the 12PU500 in Kenya closely parallels the Ghazipur experience. Despite the fact that the machine was unproven, the design was given to one of KIE's entrepreneurs, Plough and Allied Equipment, Ltd. of Kisumu, for production. The first 12PU500 was manufactured by Plough and Allied Equipment in December of 1979, and was installed on the grounds of the firm as a working prototype. Interest in the Provincial administration in windmill irrigation was, at the time, high. Without any additional testing, Plough and Allied Equipment manufactured 5 more machines which were to be funded by the Provincial administration's Rural Development Fund. They were to be installed at sites that were to be selected and surveyed by the Provincial Irrigation Unit (PIU).

At this stage, management and financial problems were encountered by the KIE in its dealings with Plough and Allied Equipment. Because KIE's mandate is to stimulate small to medium-scale industrial development, it gives priority assistance to new manufacturers. Although the windmill design could have been given to an established workshop in Kisumu, instead it was given to Plough and Allied Equipment which was a new company with very little experience in small business management or in product development. The original estimate that Plough and Allied Equipment could build and install windmills for the PIU for KSh 16,000 each was probably a gross underestimate, especially considering that similar machines were being constructed in Ghazipur, where unit labor costs are much lower than in Kenya, for the equivalent of KSh 19,000 each. Perhaps inevitably, Plough and Allied Equipment suffered financial losses at a very early stage, and at the end of 1980, after only a year of collaboration, KIE withdrew its support from the company. Production was once again shifted to the KIE Technical Services Center in Kisumu, and Plough and Allied Equipment's windmill technical staff was taken on there as well.

Between 1981 and the end of 1982, another 12 machines were constructed at the KIE Technical Services Center. Of all the machines that had been constructed, only 7 were eventually installed, all in Nyanza Province. The record of these machines has been difficult to track down, but it is believed that of the 7 that were installed, only 1 is still operating at its original site, and another 2 have been refitted and are being operated as part of a monitoring program. The first machine, installed at Dunga Point with the collaboration of the Ministry of Works, was to provide water for irrigation and for a nearby village. The water supply system was of an amazingly and badly over-engineered design. Water was pumped through over 450 meters of elevated pipes which buckled because of thermal expansion. After repeated repairs, the entire system was finally removed by KIE, ostensibly because the community began receiving water through water mains which were installed by the municipality of Kisumu. A second machine was installed to provide water for a commercial fish farming operation in Kabonaya. It has since gone out of business and the machine has been removed. A third machine was installed at Aguko by the PIU to provide water for a horticultural scheme. The project seems to have been badly managed and "artificially organized" as one observer noted. The windmill is lying idle and may be moved to another location. A fourth machine was installed in Kamsar by the Lake Basin Development Authority (LBDA) for an irrigation scheme which never got off the ground. A fifth machine was installed as part of a women's project in Rongo Nyagowa for small-scale irrigation. There are reports that this machine may be operational some of the time, but that it has been supplemented by a diesel pumpset because the small-scale irrigation scheme apparently has been expanded. It should be pointed out that in most of these cases, the problems were not clearly technical in nature, but that the projects have suffered because of bad planning and from the lack of an adequate evaluation of the need for pumped water.

Some time after the German Special Energy Program (SEP) became involved with the project in late 1981, production of windmills was brought to a halt. The decision to do so was especially sound, as there had been no monitoring of the machines, nor had there been any comprehensive attempt to redesign them so they would be more appropriate for Kenyan conditions. Many of the technical problems encountered with the 12PU500 machines that had been installed in Ghazipur were also discovered in the KIE machines. The key difference between the two rural environments, however, has been that strong technical support is easily available in Ghazipur, but is not in Nyanza. KIE ultimately reached the same conclusion as the windmill designers at BHEL : if a windmill is to remain functional, it must be designed so that it will be virtually maintenance-free.

A redesign effort was begun by KIE through the SEP in early 1983 and resulted in the development of a machine that meets this essential prerequisite. In September of 1983, 2 of these windmills were installed that incorporated structural improvements to the windmill itself and to the pumping unit (which had been very prone to losses in efficiency because of wear caused by high levels of water-borne sediments). One of these machines was installed at Kaloka and lifts water from Lake Victoria at a total dynamic head of around 20 meters as part of a rural water supply project. It has been estimated that the supporting infrastructure -- a 20 m^3 water tank, a sand filtration unit, and a communal water tap -- cost in excess of KSh 70,000, without the windmill. Because the machine has been operating for over a year without any maintenance problems, KIE is confident that now, 6 years after it first became involved with the project and 8 years after the project was initiated, it has developed a technically sound machine which is quite appropriate for Kenyan conditions. The future direction, however, of this component of KIE's Renewable Energy Program is unclear.

KIE has also been involved in a collaboration with an entrepreneur affiliated with Sound Communication, Inc. of Nairobi to develop a commercially viable electricity generating windmill. The technology is fairly straightforward and is appealingly simple. A 3-bladed wind rotor is used to turn a standard lorry generator which produces a 12 volt current for charging batteries. The generator uses commonly available automobile parts, and any mechanic who is familiar with lorry generators would be able to repair it if maintenance were needed. One would think that maintenance demands would be fairly low, simply because lorry generators are very heavy-duty technologies and are made to withstand a tremendous amount of abuse. KIE's involvement has mostly been limited to assisting in the development of an efficient rotor technology. After having experimented with aircraft aluminum, which is not easily or cheaply available, the entrepreneur has mastered the construction of a rotor made out of laminated wood. Several prototypes have been constructed. The markets for these machines in Kenya are very limited, and there is speculation at KIE that the entrepreneur may lose interest in commercial production.

In any case, within the Renewable Energy Program of KIE, wind energy has assumed a very low priority. It is unclear whether or not commercial production of the 12PU500 windmill will ever commence because, as one of the engineers involved with the program commented, "Even if we have the best windmill technology in the world, other non-technical problems would probably be more difficult to surmount." There is a real uncertainty (not shared by BHEL) about the commercial potential of a small windmill in Kenya, and whether or not <u>wananchi</u> are the slightest bit interested in wind-powered water pumping technologies. It seems likely that the production of the 12PU500 will probably be deferred indefinitely and that KIE may focus on simpler water pumping technologies such as handpumps. A proposed collaboration between KIE and CWD Consultancy Services (an affiliate of the Steering Committee for Wind Energy in Developing Countries based in the Netherlands) to develop yet another windmill for Kenya(51) has not been especially encouraged by those in KIE who are familiar with the history of its own involvement in the wind energy area. In the meantime, the Renewable Energy Program of KIE will continue its activities in other areas, such as in the commercial development of solar water heaters and in the production of medium-sized biogas generators.

KIE's wind energy project provides something of a contrast with the BHEL experience. What seems to have been lacking in the KIE effort from the start was a committment to the development of a commercially-viable technology, which is perhaps why it has taken so long for a suitable windmill to be developed. The respective differences between the KIE and BHEL experiences underline the basic differences between public and private sector commercial product development efforts. The public sector's risk in supporting renewable energy technology development is low; there is no market pressure to streamline research and development efforts. Moreover, broadly-based judgements and criteria are used. Public sector officials want to know, for example, whether or not a certain technology is yet "economic." The private sector's risk, on the other hand, is much greater because of the need to get the product on the market. Private sector entities do not necessarily care whether a technology is, by and large "economic." Entrepreneurs are interested in the profitability of specific projects. They do not always make money on renewable energy technologies which are economically viable in the abstract.

Even now, KIE questions whether or not there are markets in Kenya for the 12PU500 windmill, and rightly it should. That critical question however should have been asked 8 years ago. Certainly until the German SEP became involved with the effort, one has the impression that no one had ever asked whether or not windmill manufacture could be a commercially viable activity in Kenya. The initial failure to arrive at an appropriate design, and the later introduction of the 12PU500 under the assumption that it was a mature technology, were clear drawbacks to project development. The early rapid turnover of various expatriate "experts" further hindered the improvement of the available technology. Finally, with the machines which were installed, it seems that no effort was made to determine beforehand if the communities which were supposed to benefit from the introduction of a water pumping technology had any interest in the proposed end-uses : irrigation, fish farming, and a village water supply.

Regardless of these drawbacks, one can conclude that a great deal has been learned from the KIE experience (although at substantial cost) about the complex process of technology transfer. The risks of repeating such an exercise may seem obvious, but it is unclear if development agencies which have a vested self-interest in promoting these kinds of activities will avoid such a repetition. In large part, the responsibility falls on the host government to discourage poorly-conceived and badly-planned exercises in technology transfer where the clear need for such a process may not exist.

3. The Homa Hills Centre : Windmill technology development

The Homa Hills Centre is the focus of a community development project in the Kendu Division of Nyanza Province which is being supported and developed by Redd Barna - Kenya (the Norwegian Save the Children organization). It is situated in a very underdeveloped part of the region where many basic needs of the population have been overlooked by larger development efforts. The Centre was established to promote the goals of "self-reliance, decentralization, and the improvement of social and economic development at the community level."(52) With these aims in mind, several different project focuses have evolved, and have resulted in the construction of an Agricultural Section, a Health Section, a Course Center, and a Rural Technology Section on the grounds of the compound. The Centre functions largely as a demonstration farm, and good efforts have been made to introduce new agricultural technologies which would be appropriate for the social and economic conditions prevalent in the immediate vicinity. Extension activities are seen as a critical part of the Centre's activities and numerous short courses and seminars are offered in relevant areas.

The Rural Technology Section has been responsible for developing locally appropriate technologies for construction in the Section's metalworking and woodworking shops. Around 70 casual laborers are employed by the Section, and they are involved in activities as diverse as agricultural implement repair and maintenance, the construction of donkey carts, and furniture construction. To a large extent, the Section has become self-supporting, as there is considerable local demand for the products and services it can provide. In the area of appropriate technology, the Section has constructed improved _jikos_, biogas generators, solar technologies, and has developed a windmill design for use by smallholders in the vicinity.

The history of the development of this windmill technology provides a useful example of the process of technical innovation outside of the commercial and entrepreneurial framework. From the start, the intention was to develop (like BHEL) an inexpensive "intermediate technology" windmill which could be afforded by the rural smallholder, but that still would be reliable, technically sound, easily repaired, and relatively maintenance free. At the same time, the Rural Technology Section was not operating under the same constraints as BHEL. Most of the capital investment in metalworking tools had already been made in the normal course of starting up the metalworking shop. Although the Section is a not-for-profit operation, the fact that other products were being sold kept windmill technology development from being a considerable financial burden. Finally, one of the most valuable benefits of the windmill effort has been that it has provided the opportunity for the development of local skills through vocational training activities.

The windmills that have been constructed at the Homa Hills Centre have very much been the result of the efforts of a Danish volunteer, Mads Norlov, who has been working in Nyanza for around 5 years. Prior to his employment with Redd Barna, he worked with a Catholic priest, Father Tielen, who runs a village polytechnic in Mbita. Father Tielen sponsored the development of earlier fixed-head windmills and other rural technologies at the village polytechnic, but discontinued the windmill program in 1982 because of a number of social, technical, financial, and manpower constraints. Van Lierop and van Veldhuizen provide the best documentation of the Mbita windmill project.(53) Little other documentation is available. Father Tielen has since moved on to other projects with enthusiasm : the construction of donkey carts, biogas generators, and small engine repair. According to Father Tielen, of the 6 machines constructed at Mbita, only 3 are still operational, and those are on the Church compound.

When Mads Norlov began working at the Homa Hills Centre, he took the technical experience he had gained at Father Tielen's, and bega the construction of a new and more sophisticated machine. The windmills at Mbita, though simple in design and construction, were subject to periodic breakdowns. Without close attention, they quickly became non-functional. Unlike BHEL, which eventually decided to produce a product which could compete with imported machines, Norlov wanted to develop a windmill for low-head high-volume uses along Lake Victoria that was both inexpensive and reliable. He concluded that anyone could build a windmill, but that meeting these two criteria would take special effort. He greatly improved on earlier designs by strengthening the transmission, by changing the fixed-head configuration of the rotor to take advantage of changes in wind direction, and by adapting the tower, like the Kijito, so the machine and tower could be assembled on the ground and then winched into position or lowered for repairs. (It should be noted that there are a number of similarities between the Homa Hills machines and the Kijito. This is in large part due to technical assistance that was voluntarily provided by one of BHEL's project engineers.) The weakest part of Father Tielen's machines at Mbita was the pump. Although it could pump high volumes of water at low heads and was unique in design -- very basically constructed out of a rubber tire that acted as a suction diaphragm -- it required constant maintenance. The Rural Technology Section has since developed a simple two-stage reciprocating pump, constructed out of 4-inch diameter plastic sewer pipe, pistons and foot valves machined in the metal shop, and leather seals formed around the piston perimeter. The pump is well-suited for very low-head applications and benefits greatly from its simple construction.

The Homa Hills machines have 8 and 10-foot diameter rotors mounted on 25-foot high towers. They are designed to be manually furled when windspeeds are too high. The first machine was installed in December of 1982 on a 2-hectare plot. Since then, a total of 7 have been installed, with 2 irrigating a 1.2-hectare plot at the Centre. Norlov estimated the machines cost between KSh 25,000 and 30,000 in materials and labor to construct, but the Centre will sell them to women's groups or to farmer's cooperatives for a subsidized price of KSh 8,000 (which can be paid in installments).

There has been painfully little monitoring of these machines in operation. They operate at very low-heads of not greater than 3 meters. With an average windspeed of 3.5 to 4 meters per second, water output is high, perhaps as much as 100 m^3 per day. As part of the Centre's extension effort, the condition of the windmills is checked fairly often, and maintenance problems can be dealt with on the spot, or parts can be removed and taken back to the shop if it becomes necessary. The close proximity of all the machines, within 30 miles of the Centre, has meant that maintenance can quickly be attended to, and has made it relatively easy for even minor design changes to be incorporated into the operating machines. A number of technical problems have been encountered with both the windmill and the pumping unit. The machine is still not technically mature, and continued design changes will probably be necessary for some time. Although the Centre hopes to install more machines in the future, any major effort should probably be discouraged until their operating record is improved. A comprehensive monitoring effort of this activity would be well worthwhile.

The Centre has encountered similar problems as KIE in targetting the machines for specific end-uses, as only 4 of the 7 machines are being used to their full potential. The fact that the machines must be purchased, although at a subsidized price, has meant that local windmill users are much more interested in seeing their investment pay off than if the windmill had been given to them outright. It should be added that the Homa Hill Centre's extension efforts have also greatly facilitated the introduction of this rural technology by providing a means for coping with problems that have arisen from introducing irrigation technologies : the unfamiliarity of cultivating 4 or 5 crops a year instead of 2; problems associated with marketting; arriving at a means of equitabley distributing earned income among members of women's groups and farmers' cooperatives, etc.

4. Summary

These three windmill technology transfer projects have differed greatly in their conception and in their respective levels of success. BHEL's windmill commercialization efforts are an excellent example of a successful collaboration between a "Northern" appropriate technology-oriented engineering and design organization with a "Southern" private sector concern. The result has been the development of a technically viable rural technology, but only after "building down" from an earlier high-technology design. KIE as a public sector entity attempted to facilitate the process of technology transfer to a Kenyan firm, under the incorrect assumption that the technology was mature and suitable for use in Kenya. The lack of adequate end-use analyses, irregular technical support, and poorly-defined incentives to engage in commercial windmill production greatly hindered the introduction of KIE's windmill. The Homa Hills Centre's windmill project involved the transfer of technologies from two other efforts (BHEL and the Mbita windmill project) to develop rurally appropriate windmills for Nyanza Province, and has greatly benefitted from these earlier experiences. To a certain extent, the lack of an adequate end-use analysis has hampered the introduction of their windmill technology as well, but the ability to provide strong technical support and extension has been a real asset to this non-commercial project.

V. IRRIGATION DEMAND REQUIREMENTS AND SUPPLY OPTIONS

The theoretical demand for water for irrigation is highly variable from site-to-site and is determined by independent variables such as rainfall, levels of evapotranspiration, cropping patterns, and the size of the smallholding. The usual convention is to determine these locationally dependent variables for a given site and for a given landholding of 1 hectare in size, and then to compare the water balance under these conditions with the amount of water that could be provided by a specific pumping technology. The ratio of the amount of water that could be pumped by a specific technology to the amount of water that is required under the stated site-specific conditions is called the command area, and reflects the size of a holding which could be irrigated by a single pumping unit.

It should be understood from the start that these calculations are purely arbitrary -- which is precisely why we have chosen not to dwell on them at length. While physical parameters such as rainfall, the wind regime, levels of insolation, and the depth of the water table can be determined fairly easily, the real variable in this analysis is the cropping pattern that is chosen. The over-riding singularity of all large-scale irrigation schemes is that the farmers do not own the land they till, and that a complex management system has been established to ensure that tenants crop the land according to established specifications. It is unclear if such a management framework would be desirable, feasible, or economically effective for small-scale schemes.

If a farmer had a latitude of choice about his cropping pattern, he would likely decide to grow certain crop combinations based on his own perception of the rural economy, defined by his own capital and labor constraints, rather than on some theoretically arrived at "optimal" cropping pattern. From the farmer's point of view, food crop production would perhaps take priority; but where project profitability is a concern, cash crop production would take priority, especially in project feasibility and planning studies. In this analysis, we have chosen to start from a limited set of assumptions about possible cropping patterns in order to determine the outcome based <u>on those sets of assumptions</u>. Any other conclusions about particular technologies used under any other conditions would have to be arrived at by considering an alternative set of assumptions.

Gross irrigation requirements have been determined for 3 different locations in Kenya in Table 11, and are based on data provided by Gabrowski et al.(54) and by van Lierop and van Veldhuizen.(55) These locations are in Kisumu, at Hola along the lower Tana River, and at a site (an FAO irrigation project) about 50 miles from Lodwar in the northeast. The sites were chosen because information about the wind regime and the insolation is available and because solar and wind-powered water pumping technologies have been considered for use in the area, or are already being used. The monthly wind regime and insolation for each of these locations is given in Table 4. The potential pump output is determined, based on the performance characteristics of each pump, and is included with the calculations of the command areas in Table 12.

VI. FINANCIAL ANALYSIS

It is difficult to arrive at a useful standard for comparing costs of different water pumping technologies. This difficulty is made somewhat more so because we would also like to determine the sensitivity of a technology's cost to other dynamic and costed inputs, for instance, the cost of capital, changes in our assumption of the expected useful life of the technology, changes in the costs of components, and so on. A number of conventions have been suggested, for instance, by Fraenkel(56) and French.(57) Fraenkel points out that the main elements involved in costing an energy converter are :

-- the initial investment costs;

-- the cost of fuel; and

-- the cost of maintenance and repair.

The latter two costs may become inflated over the life of the technology. Fraenkel concludes that a useful method which allows us to compare costs is to calculate annual cost flows related to capital investment, fuel costs, and operation, maintenance and repair costs. After having discounted for future costs at an appropriate discount rate, an annualized charge for total project costs is arrived at by using the equation :

$$C_{aa} = [C_{np}][R(1+R)^n]/[(1+R)^{n-1}]$$

where C_{aa} is the average annual cost, C_{np} is the net present cost, R is the real rate of interest that would be gained if the same amount were invested, and n is the life of the project.

Gingold points out that this method is an imperfect model for comparing different water pumping technologies.(58) Especially in irrigation projects, there is considerable scope for substituting capital costs with recurrent costs. Characteristically, low capital cost technologies and projects often generate high recurrent costs or replacement costs and vice versa. To a large extent, the discount rate that is selected for comparing alternatives will be crucial in determining the optimal mix of capital and recurrent costs. A high discount rate will favor an increased emphasis upon lowering capital costs by increasing recurrent costs. The point is significant, for instance, when comparing fossil fuel and photovoltaic-powered technologies. In the former, fuel costs are recurrent costs; in the latter, they are capital costs. Consequently, fossil fuel costs will be discounted, and photovoltaic costs will not. In order to get around some of these drawbacks to the annuitization methodology, we have chosen to incorporate several sensitivity analyses into our assessment.

If this were to reflect the "real world" economy of the rural smallholder, other assumptions would have to be made about the likelihood that estimates of annualized costs would reflect the farmer's financial costs in having made an investment in a renewable energy technology. Other costs that would result from bringing land under irrigation -- costs of added fertilizer and labor inputs -- would be difficult to assess in this analysis. Even more crucial is the question of whether or not investment capital is available to the rural smallholder. If it is available at a reasonable rate of interest, other constraints may keep the smallholder from accessing it. The smallholder may not have adequate collateral, or if he does have collateral, he may be unwilling to risk losing it. The traditional value which is placed on land ownership in Kenya, for instance, suggests that the smallholder would be hesitant to use his landholding as collateral -- regardless of what the potential returns to his investment might be. Given the limited availability of his own capital and labor resources, risk aversion will very likely characterize most rural smallholder's investment decisions.

If a rural smallholder does have access to investment capital, beyond the question of the availability of collateral, the cost of borrowing money may be prohibitive. Despite a major decline in inflation since 1982, most real rates of interest in Kenya (nominal rates adjusted for inflation) have remained negative, and the effect has been that borrowers have been subsidized at the expense of savers. This fact notwithstanding, commercial bank loans were available in 1983 at a nominal interest rate of 15 percent, which, adjusted for an inflation rate in 1982 of 14.6 percent, gives a real interest rate of 0.4 percent.(59) The actual rate a rural smallholder may pay may be much higher. A real interest rate of 10 percent is commonly used in many financial analyses of agricultural projects, but this rate probably bears little relationship to typical interest rates for agricultural credit. A World Bank study of agricultural credit placed the average real interest rate worldwide at 32 percent.(60) Because of these substantial variations, we will include an analysis of the sensitivity of annualized costs to the cost of capital.

For solar pumps, the question of the "real world" economy of the rural smallholder is probably irrelevant (although less so for windmills). The market for solar pumps among smallholders (if indeed there is one) has never been penetrated, and it seems unlikely that it will be in the foreseeable future. (See Section VII of this paper.) Government, development assistance, and charitable organizations have been the largest group of investors in both windmill and solar water pumping technologies in Kenya, and very likely will remain so. The investment criteria of these agencies is somewhat different than the rural smallholder's. For example, consideration might be given to the impact of an investment in a technology on employment, on distributive effects, and on other social benefits like improved nutrition and health. For many agencies, this economic "bottom line" assumes great importance in the project identification process. Simply put, will the benefits (economic and financial) that would come out of a project investment be greater than the costs of the investment? Economic cost-benefit analyses which evaluate this question are an important input into the project planning process, but are beyond the scope of this paper. Using either economic or financial project identification criteria, the annuitization method would help to allow development planners to arrive at reasonable conclusions about the respective costs of different technologies. Finally, because of the variability in renewable energy resource availability in Kenya, annualized cost estimates provide a normative basis on which to evaluate the costs of pumped water, depending on the insolation or the wind regime.

A. Financial Costs of Solar-Powered Water Pumping Systems

In this analysis, we have chosen to examine the two solar pumping systems already mentioned : the SEI 300M and the Grundfos SP4-8/35-5. We will determine cost estimates, under given assumptions of life expectancy, interest, operation, maintenance, repair and replacement costs, and shipping and installation costs. Because solar pumping systems are entirely imported and because of the volatility of the exchange rate, we have calculated annualized costs in U.S. dollars. Costs in K.Pounds are estimated at an exchange rate of KSh 14.7 per dollar.

Several considerations could be expected to have an impact on the overall cost of a solar pump. Firstly, because the cost of photovoltaic cells account for a significant percentage of a solar pumping system's capital costs, any significant changes in these costs would have a noticeable impact on the cost of the total system. This analysis will include an assessment of the sensitivity of total system costs to changes in the price of photovoltaics. Secondly, photovoltaic panels are expected to have a fairly long life of around 20 years, and if system failure occurs, it will be much more likely to be due to a failure in the pumping unit than in the photovoltaic modules themselves. Some manufacturers argue that their pumps have particularly long life expectancies. The extent to which pump replacement costs will influence total costs is unclear. Consequently, we have carried out an analysis of the sensitivity of total costs to changes in the expected life of the pumping units. Finally, an investment in a solar pump is characterized by high capital costs and low recurrent costs; because of this, we have included an analysis of the sensitivity of annualized costs to changes in the real rate of interest.

In this analysis, we have assumed a project life of 20 years. Our "base case" assumptions for the SEI 300M include that

-- the pump can be expected to have a useful life of 5 years;

-- the photovoltaic modules can be expected to have a useful life of 20 years;

-- the prevailing real interest rate will be 10 percent;

-- operation, maintenance, and repair costs will be equal to 0.5 percent of the pumping system's capital costs per annum; and

-- recurrent costs will not be inflated over time.

Under these assumptions, anticipated annual cost flows are indicated in Table 9. By discounting future costs, we find the total net present cost of the system to be $6924 (K.Pounds 5089), which includes capital costs of $5290 (K.Pounds 3888). At a real rate of interest of 10 percent, average annualized costs are $813 (K.Pounds 598) per annum over the life of the project. If we hold our other assumptions constant and double the rate of interest to 20 percent, average annualized costs increase by 53 percent.

Our "base case" assumptions for the Grundfos SP4-8/35-5 are very similar to our assumptions for the SEI 300M, and include that

-- the pump can be expected to have a useful life of 10 years;

-- the photovoltaic modules can be expected to have a useful life of 20 years;

-- the prevailing real interest rate will be 10 percent;

-- operation, maintenance, and repair costs will be equal to 0.5 percent of the pumping system's capital costs per annum; and

-- recurrent costs will not be inflated over time.

Under these assumptions, anticipated annual cost flows are indicated in Table 9. By discounting future costs, we find the total net present cost of the system to be \$17444 (K.Pounds 12821) which includes capital costs of \$15367 (K.Pounds 11295). At a real rate of interest of 10 percent, average annualized costs are \$2049 (K.Pounds 1506) per annum over the life of the project. If we hold our other assumptions constant and double the rate of interest to 20 percent, average annualized costs increase by 63 percent per annum. See Table 10 and Figure 11.

Excluding the price of the pumping unit itself, photovoltaics and Balance-of-System (BOS) costs for the SEI 300M and the Grundfos SP4-8/35-5 are \$10.73 (K.Pounds 7.89) per peak watt and \$7.18 (K.Pounds 5.28) per peak watt respectively. This substantial difference can, in part, be accounted for by certain economies of scale : the basic hardware needed to support 35 Solarex panels is less, per panel, than is the hardware required to support 8 ARCO Solar panels. It is also likely that because Solarex is selling a large number of panels, it is more willing to reduce its profit margin per panel than ARCO Solar, which is selling only a quarter as many panels per pump. Even so, SEI will reduce the price per pumping system only if 6 or more units are purchased, reducing costs to \$10.07 per peak watt. This leads one to suspect that their profit margins are probably not very substantial, or that ARCO Solar simply sells a more expensive photovoltaic module than Solarex. It should also be kept in mind that SEI is a relatively small company without the access to the financial resources of Grundfos or Solarex. Its overhead costs per unit sold are probably greater than Grundfos or Solarex, both of which can rely on sales of an extensive line of other products to help finance the marketting and distribution networks for their solar pumping systems.

Because the costs of photovoltaic modules are capital costs, any changes in the prices of photovoltaics will cause a linear change in average annualized costs. Because more photovoltaics are used to power the Grundfos system, it can be expected that annualized costs for the Grundfos system will be much more sensitive to changes in the prices of photovoltaics than for the SEI system. If we examine changes in average annualized costs in response to changes in the cost per peak watt, we find average annualized costs (in dollars) can be determined by the equations :

$$C_{aa} = 154C_{pW} + 869 \quad \text{for the Grundfos system, and}$$
$$C_{aa} = 35C_{pW} + 435 \quad \text{for the SEI system,}$$

where C_{aa} is the average annualized cost, and C_{pW} is the cost per peak watt. By comparing the slopes of the two lines, we find that average annualized costs for the Grundfos system are much more sensitive to changes in the costs of photovoltaics than the SEI system. This fact also helps to account for the subtantial differences in the prices of photovoltaics as a percentage of total costs in the respective systems. Because, relatively speaking, total SEI system costs are less sensitive to changes in the prices of photovoltaics, it makes small difference in our annualized cost estimates whether or not ARCO Solar provides PV-modules for \$10 or \$7 per peak watt. By reducing the price of Solarex panels by 50 percent, average annualized costs of the Grundfos system decline by 29 percent. By reducing the price of ARCO Solar panels by 50 percent, average annualized costs of the SEI system decline by 23 percent. If we reduce the price of photovoltaic panels for both systems from their current prices to \$2 per peak watt (which would be a conceivable cost breakthrough in 10 years or so), average annualized costs would decline by 42 percent for the Grundfos system, and by 38 percent for the SEI system. Even under these conditions, the Grundfos system would still be more expensive than the SEI system is now. See Table 10 and Figure 12.

The impact of changing our assumptions concerning the life expectancy of the pumping units is also much what we would expect. If we double the life of the SEI pump from 5 to 10 years, average annualized costs decrease by 15 percent per annum. If we double the life of the Grundfos pump from 10 to 20 years, average annualized costs decrease by 8 percent per annum. Because the cost of the pump as a percentage of total capital costs is higher for the SEI system than for the Grundfos system, doubling the life of the pump could be expected to have a greater impact on the annualized costs of the SEI system. Further, doubling the life of the Grundfos pump means making no replacements over the entire 20 year project life, instead of 1 replacement if the pump lasted for only 10 years. Doubling the life of the SEI pump means making 1 replacement in 20 years, instead of 3 replacements if the pump lasts for only 5 years. So the impact of doubling the life of the SEI pump on total system costs would tend to be greater than doubling the life of the Grundfos pump. Even so, it could hardly be said that altering our assumptions about pump life expectancies has much of an overall impact on annualized costs. See Table 10 and Figures 13 and 14.

In this analysis, we have not included the cost of import duties or sales tax on either system. According to the current schedule of import duties,(61) reciprocating, centrifugal, or vertical turbine pumps can be imported duty-free, but are assessed a 17 percent sales tax. The import duty on photovoltaic panels is 45 percent ad valorem (down from 55 percent in 1983), plus a 17 percent sales tax. These duties and sales taxes would have the effect of increasing the net capital costs of an SEI system by 45 percent, and of a Grundfos system by 50 percent. Two considerations have led us to discount the importance of import duties and sales tax in this analysis. Firstly, if a solar pump can be imported as a unit, with photovoltaic panels packed together with the pump, and clearly identified as agricultural equipment, it could be imported duty-free. Solar pumps, per se, are not classified in the current schedule of import duties, and so would be classified as "agricultural equipment, not elsewhere specified," and would be exempt from duties. SEI has taken advantage of this classification, but it is unclear whether or not Grundfos or Solarex are aware of this provision. The second consideration that led us to exclude import duties and sales tax from this analysis is that development aid and charitable organizations are exempt from paying duties and sales tax on imported equipment. Consequently, until other markets are penetrated, import duties and sales tax will not enter into the financial analysis. Other considerations regarding the taxation of solar panels as an energy-producing technology are discussed in a subsequent section.

Finally, using our evaluation of average annualized costs, and under certain assumptions of insolation and total dynamic head, we can determine the cost per cubic meter of water pumped with the SEI and Grundfos systems. If we assume an insolation of 5.5 kWh/m^2 day, which is roughly the average for Kenya, and consider the performance of the SEI 300M at a 5 meter head, and the performance of the Grundfos SP4-8/35-5 at heads of 15 and 25 meters, we find that costs go up dramatically as the head is increased. Under these conditions, the SEI system will pump around 51 m^3 per day, and the Grundfos system will pump 50 m^3 and 37 m^3 per day at heads of 15 and 25 meters respectively. At an average annualized cost of $813 (K.Pounds 598) for the SEI system and $2049 (K.Pounds 1506) for the Grundfos system, costs of pumped water are $.044/$m^3$ (KSh 0.642) for the SEI system pumping at a head of 5 meters and $.112/$m^3$ (KSh 1.65) and $.152/$m^3$ (KSh 2.23) for the Grundfos system pumping at heads of 15 and 25 meters respectively. In this analysis, the costs per cubic meter of pumped water increase by $.0054 for every meter of head.(62) Because insolation is highly variable from site-to-site, these costs are only indicative for the stated conditions and will also be highly variable.

B. Financial Costs of Windmills for Pumping Water

Most unfortunately, there is not a very broad specturm of information available about the cost of water pumping windmill technologies in Kenya. The KIE machine, the 12PU500, has not been under commercial production since the end of 1982, and even then, it is unclear if the market price of the machine was an accurate reflection of its production costs. Windmill production at the Homa Hills Centre is hardly "commercial" in that windmills are not being manufactured to meet a clear external market. As a result, the Centre is not subject to the same constraints as an on-going commercial manufacturing enterprise. Rather, windmill irrigation has become an integrated part of the Centre's rural development efforts. In a sense, they are their own best customers for the machines they produce. Because of these basic differences between private sector entrepreneurs (like BHEL) and charitable organizations (like the Homa Hills Centre), it would be somewhat short-sighted to evaluate the costs of their respective machines using the same criteria.

Because BHEL is commercially producing its machines for several specific markets, their costs perhaps most accurately reflect the costs of investment, development, and production of these new technologies. Of particular interest are the Wananchi windmills -- the machines with 8 and 12-foot diameter rotors which were designed to be produced cheaply for the smallholder market. The costs of BHEL's larger machines, the 16 and 20-foot models, have been exhaustively reviewed,(63) but it would be useful in this analysis to evaluate them with respect to the smaller machines and to photovoltaic-powered pumps.

Windmills require a large capital cost but have low recurrent costs. Like solar pumps, the sensitivity of average annualized costs to changes in the real rate of interest could be significant. High capital costs would generally not allow a smallholder to invest in a windmill technology unless capital were available at an affordable price. Because of this, we have included an analysis of the impact of changes in the cost of capital on average annualized costs.

A second variable that would affect our cost estimates would be the cost of operation, maintenance, and repair (OMR). Windmill operational costs will be low, compared with conventional pumping technologies which might require the hire of a pumpman to ensure that the pump is properly and regularly fueled. Maintenance and repair costs are generally low, as the machines need to be painted occasionally and to have their bearings greased. Where OMR costs are low, a common convention in financial analyses of water pumping projects is to include them as annual recurrent costs expressed as a percentage of capital investment costs per annum. Depending on the windmill technology, on site conditions, and on conditions of ownership, these costs may range from 1 or 2 percent of capital investment costs per annum, to as high as 8 or 9 percent. For instance, a windmill sited in coastal areas will require more frequent repainting to prevent rust than a windmill which is sited in inland areas. Further, conditions of ownership are often overlooked in financial analyses. A large cattle rancher who invested a great deal of money in an expensive machine is likely to keep his future costs down by providing regular maintenance. A windmill which has been installed in a remote location, perhaps by a charitable organization, may be poorly maintained because no clear local responsibility for the machine has been defined, and subsequent maintenance costs may be higher than the cattle rancher's. To reflect these various site-dependent conditions, we have included an analysis of the sensitivity of annualized costs to changes in OMR costs.(64)

Except for machines which are exported, a sales tax of 17 percent is levied on BHEL's machines. Especially on their larger machines, sales tax can be quite substantial -- over KSh 20,000 on their 20-foot model. In light of the import duties and sales tax already assessed on raw materials, taxes can account for a significant percentage of a windmill's total price. To a certain extent, they are government imposed levies which act as disincentives for private investors to purchase these technologies. Consequently, we have included an analysis of the effect of changing the rate of sales tax on average annualized costs.

For each of BHEL's machines, we have made some common assumptions in our "base case" analysis :

- the windmill can be expected to have a useful life of 20 years;
- the pump will have to be replaced after 10 years;
- annual OMR costs will be equivalent to 3 percent of the machine's capital investment costs (including sales tax but excluding transport and installation) and will not be inflated over time;
- the prevailing real interest rate will be 10 percent;
- other costs (pump rods, piping, etc.) will be determined based on installations of the 8 and 12-foot machines pumping from a head of 5 meters, and installations of the 16 and 20-foot machines pumping from heads of 15 and 25 meters respectively.

Because Kijito windmills are Kenyan technologies which are manufactured primarily for the Kenyan market, we have calculated costs in shillings. (US dollar estimates have been included in the sensitivity analyses in Figures 17, 18, and 19.) Under these assumptions, anticipated annual cost flows are indicated in Table 15 for the 8, 12, 16, and 20-foot BHEL windmills.

An omission in this analysis, which is often included in other analyses, is the cost of water storage tanks. Wind does not always blow when water is needed for irrigation, and a storage tank would provide a means to irrigate when the water is needed most. The difficulty of including the cost of water tanks in this analysis arises in part because the need for a water tank of a particular size will be dependent on the wind regime, the size of the windmill, and on the local demand for water. These conditions are obviously highly variable. Another point to consider is the economy of scale that is involved. The more expensive it is to pump water, the more logical it is to build a tank to store it. At the same time, the smallholder is looking for cheap technologies and the added cost of building a water tank may be enough of a disincentive to prevent him from buying a windmill. It could be argued that if a consumer chooses to invest in a "soft" renewable energy technology, then he must have "soft" expectations. We have used the same argument for solar pumps by not including the cost of expensive backup systems or battery storage devices in our analysis. In any case, we do however point out that often, water tanks are a critical part of rural water supply systems, and their costs should not be overlooked.

The 8 and 12-foot Wananchi windmills are relatively close is price to each other, especially when compared with the 16 and 20-foot machines. In our sensitivity analyses, average annualized costs for these machines responded very similarly to changes in our cost assumptions. Perhaps more importantly, there are significant, but not clearly obvious, economies of scale involved in investing in a 12-foot machine rather than in an 8-foot machine. The 12-foot machine has annualized costs only 11 percent greater than the 8-foot machine, and is still less than half as expensive as the 16-foot machine. Further, the "swept area" of the 12-foot machine is over twice the swept area of the 8-foot machine. Recalling that power output is proportional to the swept area, investing an additional 11 percent in the 12-foot machine doubles the amount of water that could be pumped by an 8-foot machine from the same head. In fact, if we compare the costs per cubic meter of pumped water under identical conditions of windspeed, the 12-foot machine pumps water for less than half the price per cubic meter than the 8-foot machine pumping at the same head. The 8-foot machine pumps water from a head of 5 meters for roughly the same cost per cubic meter as the 20-foot machine pumping at a head of 25 meters. See Table 16. While the wind regime and the level of the water table are critical variables in determining the size of the windmill needed to provide the required water output, in the case of the 8 and 12-foot machines, a small increase in the capital investment could greatly increase potential power output.

The rate of interest at which capital can be obtained has the most significant impact on average annualized costs of the variables we have considered. For all 4 machines, if we double the rate of interest from 10 to 20 percent, average annualized costs increase by around 60 percent. With this degree of sensitivity to interest rates, windmill technologies which may initially appear to be affordable quickly become much less so. If agricultural credit in Kenya were available at the average real rate cited by the World Bank of 32 percent, the returns to windmill irrigated agriculture would have to be particularly high before such an investment could pay off -- virtually eliminating the possibility of smallholder investment in windmill technologies for irrigating food crops. See Table 17 and Figure 17.

The response of average annualized costs to changes in OMR costs is very close to being linear. See Table 17 and Figure 18. Doubling OMR costs from 3 to 6 percent of capital investment costs (including sales tax but excluding costs of installation and transport) increases average annualized costs between 16 and 19 percent. In absolute terms, these changes are relatively small for the 8 and 12-foot machines, increasing average annualized costs by around K.Pounds 70 per annum. For the larger machines, they are much more substantial because of the higher capital costs involved, increasing average annualized costs by K.Pounds 163 and K.Pounds 246 for the 16 and 20-foot machines respectively. If a machine is regularly maintained, there is no reason to think that OMR costs might be much higher than 2 or 3 percent. If however, a machine is not well maintained, the costs of keeping the machine functioning will very likely be much higher after it has been in operation for a number of years. It seems like an obvious point, but the responsibilities for regular maintenance must be clearcut in order to keep these costs down. These responsibilities are perhaps most easily defined when ownership is clearly defined. This may be especially difficult in development projects where the investment costs of the technology have been competely assumed by an external funding organization. Questions of maintenance responsibilities are much more easily clarified when a group or community has initiated the project or has financed the purchase of the technology. It is unclear how this process could be facilitated through the normal channels of development assistance.

Of the variables we have examined so far, average annualized costs are perhaps least affected by changes in the sales tax on windmills. In relative terms, eliminating the sales tax on windmills would reduce average annualized costs by 7 to 10 percent. In absolute terms, average annualized costs would be reduced by about K.Pounds 30 for the smaller machines, and K.Pounds 77 and K.Pounds 120 for the 16 and 20-foot machines respectively. Especially if these costs are borne as capital costs however, they would be an obvious disincentive to the potential investor in a windmill, and there would probably be some latitude for the government to consider eliminating these duties. The question is more fully addressed in a subsequent section of this paper.

Using our evaluation of average annualized costs and under moderate windspeed conditions, we can determine the costs per cubic meter of water pumped with each of the BHEL machines. These costs are given in Table 16. Because the wind regime in Kenya is highly variable, these costs are only indicative for the stated conditions, and will also be highly variable.

C. Financial Costs of Conventional Water Pumping Technologies.

Whether or not an investment in a water pumping technology will pay off will be as much a function of the cost of the technology itself as it will be a function of its impact on income generation in the agricultural sector. A cheaper technology will increase the margin a farmer could hope to earn if the tehnology could provide as much water at a lower cost. In order to evaluate how windmills and solar pumps could increase this margin, it is necessary to compare them with conventional water pumping technologies. From the start, there is no way that diesel, windmill, or solar pumping can possibly compete with electrically-operated irrigation pumps powered by the main grid. Obviously though, the limited extent to which rural areas in Kenya have been electrified is the biggest constraint to the use of the grid for irrigation. This analysis will focus instead on the cost of remote conventionally-fueled pumping technologies to see how they compare with renewable energy technologies.

The choice of conventional pumping technologies available in Kenya are numerous, and include petrol and diesel centrifugal and vertical turbine pumps, or electric pumps powered by remote electric or diesel generators. We have chosen to compare the costs of two diesel pumpsets : a 5HP centrifugal pumpset for pumping from a head of 5 meters; and an 8HP vertical turbine pumpset for pumping from heads of 15 and 25 meters. For both pumpsets, we will assume :

- the diesel engine will require an overhaul after 10 years of operation;
- the pump will have to be replaced after every five years;
- the prevailing interest rate will be 10 percent;
- the pump will operate at an efficiency of 25 percent and the diesel engine will operate at an efficiency of 34 percent ;(65)
- fuel costs will increase by 5 percent per annum; and
- OMR costs will be 25 percent of fuel costs.

Under these assumptions, anticipated annual cost flows, excluding OMR and fuel costs, are indicated in Table 18.

The most signficant variable in this analysis will be the cost of fuel. We have arrived at average annual fuel costs by considering the cost of diesel available in Nairobi (KSh 5.95/liter) and then have carried out a second analysis by increasing these costs by 50 percent, to reflect higher prices for diesel in remoter areas.

Fuel costs and OMR costs are directly proportional to the load under which the pump operates, and so average annual costs will, in the end, be determined by the daily pumping output. We have annualized the costs of the pumpsets and subsequent major repairs (as in Table 18) and then have added average annualized costs for diesel and OMR (also in Table 18), inflated at an annual rate of 5 percent. Under our "base case" assumptions, total average annualized costs in K.Pounds can be determined from the following equations :

$$
\begin{aligned}
C_{aa}[5] &= 3.65Q + 375.7 \\
C_{aa}[15] &= 10.93Q + 477.0 \\
C_{aa}[25] &= 18.20Q + 491.0
\end{aligned}
$$

where $C_{aa}[x]$ is the average annualized cost of a diesel pump operating at a head of x, and Q is the average daily pumping output in cubic meters per day. The y-intercepts are equal to the average annualized costs of the installed pumpsets at the different heads. The relationship between average annualized costs and daily pumping output is shown in Figure 19.

D. Summary of the Costs of Wind, Solar, and Diesel-Powered Water Pumping Technologies

There are really two different sets of conclusions that can be drawn from this analysis. The first group of conclusions has to do with the cost of renewable energy technologies vis-a-vis diesel pumping technologies and reflects the financial conditions which would bias a potential investor for or against a conventional or a renewable energy water pumping technology. The second group of conclusions reflects the results of our financial and sensitivity analyses, and identifies issues which could be addressed by public sector decision making or perhaps by private sector initiatives.

Referring again to Figure 19, we have also indicated the average annualized costs of the solar and windmill pumping technologies covered in this analysis. By including these, the basic difference between renewable energy technologies and conventional technologies becomes clear : regardless of the amount of water that is pumped by a renewable energy technology, average annualized costs will stay the same, hence the horizontal cost lines for wind and solar technologies in Figure 19; but in order to increase the pumping output of a conventional pumping technology, average annualized costs will have to increase to reflect the added costs of fuel and maintenance, hence the upward sloping cost lines for diesel pumping technologies. In order to compare the financial costs of each technology operating at identical heads, there is a "break-even" pumping output, below which it is cheaper to use a diesel pumpset, and above which it may be cheaper to use a renewable energy technology. That break-even point is simply where the horizontal cost line for a renewable energy technology intersects with the upwardly sloping cost line of a conventional pumping technology. For instance, if we look at the upwardly sloping cost line for a diesel pumpset operating at a head of 25 meters, we notice that it intersects with the horizontal cost line for a 20-foot Kijito windmill pumping at a head of 25 meters at a break-even output of 45 m^3 per day. Simply put, if we installed a 20-foot Kijito pumping at a head of 25 meters in a location where the wind was strong enough so that it would pump at least 45 m^3 per day, then it would be cheaper than installing a diesel pumpset.

Under our "base case" assumptions, and depending on the windspeed, BHEL's windmills can be extremely competetive with diesel pumping technologies pumping at heads of 5, 15, and 25 meters. On each of the cost lines for the Kijito and Wananchi windmills in Figure 19, we have indicated the daily output for each machine operating in a moderate wind of 3.5 meters per second. For each machine, this output is far greater than the break-even output, and so we can conclude that over a wide range of windspeeds, these windmills will be quite competetive with diesel pumpsets. Because the average annualized costs of an 8-foot machine operating at a head of 5 meters are cheaper than the costs of an installed and non-operating diesel pumpset, it is competetive regardless of the wind regime. If it pumps any water at all, it will be cheaper than if a diesel pump had been installed. The 12-foot machine pumping at a head of 5 meters is cheaper than a diesel pumpset if the wind regime is sufficient for it to pump at least 19 m^3 of water per day. At this head, and with a windspeed averaging 3.5 meters per second, a 12-foot machine will pump around 100 m^3 orf water per day. The 16-foot machine pumping at a head of 15 meters is cheaper than a diesel pumpset if the wind regime is sufficient for it to pump at least 39 m^3 per day. At this head, and with a windspeed of 3.5 meters per second, a 16-foot machine will pump around 127 m^3 of water per day. As we have already pointed out, the 20-foot machine is cheaper than a diesel pumpset operating at a head of 25 meters if it can pump at least 45 m^3 per day. At this head and with an average windspeed of 3.5 meters per second, a 20-foot machine will pump 134 m^3 of water per day. Noting the gap between the break-even output and the potential output of Kijito machines which operate in moderate winds decreases somewhat at greater heads, we might conclude that diesel could become somewhat more competetive at deeper heads. In fact, this may be the case, but ultimately, cost-competetiveness will be determined by the output of the windmill given the site-specific wind regime.

Realizing that diesel prices in Nairobi are very likely not indicative of prices for diesel in remoter parts of Kenya, we have added a second set of cost lines for diesel pumps that indicate average annualized costs if diesel were to cost 50 percent more than it currently does (still inflating the price of diesel at 5 percent per annum). This effectively reduces the break-even pumping output even lower to 12 m^3 per day for the 12-foot machine pumping at a head of 5 meters, 26 m^3 per day for a 16-foot machine pumping at a head of 15 meters, and 30 m^3 per day for a 20-foot machine pumping at a head of 25 meters.

Comparing the costs of solar pumps vis-a-vis diesel pumps does not give as conclusive results as our analysis of the costs of windmills. The break-even points for the Grundfos system pumping at heads of 15 and 25 meters are 94 m^3 and 56 m^3 per day respectively. These outputs are greater than the Grundfos system can pump at peak power -- around 60 m^3 and 54 m^3 per day at heads of 15 and 25 meters. If we increase the price of diesel by 50 percent, at a 15 meter head, the break-even output for the Grundfos system of 63 m^3 per day is still greater than the maximum the system can pump. At this head, unless the price of diesel in remote areas is much greater, the Grundfos system will very likely be more expensive to purchase and operate than a diesel system. However, at a head of 25 meters, the break-even output is reduced to 37 m^3 per day if the price of diesel is increased by 50 percent. With an average insolation of 5.5 kWh/m^2 day, the Grundfos system will pump between 35 m^3 and 40 m^3 per day. It is quite conceivable that in remote areas of Kenya that received a lot of sunshine, the Grundfos system pumping at a head of 25 meters would be marginally competetive with a diesel system, but this likelihood is not clearcut.

The SEI system fares somewhat better than the Grundfos system in this analysis. Pumping at a head of 5 meters, the break-even pumping output is around 61 m^3 per day. Under conditions of good insolation in Kenya (around 7 kWh/m^2 day), the SEI system will pump around 10 m^3 per day more than this. The competetiveness of the SEI system is increased if diesel prices are increased by 50 percent, as the break-even output is lowered to 41 m^3 per day. The SEI system is a reasonably competetive technology, but it is much more viable in remote areas where diesel is expensive. Import duties and sales tax would greatly reduce the likelihood that the SEI system could compete with diesel technologies.

Having made these conclusions, the results of the sensitivity analysis indicate how the break-even output for each pumping system could be raised or lowered, depending on appropriate public policy options or on private sector initiatives. The most critical variable in this analysis has been the cost of capital. If agricultural credit policies are restrictive, smallholders will be biased toward conventional irrigation technologies which generally are characterized by lower capital costs and higher recurrent costs -- but which may be more costly in the long run than a renewable energy pumping technology. Another important, though less critical variable are the costs of operation, maintenance, and repair. Total system costs are somewhat sensitive to changes in OMR costs or to changes in the life expectancy of the pumping unit. From the private sector's perspective, it is in their interest to lower these costs as much as possible by producing durable technologies -- as manufacturers of windmills and solar pumps seem to have successfully done. Certainly in the case of publicly-funded water pumping projects however, where there are no clearcut responsibilities for maintenance, OMR costs may be greatly increased. Development aid and other funding organizations would make their investments in renewable energy technologies much more worthwhile if they explored ways of giving greater project responsibility to the target group or community, for instance, by promoting projects which develop out of community or group initiatives. Finally, sales tax accounts for a relatively small percentage of windmill costs, although in absolute terms, for larger machines they are quite substantial. Because the primary consumers of solar pumps are exempt from sales tax and import duties, a reduction or elimination of these levies would have no overall impact on system cost. If, however, the markets for solar pumps are to be expanded, both of these levies would be a significant disincentive to smallholder investment. Questions regarding policy approaches toward reducing the cost of capital, lowering OMR costs, and changing the structure of duties on wind and solar technologies are dealt with more fully in Section VII of this paper.

VII. OPPORTUNITIES, CONSTRAINTS, AND POSSIBLE INTERVENTIONS TO AFFECT THE USE OF RENEWABLE ENERGY TECHNOLOGIES FOR SMALL-SCALE IRRIGATION

There are really several fairly discrete groups of potential users of solar pumps and windmills for small-scale irrigation in Kenya. They include individual rural smallholders, groups of farmers or farmers' cooperative societies, larger landholders, and government, development aid, and charitabley-sponsored development activities. The problems of investment in renewable energy technologies for small-scale irrigation by each of these groups are fairly unique, and so it is difficult to arrive at any generalizations about the likelihood that the use of wind and solar technologies for small-scale irrigation could be expanded or otherwise popularized.

In a number of small-scale irrigation projects, there has been an underlying assumption that, if water is made available for irrigation through infrastructural improvements, it should, could, and will be used for that end-use. This approach reflects a particularly technological bias. More often than not, it has been discovered in these projects that the pumping technology is not the biggest constraint to the introduction of irrigation as a new agricultural technology. While the risks of investing in a renewable energy water pumping technology per se are relatively low -- i.e. by themselves, they seem to be as technically reliable as their manufacturer's claim -- these risks are greatly compounded because irrigation as an agricultural technology is unknown in many parts of Kenya.

Especially because of this last point, it becomes clear that the constraints and opportunities for increasing the use of renewable energy technologies for small-scale irrigation are closely related to the introduction of wind and solar technologies themselves and, perhaps more importantly, to the process of introducing small-scale irrigation as an agricultural technology. Constraints to the use of renewable energy technologies for small-scale irrigation include physical limitations which cannot be easily affected by external interventions, such as inadequate insolation or wind and the lack of easily accessible ground or surface water resources. Other constraints that could perhaps be more easily addressed by policy interventions include financial and technology-transfer issues. Constraints to the use of small-scale irrigation as an agricultural technology in Kenya include issues as diverse as labor constraints, pricing policies and marketting infrastructure, cash-crop/subsistence-crop farming patterns, and the need for agricultural extension and education about the proper uses of irrigation. Policy interventions which address the introduction of solar and wind technologies may have a relatively small impact on the use of renewable energy technologies for small-scale irrigation unless adequate interventions are made to deal with the problems of introducing any small-scale irrigation technology into the rural agricultural economy. While the intention in this study was to focus on the first set of issues, recognizing this last point has led to the inclusion of a brief discussion of some of the constraints and opportunities for introducing irrigation technologies generally in Kenya.

Very broadly described, constraints to the introduction of renewable energy technologies for small-scale irrigation fall into two general categories : financial constraints and technology-transfer associated constraints. There is a certain amount of intersection between these categories, and it could be argued that the distinction is somewhat artificial. Nevertheless, it allows us to examine possible policy interventions to alleviate these constraints more closely.

A. Alleviating Financial Constraints to Investments in Renewable Energy Technologies for Small-Scale Irrigation

Financial constraints generally reflect the fact that renewable energy technologies are, by and large, very expensive. Investments in wind and solar pumping technologies are characterized by high capital costs and low recurrent costs. A rural smallholder very likely perceives an investment at a high rate of discount : his interest in an investment extends to its impact on the next several planting seasons, and certainly not to his returns over the 20-year time horizon we envisioned in our financial analysis. Because of this, even though total system costs with conventional pumping technologies may be higher in the long run, a smallholder will be biased toward technologies with lower first costs. Possible policy interventions that deal with financial constraints to the use of renewable energy technologies for small-scale irrigation would ultimately either reduce the smallholder's tendency to greatly discount the future, or would instead reduce in real terms the required capital investment costs of these technologies.

The assumption, of course is that these constraints should be alleviated, and this is admittedly something of a value judgement. We have assumed that, in some sense, these technologies should be favored because they are economically efficient. Our financial analysis compared wind and solar pumps with conventional technologies, and this gives some indication of the conditions under which renewable energy technologies might be more cost-effective in the long run. However, the comparison with diesel pumping technologies is made assuming that diesel fuel is available at any cost and that pumped irrigation schemes are cost-effective in the long run. Generalizations about either of these points would be unsound. Ultimately, the question becomes one of whether or not the water that a solar or wind pump could provide for irrigation would increase crop production enough to pay for itself, depending on our investment criteria, in financial or economic terms. A thorough site-specific economic benefit-cost analysis would provide the necessary information to make such a judgement, but is beyond the scope of this paper. A very simplistic alternative is to compare returns to irrigated agriculture to see if they might come anywhere near to meeting total system costs of a renewable energy technology.

Production characteristics of 6 large-scale irrigation schemes managed by the National Irrigation Board are given in Table 2. Reported gross returns in 1981/82 ranged from K.Pounds 254 per hectare for the Ahero Rice Paddy Pilot Project to K.Pounds 810 per hectare for the Perkerra Scheme. (During periods of drought-induced scarcities, reported returns may be much lower than actual returns, as it can be expected that a certain amount of production will be sold illicitly through channels which command much higher prices.) The Homa Hills Centre reported that in 1982, its irrigated holdings of cabbages, kale, onions, and tomatoes yielded around K.Pounds 924 per hectare. Actual returns to other schemes are often not well reported because of the lack of established marketting and farm management infrastructures. Nevertheless, if we substract other costs of production from these estimated gross returns, net margins may be rapidly diminished.

So, even if wind and solar technologies under certain conditions are less costly than diesel irrigation technologies in the long run, it is not at all clear whether investments in these technologies could be justified, even in these cases, on the basis of their potential income generating value.

In terms of income generation from small-scale irrigation projects, it is very unlikely that under the current pricing structure the Grundfos solar pump and the 16 and 20-foot Kijito windmills could be afforded under any situation by rural smallholders. The SEI solar pump could perhaps be afforded if agricultural credit were available. At an annualized cost of around K.Pounds 600, it is conceivable that returns from an irrigated highly-valued cash crop could be sufficient to cover investment costs. The Wananchi 8 and 12-foot windmills are perhaps the most affordable of the technologies we have reviewed in this study. High first costs, however, might still make it difficult for a smallholder to purchase any of these technologies, and access to subsidies or credit might be an important prerequisite for smallholder investment.

In any case, reasonable public sector interventions have some potential for increasing net returns to smallholders who use wind and solar-powered irrigation technologies by reducing the farmer's costs in using these technologies. Cost reductions could come in the form of reductions in the costs of the technology itself, or in reductions in the cost of the borrowed capital that might be needed to finance first costs. These cost reductions could come in the form of, for instance, direct consumer subsidies, special concessionary loan funds for renewable energy technologies, and so on. Perhaps the clearest costs which could be directly affected by public policy interventions are sales taxes and duties on imported technologies and on raw materials.

1. Tariff Barriers to the Production, Importation, and Purchase of Renewable Energy Technologies for Small-Scale Irrigation

Duties on solar pumps and windmills can account for a substantial amount of private purchase costs. For windmills, import duties and sales taxes on raw materials and on the manufactured product account for around 30 percent of the consumer's initial investment costs. For privately purchased solar pumps, duties can account for as much as 35 percent of investment costs (assuming of course that the purchaser is unable to import the units duty-free).

Recent changes in the schedule of duties and tariffs have somewhat reduced the cost of privately purchasing imported solar pumps and Kenyan-made (or imported) windmills. BHEL estimates that, since the revised Import Licensing Schedule came into effect in July of 1984, their raw material costs have declined on average by about 10 percent. Lowered duties on PV-panels have reduced the overall costs of modules by around 6 percent. These changes have been part of a general liberalization in the government's policy toward imports, especially of raw materials, to promote the export of Kenyan-manufactured goods during the Kenyan Export Year.

Especially for imported steel used in windmill manufacture, the prospect of further reductions in the cost of raw materials is likely, as steel importers take advantage of the tiered schedule of duties for goods originating in the Preferential Trade Area (PTA). The Treaty for the Establishment of the Preferential Trade Area for Eastern and Southern African States, signed on 30 September 1982, was designed to reduce tariff and non-tariff barriers to trade between its signatories over the next 10 years. Current member states of the PTA include Kenya, Ethiopia, Somalia, Rwanda, Uganda, Malawi, Burundi, Djibouti, Lesotho, Swaziland, Mauritius, the Comoro Islands, Zambia, and Zimbabwe. It is expected that Tanzania, Angola, Botswana, Mozambique, Malagasey and the Seychelles will also become members at a PTA summit planned for the end of 1984. The impact of the tiered schedule of duties on the prices of some commodities has been substantial. In 1983, for instance, metal pipe with a diameter of greater than 12.5 cm was surcharged at a rate of 93 percent of its value in import duty and sales tax. The new schedule of duties reduces this surcharge to 80 percent for imports from non-PTA countries, and to only 23 percent for imports from PTA countries. Sheets of steel less than 1.5 mm in thickness were taxed at an effective rate of 76 percent. The revised rate for non-PTA countries is 46 percent, and for PTA countries is only 13 percent. In spite of these especially low rates for PTA countries, it may be some time before importers are able to take full advantage of the new tariff structure. Necessary changes in the transportation infrastructure, for example, may have to be implemented. The recent introduction of containerized freight in Kenya is a sign that steps are being taken in the right direction.

For BHEL, reductions in the prices of raw materials will be particularly helpful in the long run, and will increase their ability to compete with manufacturers of foreign-made windmills. An Argentine manufacturer of windmills, for instance, has been able to produce a machine comparable in size and quality to the Kijito, but with an *ex factory* price equivalent to what BHEL pays for its raw materials. Roughly 20 to 30 percent of the cost of a Kijito has in the past been accounted for by taxes of one sort or another. Any future government initiative to further reduce this substantial burden on the cost of production would perhaps be the most effective means of subsidizing the development of this innovative small manufacturing concern.

The question of the tariff structure for solar pumps which are purchased by private individuals (who must pay regular duties, unlike government, development aid, and charitable organizations) is somewhat more difficult to address, primarily because there are substantial opportunity costs involved in using foreign exchange for their purchase, and because the tariff structure of other energy generating devices and of conventional fuels is not particularly consistent. There are admittedly some opportunity costs for using foreign exchange for building windmills. However, while foreign exchange costs account for only around 30 percent of the total cost of a windmill, they account for 100 percent of the cost of a solar pump. Further, nearly 20 percent of BHEL's production has been geared for the export market, and so some of these opportunity costs are recovered. In any case, it would be useful to look at the tariff structure of conventional fuels and of other energy conversion technologies. Pumps themselves will not enter into this discussion, because they are all taxed at equivalent rates, whether they are powered by a windmill or by photovoltaic cells or by a remote generator.

The tariff structure of other renewable energy technologies is not particularly consistent. Water wheels and producer gas generators are taxed at a rate of 25 percent import duty and 17 percent sales tax. Hydraulic rams, which are used for pumping water using energy from a flowing stream, can be imported duty-free and are exempt from sales tax. Windmills are taxed at a rate of 35 percent import duty, and 17 percent sales tax. Among renewable energy technologies, photovoltaic panels are taxed the highest at a rate of 45 percent import duty and 17 percent sales tax.

Conventional energy conversion technologies are taxed somewhat more consistently than renewable energy technologies. A.C. and D.C. generators are assessed a 25 percent import duty, but are exempt from sales tax. Most internal combustion engines which could be used, for instance, to power a generator, are assessed a 35 percent import duty and a 17 percent sales tax. However, if anyone ever decides to import a nuclear reactor into Kenya, the import duty would be only 20 percent, plus 17 percent sales tax.(66)

The basic difficulty in evaluating the structure of the tariff for photovoltaic modules comes from the question of whether they bear enough similarities to other energy conversion technologies to classify them as such. Conventional energy conversion technologies convert usually costed forms of energy into other forms. Over the life of the technology, energy inputs account for most of the recurrent costs that are involved. Solar panels convert solar energy into electricity, and so no recurrent costs are involved. On the one hand, we could look at solar panels as energy conversion technologies, and could evaluate their tariff structure by comparing them with other conversion technologies such as A.C. and D.C. generators. On the other hand, because the capital investment in the technology is the only cost involved, perhaps the tariff should reflect the amount and quality of the energy produced during its lifetime. This would be the basis for the argument of some advocates of the use of solar energy for irrigation who suggest that they should not be assessed any import duties at all because no duties are assessed on diesel fuels -- which are used to power conventional pumping technologies.

In order to make comparisons between photovoltaic-produced electricity and conventionally-produced electricity for small-scale irrigation, it would be useful to analyze the costs involved based on an "energy theory of value," which would reflect the costs of particular technologies or fuels based on their useful energy output. If we assume diesel and petrol can produce electricity at a thermal conversion efficiency of 34 percent, 1 liter of diesel could produce 3.36 kWh of electricity, and 1 liter of petrol could produce 2.90 kWh of electricity.(67) Based on the prices of these fuels sold in Nairobi, KSh 5.95 and KSh 8.13 for diesel and petrol respectively, and excluding the costs of the conversion technology, the cost of electricity generated by either of these fuels would be KSh 1.77 per kWh for diesel, and KSh 2.80 per kWh for petrol. If we assume a 40 pW solar panel operates for 9 hours a day, producing 70 percent of its peak power capacity, it will produce 92 kWh of electricity per year. If we also assume a cost per panel of KSh 7158 (US$ 487), a panel life of 20 years, and a 10 percent interest rate, average annualized costs are around KSh 841, or KSh 9.14 per kWh. If we don't annualize our costs, and don't discount the value of future electricity production, a panel under the same conditions would produce 1840 kWh over 20 years at a cost of KSh 3.89 per kWh. These estimates compare with grid-produced electricity which is available to consumers at a regular rate of KSh 0.71 per kWh. (These rates may be much lower for electricity which is used for irrigation.)

Having made this comparison, we can also evaluate the respective rates of duty per unit of generated electricity. Costs and duties are summarized in Table 13. Duties on petrol are currently KSh 3.078 per liter, or KSh 1.06 per kWh of generated electricity and represent an effective import duty and sales tax of 61 percent. Diesel is exempt from duties and sales tax. Duties on photovoltaics would be KSh 2939 per 1840 kWh, not annualizing costs or discounting the value of future electricity production, and are equivalent to KSh 1.60 per kWh. This represents an effective import duty and sales tax of 70 percent. If we annualize these costs, duties would be KSh 3.75 per kWh. These duties compare with the tax assessed on grid-produced electricity of KSh 0.01 per kWh, which is an effective duty of around 1 percent.

High duties have caused an obvious distortion in the price of petrol. The artificially high price of petrol caused by the imposition of significant duties, is a reflection of the government's policy to encourage the use of other more energy efficient fuels such as diesel and gasoil in the transportation sector, despite the fact that the increased production of these fuels may cause problems in matching refinery yield with market demand. Engines which use these fuels are also heavier, so in the transportation sector at least, some of these gains in efficiency will be lost because of the added energy cost of moving a vehicle with a heavy engine.

If we use energy-valued criteria for establishing respective rates of duty, we could rightly say that the duties on petrol and on photovoltaic panels are probably much higher than they should be, or that the duties are diesel are much too low. We could draw this conclusion if the opportunity costs of importing and refining diesel and petrol were the same as the opportunity costs of importing photovoltaic modules. However, they are not. Because petrol and diesel are used primarily by the transportation sector (which accounts for over 40 percent of total petroleum product consumption in Kenya),(68) public policy options which affect their rates of consumption are determined primarily by the impact they will have on the transportation sector, and not necessarily on the agricultural sector. The significant contribution that the transportation sector makes to the national economy, and its heavy dependence on petroleum-based fuels, is reason enough for why duties on petrol and diesel are lower than duties on photovoltaics. If photovoltaics have any potential for making significant contributions to the national economy, then duties on them should perhaps be lowered. However, it is unclear whether or not we could draw this conclusion, primarily because of the substantial cost of generating electricity with photovoltaic cells, even if there were no duties assessed on them.

We have made some fairly generous assumptions in this analysis. We have arrived at cost estimates by using relatively cheap Solarex photovoltaic panels. We have not included photovoltaic shipping or installation costs, nor have we included the costs of transporting diesel or petrol to a remote site, or the cost of the conventionally fueled conversion technology. Few people would argue that photovoltaic produced electricity is cheap. Rather, the primary advantage of using PV-modules would be one of assuring a guaranteed supply of energy when other supplies may not be available. The extent to which this variable can be costed and entered into our analysis is unclear. Perhaps the soundest conclusion we can arrive at from this analysis is that there is no straightforward answer to the question of whether or not duties on solar panels are too high or too low, or whether or not photovoltaics can provide an economically competetive means of generating electricity in remote areas. However, until a clearcut rationale can be arrived at for justifying a reduction in duties on photovoltaic cells, for instance because photovoltaics could significantly contribute to national economic development, or because the opportunity costs of foreign exchange could be reduced, any further liberalization in the current tariff structure would probably be unsound.

2. Increasing the Availability of Capital for the Purchase of Renewable Energy Technologies for Small-Scale Irrigation

Outside of direct government subsidies and the reduction of sales taxes and import duties, there are few other public policy options which could directly contribute to lowering the production costs of renewable energy technologies in Kenya. Although we should not completely rule out the possibility of direct public subsidies, either to manufacturers or to purchasers of renewable energy technologies for small-scale irrigation, the likelihood that such a program would be initiated is nil. There is a clear and emerging focus on the need for public sector austerity in Kenya. As the current Development Plan points out, "Recent high levels of Government borrowing have unduly restricted the private sector's access to credit . . . and the scale of total Government borrowing must be progressively reduced."(69) The limits established by the current program of Government austerity would probably mean that the public sector financing of wind and solar-powered pumps within any kind of agricultural development program would take a low priority.

If we exclude the possibility of direct public sector subsidies for solar pumps and windmills, other options for directing capital resources toward investments in these technologies include grant and loan programs administered either by private banks, by the government, or by international development assistance agencies. Private banks are probably the most fiscally conservative of these three groups, as banking institutions are in the business of making money. In the past several years, bank credit simply has not been easily available. Government borrowing has almost crowded the private sector out of the financial markets. Around 30 percent of the total credit available in the banking system in 1983 was borrowed by the government. Around 17 percent of the available bank credit is targetted by the Central Bank specifically for loans to the agricultural sector, but actual sectoral credit has rarely exceeded 15 percent. Much of this capital has been borrowed by agriculturally-oriented parastatal industries. Because of this fact, and because of the high-return, low-risk nature of large-scale agriculture, the smallholder agricultural sector receives relatively low priority for private capital financing.(70) Limited capital availability, as well as the difficulties of acquiring and committing sufficient loan collateral virtually eliminates smallholders from the private financial market. Finally, the few bank loans that are available to smallholders are usually short-term credits and would be insufficient for the longer-term financing that would be needed to finance wind and solar pumping technologies.

A certain amount of smallholder financing is available through a number of public-sector programs such as the Government-administered Seasonal Credit Scheme. This too is a short-term loan program, and is not a source of longer-term capital financing. Even so, the record of farmer repayments to the Scheme has been very poor. The Scheme was designed as a revolving fund, and repayments of old loans were intended to finance new credits. Currently however, only one-third of the loans are being repaid, and loan capital which should be available through the Scheme has become scarce.(71) The credit system is reportedly being restructured to improve the repayment record, however, experience with this scheme has indicated that it would be unlikely that a program for administering longer-term loans for renewable energy technologies would have much chance of success.

Considering the limited availability of capital financing either through the Government or through private financial markets, probably the most likely option for increasing capital availability for the purchase of solar pumps and windmills is through charitable and development aid organizations. At least half of BHEL's windmills have been purchased by development assistance or by private voluntary organizations such as churches and charitable aid groups. A single solar pump in Kenya has been privately purchased (by a farmer in Rumuruti). Like windmills, the rest have been purchased using various forms of international development aid. The number of private investors in each technology is indicative both of the degree of difficulty involved in penetrating local markets for them, as well as of the primary markets that have been addressed thus far.

In some cases, financing from development aid agencies has been made available to groups of smallholders through farmers cooperatives or to schools and community groups. In virtually no instances have aid agencies financed the purchases of these technologies for individual farmers or smallholders. Such financing would be antithetical to the distributive objectives which most aid agencies support. We could probably rule out that aid agencies would undertake this type of activity in the future, except perhaps through already functioning agricultural credit schemes -- rather than through the establishment of a specific grant or loan fund specifically for windmills or solar pumps.

So far, development aid organizations have financed the purchase of windmills and solar pumps primarily through specific development projects such as settlement schemes, hospitals, or through other projects such as the Homa Hills Centre. The European Economic Community has financed the installation of 2 Kijito machines at Kaikor near the Kenya-Sudan border as part of the Turkana Rehabilitation Project. Although this system was originally designed to provide water for nomadic people and their livestock herds, overflow water is being used to irrigate several hectares of sorghum, beans, and maize. The GTZ (German Agency for Technical Cooperation) has installed a number of windmills as part of settlement schemes in Mtwapa and Mpeketoni. In addition to its windmill activities, Redd Barna is using an SEI solar pump to irrigate a small shamba of cabbages, beans, tomatoes, and a number of other crops about 5 miles from Lodwar.

One of the problems of promoting wind and solar-powered irrigation schemes in specific externally-assisted development projects is that there is the risk that a technical bias toward energy-producing technologies will obscure basic end-use needs -- irrigation and not energy *per se* -- that these technologies can provide. These end-use needs are perhaps clearest in projects which are initiated by communities and groups. Especially when local groups have clear interests in specific productive projects, the likelihood of success may be much greater in the long run than for projects which are externally conceived, initiated, and carried out. For a number of reasons, aid agencies generally shy away from projects of this nature. They often require close project supervision. Further, project impacts are not as politically significant or as measurable as the impacts of large-scale projects. The impact of the occasional installation of a windmill or a solar pump, for instance, would be difficult to gauge, unlike the impact of commodity assistance or food aid programs. Finally, bilateral assistance is often tied to the procurement of goods and services originating from donor countries which may not be appropriate for small-scale and community-oriented activities.

The tendency of some aid agencies to rely on their own political considerations instead of on the interests of the host country can result in poorly conceived and poorly executed projects. A recent proposal for a bilaterally-funded project to popularize the use of wind energy technologies in Kenya -- at a cost of around KSh 17.2 million -- suggested some positive approaches for facilitating the introduction of wind technologies, for instance through demonstration projects and training activities. The proposal went on to suggest however, that Kenyan windmill designs were inadequate and that a new design effort needed to be initiated -- of course employing engineers and technicians from the donor country. Over the course of the 3-year project, 23 windmills were to be installed. For the same amount of money, over 200 12-foot Kijitos could be installed *and* maintained for 20 years. If donor governments were seriously interested in popularizing the use of windmills in Kenya, then they could be much more effective if they attempted to establish a mechanism by which capital could be accessed to financed purchases of locally available and technically mature machines.

Some agencies have attempted to do just that,, although their mandate is usually much broader. The office of the American Ambassador, for instance, administers a "Self-Help Fund" and a "Small Projects Assistance Program" for projects which are conceived by community groups, schools, or by groups of farmers. Technically, these are U.S.AID projects, but are almost completely independent of the usual U.S.AID bureaucracy which often requires special wavers for the purchase of non-American made goods. Among many other projects, these funds have financed the purchase of a Kijito windmill for the Gitero Farmer's Cooperative Society near Naro Moru, and the purchase of two SEI 300M solar pumps: one for a community water project in Chilulu on the coast and the other for an irrigation project at the Budalangi Secondary School close to Busia.(72) Each of these projects benefitted from the input of exaptriate volunteer workers who could effectively provide technical assistance while linking the interested groups up with the financial resources necessary to complete the project. Projects financed by the Self-Help Fund and the Small Projects Assistance Program often require substantial local contributions of labor and material before they will be funded. Other bilateral assistance programs will support similar types of projects, but there is currently no formal means of providing development assistance from any agency specifically for the purchase of these types of technologies.

Another possible source of financial assistance for windmills and solar pumps is the Energy Development Fund (EDF),(73) originally administered by the Ministry of Energy, but recently transferred to KENGO (Kenya Energy Non-Governmental Organizations). The EDF is to be used as a fund to finance energy-related projects initiated by NGOs, such as improved cookstove construction, agroforestry, and the development and dissemination of hydraulic ram technologies. Its mandate does not specifically include financing for groups outside of the NGO sector such as farmers' cooperatives, but its mandate could be conceivably broadened if other donors considered the usefulness of such a mechanism. If an aid agency claims to want to popularize the use of specific energy-producing technologies, the EDF could be an effective means of providing directed financial assistance in a developmentally positive way -- rather than figuratively littering the Kenyan landscape with new technologies in the hopes that benefits might accrue to the rural communities where they might be installed.

Financing for solar and wind technologies could be provided through a revolving loan fund (perhaps through the EDF) where future loans are financed by repayments of old loans. There are several arguments in favor of providing outright grants for these technologies rather than loans. The poor repayment record of other revolving loan funds such as the Seasonal Credit Scheme would suggest that there may be difficulty in ensuring repayment for these technologies. The long-term repayment schedule that solar and wind technologies would probably require would also make cost recovery less likely. Rather than incurring the administrative costs of providing loans which would eventually be in default, a small grants program which required an amount of cost sharing would perhaps be a logical alternative.

Another alternative within the same type of management framework would be the establishment of a scheme for technology-leasing. This kind of scheme would be more appropriate for portable solar pumps than it would be for stationary windmills, but the logistical and administrative problems of such a scheme could be quite complex. It is unlikely that total cost recovery could be realized through such a scheme, but it still would provide a means of subsidizing the use of these technologies in an equitable manner. The difficulties of carrying out this kind of arrangement using commercial bank credit reflect the fact that private financing is largely unavailable, especially where cost recovery could not be assured.

The question of cost recovery in water development projects has often been a perplexing one for development planners. The World Bank's policy has been to require cost recovery through the assessment of water charges to cover at least operation and maintenance costs, and up to 100 percent of other direct project costs. According to a 1975 survey of a number of Bank-financed irrigation projects, recoveries averaged only 30 percent of total costs. It was suggested that between 75 and 125 percent of total costs could be recovered through a more stringent method of assessing water charges.(74) Water charges should be assessed on the basis of the need of the project management organization (such as the National Irrigation Board) for fiscal resources, as well as on the poverty level of the beneficiaries, and their respective levels of income distribution above the poverty level. Simply by initiating a system for cost recovery, project management costs would be somewhat increased. Especially for very small projects, the marginal costs of cost recovery efforts could be greatly in excess of the marginal benefits that could be accrued as a result. Regardless of the criteria which are used to arrive at equitable water charges, the decision to assess them is ultimately a political one. In multilaterally and bilaterally-funded large-scale irrigation projects, the political choice is perhaps limited by the terms of the project agreement. One could anticipate that, for individual micro-irrigation projects, there would be somewhat more latitude of choice.

There has been very little experience with the assessment of water charges for wind and solar-powered irrigation projects. Although outside of the Kenyan experience, a Solar Irrigation Project in Shirati (northern Tanzania) on the shores of Lake Victoria, included provisions for the assessment of water charges.(75) Four SEI 300M solar pumps are used to irrigate 3 hectares of good quality land which has been broken up into small plots which are being used for growing onions, tomatoes, cabbages, collards, peanuts, beans, potatoes, and citrus. The water charges are used to cover part of the costs of hiring 4 full-time laborers. There is little documentation about the usefulness of the system of water charges, but at least one observor has suggested the assessments for this project are much too low.(76)

Finally, there is the arguable point of whether public sector projects should be pursued which end up benefitting just a few manufacturers of these technologies. There was almost universal agreement among public and private sector participants in a recent workshop in Nairobi(77) that development assistance should be used to provide for the consumer's energy-dependent end-use needs, rather than to specifically support private sector manufacturers. Yet, where manufacturing concerns are few in number, any action to support the dissemination of any specific technology will ultimately benefit these commercial concerns. The point is simply that these concerns should not be the focus of any concerted development effort. Even so, perhaps the best mechanism for project identification may be the commercial concerns themselves. Numerous direct requests for windmills and solar pumps have been turned down by these companies, simply because financing has been unavailable. The establishment of a third-party mechanism to field and direct these request for potential funding would be a useful means of avoiding obvious conflicts of interest.

Especially since the 1981 United Nations on New and Renewable Sources of Energy, most multilateral and bilateral development assistance agencies have incorporated politically visible energy initiatives into their aid programs. The German Special Energy Program (SEP) and the International Programs Division of the Agence Francaise Pour La Maitrise de L'Energie (AFME - French Agency for Energy Management) are 2 cases in point. A basic difficulty that has been encountered with these initiatives has been that of taking the promotion of these technologies into other programmatic sectors, for instance, into agricultural or water development programs. While energy planners may be convinced of the economic or technical viability of renewable energy technologies, agricultural planners for instance may have the perception that these technologies are still somehow experimental or are at best "trendy" and not yet viable. These are basically technology-transfer issues which affect the project planning activities of aid agencies as much as they may affect developmental priorities in different ministries of the Kenyan Government which may have an interest in developing the means for providing rural agricultural water supplies.

B. Alleviating Constraints to the Transfer of Wind and Solar Technologies for Small-Scale Irrigation

The term "technology-transfer" has often been used to describe the process by which information about new technologies is systematically exchanged between groups, individuals, or commercial concerns often, but not always between "North" and "South." In this discussion, we use the term to describe the process by which end-users may become familiar with wind and solar-powered irrigation technologies in order to predicate their introduction into the rural agricultural economy. The promotion of this type of technology-transfer involves much more than simply installing a functioning windmill or solar pump. It requires the development of a local understanding, however basic, of how a technology works, what it is capable of doing, and what its limitations are.

In the commercialization process, there are several stages of technology-transfer. The first stages involve the adaptation of the technology itself so that it is appropriate for local conditions and markets. The final stages result in the widespread dissemination of the technology. A necessary intermediate stage involves the use of demonstration projects to link the early research and development stages with later marketting and dissemination stages. Demonstration projects usually involve the installation of these technologies in pilot projects, and often include necessary extension and education efforts that would be needed in order to keep the machines operating within their designed capacities.

For renewable energy technologies, the process of technology-transfer may be difficult to facilitate, even with comprehensive demonstration efforts. To the casual observer, the function of a windmill or solar pump may not be immediately clear. For instance, one farmer, after seeing a windmill in operation at the 1983 Nairobi International Show inquired if the water was what made it work. Another, after having visited the school on Rusinga Island where a Kijito had been installed wrote to BHEL about the possibility of obtaining one of these machines, but only after it had occurred to him that it actually pumped water. The function of a solar pump may be somewhat clearer, but certainly a peception of its operating principles will largely be lacking (and perhaps not necessary) in most rural areas. Further, regardless of the type of water pumping technology that is used, irrigation itself may be completely unfamiliar in rural areas, and may require extensive agricultural extension work to familiarize smallholders with its potential benefits. Often, what development planners casually accept may be a revolutionary concept in a rural setting.

There has not been any concerted effort to demonstrate either solar pumps or windmills in rural areas of Kenya. At least in terms of official interest in Kijito windmills BHEL has suffered from benign neglect. Of all of BHEL's machines, only one has been purchased by the Government (by the Ministry of Education for installation at a school). On the other hand, at least one-quarter of SEI's purchases have been directly financed by various offices and ministries within the Government. One possible means of mounting a demonstration program for wind and solar pumps would be to install them at Farmer's Training Centres. Such installations would provide a means for familiarizing farmers with their possible uses and maintenance demands. Most often, early privately-financed installations (either by individuals or development aid organizations) of these technologies have had an important demonstration effect. It has been even more important that these installations have been maintenance-free, as their success or failure at water pumping would likely be widely reported among interested parties. BHEL still suffers to a certain extent from its early design problems because word travelled that the Kijito was a defective technology. These attitudes are slow to change and will disappear eventually, but they have occasionally been major hurdles in BHEL's marketting experience.

There has been some evidence that there has been an important demonstration effect in Nyanza Province because of the many windmill activities that have been initiated around Lake Victoria. BHEL has reported that it has received numerous request for information about their machines from groups and individuals in the area. One can anticipate that, at least in this part of the country, the process of technology dissemination is perhaps beginning to accelerate and that windmills may become somewhat more widely known in the foreseeable future.

There is perhaps a very basic conflict between promoting publicly-financed demonstration efforts and providing financial assistance for the purchase of wind and solar-powered irrigation technologies. In the former, the promotion of the technology is perhaps the focus. In the latter, matching the technology with end-use needs, while relying on local inputs of labor and material, emphasizes the fact that these technologies cannot be forced upon an unwilling smallholder population -- regardless of their theoretical or potential benefits. The successful utilization of these technologies will be dependent on their ability to fill a niche in the existing rural agricultural economy, and not on whether a place for them can be forced into existence.

The process by which solar pumps and windmills are matched with appropriate end-uses in Kenya is dependent on the perception of the purchasing individual or organization of the immediate demands for water. According to BHEL, only one of their machines is being used exclusively for irrigation. Another one-third of their machines are being used for multiple purposes which include irrigation. The remainder are being used for providing both domestic water supplies and water for livestock. Most of the SEI pumps that are installed in Kenya are used primarily for irrigation and for providing domestic water supplies. That these technologies are often used for multiple purposes is perhaps an indication of the consumer's risk reducing behavior. By using these machines to meet multiple demands, surplus water is not wasted, and when water output falls because of reduced radiation or windspeeds, the water that is available is used to its maximal benefit. In the project planning process, this characteristic of multiple end-use demand management would be helpful in identifying possible projects where the risks of failure -- judged by whatever standard -- may be somewhat lower.

C. Constraints to the Introduction of Small-Scale Irrigation as an Agricultural Technology for Kenyan Smallholders

It was not the intention in this study to dwell at length on constraints to the introduction of irrigation as an agricultural technology in Kenya, but as we pointed out at the beginning of this section, policy interventions which address the introduction of solar and wind energy technologies may have a relatively small impact on the use of renewable energy technologies for small-scale irrigation unless adequate interventions are made to deal with the problems of introducing any small-scale irrigation technology into the rural agricultural economy. Because of this, a few brief observations would be appropriate. These constraints are as diverse as the lack of adequate labor, distorted pricing policies and inadequate marketting infrastructures, a predominance of subsistence farming, and a basic lack of knowledge about the use of irrigation to increase crop production.

The process of technology transfer in the rural agricultural sector can be a slow one. Independent of whether one chooses a windmill or a solar pump, the real problem becomes one of how one can facilitate the introduction of irrigation in the agricultural sector as a new and economically productive technology while at the same time minimizing the risk of financial loss. Especially for renewable energy technologies, the financial cost of making an incorrect assessment of the ease with which irrigation technologies could be introduced could be quite substantial. In this sense, conventional irrigation technologies are a much lower risk because capital investment costs are much lower, although recurrent costs may be high.

Whether or not water pumping technologies are rurally appropriate for small-scale irrigation will depend in part on how the availability of water will affect the rural sector's traditional means of capital formation. For instance, around Lake Victoria where the windmill activities of the Mbita Catholic mission and of the Homa Hills Centre have provided a means of increasing local crop production, recurrent problems have arisen in promoting the transition from subsistence to cash crop farming. If cost recovery is an element of an irrigation project, then cash crop farming will be essential. Windmill irrigation in Nyanza has provided a means of raising as many as 5 crops a year instead of 2, but many farmers have neither the means nor the desire to hire the additional labor that would be required. Indeed, in a subsistence agricultural economy, the idea of hiring labor is virtually unknown, and so the introduction of cash cropping would be a tremendous innovation.

In order to facilitate the introduction of irrigation as an agricultural technology, extension and education efforts would have to be carried out in conjunction with the introduction of any water pumping technology. The windmill project at Mbita was discontinued in part because of the lack of any means for carrying out needed extension work. However, a real strength of the Homa Hills Centre's windmill efforts is precisely that it has been able to coordinate the introduction of windmills with a comprehensive extension program. Even so, many extension efforts are targetted at the heads of households. For instance, nationally, around 39 percent of the heads of households have attended courses in crop production at Farmer's Training Centres.(78) On the other hand, the distribution by sex of rural farming labor is heavily skewed because the bulk of the labor is provided by women. The Integrated Rural Surveys (IRS-4) reported, for instance, that around 87 percent of the women over 15 years of age regularly plant and harvest maize, while only 54 percent of the men in the same age group do the same.(79) The distribution is somewhat more equitable for cash crops, but nevertheless, if small-scale irrigation is to be introduced on any scale, women will have to be targetted for more extensive extension efforts.

Because of the extension and institution-building work which would be required, it would likely be especially difficult to introduce irrigation into subsistence economies. In Nyanza, Eastern, and Coast Provinces, it has been estimated that around 54 percent of the smallholdings are being used for subsistence agriculture, and that around 33 percent are being used for a combination of subsistence and cash cropping. In Western Province however, the figures are nearly the reverse, with mixed subsistence/cash crop farming accounting for 57 percent of the smallholdings, and primarily subsistence farming accounting for 38 percent of the smallholdings.(80) Regardless of the specific technology involved, where cash cropping is already being carried out, even on a limited scale, it is very likely that irrigation may be more readily accepted. An essential prerequisite to irrigation project planning is the evaluation of the cash crop/subsistence farming mix. One can only conclude that the failure of schemes like Bura and Kano to yield projected returns can in part be due to an inadequate assessment of this characteristic of the rural agricultural economy.

The Lower Tana Village Irrigation Project provides a good example of some of the difficulties involved in introducing pumped irrigation technologies. The objective of this project, which was begun in 1980, has been to secure food production among poor smallholder families living along the Tana by means of irrigating small plots of between 40 and 100 hectares. By the middle of 1982, the main irrigation network had been constructed, and a pumping system was installed. Donors were to cover the costs of the initial capital investment, and it was expected that smallholders would be able to cover the recurrent costs of the pumping system with cash generated by increased production. A recent review of the project noted that "the introduction of the pumping system had various consequences and side effects with which the average participating farmer could probably not cope, now, nor in the future."(81)

The report went on to say that the major constraints to the scheme included that :

-- there was the need for an organized means of ensuring an adequate cash flow and system of credit to maintain the pumping system and to ensure that other essential inputs would be provided;

-- that because of the poor local health situation (around 90 percent of the women are seriously anemic) the availability of an assured supply of labor was uncertain;

-- that it would have been simpler for a farmer to increase his production and income by expanding the area he farmed under flood fed and rainfed agriculture; and that

-- the pumped irrigation scheme increased the risk of farming in the area, in part because of its high cost.

The report concludes that the main constraint was the pumping system, and suggests that the introduction of a gravity-fed system would have been more cost-effective.

Even so, the implicit assumption is that irrigation will somehow improve the existing rural agricultural economy on the Lower Tana. The evidence to support this assumption is not particularly clear. Traditionally, farmers have grown their crops on a number of small plots spread out over a large area. Farming risks were reduced because all plots were affected differently by drought and by flood. Even if a few plots failed, the probability that all plots would fail was low. Admittedly, gravity-fed irrigation technologies would be much less risky than pumped irrigation technologies. At the same time, shifting the structure of production from multiple and decentralized holdings to single and centralized holdings would be a significant change in the existing farm management system. Without carrying out a proper evaluation of the potential impact of changing the basic structure of local agricultural production, the inherent risk in making this change may in fact be much greatly understated.

With any externally-assisted micro-irrigation project, the distributive impacts are perhaps not easily equalized among different income groups. This is because only a small number of farmers can benefit from individual installations of water pumps. Especially with particularly expensive technologies (such as solar pumps and large windmills), inequalities may be even more pronounced. The Shirati Hospital Solar Irrigation Project (in Tanzania), mentioned earlier, is a case in point. Technically, the system works superbly and if anything, the solar pumps are underutilized. A system for assessing water charges has been established, and a good mix of subsistence and cash crops are being produced. However, project beneficiaries are relatively few in number, and most are closely associated with the hospital itself. There is reportedly a perception in communities nearby that the hospital, which receives most of its funding from international aid organizations, contributes to growing inequalities in income distribution in the area, and that the Solar Irrigation Project is just another symptom of a larger local problem brought about by the presence of the hospital. The problem of equalizing the distributive impacts of this project is made less so because of the system of water charge assessments, but even so, it would be much less of an issue where local smallholders contributed to a greater percentage of total project costs.

Another problem with small-scale and micro-irrigation projects is the question of project management. Large-scale irrigation schemes are characterized by a complex system of farm management which is intended to maximize yields and returns. Farmers do not own the land they till, and their involvement in the scheme is dependent on their ability to meet the project management's requirements for planting, irrigating, fertilizing, weeding, and so on. Failure to do so can result in expulsion from a scheme. Obviously, the costs of implementing a similar management structure for small-scale or micro-irrigation projects could be substantial, especially if there were a large number of pumps installed in many different locations.

Rather than exhaustively reviewing the limited Kenyan experience with small-scale irrigation, we have covered just a few points that would be of significance to development planners interested in funding wind and solar-powered small-scale irrigation projects. Even though there is a growing emphasis in Kenya on the need for irrigation projects which are less expensive than large-scale schemes, it is unclear if small-scale pumped irrigation schemes are a viable alternative.

VIII. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Any brief summary of the results of this effort would tend to understate the complexity of the issues involved in evaluating the potential for the use of solar pumps and windmills for small-scale irrigation in Kenya. Beyond the physical requirements of an adequate site-specific wind regime, insolation, and ground or surface water resources, are the technical limitations of the technologies involved, cost issues, and the question of whether or not small-scale irrigation can be made a productive and cost-effective rural agricultural technology in Kenya.

Briefly, however, it can be concluded that :

1.) The windmill and solar pumping technologies which are available on the Kenyan market are technically sound and have relatively few maintenance demands.

2.) Depending on site-specific conditions, there are adequate solar, wind energy, and ground and surface water resources so that these technologies can be used for pumping water under a variety of loads and operating conditions.

3.) Under average conditions of insolation or moderate windspeeds, these technologies are financially competetive with diesel pumping technologies of a similar scale when pumping from low heads of up to 10 meters for irrigating relatively small areas of only 1 or 2 hectares. Their ability to compete with diesel technologies is greatly enhanced where diesel is unavailable or costly.

4.) Average Annualized Costs of these technologies are most sensitive to the cost of capital, and somewhat less so to the cost of Operation, Maintenance, and Repair. Because high first costs may require capital financing, the availability of capital may be a serious constraint to the use of these technologies.

5.) Because of the limited availability of capital from both the commercial banking credit system and from government-administered programs, a possible option for funding these technologies is through development aid and charitable organizations.

6.) Regardless of whether or not solar pumps and windmills are marginally competetive with diesel technologies, it is unclear whether pumped small-scale irrigation schemes are economically or financially viable. In some cases, pumped irrigation schemes have been more risky than the rural agricultural management systems which they have replaced. Although renewable energy technologies are not terribly risky investments by themselves, any risks associated with windmills and solar pumps which are used for small-scale irrigation are greatly compounded because of the risks of introducing any irrigation technology in rural areas of Kenya.

There are a number of major constraints to the widespread use of these technologies. They include :

I. Cost Issues and Financial Constraints :

1. Import duties and sales tax. Import duties and sales taxes on raw materials for windmill manufacture and import duties on photovoltaic panels greatly increase the costs of these technologies above other costs of production by up to 35 percent. Development aid and charitable organizations are exempt from most of these duties, but they may be a real disincentive to private investors.

Recommendations : Except within the established framework for reducing the costs of raw materials by importing them from countries of the Preferential Trade Area, it is unlikely that import duties on steel used in windmill manufacture could be equitably reduced in the future. In absolute terms, reducing or eliminating the sales tax on Kenyan-manufactured windmills would have a significant impact on reducing the costs of larger 16 and 20-foot machines. A significant disincentive to the private purchase of Kenyan-made windmills would be removed if the sales tax on these machines were eliminated. It would be difficult to make a strong case for eliminating the substantial import duties on photovoltaic panels, however, as long as solar pumps can be imported as agricultural equipment, import duties and sales tax on them are not really much of an issue.

2. High first costs and the lack of available capital. High first costs will often require the availability of financing for these technologies. Even though in the long run, the costs of operating a windmill or solar pump may be lower than the costs of operating a diesel pumping technology, high capital costs of both windmills and solar pumps may make their purchase prohibitive because credit may not be available at a reasonable price. Smallholder credit with the long-term repayment schedule that would be required for the purchase of solar and wind pumping technologies is virtually unavailable from private financial markets or from Government-administered sources.

Recommendations : Multilateral and bilateral development assistance agencies hold some potential for financing the purchase of these technologies. The difficulties of administering any kind of credit program while expecting full cost recovery would make such a program unsound from the start. At the same time, a *small-grants program funded by development aid which financed communities or groups of farmers to purchase these technologies, with a provision for partial cost sharing, would provide financial capital within the framework of distributionally equitable and developmentally positive assistance*.

II. Constraints Associated with Renewable Energy Technology-Transfer :

1. Windmills and solar pumps are unfamiliar technologies. The promotion of the transfer of windmill and solar pumping technologies to rural agricultural economies requires the development of a local understanding, however basic, of how these technologies work, what they are capable of doing, what their limitations are, and how to repair them. There is currently no mechanism for ensuring that any of these needs can be met. In terms of public policy actions that might affect the use of these technologies, they have suffered from a sort of official benign neglect.

Recommendations : Within the framework of the government's current energy and agricultural policies, *demonstration installations of windmills and solar pumps at Farmer's Training Centres or in functionally similar locations with adequate wind regimes or insolation would help to familiarize rural smallholders with these technologies*. In conjunction with the installation of these technologies, a comprehensive education and extension effort would be needed to provide information about maintenance demands and an understanding of their operating capacities and limitations.

2. Poor understanding of the process by which technologies are matched with end-uses. There is little adequate information available about the productivity of plots which are being irrigated with windmills and solar pumps in Kenya. Except for privately-financed purchases of these technologies, end-use applications may have little bearing on the real demand for pumped water.

Recommendations : *A more thorough review of the uses for solar pumps and windmills in Kenya would help in matching the available technologies with end-use needs in future activities*. Multiple end-use demand management, characteristic of most solar pump and windmill installations in Kenya, should be explored as a possible means of maximizing the benefits of pumping water using these technologies.

III. Constraints Associated with the Use of Small-Scale Irrigation Technologies :

These constraints reflect the fact that small-scale irrigation requires different methods of extension, marketting, and basic agricultural management than large-scale irrigation schemes. *A comprehensive review effort of the existing small-scale irrigation schemes would provide an opportunity for evaluating the cost-effectiveness of this approach towards agricultural development*. Any policy interventions which might affect the use of solar pumps and windmills may have a relatively small impact on the use of renewable energy technologies for small-scale irrigation unless adequate interventions are made to deal with the problems of introducing any small-scale irrigation technology into the Kenyan rural agricultural economy.

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REFERENCES

1. Peter A. Dewees. Renewable Energy Technologies in Kenya: A Place in the Sun for the Private Sector?. Nairobi: Institute for Development Studies (Working Paper Number 402), 1984.

2. It was originally proposed to include biomass gasifier technologies in this analysis. While there would be some utility in including them in this effort, a number of considerations militate against their inclusion. In many respects, they more closely resemble conventional irrigation technologies than either windmills or solar pumps because there may be significant opportunity costs involved in assuring a guaranteed supply of fuel. Further, although smaller units are available, large biomass gasification systems are more commonly used for intermediate-scale sprinkler irrigation schemes. Wind and solar pumps, on the other hand, are most appropriate for micro-irrigation applications and it is useful here to compare those two technologies because they have similar end-uses. Interested readers are referred to the Manager of General Systems, Ltd. of Nairobi which manufactures the Amica Biomass Gasifier.

3. International Labor Office. Employment, Incomes, and Equality: A Strategy for Increasing Productive Employment in Kenya. Geneva: International Labor Office, 1972. p.33.

4. Excluding Mombassa and Nairobi Districts. See: Republic of Kenya, Ministry of Economic Planning and Development. Statistical Abstract, 1983. Nairobi: Central Bureau of Statistics, 1983. p.13.

5. Republic of Kenya, Office of the President. Development Plan, 1984 - 1988. Nairobi: Government Printer, 1983. p.177.

6. This is, in general, true primarily because the area of smallholdings which is allowed to lie fallow is much less than the fallow area of large farms. It is arguable whether productivity and employment per hectare on cultivated lands is higher on smallholdings than on large farms, but the evidence seems to suggest this is true. See: World Bank. Growth and Structural Change in Kenya: A Basic Economic Report (Annex II: Issues in Kenyan Agricultural Development. Washington, D.C.: World Bank, 1982. pp.68-70. Much of the analysis of the agricultural sector in this paper has been drawn from the World Bank report.

7. Hans Ruthenberg. Outline of a Strategy for Agricultural Development in Kenya. mimeographed, 1978.

8. This compares poorly with other countries such as India where irrigation has had high priority in its development plans. Around 15 to 20 percent of India's land is irrigated, and over a million hectares a year are being brought under irrigation every year. See: The Economist. 292: 7355 (18 August 1984), p.58.

9. World Bank, op.cit., 1982. p.35.

10. Development Plan, 1984 - 1988. pp.163 and 183.

11. Robert Chambers. "The Perkerra Irrigation Scheme: A Constrasting Case," in: R.Chambers and J.Moris (eds.). Mwea: An Irrigated Rice Scheme. Munich: Weltforum Verlag, 1973. pp.334-353.

12. Kenya Colony, Department of Agriculture. Annual Report for 1953. Nairobi: Government Printer, 1953. p.55.

13. Statistical Abstract, 1983. p.115.

14. Alan Fowler. Review of the Lower Tana Project. Nairobi: National Christian Council of Kenya (NCCK), 1980. p.13.

15. J.C.deWilde. Experiences with Agricultural Development in Tropical Africa. Baltimore: Johns Hopkins Press, 1967. pp.109-115.

16. National Irrigation Board. Joint Evaluation of the Role of the Operational Research and Training Project in the National Irrigation Board, Government of Kenya - Government of the Netherlands. Nairobi: National Irrigation Board, 1982. p.38.

17. Republic of Kenya, Ministry of Water Development. National Master Water Plan: Stage I (Volume I: Summary and National Plan). Nairobi: Ministry of Water Development, 1980.

18. G.O.P.Obasi and N.N.P.Rao. "Solar Energy Resources in Kenya," in: C.P.M.Khumala and J.B.Castelino (eds.). Energy Resources in East Africa. Nairobi: Kenya National Academy for Advancement of Arts and Sciences, 1979. pp.32-52.

19. East African Meteorological Department. Climatological Statistics for East Africa, 1968 - 1973. Nairobi: Government Printer, 1973.

20. One Langley is equivalent to 1 calorie per square centimeter. There are 86 Langleys per kWh per square meter.

21. S.Forman. "Photovoltaic module performance and degradation," in: Proceedings of the 1979 International Congress of the International Solar Energy Society. Victoria (Australia): International Solar Energy Society, 1979.

22. W.E.van Lierop and L.R.van Veldhuizen. Wind Energy Development in Kenya (Executive Summary; Volume I: Past and Present Wind Energy Activities; Volume II: Wind Potential; Volume III: End Use Analysis). Amersfoort (the Netherlands): Steering Committee for Wind Energy in Developing Countries, 1982.

23. G.B.Chipeta. A Study of Wind Power Availability in Kenya. Nairobi: University of Nairobi (M.Sc. Thesis), 1976.

24. ILACO Consulting Engineers. Mbita Water Supply and Irrigation Pre-feasibility Study. Nairobi: Ministry of Water Development, 1977.

25. A.van Vilsteren. Windmills for Water Lifting: Feasibility Study. Nairobi: Small-Scale Irrigation Unit (Ministry of Agriculture), 1980.

26. See for instance: P.K.Gingold. "The Cost-Effectiveness of Water Pumping Windmills," in: Wind Engineering, 3: 4(1979), pp.231-262.

27. Sir William Halcrow and Partners. Project Report: World Bank/UNDP Project GLO/80/003, 1983.

28. The "peak watt" is the standard convention which is used for reporting on the performance of solar cells. It refers to the number of watts a photovoltaic cell, module, or array of modules will produce under peak illumination of 1 kW/m^2 and at standard atmospheric and temperature conditions. Costs per peak watt generally include the costs of the module, electrical connections, and the costs of the supporting structure as well. These latter costs, excluding the costs of the photovoltaic cells themselves are often called Balance-of-System (BOS) costs.

29. U.S.Department of Energy. Electric Power from Solar Cells. Washington, D.C.: Government Printing Office, 1980.

30. Larry N. Stoiaken. "A New Generation of Photovoltaic Commercialization Efforts Gain Momentum," in: Alternative Sources of Energy. 67: 9, 1984.

31. Solarex Corporation. Technical Proposal: Photovoltaic Pumping Systems for Mali. Rockville, MD. (United States): Solarex Corporation (Technical Proposal F4-13), 1984.

32. This discussion is drawn from interviews with J.L.M.Goodwin of Animatics, Ltd., and with James Kenney of SEI. Performance data is drawn from information provided by SEI.

33. Derived from the relationship: $P = [H][Q][9.81]$

    where P is the power expressed in watts, H is the head expressed in meters, Q is the flow is expressed in liters per second, and 9.81 is the gravitational constant.

34. This facility is powered by photovoltaic cells which produce 200kW of peak power. Power output is sufficient to operate the photovoltaic production process, hence the name "Solar Breeder."

35. Another advantage behind this strategy has been that a solar pump which is imported into Kenya as agricultural equipment can be imported duty-free, while solar panels which are imported separately are charged a 45 percent import duty and 17 percent sales tax. To a certain extent, this is a moot point, as development aid and charitable organizations which make up the primary markets for these pumps are able to import equipment into Kenya duty-free anyway.

36. Solarex Corporation. op.cit.

37. National Academy of Sciences. Energy for Rural Development: Renewable Resources and Alternative Technologies for Developing Countries. Washington, D.C.: National Academy of Sciences, 1976. pp.113-115.

38. van Lierop and van Veldhuizen, op.cit. p.52.

39. ibid.

40. This discussion is drawn from interviews with Andrew Challoner (General Manager) and George Anywar (Production Manager) of BHEL. See also:

    van Lierop and van Veldhuizen. op.cit. (Volumes I and III);

    Peter Byrne. Wind and Water: The Application and Suitability of Windpumps in Kenya. Washington, D.C.: International Institute for Environment and Development, 1983;

    Fred Nyanga. "The All-Important Kijito Windpumps," in: Kenya Farmer, July 1984. pp.8-10.;

    BHEL. An Introduction to Kijito Windpumps. Thika: BHEL, 1983.

41. For an interesting account of this project, see:
    Peter Fraenkel. Food from Windmills. London: Intermediate Technology Development Group, 1975.

42. "Kijito" is a Kiswahili word for "stream of water."

43. By late 1981, Mike Harries had managed to pull together about U.S.$1 million in risk capital for the venture, including a special loan from the Barclay's Bank (International) Development Fund.

44. W.Adams. The ITDG Windpump Program: An Example of Technology Transfer. London: IT Consulting Engineers, 1980.

45. Especially for the 16 and 20-foot models, there is some question in Figure 16 of whether the output could be as high as predicted, especially at low windspeeds. When the output is known, we can use the following relationship to determine the C_p:

$$C_p = [H][Q][K]/[V^3][A]$$

where H is the head in meters, Q is the output in cubic meters per day, V is wind velocity in meters per second, and A is the swept area in square meters. K is a constant (0.1836) which incorporates several conversion factors, as well as the gravitational constant. If we examine the efficiencies for the 20-foot machine, operating at a wind run of 200 km/day (or 2.3 meters per second), we find that, at a head of 25 meters, and with an output of $63 m^3$ per day, the C_p is 0.8 -- which exceeds the Betz Maximum of 0.59. Presumably accurate performance data are available through the the monitoring efforts of ITIS, and it is highly recommended that BHEL incorporates this data into comprehensive performance curves which reflect output versus windspeed at varying heads for each of their machines.

46. P.R.Gingold. op.cit.

47. ILACO Consulting Engineers. op.cit.

48. K.Jensen. Feasibility of Manufacturing Wind-Powered Water Pumping Equipment. Nairobi: UNDP/UNIDO (Project SI/KEN/75/802), 1978.

49. Much of this discussion has been drawn from:
van Lierop and van Veldhuizen. op.cit. (Volume I).

50. TOOL Foundation. TOOL-ORP Windmill Project: Evaluation Report. Ghazipur (India): TOOL Foundation (Technical Development for Developing Countries) and ORP (Organization of the Rural Poor), 1980.

51. CWD Consultancy Services. Proposal for a Kenya Wind Energy Project. Amersfoort (Netherlands): CWD Consultancy Services, 1984.

52. Redd Barna-Kenya. 1983 Annual Report. Kisumu: Redd Barna, 1984.

53. van Lierop and van Veldhuizen. op.cit. (Volume I).

54. Gabrowski and Poort Consulting Engineers. Lower Tana Village Irrigation Program: A Technical Study (Interim Report). Nairobi: Ministry of Agriculture, 1981.

55. van Lierop and van Veldhuizen. op.cit. (Volume III).

56. Peter Fraenkel. The Power Guide: A Catalogue of Small-Scale Power Equipment. London: Intermediate Technology Development Group, 1981.

57. David French. The Economics of Renewable Energy Systems for Developing Countries. Washington, D.C.: Agency for International Development, 1979.

58. P.R.Gingold. op.cit.

59. Republic of Kenya, Ministry of Finance and Planning. Economic Survey, 1984. Nairobi: Central Bureau of Statistics, 1984. pp.63-65.

60. World Bank. Agricultural Credit Sector Policy Paper. Washington, D.C.: World Bank, 1975. pp.29 and 79.

61. Republic of Kenya, Ministry of Commerce and Industry. Import Licensing Schedules, 1984. Nairobi: Government Printer, 1984.

62. Using a least-squares fit line

$$y = 0.0054x + 0.0217$$

where x is head in meters, and y is total cost per cubic meter in dollars.

63. See for instance:
van Lierop and van Veldhuizen. op.cit. (Volume III); and
Peter Byrne, op.cit.

64. We included OMR costs in our analysis of solar pumps at a rate of 0.5 percent of capital costs. We chose not to assess the sensitivity of solar pumping costs to changes in these OMR costs because they will likely remain very low and because we did carry out an assessment of the sensitivity of total costs to changes in the life expectancy of solar pumps. Major recurrent costs for solar pumping systems will consist of periodic pump replacements, and not of standard costs for OMR.

65. Pumping efficiency of 25 percent is suggested by Gingold, *op.cit.* Thermal conversion efficiency for diesel engines of 34 percent is commonly used. See: World Bank. *The Energy Transition in Developing Countries*. Washington, D.C.: World Bank, 1983. p.xvi.

66. *Import Licensing Schedules, 1984*.

67. See: World Bank. *The Energy Transition in Developing Countries*. We have excluded the cost of the conversion technologies here because we are interested in the costs and duties on energy sources, and not on the conversion technologies *per se*.

68. Lee Shipper, et al. *Energy Conservation in Kenya's Modern Sector: Progress, Potential, and Problems*. Washington, D.C.: Resources for the Future (unpublished Discussion Paper D-73i), 1982.

69. *Development Plan*, p.44.

70. *ibid*., p.117.

71. *ibid*., p.48.

72. The Self-Help Fund has also financed the purchase of 5 inexpensive American-made windmills for a project which never got off the ground because of an inadequate wind regime. Several of these machines have been installed in other locations.

73. The EDF is also financed by U.S.AID.

74. Paul Duane. *A Policy Framework for Irrigation Water Charges*. Washington, D.C.: World Bank (Bank Staff Working Paper No. 218), 1975.

75. Tom Frantz. *Shirati Hospital and Leprosy Control Center: Solar Irrigation Project*. (mimeographed). 1982.

76. Interview with Harold Miller, Mennonite Central Committee Regional Office, Nairobi.

77. Todd Bartlem. *Alternative Energy in Kenya: Prospects for Public and Private Action*. (Report of a Workshop to Catalyze Investments in Renewable Energy and Energy Efficiency, Nairobi, 15-16 June 1983). Washington, D.C.: International Institute for Environment and Development, 1983.

78. Republic of Kenya, Ministry of Economic Planning and Development. *The Integrated Rural Surveys, 1976-1979: Basic Report*. Nairobi: Central Bureau of Statistics, 1981. p.39.

79. *ibid.*, p.74.

80. *ibid.*, p.87.

81. Republic of Kenya, Ministry of Agriculture. *Review Study of the Lower Tana Village Irrigation Programme*. Nairobi: Irrigation and Drainage Branch (Ministry of Agriculture), 1983.

TECHNICAL APPENDICES
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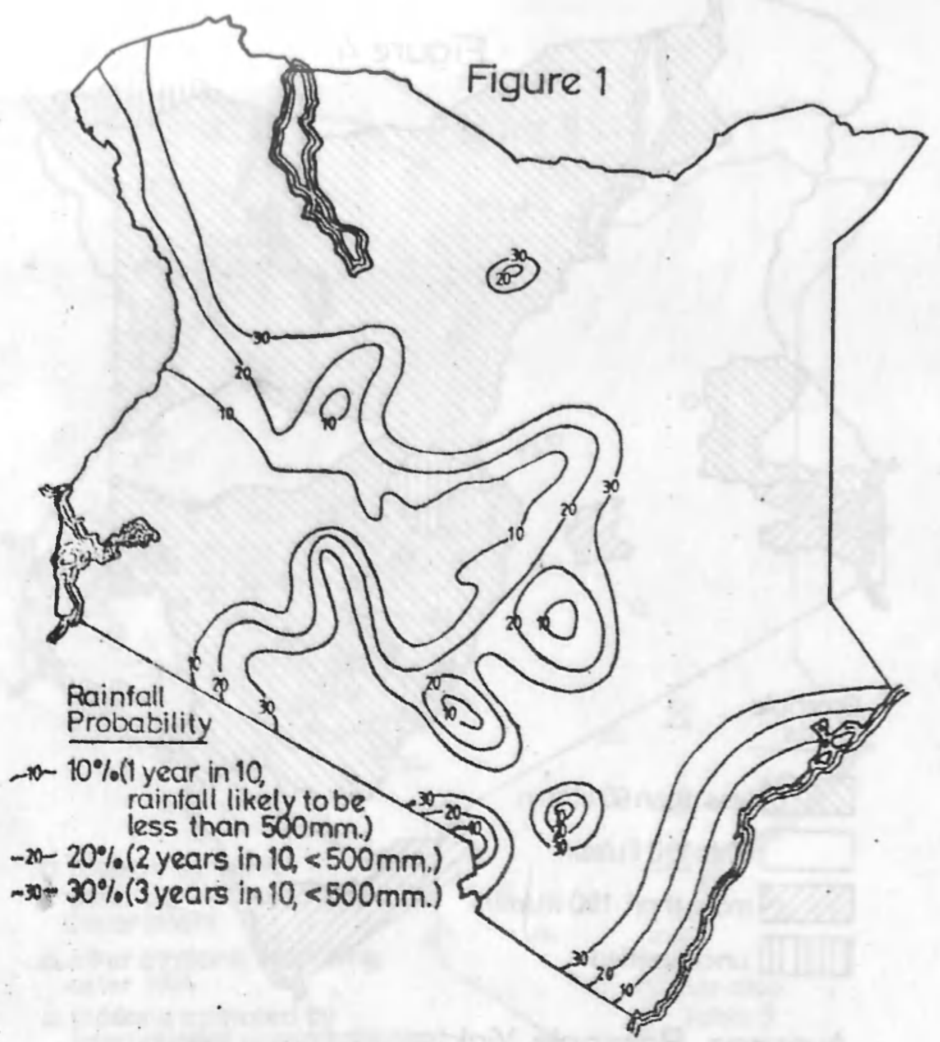
TECHNICAL APPENDICES (Table of Contents, continued)

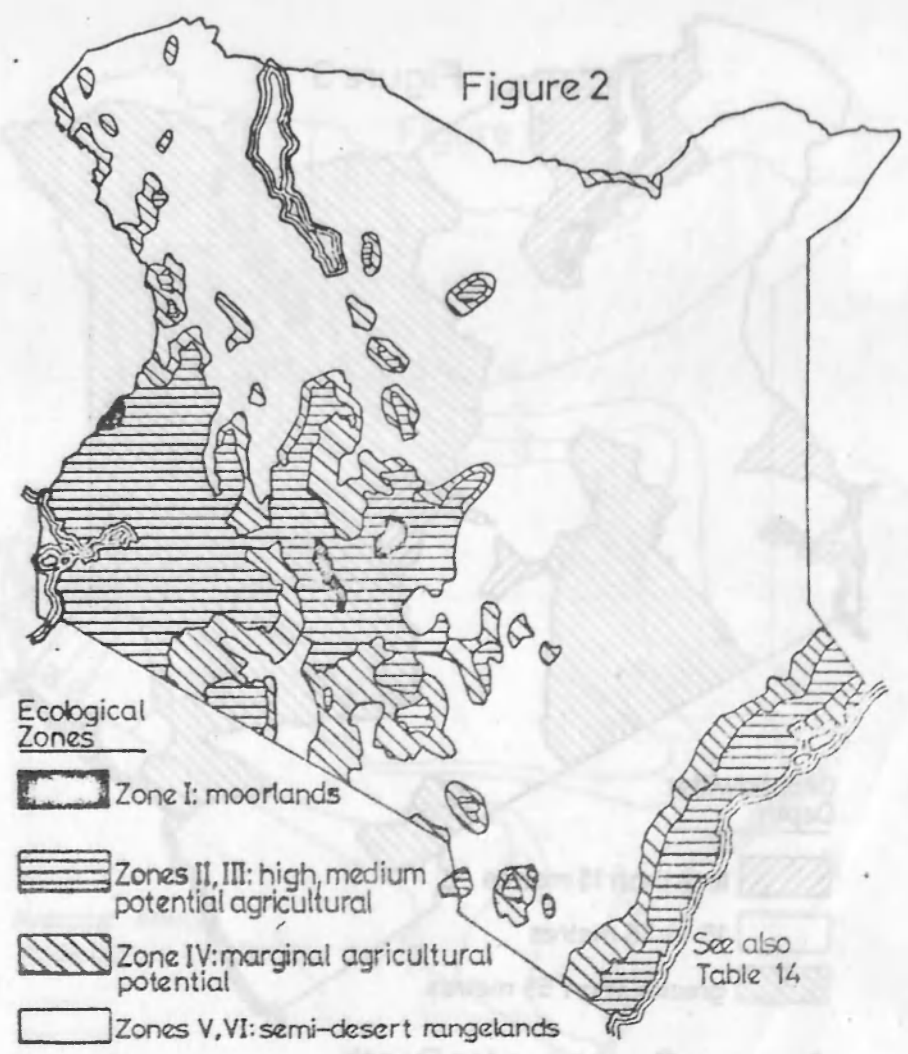
List of Tables

Figure 1



Probability of Rainfall in High Potential Agricultural Areas

Figure 2



Zones of Agro-Ecological Potential

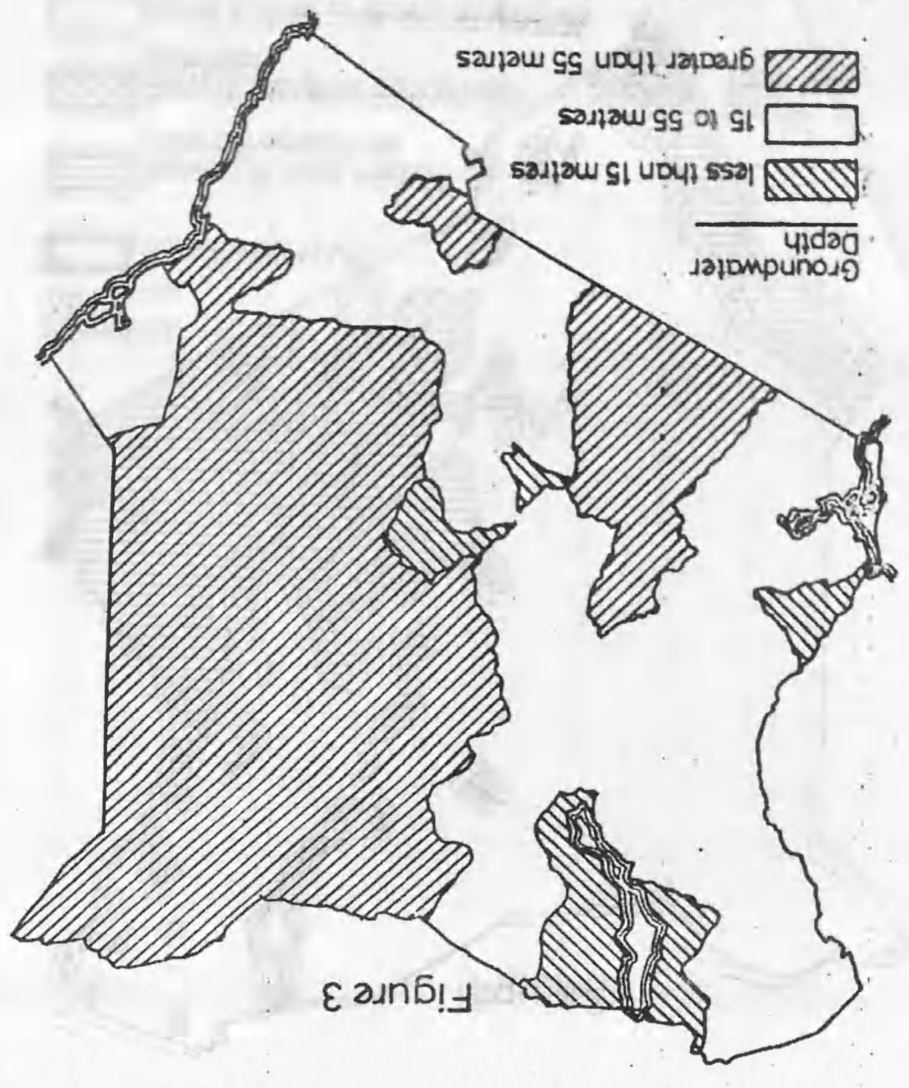


Figure 3

Average Groundwater Depth by Drainage Basin

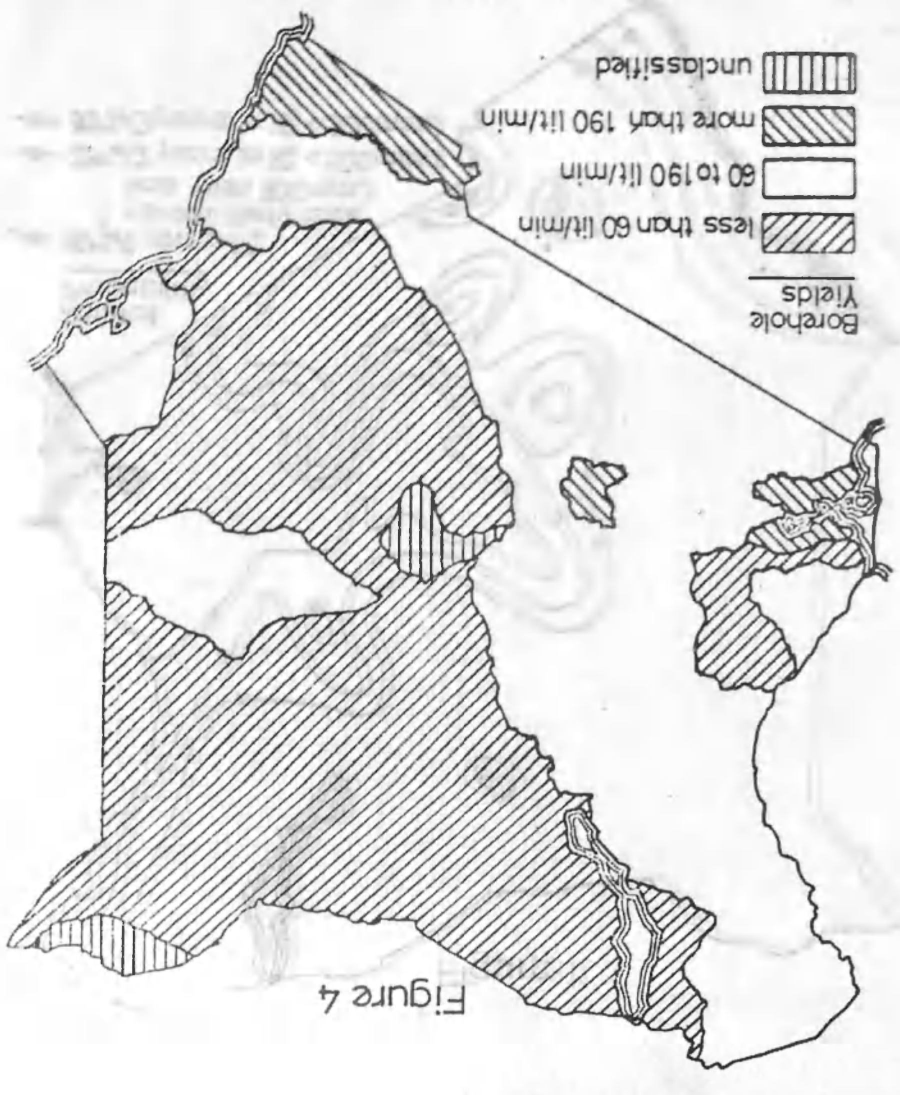
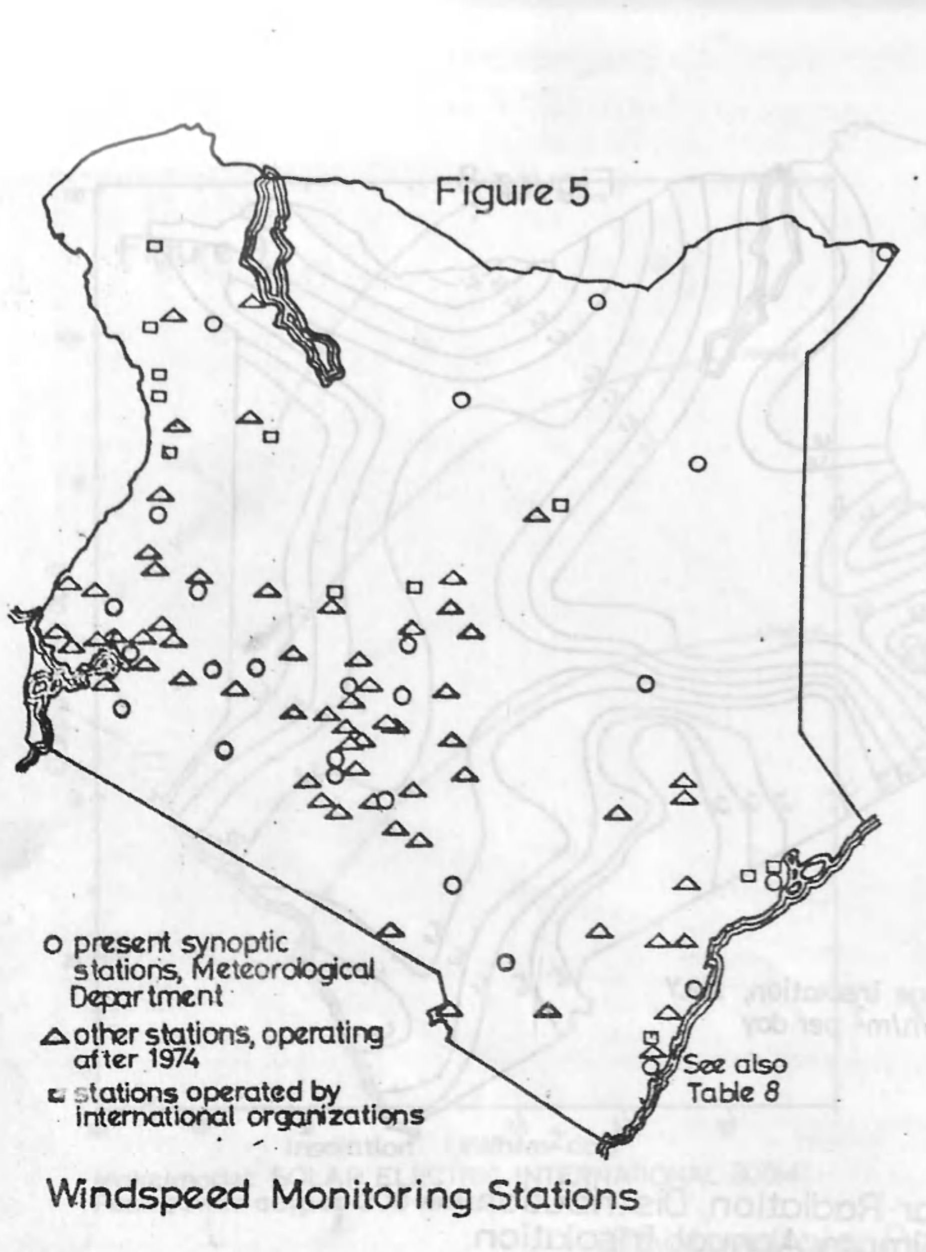


Figure 4

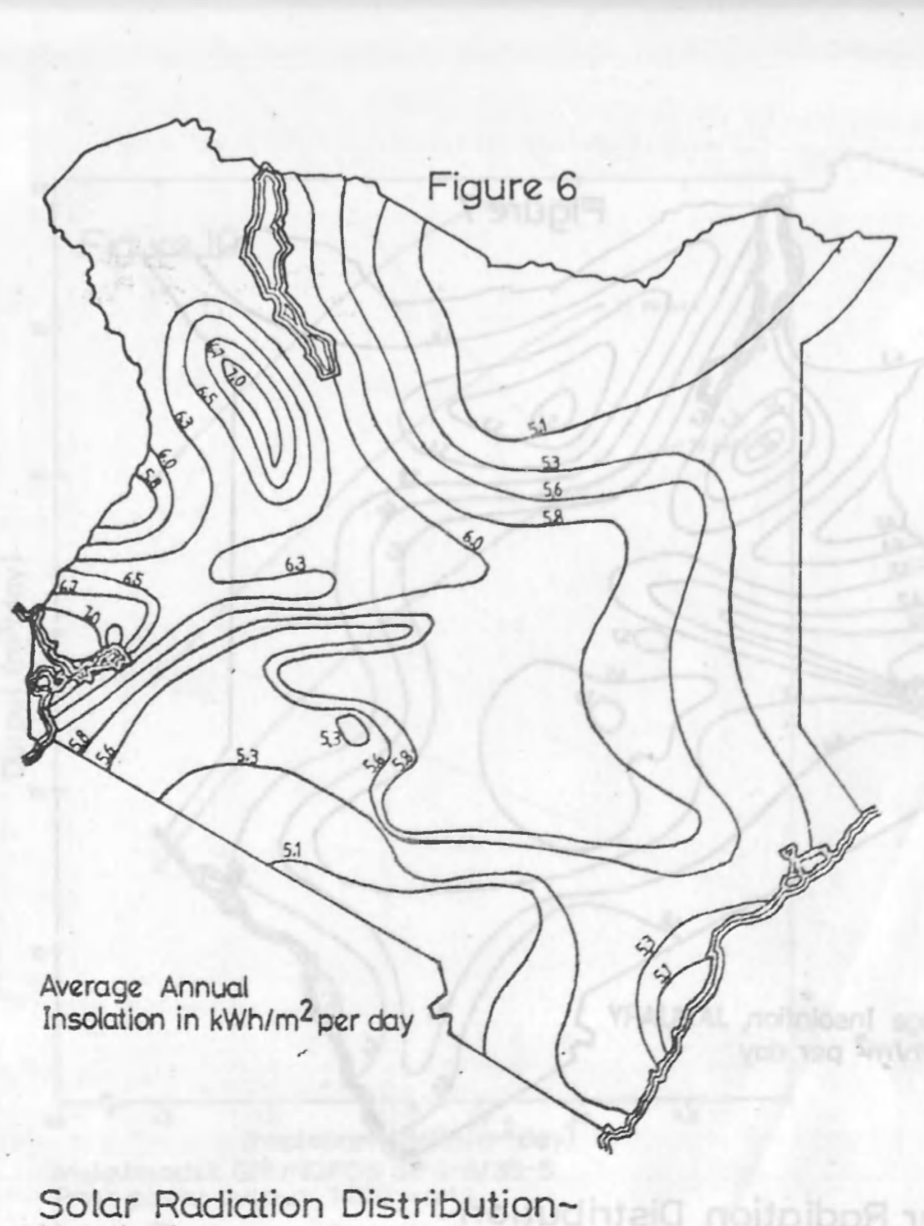
Average Borehole Yields by Drainage Basin

Figure 5



Windspeed Monitoring Stations

Figure 6



Solar Radiation Distribution– Yearly Average Insolation

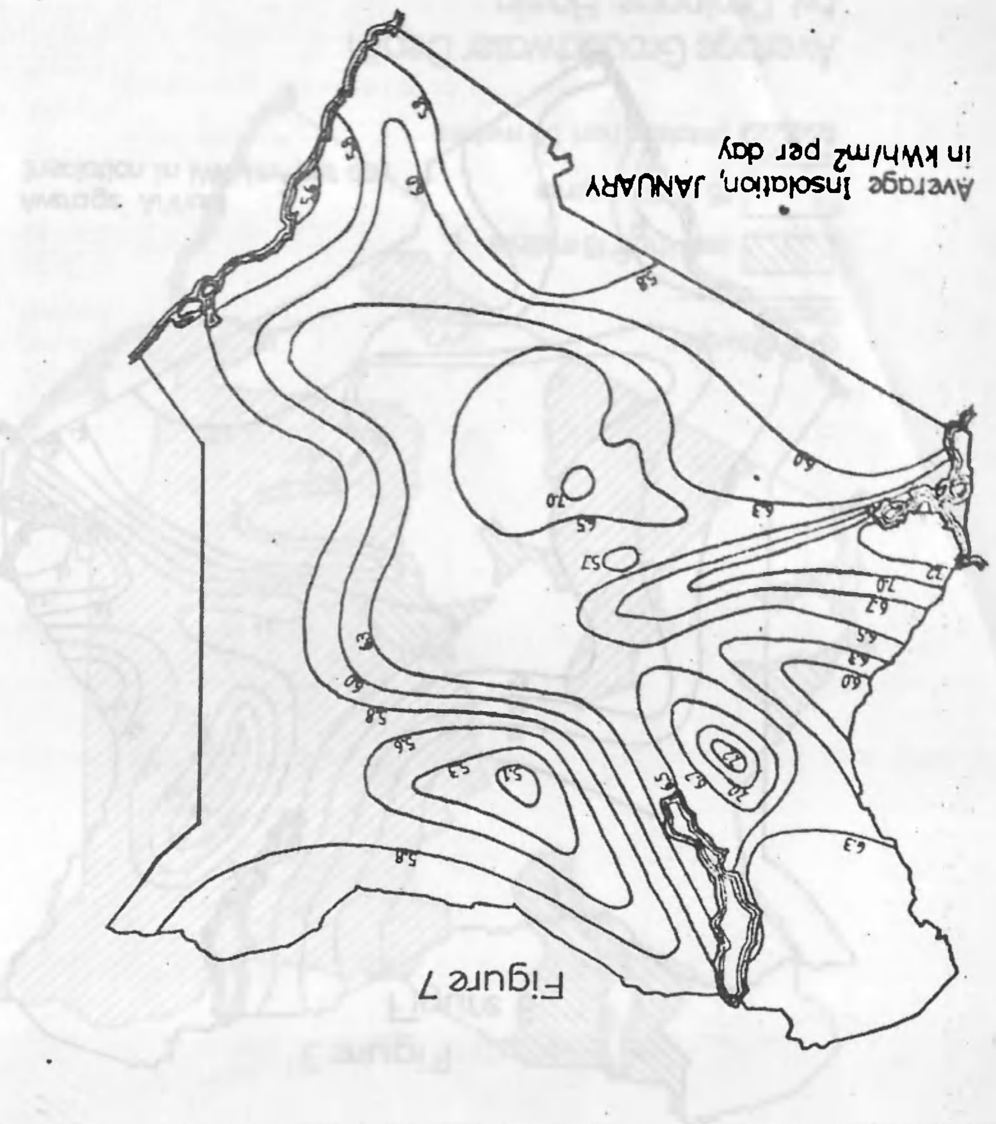


Figure 7

Average Insolation, JANUARY
in kWh/m2 per day

Solar Radiation Distribution--
Maximum Annual Insolation

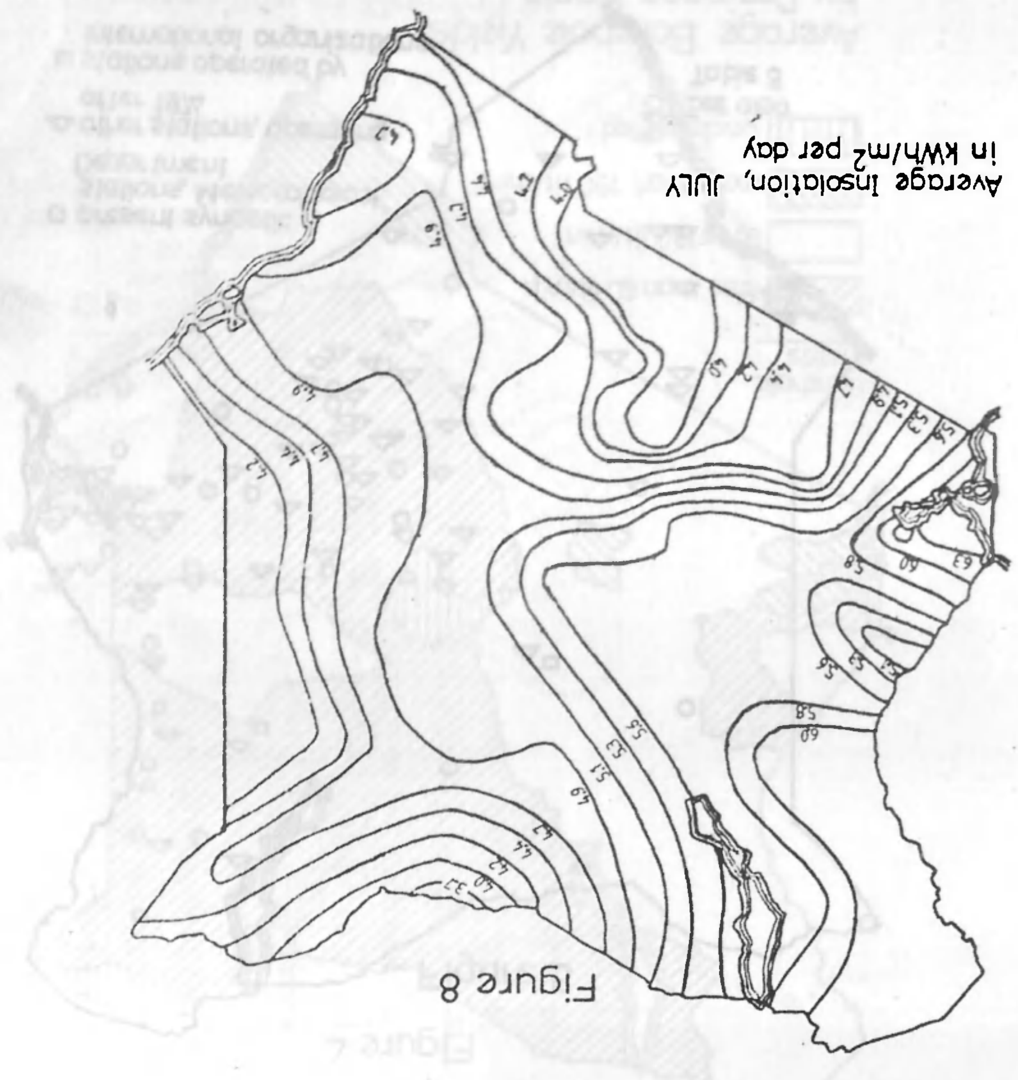
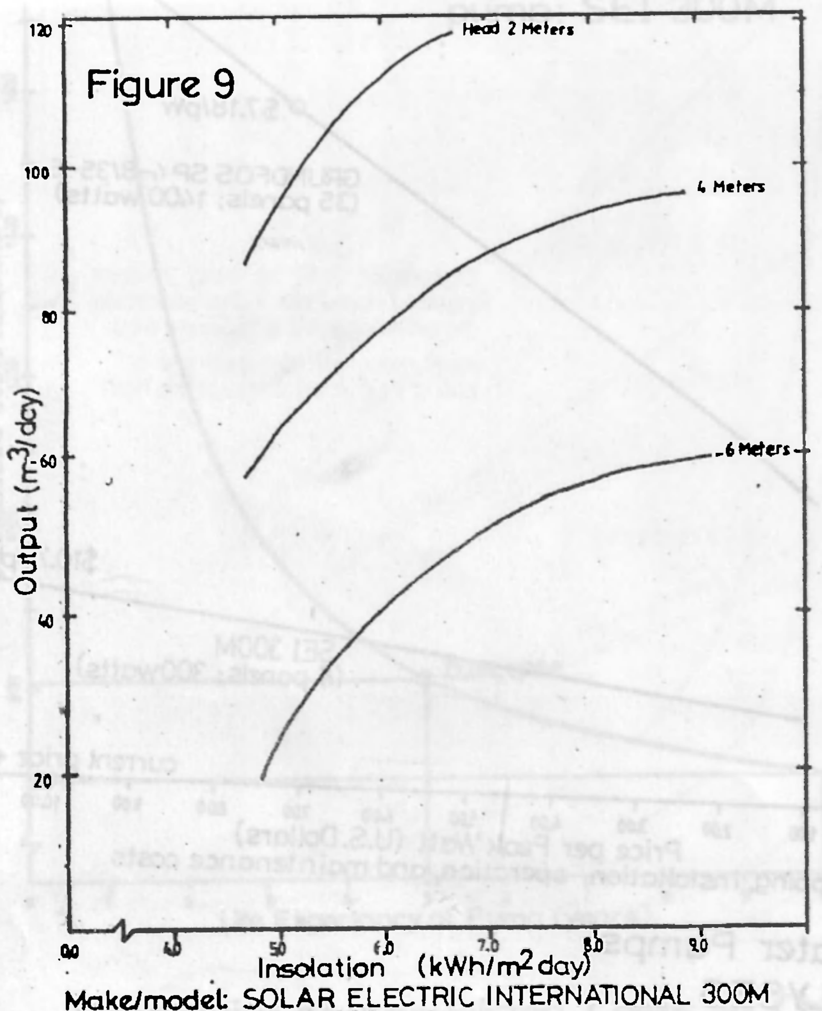


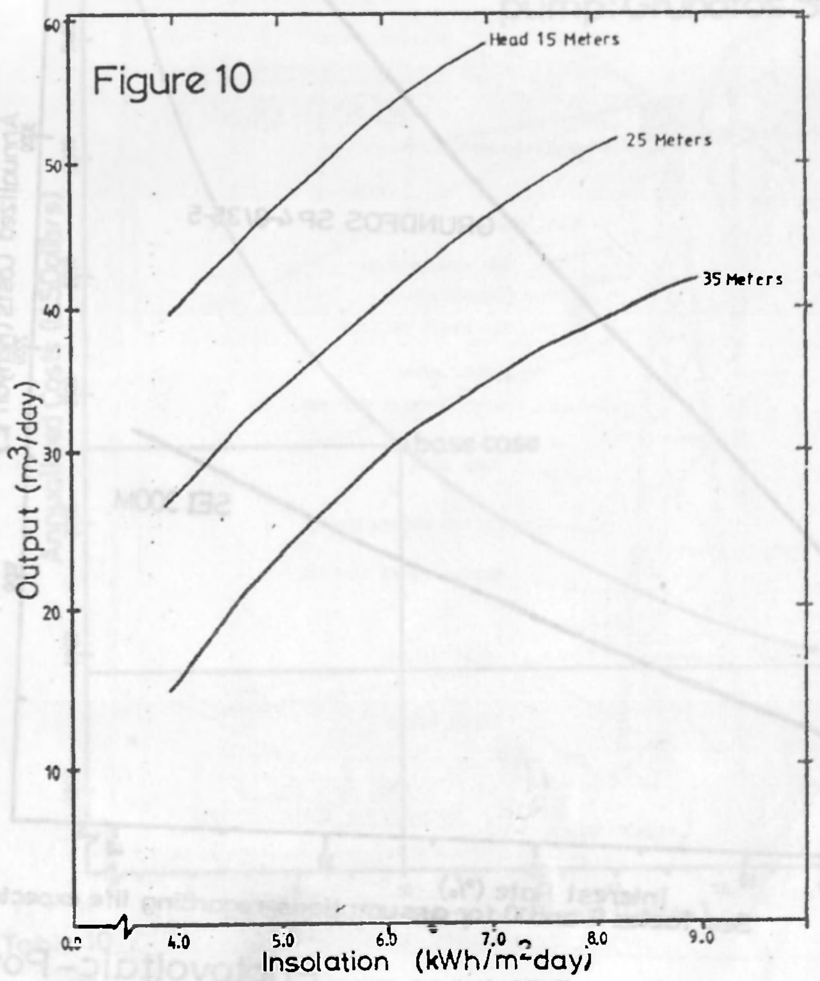
Figure 8

Average Insolation, JULY
in kWh/m2 per day

Solar Radiation Distribution~
Minimum Annual Insolation



Make/model: SOLAR ELECTRIC INTERNATIONAL 300M
Peak power output: 300 watts

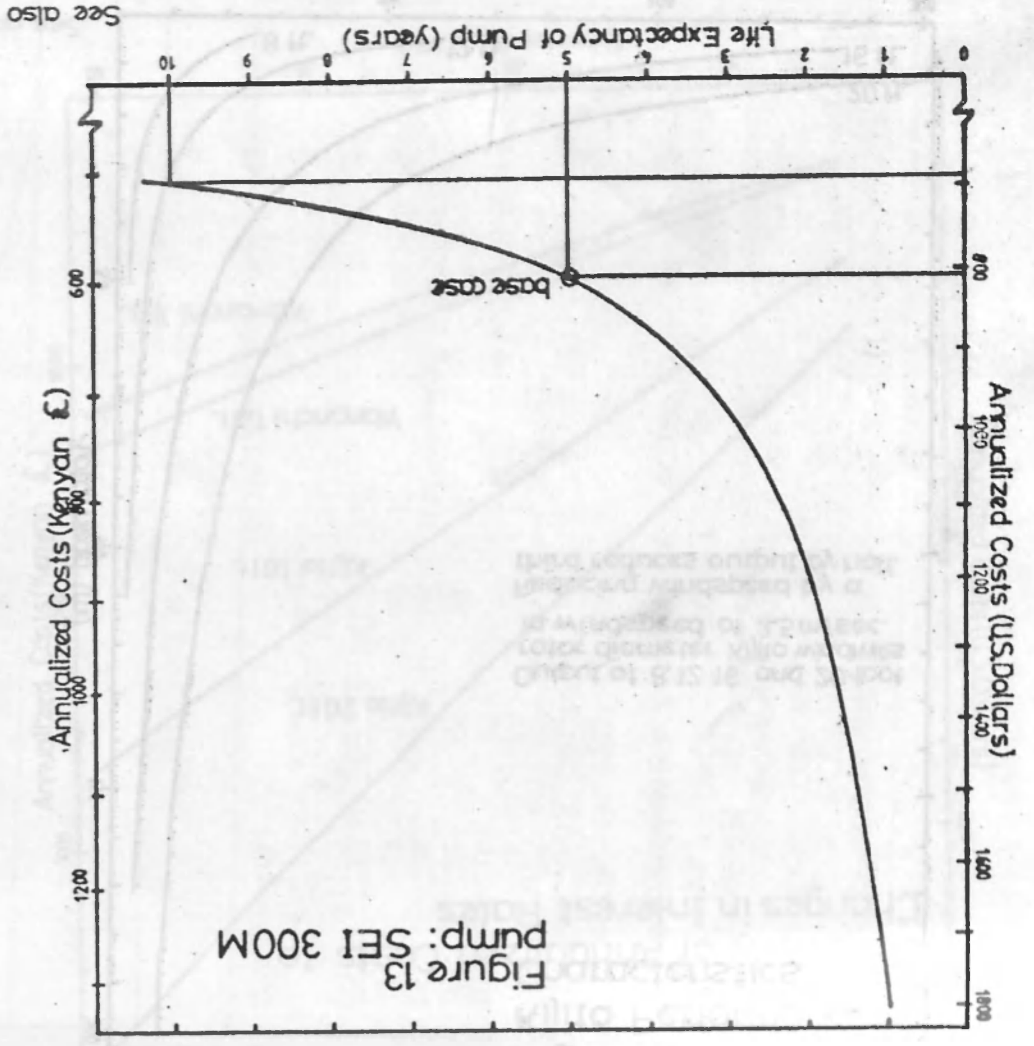


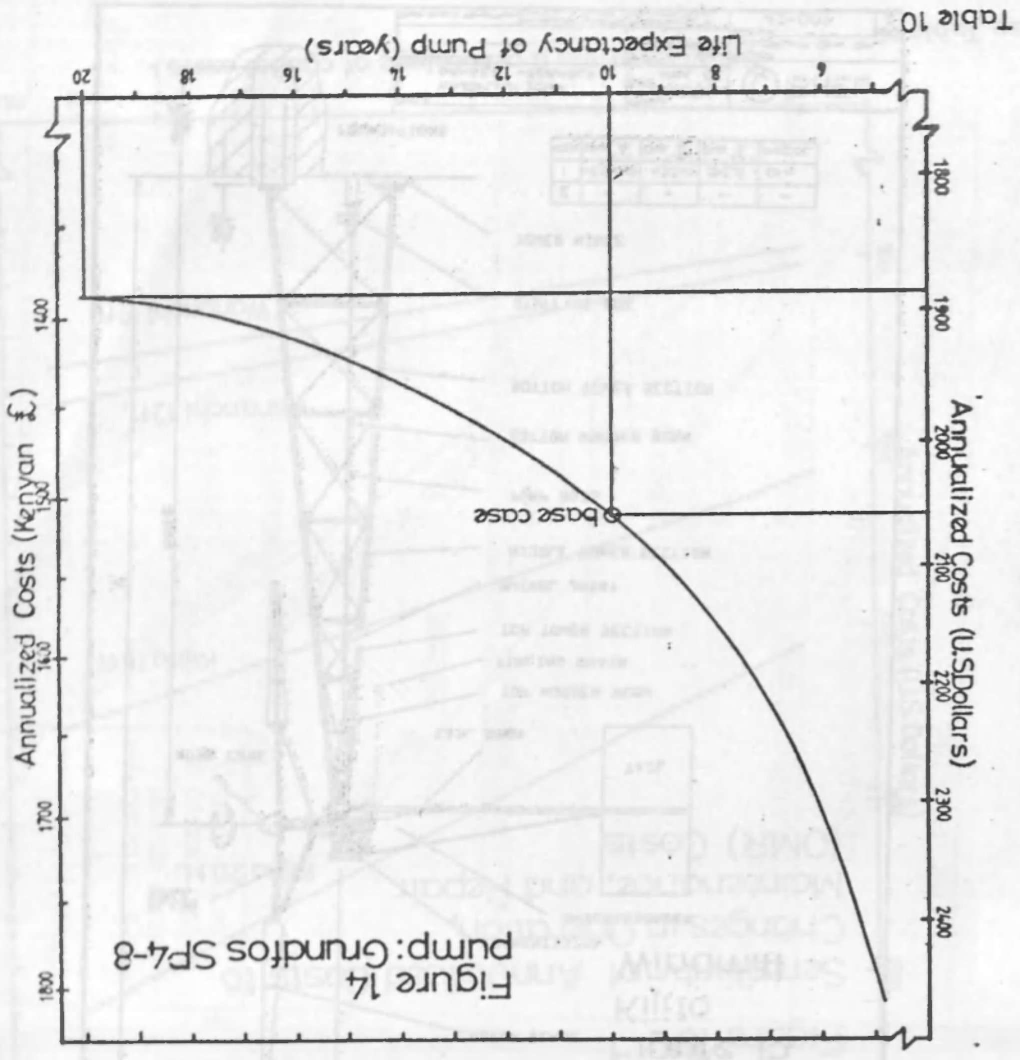
Make/model: GRUNDFOS SP4-8/35-5
Peak power output: 1400 watts

Photovoltaic-Powered Water Pumps
PERFORMANCE CHARACTERISTICS

Sensitivity of Annualized Costs to Changes in Life Expectancy of Solar-Powered Water Pumps

See also Table 10





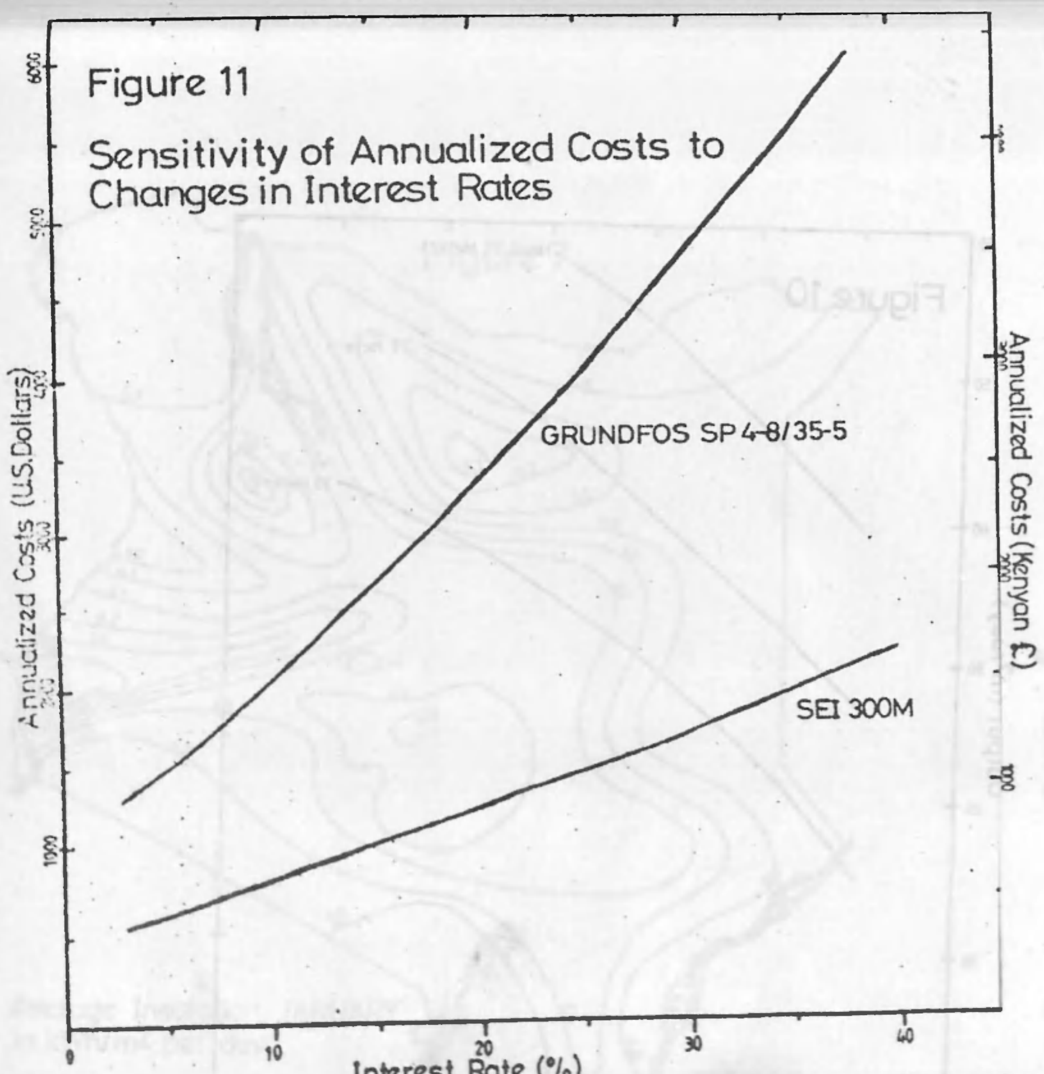


Figure 11

Sensitivity of Annualized Costs to Changes in Interest Rates

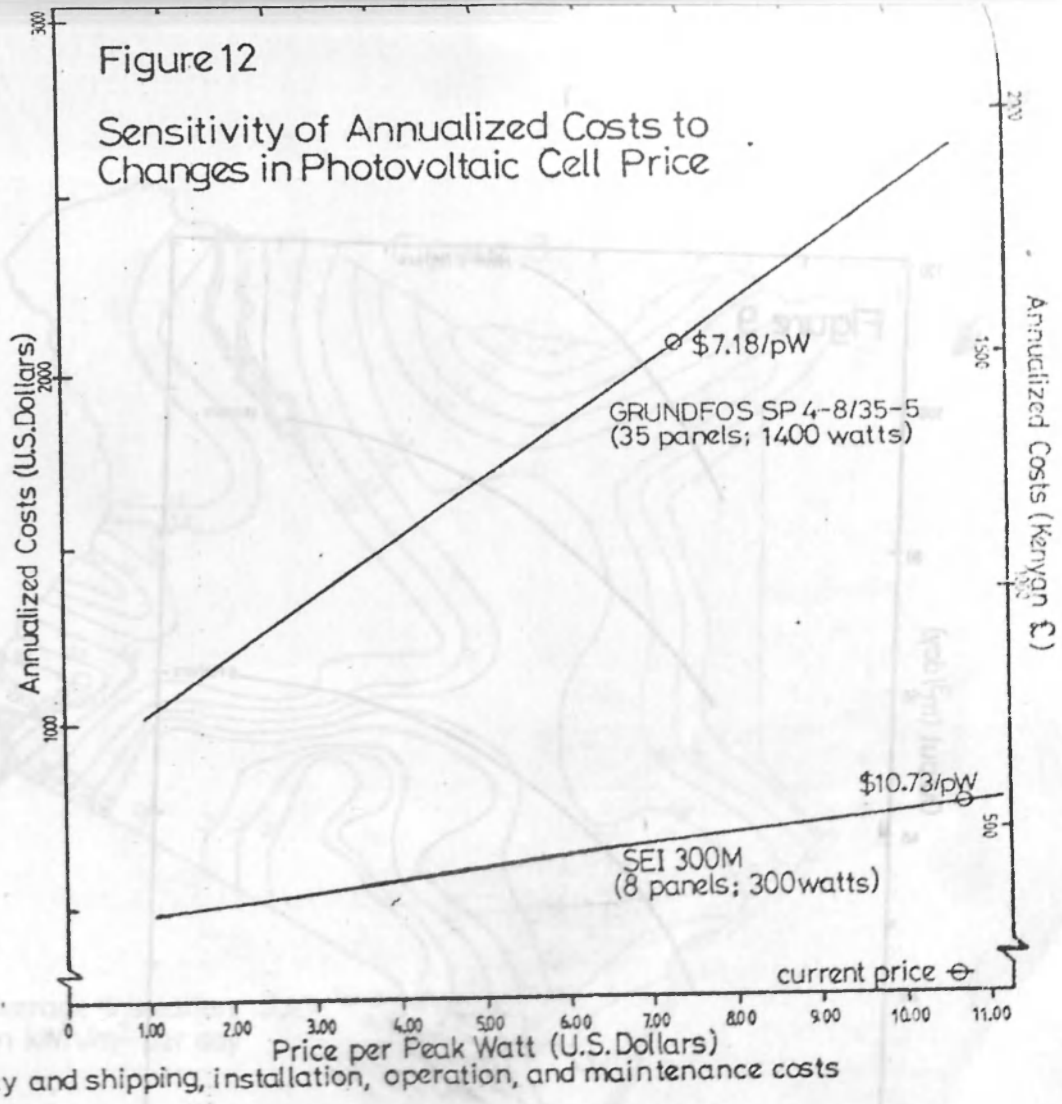


Figure 12

Sensitivity of Annualized Costs to Changes in Photovoltaic Cell Price

See Tables 9 and 10 for assumptions regarding life expectancy and shipping, installation, operation, and maintenance costs

Photovoltaic-Powered Water Pumps
SENSITIVTY ANALYSES

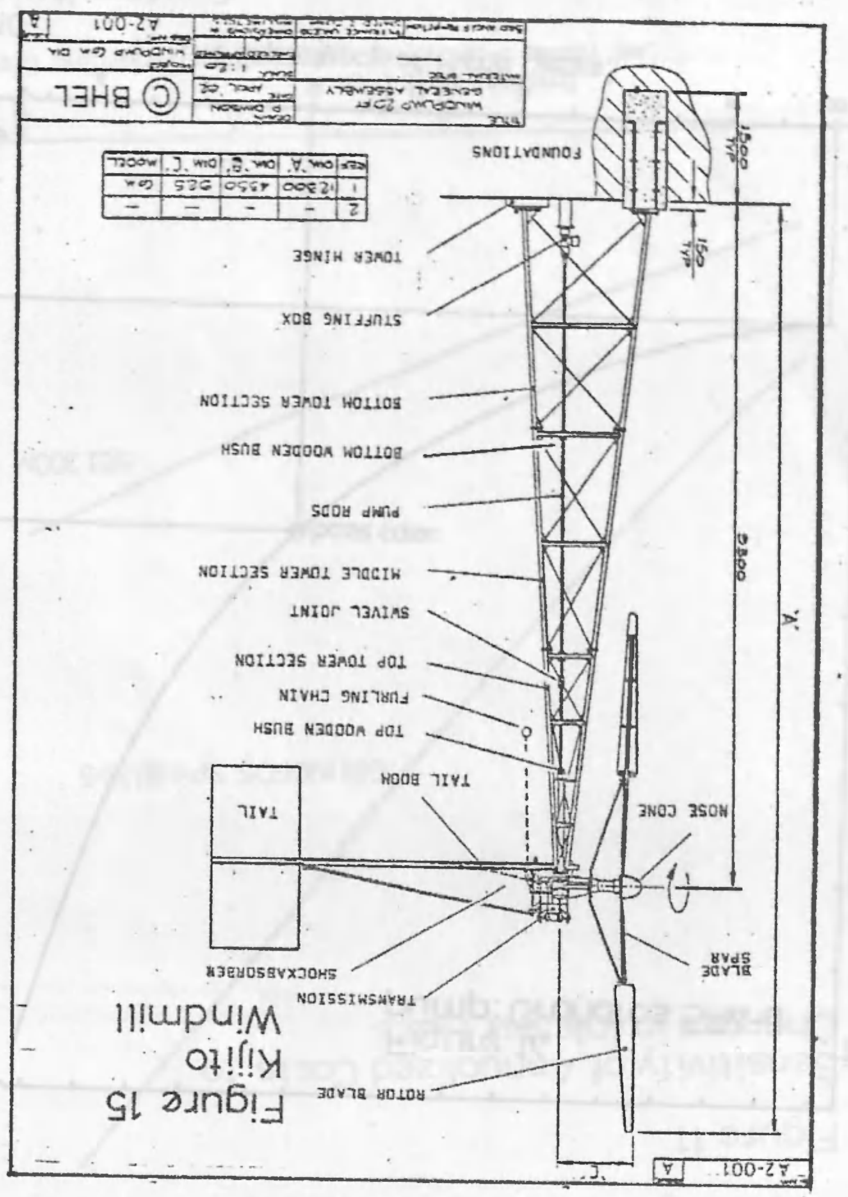


Figure 15
Kijito
Windmill

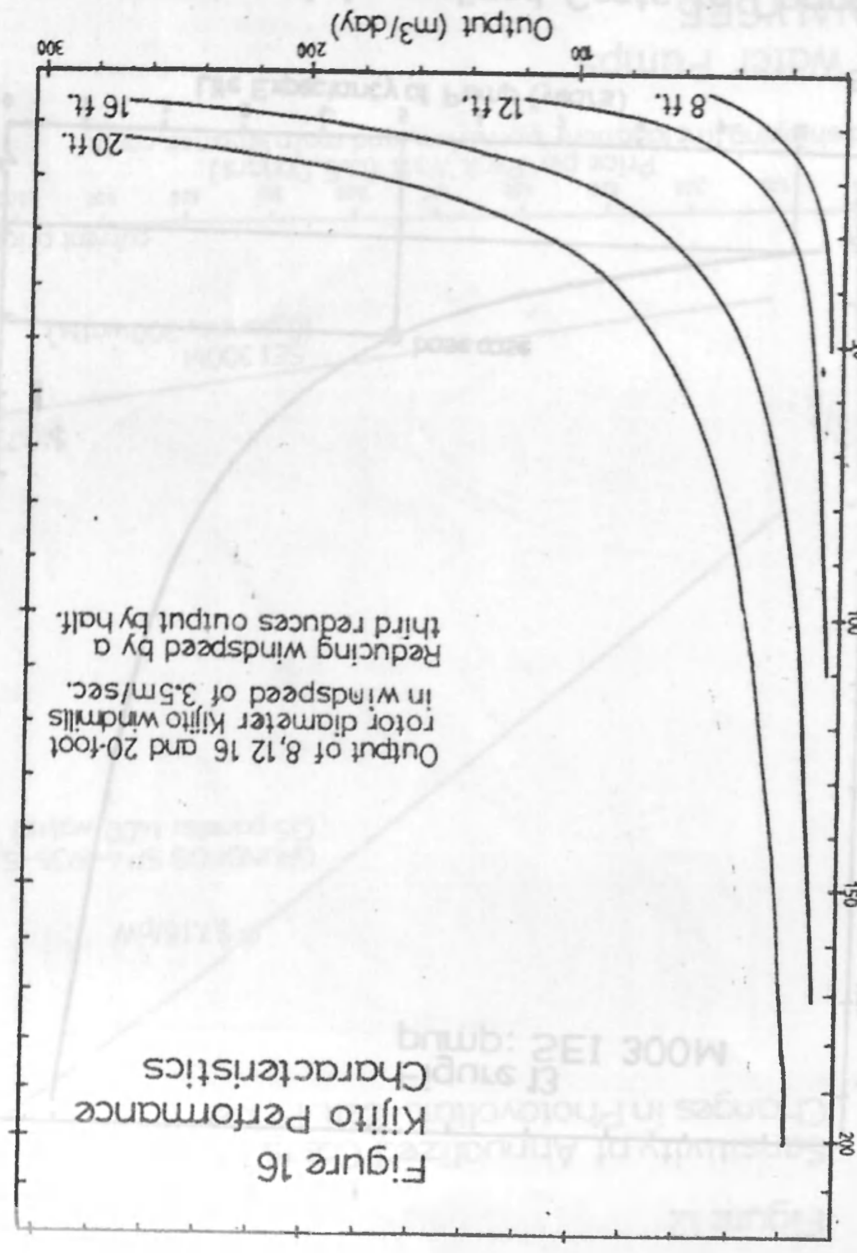


Figure 16
Kijito Performance
Characteristics

Output of 8,12 16 and 20-foot rotor diameter Kijito windmills in windspeed of 3.5m/sec.
Reducing windspeed by a third reduces output by half.

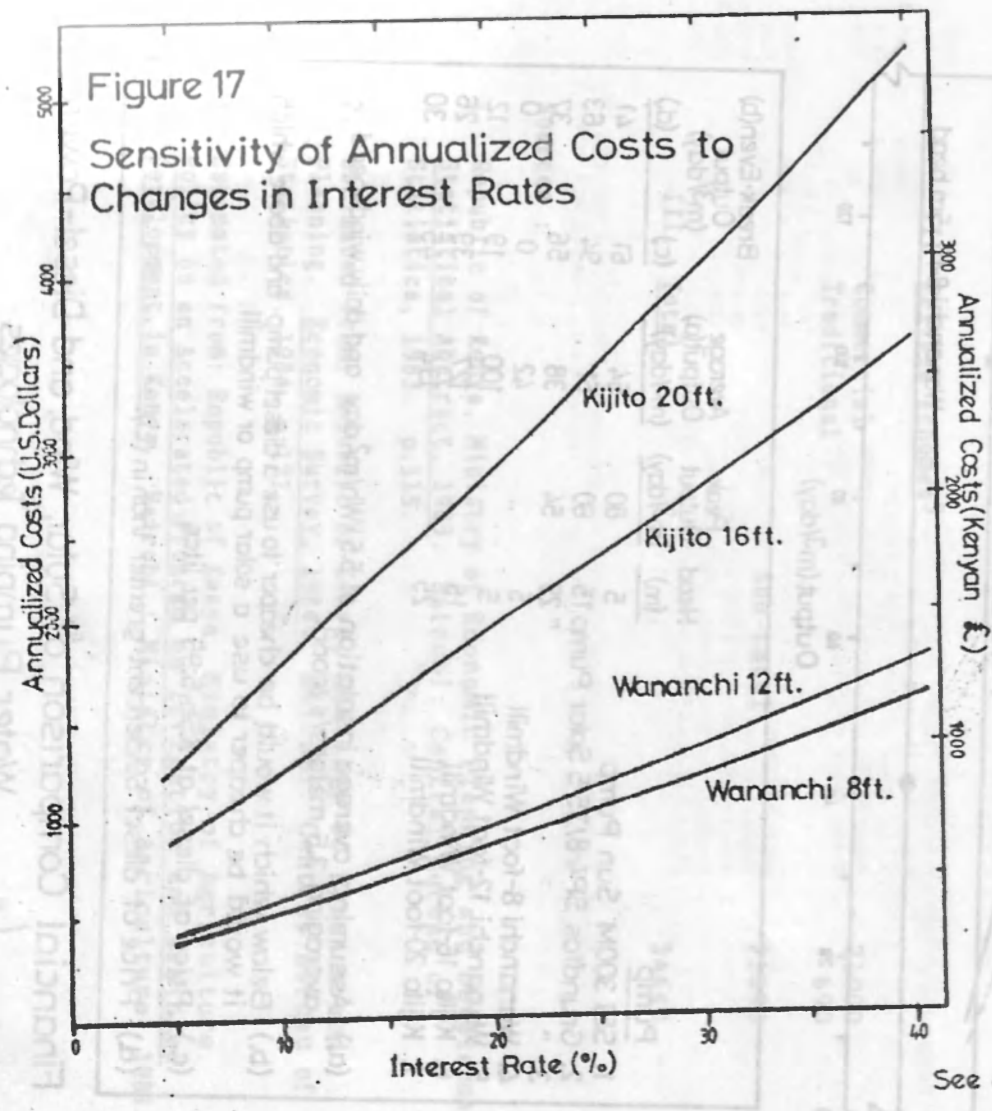


Figure 17
Sensitivity of Annualized Costs to Changes in Interest Rates

See also Table 17

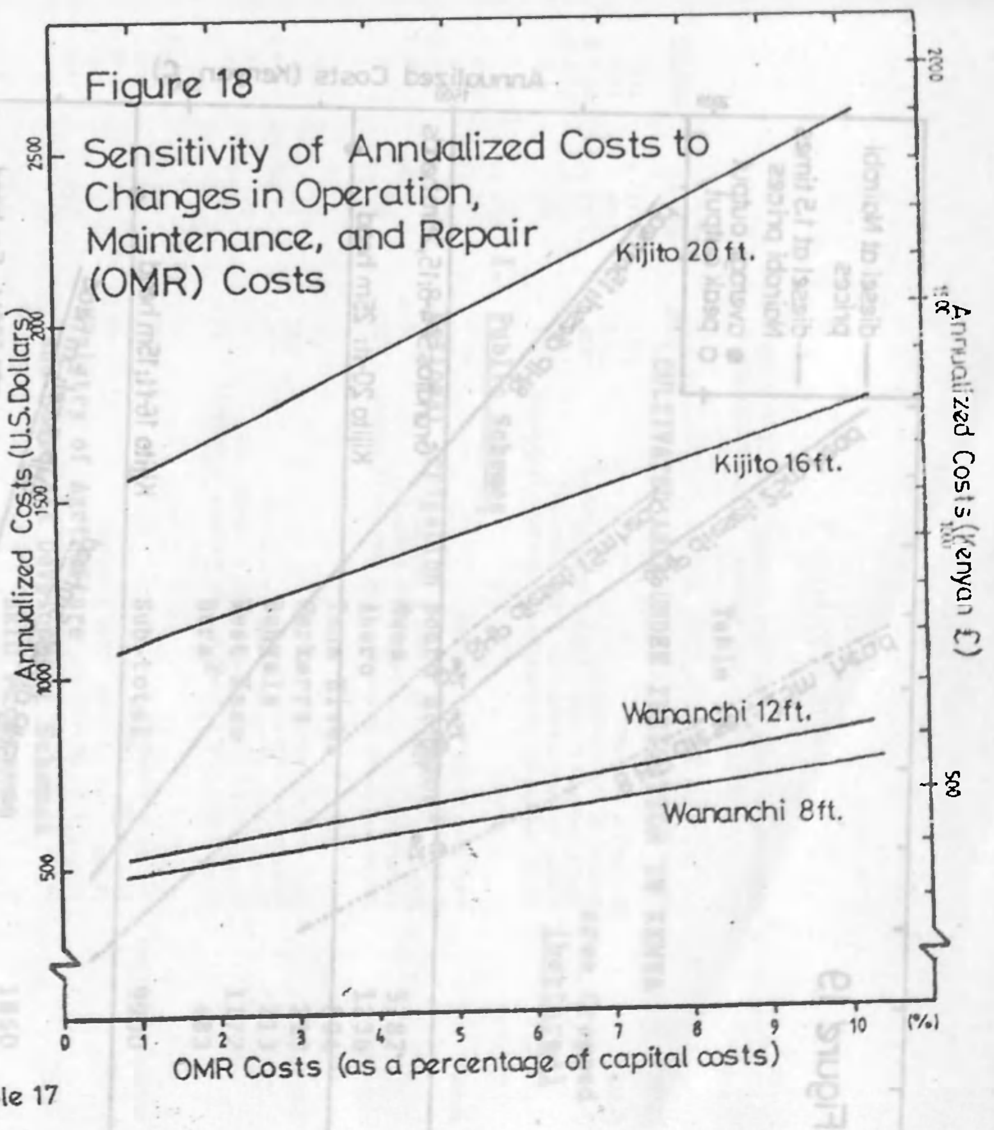
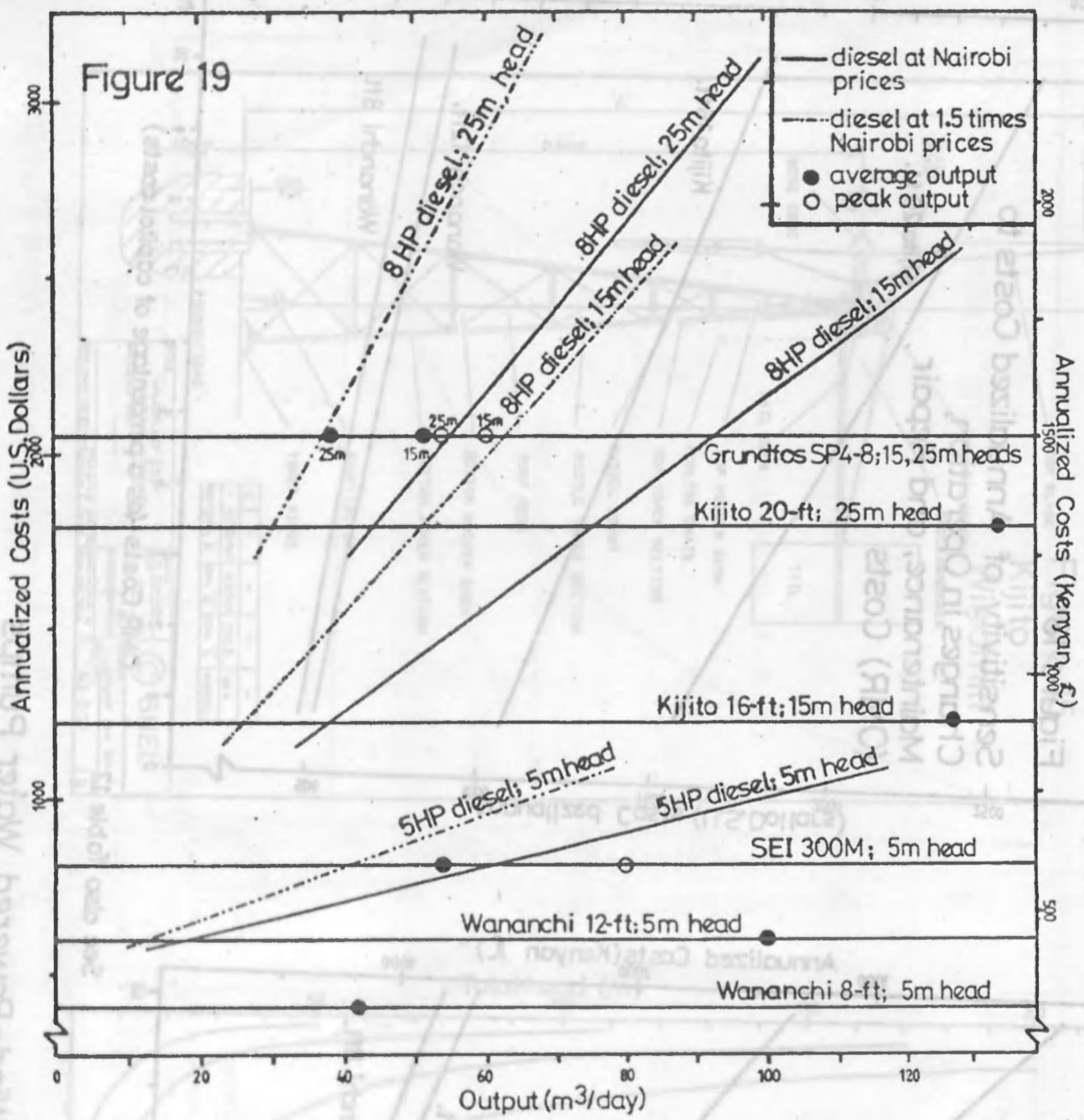


Figure 18
Sensitivity of Annualized Costs to Changes in Operation, Maintenance, and Repair (OMR) Costs

Wind-Powered Water Pumps
SENSITIVITY ANALYSES

Figure 19



Pump	Head (m)	Peak Output (m3/day)	Average Output(a) (m3/day)	Break-Even(b) Output (m3/day) (c.)	Break-Even(b) Output (m3/day) (d.)
1. SEI 300M Sun Pump	5	80	54	61	41
2. Grundfos SP4-8/35-5 Solar Pump	15	60	51	94	63
3. "	" 25	54	38	56	37
4. Wananchi 8-foot Windmill	5	..	42	0	0
5. Wananchi 12-foot Windmill	5	..	100	19	12
6. Kijito 16-foot Windmill	15	..	127	39	26
7. Kijito 20-foot Windmill	25	..	134	45	30

(a.) Assuming average insolation of 5.5 kWh/m^2 day and daily windspeed averaging 3.5 meters/second.

(b.) Below which it would be cheaper to use a diesel pump and above which it would be cheaper to use a solar pump or windmill.

(c.) Price of diesel at KSh 5.95 per liter.

(d.) Price of diesel 50 percent greater than in (c.).

Financial Comparison of Solar, Wind, and Diesel-Powered Water Pumping Technologies

Table 1

CULTIVATED AREA UNDER IRRIGATION IN KENYA

		Area Cropped (hectares)
I. Public Schemes		
National Irrigation Board Schemes[1]		
	Mwea	5782
	Ahero	1236
	Tana River	804
	Perkerra	210
	Bunyala	213
	West Kano	1172
	Bura[2]	483
	Sub-total	9900
Ministry of Agriculture and Livestock Development Schemes		
	ARID Programme	1850
	SSID Project	1000
	Sub-total	2850
II. Private Schemes[3]		
Commercial		21000
Traditional		690
	Sub-total	21690
III. Total		34440

Sources :

1. Republic of Kenya, Ministry of Economic Planning and Development. Statistical Abstract, 1983. Nairobi: Central Bureau of Statistics, 1983. p.115.
2. Estimated from: Republic of Kenya, Ministry of Finance and Planning. Economic Survey, 1984. Nairobi: Central Bureau of Statistics, 1984. p.121.
3. Estimated from: Republic of Kenya, Ministry of Agriculture. Policy on an Accelerated Program on Irrigation and Drainage Development in Kenya. Nairobi : Ministry of Agriculture, 1981.

Table 2

PRODUCTION CHARACTERISTICS OF LARGE-SCALE IRRIGATION SCHEMES MANAGED BY THE NATIONAL IRRIGATION BOARD

Scheme	Primary Crops	Production Characteristics	1979/80	Year 1980/81	1981/82
Mwea	Paddy	Hectares cropped	5757	5771	5782
		Number of plotholders	3150	3150	3150
		Gross value of crop ('000 K.Pounds)	1636.5	2028.6	3330.8
		Payments to plotholders ('000 K.Pounds)	1411.7	927.1	1746.2
		Gross value of production per hectare (K.Pounds)	284	352	576
Ahero	Paddy	Hectares cropped	1315	1348	1236
		Number of plotholders	527	556	491
		Gross value of crop ('000 K.Pounds)	250.0	269.4	314.5
		Payments to plotholders ('000 K.Pounds)	98.3	91.5	108.1
		Gross value of production per hectare (K.Pounds)	190	200	254
Tana River	Cotton	Hectares cropped	872	872	804
		Number of plotholders	606	606	607
		Gross value of crop ('000 K.Pounds)	21.7	419.4	318.2
		Payments to plotholders ('000 K.Pounds)	93.6	164.7	129.2
		Gross value of production per hectare (K.Pounds)	25	481	396
Perkerra	Onions, Chillies	Hectares cropped	321	164	210
		Number of plotholders	330	330	330
		Gross value of crop ('000 K.Pounds)	199.1	181.2	170
		Payments to plotholders ('000 K.Pounds)	89.5	94.5	71.9
		Gross value of production per hectare (K.Pounds)	620	1105	810
Bunyala	Paddy	Hectares cropped	207	213	213
		Number of plotholders	131	131	130
		Gross value of crop ('000 K.Pounds)	47.4	59.7	128.3
		Payments to plotholders ('000 K.Pounds)	19.2	29.0	67.3
		Gross value of production per hectare (K.Pounds)	229	280	603
West Kano	Paddy, Sugar Cane	Hectares cropped	1056	1228	1172
		Number of plotholders	809	961	961
		Gross value of crop ('000 K.Pounds)	341.2	340.8	452.8
		Payments to plotholders ('000 K.Pounds)	157.7	100.3	1174.3
		Gross value of production per hectare (K.Pounds)	323	278	386
Total		Hectares cropped	9528	9596	9417
		Number of plotholders	5553	5734	5669
		Gross value of crop ('000 K.Pounds)	2495.9	3296.0	4714.7
		Payments to plotholders ('000 K.Pounds)	1869.9	1407.1	2247.0
		Gross value of production per hectare (K.Pounds)	262	343	501

Source : Republic of Kenya, Ministry of Economic Planning and Development. Statistical Abstract, 1983. Nairobi : Central Bureau of Statistics, 1983. p.115. (excludes data from the Bura Scheme.)

Table 3

MAJOR SURFACE WATER SYSTEMS IN KENYA

Riverine Systems

Riverine System	Perennial length (km)	Seasonal length (km)	Catchment area (km^2)	Annual runoff (million m^3)
Athi	547	--	44,029	749
Ewaso Ngiro (North)	290	241	56,986	739
Ewaso Ngiro (South)	97	40	5,180	,,
Kerio	113	241	6,475	,,
Nzoia	258	--	12,956	1,920
Tana	708	--	62,160	4,700
Turkwell	145	209	20,720	,,
Voi	80	129	5,439	293
Total	2,238	860	213,945	,,

-- only perennial flowing
,, runoff estimate not available

Lacustrine Systems

Lake	Area (km^2)	Average depth (m)
Victoria (area in Kenya)	3,755	46
Turkana	6,405	--
Baringo	129	5
Magadi	104	--
Naivasha	114-191	3
Amboseli	0-114	0-0.6
Jipe	39	--
Bogoria	34	--
Nakuru	5-31	.6
Elmenteita	18	--

Source : R.B.Ogendo and F.F.Ojany. Kenya: A Study in Physical and Human Geography. Nairobi: Longman Kenya, Ltd., 1981.

Table 4

WIND REGIME AND INSOLATION CHARACTERISTICS OF KISUMU, HOLA, AND LODWAR VICINITY

I. Kisumu Meteorological Station

Month	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Average Windspeed[1] (m/sec)	3.3	3.3	3.4	3.0	2.3	2.3	2.3	2.5	2.5	2.7	2.8	3.1
P_t [2] for $A = 1\ m^2$ (kWh/m^2 day)	2.48	2.48	2.71	1.86	0.84	0.84	0.84	1.08	1.08	1.37	1.51	2.05
Insolation[3] (kWh/m^2 day)	7.2	7.0	7.0	6.3	6.3	6.3	6.0	6.2	6.7	6.7	6.5	7.0

II. Hola (Irrigation Project Meteorlogical Station)

Month	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Average Windspeed[1] (m/sec)	2.1	2.2	2.5	3.0	3.7	4.2	4.3	4.7	4.2	3.7	1.9	1.7
P_t [2] for $A = 1\ m^2$ (kWh/m^2 day)	0.70	0.80	1.18	2.03	3.81	5.57	5.97	7.80	5.57	3.81	0.52	0.38
Insolation[3] (kWh/m^2 day)	6.3	6.3	6.5	5.9	5.5	5.1	4.9	5.2	5.7	6.2	6.4	6.3

III. Lodwar Vicinity (FAO Irrigation Project Meteorological Station)

Month	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Average Windspeed[1] (m/sec)	4.2	4.5	5.0	4.5	4.5	4.2	3.8	4.5	5.0	5.2	4.5	3.8
P_t [2] for $A = 1\ m^2$ (kWh/m^2 day)	5.57	6.85	9.39	6.85	6.85	5.57	4.12	6.85	9.39	10.56	6.85	4.12
Insolation[3] (kWh/m^2 day)	6.4	6.3	6.3	6.6	6.0	6.2	6.7	6.5	7.0	6.5	6.3	6.5

Sources :

1. W.E.van Lierop and L.R.van Veldhuizen. Wind Energy Development in Kenya (Volume II : Wind Potential). Amersfoort (the Netherlands) : Steering Committee for Wind Energy in Developing Countries, 1982.
2. Ibid. See discussion in Section III.B of this paper.
3. G.O.P.Obasi and N.N.P.Rao. "Solar Energy Resources in Kenya," in : C.P.M.Khumala and J.B.Castelino (eds.). Energy Resources in East Africa. Nairobi : Kenya National Academy for Advancement of Arts and Sciences, 1979. pp.32-52.

Table 5

WINDSPEED MONITORING STATIONS IN KENYA
(See also Figure 5)

Key to Operating Organizations :

GTZ	German Agency for Technical Cooperation	HY	Hydrometeorological Survey of the Lake Victoria Basin
ITIS	Intermediate Technology Industrial Services	MALD	Ministry of Agric. and Livestock Dev.
NIB	National Irrigation Board	ME	Ministry of Educ.
MD	Ministry of Transport and Communications, Meteorological Department	P	Private
	/A Agromet Station	AF	Kenyan Air Force
	/H Hydrological Station	FAO	Food and Agric. Organization
	/S Synoptic Station	FD	Fisheries Dept.

	Location	Organization
1.	Ahero Irrigation Scheme	MD/A
2.	Amolem Small-scale Irrigation Project	FAO
3.	Archer's Post Met. Station	MD
4.	Bachuma Range Research Station	MALD
5.	Bungoma Hydromet station	HY
6.	Busia Cotton Experimental Station	MD/A
8.	Chemilil Sugar Scheme	MD/A
9.	Eldoret Experimental Farm	MD/A
10.	Eldoret Met. Station	MD/S
11.	Embu Met. Station	MD/S
12.	Embu Mwea Experimental Station	MD/A
13.	Equator Met. Station	MD/S
14.	Ferguson's Gulf	MD
15.	Galana Ranching Scheme	MD/A
16.	Galole Irrigation Scheme (Hola)	MD/A
17.	Garissa Met.Station	MD/S
18.	Garsen Met. Station	MD/H
19.	Gatare Forest Station	MD
20.	Isiolo Met. Station	MD/H

	Location	Organization
21.	Kabarnak Hydromet Station	HY
22.	Kabete University Field Station	MD
23.	Kendege Hydromet Station	HY
24.	Kadenge Met. Station	MD
25.	Kakamega Met. Station	MD/S
26.	Kakuma Mission	GTZ
27.	Kapenguria Cherwoyet School	MD
28.	Kapsabet Met. Station	MD
29.	Katilu Mission	ITIS
30.	Katilu Irrigation Scheme	FAO
31.	Katumani Experimental Station	MD/A
32.	Kedong	MD
33.	Keekorok Hydromet Station	HY
34.	Kekorongole Irrigation Scheme	MD
35.	Kenyatta Settlement Scheme (Mpeketoni)	GTZ
36.	Kenyatta Settle. Scheme (Tree nursery)	GTZ
37.	Kericho Hail Research Station	MD
38.	Kericho Timbilil Tea Research	MD/S
39.	Kiambu	MD
40.	Kiandogoro	MD
41.	Kiboko National Range Research Station	MALD
42.	Kibos Cotton Experimental Station	MD/A
43.	Kibos Sugar Research Station	MD/A
44.	Kimakia Forest Station	MD
45.	Kindarumba Fisheries	MD
46.	Kisii Coffee Substation	MD/S
47.	Kisii Hydromet Station	HY
48.	Kisume Met. Station	MD/S
49.	Kitale Met. Station	MD/S
50.	Kitale National Agri. Research Station	MD/A
51.	Kitui Dam	MD/H
52.	Kom Coffee Board Station	MD
53.	Lamu Met. Station	MD/S
54.	Lamuria	MD/H
55.	Lodwar Met. Station	MD/S
56.	Loitokitok Outward Mountain School	MD

WINDSPEED MONITORING STATIONS (continued)

Location	Organization
57. Lokitaung	MD
58. Lokori Met. Station	MD/H
59. Lokori Mission	ITIS
60. Machakos Dam	MD/H
61. Magadi Met. Station	MD
62. Magarini Settlement Scheme	MD/H
63 Makindu Met. Station	MD/S
64. Makueni	MD
65. Malindi	MD
66. Malindi Met. Station	MD/S
67. Malkadaka Irrigation Scheme	MD
68. Mandera Met. Station	MD/S
69. Marafa Met. Station	MD/H
70. Maralai	MD
71. Marienne Coffee Research Sub-Station	MD/A
72. Marigat Perkerra Irrigation Scheme	MD
73. Marsabit Met. Station	MD/S
74. Merti Irrigation Scheme	FAO
75. Merti Malkadaka Irrigation Scheme	NIB
76. Meru Met. Station	MD/S
77. Meru Marimanti	MD
78. Molo Pyrethrum Research Station	MD/A
79. Mombassa Airport Met. Station	MD/S
80. Mombassa Fisheries Research Station	FD
81. Mombassa Town Met. Station	MD
82. Moyale Met. Station	MD/S
83. Mtwapa Agricultural Research Station	MD/A
84. Mtwapa Settlement Scheme	GTZ
85. Muguga	MD
86. Muhoro Hydromet Station	HY
87. Mumias Sugar Project	MD/A
88. Nairobi Dagoretti Corner Met. Station	MD/S
89. Nairobi Eastleigh Airport	MD
90. Nairobi Jomo Kenyatta Airport	MD/S
91. Nairobi National Aeronautic Lab.	MD
92. Nairobi Wilson Airport	MD/S
93. Naivasha Ministry of Water Devel.	MD/H
94. Nakuru Airfield Met. Station	MD
95. Nakuru District Commissioners Office	MD
96. Nakuru Showground Met. Station	MD/S
97. Nanyuki Airfield Base	AF
98. Nanyuki Eland Downs	ITIS
99. Nanyuki Lewen Downs	ITIS
100. Nanyuki Met. Station	MD
101. Narok Met. Station	MD/S
102. Njoro Egerton College	MALD
103. Njoro Plant Breeding Station	MD/A
104. Nyeri Met. Station	MD/S
105. Nzoia Forest Station	MD
106. Nzoia Irrigation Station (Bunyala)	MD/A
107. Ol Joro Orok Agric. Research Station	MD/A
108. Ras Serani Met. Station	MD
109. Rohet Ranch (Athi River)	MD
110. Ruiru Coffee Research Station	MD/A
111. Rumuruti Ministry of Works	MD/H
112. Rusinga Island Hydromet Station	HY
113. Sagana State Lodge	MD
114. Sigor Met. Station	MD/H
115. South Kinangop Forest Station	MD/A
116. Tana Irrigation Scheme (Hola)	MD/A
117. Tavete Ministry of Works	MD/H
118. Tebere Cotton Research	MD/A
119. Thika Horticultural Research Station	MD/A
120. Tinderet Tea Estate	MD
121. Turbo Forest Station	MD/A
122. Turkwell Small-scale Irrigation Scheme	FAO
123. Voi Met. Station	MD/S
124. Wajir Met. Station	MD/S
125. Wayu Chief Centre	MD
126. West Kano Irrigation Scheme	MD/A

Table 6

AVERAGE WINDSPEEDS FOR SELECTED LOCATIONS IN KENYA[1]

Station Location[2]	Windspeeds in meters per second at 10 meter height											
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
2	2.6	2.6	2.0	3.6	2.6	2.6	2.0	2.2	2.2	2.0	2.2	3.0
5	3.0	3.3	3.2	2.9	2.8	2.3	2.4	2.8	2.8	3.2	3.3	3.2
12	2.6	2.9	3.0	2.5	1.9	1.7	1.9	2.4	2.7	2.9	2.2	2.4
16	1.9	1.8	1.9	2.2	3.2	3.5	3.7	3.9	3.8	3.4	1.9	1.6
17	1.8	2.0	2.0	2.4	3.6	4.2	4.6	4.5	3.9	3.0	1.8	1.6
23	2.7	2.8	2.8	2.1	1.9	2.2	2.0	2.4	2.9	2.2	2.3	2.4
26	5.8	5.1	--	--	--	--	--	--	5.1	6.9	6.7	7.1
30	3.2	3.3	3.3	3.0	3.3	3.2	2.8	3.2	3.5	3.5	3.2	3.2
31	4.2	4.2	4.7	3.9	3.1	2.7	3.0	3.2	4.0	4.6	4.6	4.3
33	3.3	3.5	3.4	2.9	3.8	3.1	3.8	4.3	4.0	5.0	4.0	3.3
47	2.3	2.3	2.4	2.0	2.3	2.2	2.6	2.6	2.3	2.3	1.9	2.0
48	3.3	3.3	3.4	3.0	2.3	2.3	2.3	2.5	2.5	2.7	2.8	3.1
62	4.1	4.0	2.9	3.2	4.0	4.0	4.1	4.1	3.9	3.6	3.1	3.4
79	3.6	3.7	3.6	4.6	4.1	4.3	4.0	3.9	4.0	3.8	3.0	3.2
84	3.7	--	--	--	--	--	--	--	3.7	3.5	2.8	3.2
86	3.5	3.4	3.6	3.1	3.1	3.1	3.1	3.8	3.7	3.7	3.3	3.3
88	3.6	3.4	3.4	2.5	1.7	2.5	1.5	1.7	2.0	2.9	2.9	3.2
90	4.6	4.6	5.2	4.2	2.9	2.6	2.6	3.1	3.3	4.2	4.8	4.8
92	3.4	3.6	3.6	3.0	1.9	1.8	1.9	2.0	2.4	3.0	3.2	3.3
95	2.3	2.1	2.2	1.7	1.7	1.9	1.9	1.8	1.6	1.7	2.8	2.1
96	2.8	3.3	3.3	2.5	2.1	2.0	2.0	1.8	1.9	1.8	1.9	2.2
101	1.9	1.7	1.8	1.7	2.7	1.5	1.7	2.0	2.0	2.2	1.8	1.6
111	1.1	3.3	3.6	3.4	3.2	2.9	2.8	2.6	2.8	3.1	3.2	3.1
112	3.9	4.0	4.2	3.3	3.2	3.0	3.4	3.5	3.5	3.6	3.4	3.6
116	2.1	2.2	2.5	3.0	3.7	4.2	4.3	4.7	4.2	3.7	1.9	1.7
122	4.2	4.5	5.0	4.5	4.5	4.2	3.8	4.5	5.0	5.2	4.5	3.8

1. W.E.van Lierop and L.R.van Veldhuizen. Wind Energy Development in Kenya (Volume II: Wind Potential). Amersfoort (the Netherlands): Steering Committee for Wind Energy in Developing Countries, 1982.

2. See Table 5

Table 8

INSTALLED KIJITO WINDMILLS BY LOCATION, TYPE, AND END-USE

	Customer	Location	Date Installed	Rotor Diameter (feet)	Estimated Head (feet)	End Uses
1.	Ol Pejeta Ranching, Ltd.	Nanyuki	1979	24	250	livestock
2.	Vipingo Estate	Vipingo, Kilifi	1979	12	..	livestock, domestic
3.	Ol Pejeta Ranching, Ltd.	Nanyuki	1979	24	230	livestock
4.	Ol Pejeta Ranching, Ltd.	Nanyuki	1979	20	200	livestock
5.	Bobs Harries Engineering	Karamaini Estate, Thika	1979	24	..	experimental
6.	Ol Pejeta Ranching, Ltd.	Nanyuki	1980	24	320	livestock
7.	Gatatha Farmers Co-op	Molo	1980	20	400	..
8.	Ol Pejeta Ranching, Ltd.	Nanyuki	1980	24	250	livestock
9.	Ol Pejeta Ranching, Ltd.	Nanyuki	1980	24	260	livestock
10.	Lewa Downs Ranch	Isiolo	1980	20	280	livestock
11.	Kilimanjaro Safari Club	Amboseli	1980	20	50	domestic
12.	Ol Pejeta Ranching, Ltd.	Nanyuki	1980	24	..	livestock
13.	Ol Pejeta Ranching, Ltd.	Nanyuki	1980	24	500	livestock
14.	Ol Pejeta Ranching, Ltd.	Nanyuki	1980	24	500	livestock
15.	African Inland Church	Logotok, Sudan	1980	20	..	livestock, domestic, irrigation
16.	African Inland Church	Logotok, Sudan	1980	12	..	livestock, domestic, irrigation
17.	Baobab Farms	Bamburi	1981	12	50	livestock, domestic, irrigation
18.	Ngarua Farmers Co-op	Ainabkoi	1981	16	280	livestock, domestic, irrigation
19.	African Inland Church	Lotabai	1981	12	20	livestock, domestic, irrigation
20.	Nangodir	Kerio Delta	1981	12	120	livestock, domestic, irrigation
21.	Katilu Catholic Mission	Katilu, Lodwar	1981	20	270	livestock, domestic, irrigation
22.	Pent. Assembly of Canada	Namuroputh, West Lodwar	1981	20	50	livestock, domestic
23.	M.L. Jauss	Vipingo, Kilifi	1981	20	..	livestock, domestic
24.	L.K.Ruhiu	Ngong Hills	1981	20	310	livestock, domestic, irrigation
25.	Kenyatta University College	Kahawa	1981	12	..	experimental
26.	Swedish Faith Homes	Nakuyen, West Pokot	1981	24	225	livestock, domestic, irrigation
27.	J.C.Le Poer Trench	Nanyuki	1981	12	100	livestock, domestic
28.	Baragoi Secondary School	Baragoi	1981	16	465	domestic
29.	Catholic Mission	Bariadi, Tanzania	1981	16	..	..
30.	J.Block	Malindi	1981	12	..	domestic, irrigation
31.	J.L.Davies	Kilifi	1981	[illegible]	70	domestic
32.	Diocese of Lodwar	Kaikor	1981	16	140	livestock, domestic, irrigation
33.	Diocese of Lodwar	Kaikor	1981	20	160	livestock, domestic, irrigation
34.	Laremetasho, Ltd.	Ndabibi, Naivasha	1981	12	80	livestock, irrigation
35.	African Inland Church	Lokori	1981	20	25	livestock, domestic, irrigation
36.	A.D.C. Mutara Ranch	East Rumuruti	1982	16	180	livestock
37.	Antii Kuokkanen	Kiali	1982	12	100	domestic
38.	Diocese of Ngong	Gorgor, Narok	1982	12	15	livestock, domestic
39.	A.E. Enterprises	Kotido, Ugandan	1982	24	260	livestock, domestic
40.	Pent. Assembly of Canada	Baringo	1982	16	90	livestock, domestic
41.	Marianists	Kiboko River, Kajiado	1982	16	295	livestock, domestic
42.	Franz Daniels	Ilkerin	1982	20	586	domestic
43.	EEC/Diocese of Lodwar	Kachoda	1982	20	140	livestock, domestic, irrigation
44.	Dr.Ruberti	Ongata Rongai	1982	16	370	domestic
45.	ITDG	Reading, England	1982	24	..	..
46.	World Bank	Kano, Nigeria	1983	12	..	..
47.	World Bank	Kano, Nigeria	1983	16	20	..
48.	World Bank	Kano, Nigeria	1983	16	50	..
49.	World Bank	Kano, Nigeria	1983	20	..	..
50.	Ministry of Lands and Sett.	Mtwapa	1983	16	10	livestock, domestic
51.	Mr. Chege	Kiserian, Ngong Hills	1983	12	170	livestock, domestic, irrigation
52.	Ministry of Lands and Sett.	Mpeketoni, Lamu	1983	16	45	domestic
53.	Ministry of Lands and Sett.	Mpeketoni, Lamu	1983	20	50	livestock, domestic, irrigation
54.	MORAD	Rusinga Island	1983	20	150	domestic
55.	Ol Pejeta Ranching, Ltd.	Nanyuki	1983	20	430	livestock
56.	Undugu Societ of Kenya	Katangi, Kitui	1983	20	280	livestock, domestic, irrigation
57.	Ministry of Lands and Sett.	Mpeketoni, Lamu	1983	12	70	domestic, irrigation
58.	Ministry of Lands and Sett.	Mpeketoni, Lamu	1983	20	..	domestic, irrigation
59.	Anthony Ngotho	Mbiuni	1983	20	370	domestic, irrigation
60.	USAID	Naro Moru	1983	16	190	domestic, irrigation
61.	Peter Byrne	Ongata Rongai	1983	12	150	domestic
62.	Evan Fell of Africa	Soriadi	1983	20	330	livestock, domestic, irrigation
63.	CIDA	Garba Tulla Secondary Sch.	1983	20	10	domestic
64.	OUTRAM	Casuarina Point, Malindi	1983	12	50	domestic
65.	Ol Pejeta Ranching, Ltd.	Nanyuki	1984	20	230	livestock
66.	CIDA	Garba Tulla Secondary Sch.	1984	16	10	irrigation
67.	Baraki Sisters	Baraki, Tanzania	1984	20	165	domestic
68.	Project Tapis Vert	Niger	1984	20	..	..
69.	BRET Project	Botswana	1984	20	..	..
70.	BRET Project	Botswana	1984	20	..	..
71.	UNICEF	..	1984	20	..	..
72.	CIDA	Harare, Zimbabwe	1984	20	..	..
73.	Food for the Hungry	Marsabit	1984	20		

.. Information unavailable

Table 7

EXPECTED WIND PUMP POWER FOR SELECTED LOCATIONS IN KENYA[1]

Station Location[2]	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
	Wind power output, P_t, in kWh per square meter of swept area ($A = 1\ m^2$)											
2	1.21	1.21	0.55	3.22	1.21	1.21	0.55	0.74	0.74	0.55	0.74	1.86
5	1.69	2.25	2.05	1.53	1.38	0.76	0.88	1.38	1.38	2.05	2.25	2.05
12	1.10	1.53	1.69	1.48	0.43	0.31	0.43	0.87	1.23	1.53	0.67	0.87
16	0.52	0.44	0.52	0.80	2.46	3.22	3.81	4.46	4.12	2.95	0.52	0.31
17	1.44	1.76	1.92	2.73	5.28	5.93	5.99	5.94	6.94	3.94	1.41	1.06
23	1.36	1.51	1.51	0.64	0.47	0.74	0.55	0.85	1.68	0.74	0.84	0.95
26	13.44	9.14	--	--	--	--	--	--	9.14	22.62	20.71	24.60
30	2.40	2.48	2.48	1.86	2.48	2.26	1.51	2.26	2.95	2.95	2.26	2.40
31	4.64	4.64	6.50	3.72	1.87	1.23	1.69	2.05	4.01	6.10	6.10	4.98
33	2.48	2.95	2.71	1.68	3.78	2.05	3.78	5.48	4.41	8.62	4.41	2.48
47	0.76	0.76	0.87	0.50	0.76	0.67	1.10	1.10	0.76	0.76	0.43	0.50
48	2.48	2.48	2.71	1.86	0.84	0.84	0.84	1.08	1.08	1.37	1.51	2.05
62	5.18	4.81	1.83	2.46	4.81	4.81	5.18	5.18	4.46	3.51	2.24	2.95
79	3.80	4.12	3.80	7.92	5.61	6.47	5.21	4.83	5.21	4.47	2.20	2.67
84	3.81	--	--	--	--	--	--	--	3.81	3.22	1.65	2.46
86	2.95	2.71	3.22	2.05	20.5	2.05	2.05	3.78	3.49	3.49	2.48	2.48
88	4.15	4.51	4.10	2.41	1.04	0.84	0.83	1.00	1.86	2.78	3.12	3.41
90	6.10	6.10	8.80	4.64	1.53	1.10	1.10	1.87	2.25	4.64	6.93	6.93
92	4.51	4.76	4.92	3.56	1.81	1.69	1.59	1.94	2.91	3.94	4.44	4.50
95	3.17	3.29	2.77	1.84	1.11	2.04	2.08	2.11	1.82	1.87	1.95	2.89
96	1.37	2.25	2.25	0.98	0.58	0.50	0.50	0.37	0.43	0.37	0.43	0.67
101	1.28	1.24	1.49	1.63	1.40	1.28	1.32	1.28	1.76	2.18	1.49	1.04
111	1.87	2.25	2.92	2.46	2.05	1.53	1.38	1.10	1.38	1.87	1.87	1.87
112	4.09	4.41	5.10	2.48	2.26	1.86	2.71	2.95	2.95	3.22	2.71	3.22
116	0.70	0.80	1.18	2.03	3.81	5.57	5.97	7.80	5.57	3.81	0.52	0.38
122	5.57	6.85	9.39	6.85	6.85	5.57	4.12	6.85	9.39	10.56	6.85	4.12

1. W.E.van Lierop and L.R.van Veldhuizen. Wind Energy Development in Kenya (Volume II: Wind Potential). Amersfoort (the Netherlands): Steering Committee for Wind Energy in Developing Countries, 1982.

2. See Table 5

Table 9

SEI 300M ANNUAL COST FLOWS

Costs are in U.S. dollars
Exchange rate is approximately KSh 14.7 per dollar

Year	Panels[1]	Pump[2]	Shipping[3]	Installation[4]	OMR Costs[5]	Total
0	3220	900	750	420.	--	5290
1	..	..	..	..	21	21
2	..	..	..	..	21	21
3	..	..	..	..	21	21
4	..	..	..	..	21	21
5	..	..	..	..	21	21
6	..	900	175	210	21	1306
7	..	..	..	..	21	21
8	..	..	..	..	21	21
9	..	..	..	..	21	21
10	..	..	..	..	21	21
11	..	900	175	210	21	1306
12	..	..	..	..	21	21
13	..	..	..	..	21	21
14	..	..	..	..	21	21
15	..	..	..	..	21	21
16	..	900	175	210	21	1306
17	..	..	..	..	21	21
18	..	..	..	..	21	21
19	..	..	..	..	21	21
20	..	..	..	..	21	21

At a 10 percent rate of discount, the Net Present Cost of this system over 20 years is $6924 or K.Pounds 5089. At a 10 percent rate of interest, Average Annualized Costs are $813 or K.Pounds 598 per year.

1. Life of photovoltaic panels is assumed to be 20 years.

2. Life of the centrifugal pump is assumed to be 5 years.

3. FOB Malta; Shipping @ $700; Packing @ $50. Packing and shipping for the pump alone @ $175.

4. Two trips @ $420/trip (1 surveying and 1 installation); 400 km round trip @ $.50/km; labor $20.

5. Operation, maintenance and repair costs are estimated to be 0.5 percent of pumping system capital costs per annum.

GRUNDFOS SP4-8/35-5 ANNUAL COST FLOWS

Costs are in U.S. dollars
Exchange rate is approximately KSh 14.7 per dollar

Year	Panels[1]	Pump[2]	Shipping[3]	Installation[4]	OMR Costs[5]	Total
0	10045	3882	1000	440	--	15367
1	..	..	..	..	70	70
2	..	..	..	..	70	70
3	..	..	..	..	70	70
4	..	..	..	..	70	70
5	..	..	..	..	70	70
6	..	..	..	..	70	70
7	..	..	..	..	70	70
8	..	..	..	..	70	70
9	..	..	..	..	70	70
10	..	..	..	..	70	70
11	..	3882	125	220	70	4297
12	..	..	..	..	70	70
13	..	..	..	..	70	70
14	..	..	..	..	70	70
15	..	..	..	..	70	70
16	..	..	..	..	70	70
17	..	..	..	..	70	70
18	..	..	..	..	70	70
19	..	..	..	..	70	70
20	..	..	..	..	70	70

At a 10 percent rate of discount, the Net Present Cost of this system over 20 years is $17444 or K.Pounds 12822. At a 10 percent rate of interest, Average Annualized Costs are $2049 or K.Pounds 1506 per year.

1. Life of photovoltaic panels is assumed to be 20 years.

2. Life of the vertical turbine pump is assumed to be 10 years.

3. FOB United States @ $1000; Packing and shipping for the pump alone @ $125.

4. Two trips @ $440/trip (1 surveying and 1 installation); 400 km round trip @ $.50/km; labor $40.

5. Operation, maintenance and repair costs are estimated to be 0.5 percent of pumping system capital costs per annum.

Table 10

SENSITIVITY ANALYSES
FOR PHOTOVOLTAIC-POWERED IRRIGATION PUMPS

Costs are in U.S. dollars
Exchange rate is approximately KSh 14.7 per dollar

Sensitivity to the Cost of Capital

SEI 300M System

Interest Rate (%)	NPC[1]	AAC[2]
0	9565	--
5	7851	630
* 10	6924	813
15	6391	1021
20	6095	1246
25	5856	1481
30	5717	1724
35	5620	1972
40	5551	2223

Grundfos SP4-8/35-5

Interest Rate (%)	NPC[1]	AAC[2]
0	20994	--
5	18711	1501
* 10	17444	2049
15	16714	2670
20	16277	3343
25	16007	4048
30	15835	4776
35	15722	5516
40	15646	6266

* Indicates base case estimates. Other assumptions about the cost of photovoltaics and the life of the pump remain the same.

Sensitivity to the Cost of Photovoltaic Cells

Sensitivity of Average Annualized Costs to changes in the costs of photovoltaic cells can be calculated from using the equations :

$C_{aa} = 164C_{pW} + 869$ for the Grundfos system, and
$C_{aa} = 35C_{pW} + 435$ for the SEI system

where C_{aa} is the average annualized cost, and C_{pW} is the cost per peak watt. Other assumptions about the interest rate and the life of the pump remain the same.

Sensitivity to Life Expectancy of Pump

SEI 300M System

Life of Pump (years)	NPC[1]	AAC[2]
1	15241	1790
2	10031	1178
3	8323	978
4	7438	874
* 5	6924	813
6	6629	779
7	6358	747
8	6207	729
9	6047	710
10	5919	695

Grundfos SP4-8/35-5

Life of Pump (years)	NPC[1]	AAC[2]
5	20750	2437
6	19698	2314
7	18872	2217
8	18330	2153
9	17876	2100
* 10	17444	2049
11	17214	2022
12	17013	1998
13	16834	1977
14	16675	1959
15	16533	1942
16	16406	1927
17	16291	1914
18	16188	1902
19	16094	1890
20	15963	1875

* Indicates base case estimates. Other assumptions about the interest rate and the cost of photovoltaics remain the same.

[1] $\text{NPC} = \sum_{t=0}^{z} [C_t/(1+R)^t]$

where NPC is the net present cost, z is the project life of 20 years, C_t are costs in year t, and R is the prevailing discount rate.

[2] $\text{Average Annual Cost} = [\text{NPC}][R(1+R)^z]/[(1+R)^z-1]$

Table 11

GROSS IRRIGATION REQUIREMENTS FOR IRRIGATION SCHEMES IN THE KISUMU, NOLA, AND LODWAR VICINITIES

I. Kisumu[1]

Assuming year round vegetable cultivation :

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	units
Crops	VEGETABLES												
ET_o	189	174	182	154	144	142	139	145	162	172	160	169	mm per ha
K_c	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	
ET_{crops}	208	191	200	169	158	156	153	160	178	189	176	186	mm per ha
Precipitation	63	87	162	205	171	95	63	88	74	72	116	104	mm per ha
Net Irrigation Requirements	145	104	3	--	--	61	90	72	104	117	60	82	mm per ha
Gross Irrigation Requirements	93	75	25	--	--	41	58	46	69	69	40	53	m^3/ha day

II. Nola[2]

Assuming mixed cultivation of perennial and seasonal crops:

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	units
Crops -- Seasonal	M	P	P	P/R	R	R	R	R	H	P	M	M	0.7 ha
K_c -- Seasonal	0.7	--	1.0	1.1	1.2	1.3	1.2	1.1	--	--	0.5	1.0	
Crops -- Perennial	B	B	B	B	B	B	B	B	B	B	B	B	0.3 ha
K_c -- Perennial	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	
ET_o	206	193	208	190	179	163	163	180	185	206	193	189	mm per ha
ET -- Seasonal	144	--	208	209	215	212	196	198	--	--	97	189	mm per ha
ET -- Perennial	185	174	187	171	161	147	147	162	167	185	174	170	mm per ha
Precipitation	10	5	50	90	65	45	25	20	25	65	70	80	mm per ha
Net Irrigation Requirements													
- Seasonal	134	--	158	119	150	167	171	178	--	--	27	109	mm per ha
- Perennial	175	169	137	81	96	102	122	142	142	120	104	90	mm per ha
Saturation/ponding	--	--	-100	-100	--	--	--	-100	--	+100	--	--	mm per ha
Percolation	--	--	31	30	31	30	31	31	--	--	--	--	mm per ha
Net Irrigation Requirements	47	18	79	64	50	59	57	38	14	34	17	33	m^3/ha day
Gross Irrigation Requirements	94	36	158	128	100	108	114	76	21	68	34	66	m^3/ha day

Where :

M = maize and green gram	B = bananas and tree crops	R = rice
P = land preparation	H = harvest	

Before paddy can be planted, the soil has to be saturated, and a water layer on the soil has to be built up. An amount of 200 mm per ha is assumed to be required, and is applied over two months. After cultivation, some of this water is used for irrigation. Another application is applied before planting maize and gram.

Percolation from the paddy fields is assumed to be 1 mm per ha per day.

GROSS IRRIGATION REQUIREMENTS . . . (continued)

III. Lodwar Vicinity[1]

Assuming cultivation of maize, beans, and cotton :

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	units
Crops	---------------------Maize and beans (.5 ha) and Cotton (.5 ha)---------------------												
ET_o	264	248	275	234	242	244	241	248	277	292	241	235	mm per ha
K_f, maize, beans	0.8	--	0.4	0.8	1.2	1.2	0.9	0.6	--	0.4	0.8	1.1	
K_f, cotton	--	--	0.5	0.7	0.9	1.2	1.2	0.8	0.6	0.4	--	--	
ET_{crops}	106	--	138	187	266	293	265	174	83	117	96	129	mm per ha
Precipitation	9	7	21	48	25	7	14	10	13	8	13	13	mm per ha
Net Irrigation Requirements	97	--	117	139	241	286	251	164	70	109	83	116	mm per ha
Gross Irrigation Requirements	63	--	75	93	155	191	162	106	47	70	55	75	m^3/ha day

In calculating Gross Irrigation Requirements, we have assumed an irrigation efficiency of 50 percent. The variables which will determine Gross Irrigation Requirements are the irrigation efficiency, the base level of evapotranspiration (ET_o), the evapotranspiration of the crops (ET_{crops}), and the precipitation. $ET_{crops} = [ET_o][K_f]$ and Net Irrigation Requirements = ET_{crops} - Precipitation. Gross Irrigation Requirements are determined using the equation :

$$GIR\ (m^3/\ ha\ day) = [\text{Net Irrigation Requirement (mm per ha)}][10]/[\text{Irrigation Efficiency}][\text{days per month}]$$

Sources :

1. W.E.van Lierop and L.R.van Veldhuizen. Wind Energy Development in Kenya (Volume III: End-Use Analysis.) Amersfoort (the Netherlands): Steering Committee for Wind Energy in Developing Countries, 1982.
2. Gabrowski and Poort Consulting Engineers. Lower Tana Village Irrigation Program: A Technical Study (Interim Report). Nairobi: Ministry of Agriculture, 1981.

Table 12

ESTIMATED TOTAL PUMPING OUTPUT FOR WIND AND SOLAR TECHNOLOGIES, GROSS IRRIGATION REQUIREMENTS, AND COMMAND AREA CALCULATIONS FOR IRRIGATION SCHEMES IN THE KISUNU, HOLA, AND LODWAR VICINITIES

I. Kisumu (Head: 5 meters)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Pumping system water output (m^3 per day)[1]												
SEI 300M	72	70	70	63	63	63	60	62	67	67	65	70
Kijito (12-foot rotor)	88	88	94	70	36	36	36	45	45	55	60	76
Gross Irrigation Requirements[2] (m^3 of water per day)	93	75	25	--	--	41	58	46	69	69	40	53
Command Area per pumping system (hectares)[3]												
SEI 300M	0.77	0.93	2.80	n.a.	n.a.	1.54	1.03	1.35	0.97	0.97	1.63	1.32
Kijito (12-foot rotor)	0.95	1.17	3.76	n.a.	n.a.	0.88	0.62	0.98	0.65	0.80	1.50	1.43

II. Hola (Head: 15 meters)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Pumping system water output (m^3 per day)[1]												
Grundfos SP4-8/35-5	56	56	58	53	50	48	46	49	52	55	57	56
Kijito (16-foot rotor)	19	21	29	46	75	93	97	112	93	73	14	11
Gross Irrigation Requirements[2] (m^3 of water per day)	94	36	158	128	100	108	114	76	28	68	34	66
Command Area per pumping system (hectares)[3]												
Grundfos SP4-8/35-5	0.60	1.56	0.37	0.41	0.50	0.44	0.40	0.64	1.86	0.81	1.68	0.88
Kijito (16-foot rotor)	0.20	0.58	0.18	0.36	0.73	0.86	0.85	1.47	3.32	1.07	0.41	0.17

III. Lodwar Vicinity (Head: 25 meters)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Pumping system water output (m^3 per day)[1]												
Kijito (20-foot rotor)	87	98	114	98	98	87	72	98	114	119	98	72
Gross Irrigation Requirements[2] (m^3 of water per day)	63	--	75	93	115	191	162	106	47	70	55	75
Command Area per pumping system (hectares)[3]												
Kijito (20-foot rotor)	1.38	n.a.	1.52	1.05	0.63	0.46	0.44	0.92	2.43	1.70	1.78	0.96

Sources :

1. From Performance Characteristics given in Figure 16 and based on windspeed and insolation given in Table 4. It should be noted that the values for C_p which have been used are very conservative -- .049 at a windspeed of 3 meters per second and .033 at a windspeed of 5.5 meters per second.
2. From Table 11.
3. Determined by dividing the amount of water pumped by each system by the Gross Irrigation Requirements.

Table 13

COSTS AND TARIFFS OF ELECTRICITY PRODUCED USING CONVENTIONAL AND PHOTOVOLTAIC TECHNOLOGIES

Electricity Source	Costs of Electricity (KSh/kWh)	Duties (KSh/kWh)	Total Costs (KSh/kWh)	Duty Rate (%)
Petrol-produced electricity[1]	1.74	1.06	2.80	61
Diesel-produced electricity[2]	1.77	--	1.77	--
PV-produced electricity				
A.[3]	2.29	1.60	3.89	70
B.[4]	5.39	3.75	9.14	70
Grid-produced electricity	0.70	0.01	0.71	1

1. Assuming a thermal conversion efficiency of 34 percent, and a cost per liter of KSh 8.13, which includes duties of KSh 0.726 (import duty) and KSh 2.353 (sales tax). Conversion efficiencies for petrol may in reality be somewhat lower. The costs of conversion technologies are not included.

2. Assuming a conversion efficiency of 34 percent, and a cost per liter of KSh 5.95. The costs of conversion technologies are not included.

3. Assuming capital costs are not annualized and that the value of future electricity production is not discounted. Capital costs of KSh 7158 (US$ 487) are for a 40pW Solarex panel which has an anticipated life of 20 years.

4. Annualized cost basis.

Table 14

ZONES OF AGRO-ECOLOGICAL POTENTIAL IN KENYA
(See also Figure 2)

Zone	Area (km^2)	% of total	Characteristics
I. Afro-alpine	800	0.1	Very high altitude above forest lines. Mostly barren with use limited to water catchment and tourism.
II. High potential	53,000	9.3	High moisture, mostly high altitude. Used for forestry, coffee, tea, pyrethrum, intensive livestock, and maize. Cotton at lower altitudes.
III. Medium potential	53,000	9.3	Generally lower moisture and altitude than Zone II. Used for mixed farming of hybrid maize, wheat, pulses, cotton, groundnuts, oilseeds, cashews, coconuts, and livestock.
IV. Semi-arid	50,000	8.9	Marginal agricultural potential, mostly limited to sisal and quick-maturing grains. Productive grasslands. High density of wildlife.
V. Arid	300,000	52.7	Moderate rangeland potential. Wildlife important in some areas.
VI. Very arid	112,000	19.7	Low potential rangeland. Use very limited to traditional pastoralism.

Source : D.J.Pratt and M.D.Gwynme (eds.). Rangeland Management and Ecology in East Africa. London: Hodder and Stoughton, 1977.

Table 15

BHEL 8-FOOT WANANCHI WINDMILL ANNUAL COST FLOWS

Costs are in Kenyan shillings
U.S. Dollar exchange rate is approximately
KSh 14.7 per dollar

Year	Windmill, pump, and parts[1]	Replacements[2]	Transport Installation[3]	OMR Costs	Total
0	43429		11880	..	55309
1	..	..	..	1303	1303
2	..	..	..	1303	1303
3	..	..	..	1303	1303
4	..	..	..	1303	1303
5	..	..	..	1303	1303
6	..	..	..	1303	1303
7	..	..	..	1303	1303
8	..	..	..	1303	1303
9	..	..	..	1303	1303
10	..	..	..	1303	1303
11	..	2574	2000	1303	5877
12	..	..	..	1303	1303
13	..	..	..	1303	1303
14	..	..	..	1303	1303
15	..	..	..	1303	1303
16	..	..	..	1303	1303
17	..	..	..	1303	1303
18	..	..	..	1303	1303
19	..	..	..	1303	1303
20	..	..	..	1303	1303

At a 10 percent rate of discount, the Net Present Cost of this system over 20 years is K.Pounds 3400 (US$4626). At a 10 percent rate of interest, Average Annualized Costs are K.Pounds 399 (US$ 543) per year.

1. Cost of windmill @ 27000/-; cost of 3" pump cylinder @ 2200/-; cost of pump rods @ 394 (half inch, 5m @ 79/- per meter); cost of stuffing box @ 6500/-; cost of pipes @ 1025/ (5m @ 205/- per meter); plus 17 percent sales tax.

2. Pump cylinder replaced in eleventh year at a cost of 2200/- plus 17 percent sales tax; installation and transport @ 2000/- (400 km @ 5/- per kilometer).

3. Installation costs @ 6000/- (includes labor and foundation); transport @ 5880/- (two trips, 1 survey and 1 installation; 400 km round trip @ 7/35 per km)

4. Operation, maintenance, and repair costs @ 3 percent of system capital costs per annum

BHEL 12-FOOT WANANCHI WINDMILL ANNUAL COST FLOWS

Costs are in Kenyan shillings
U.S. Dollar exchange rate is approximately
KSh 14.7 per dollar

Year	Windmill, pump, and parts[1]	Replacements[2]	Transport Installation[3]	OMR Costs	Total
0	49279		11880	..	61159
1	..	..	..	1478	1478
2	..	..	..	1478	1478
3	..	..	..	1478	1478
4	..	..	..	1478	1478
5	..	..	..	1478	1478
6	..	..	..	1478	1478
7	..	..	..	1478	1478
8	..	..	..	1478	1478
9	..	..	..	1478	1478
10	..	..	..	1478	1478
11	..	2574	2000	1478	6052
12	..	..	..	1478	1478
13	..	..	..	1478	1478
14	..	..	..	1478	1478
15	..	..	..	1478	1478
16	..	..	..	1478	1478
17	..	..	..	1478	1478
18	..	..	..	1478	1478
19	..	..	..	1478	1478
20	..	..	..	1478	1478

At a 10 percent rate of discount, the Net Present Cost of this system over 20 years is K.Pounds 3767 (US$5126). At a 10 percent rate of interest, Average Annualized Costs are K.Pounds 443 (US$602) per year.

1. Cost of windmill @ 32000/-; cost of 3" pump cylinder @ 2200/-; cost of pump rods @ 394 (half inch, 5m @ 79/- per meter); cost of stuffing box @ 6500/-; cost of pipes @ 1025/ (5m @ 205/- per meter); plus 17 percent sales tax.

2. Pump cylinder replaced in eleventh year at a cost of 2200/- plus 17 percent sales tax; installation and transport @ 2000/- (400 km @ 5/- per kilometer).

3. Installation costs @ 6000/- (includes labor and foundation); transport @ 5880/- (two trips, 1 survey and 1 installation; 400 km round trip @ 7/35 per km)

4. Operation, maintenance, and repair costs @ 3 percent of system capital costs per annum

Table 15 (con't.)

BHEL 16-FOOT KIJITO WINDMILL ANNUAL COST FLOWS

Costs are in Kenyan shillings
U.S. Dollar exchange rate is approximately
KSh 14.7 per dollar

Year	Windmill, pump, and parts[1]	Replacements[2]	Transport Installation[3]	OMR Costs	Total
0	109194		13845	..	123039
1	..	..	..	3276	3276
2	..	..	..	3276	3276
3	..	..	..	3276	3276
4	..	..	..	3276	3276
5	..	..	..	3276	3276
6	..	..	..	3276	3276
7	..	..	..	3276	3276
8	..	..	..	3276	3276
9	..	..	..	3276	3276
10	..	..	..	3276	3276
11	..	5850	2000	3276	11126
12	..	..	..	3276	3276
13	..	..	..	3276	3276
14	..	..	..	3276	3276
15	..	..	..	3276	3276
16	..	..	..	3276	3276
17	..	..	..	3276	3276
18	..	..	..	3276	3276
19	..	..	..	3276	3276
20	..	..	..	3276	3276

At a 10 percent rate of discount, the Net Present Cost of this system over 20 years is K.Pounds 7684 (US$10454). At a 10 percent rate of interest, Average Annualized Costs are K.Pounds 903 (US$1228) per year.

1. Cost of windmill @ 77490/-; cost of pump cylinder (2 3/4" x 12") @ 5000/-; cost of pump rods @ 1262 (3/4 inch, 15m @ 84/15 per meter); cost of stuffing box @ 6500/-; cost of pipes @ 3076/ (15m @ 205/- per meter); plus 17 percent sales tax.

2. Pump cylinder replaced in eleventh year at a cost of 5000/- plus 17 percent sales tax; installation and transport @ 2000/- (400 km @ 5/- per kilometer).

3. Installation costs @ 7965/- (includes labor and foundation); transport @ 5880/- (two trips, 1 survey and 1 installation; 400 km round trip @ 7/35 per km)

4. Operation, maintenance, and repair costs @ 3 percent of system capital costs per annum

BHEL 20-FOOT KIJITO WINDMILL ANNUAL COST FLOWS

Costs are in Kenyan shillings
U.S. Dollar exchange rate is approximately
KSh 14.7 per dollar

Year	Windmill, pump, and parts[1]	Replacements[2]	Transport Installation[3]	OMR Costs	Total
0	163502		15175	..	178677
1	..	..	..	4905	4905
2	..	..	..	4905	4905
3	..	..	..	4905	4905
4	..	..	..	4905	4905
5	..	..	..	4905	4905
6	..	..	..	4905	4905
7	..	..	..	4905	4905
8	..	..	..	4905	4905
9	..	..	..	4905	4905
10	..	..	..	4905	4905
11	..	7043	2000	4905	13948
12	..	..	..	4905	4905
13	..	..	..	4905	4905
14	..	..	..	4905	4905
15	..	..	..	4905	4905
16	..	..	..	4905	4905
17	..	..	..	4905	4905
18	..	..	..	4905	4905
19	..	..	..	4905	4905
20	..	..	..	4905	4905

At a 10 percent rate of discount, the Net Present Cost of this system over 20 years is K.Pounds 11180 (US$15211). At a 10 percent rate of interest, Average Annualized Costs are K.Pounds 1313 (US$1787) per year.

1. Cost of windmill @ 119995/-; cost of pump cylinder @ 6020/- (2 3/4" x 24" cylinder); cost of pump rods @ 2104/ (3/4 inch, 25m @ 84/- per meter); cost of stuffing box @ 6500/-; cost of pipes @ 5126/- (25m @ 205/- per meter); plus 17 percent sales tax.

2. Pump cylinder replaced in eleventh year at a cost of 6020/- plus 17 percent sales tax; installation and transport @ 2000/- (400 km @ 5/- per kilometer).

3. Installation costs @ 9295/- (includes labor and foundation); transport @ 5880/- (two trips, 1 survey and 1 installation; 400 km round trip @ 7/35 per km)

4. Operation, maintenance, and repair costs @ 3 percent of system capital costs per annum

Table 16

UNIT COSTS OF WATER PUMPED WITH WINDMILLS

Windmill	Head (meters)	Output (m^3/day)	Output (m^3/year)	Annualized Costs (KSh)	Unit Costs (KSh/m^3)
Wananchi 8'	5	42	15330	7988	.521
Wananchi 12'	5	100	36500	8850	.242
Kijito 16'	15	127	46355	18051	.389
Kijito 20'	25	134	48910	26265	.537

Assuming an average windspeed of 3.5 meters per second.

Table 17

SENSITIVITY ANALYSIS OF KIJITO WINDMILLS

Costs are in Kenyan Shillings
U.S. Dollar exchange rate is approximately KSh 14.7 per dollar

Sensitivity to Operation, Maintenance and Repair (OMR) Costs

Average annual costs in KSh for the Kijito windmill can be closely approximated using the formulas :

$$C_{aa}[8] = 434[OMR] + 6685$$
$$C_{aa}[12] = 493[OMR] + 7372$$
$$C_{aa}[16] = 1092[OMR] + 14775$$
$$C_{aa}[20] = 1635[OMR] + 21360$$

where $C_{aa}[x]$ is the Average Annualized Cost of a Kijito with a rotor diameter of x, and where [OMR] are operation, maintenance, and repair costs, as a percentage of capital investment costs, including sales tax, but excluding transport and installation costs. Other assumptions about the cost of capital and the rate of sales tax remain the same.

Sensitivity to the Rate of Sales Tax

Average annual costs in KSh for the Kijito windmill can be determined using the formulas :

$$C_{aa}[8] = 32[ST] + 7449$$
$$C_{aa}[12] = 38[ST] + 8211$$
$$C_{aa}[16] = 91[ST] + 16504$$
$$C_{aa}[20] = 141[ST] + 23869$$

where $C_{aa}[x]$ is the Average Annualized Cost of a Kijito with a rotor diameter of x, and where [ST] is the rate of sales tax (in percent) which is assessed on the cost of the windmill. Other assumptions about the cost of capital and OMR costs remain the same.

Table 18

5 HP DIESEL ENGINE PUMPSET ANNUAL COST FLOWS EXCLUDING FUEL AND OMR COSTS

Costs are in Kenyan Shillings
U.S. Dollar exchange rate is approximately
KSh 14.7 per dollar

Year	Pump[1]	Piping	Replacements[2]	Transport/ Installation[3]	Total Cost
0	44135	1200	..	4500	49835
1	..	..	..	..	..
2	..	..	..	..	..
3	..	..	..	..	..
4	..	..	..	..	..
5	..	..	..	..	..
6	..	..	5000	2000	7000
7	..	..	..	..	..
8	..	..	..	..	..
9	..	..	..	..	..
10	..	..	..	..	..
11	15500	..	5000	4000	24500
12	..	..	..	..	..
13	..	..	..	..	..
14	..	..	..	..	..
15	..	..	..	..	..
16	..	..	5000	2000	7000
17	..	..	..	..	..
18	..	..	..	..	..
19	..	..	..	..	..
20	..	..	..	..	..

At a 10 percent rate of discount, the Net Present Cost of this system over 20 years is KSh 63897. At a 10 percent rate of interest, Average Annualized Costs are KSh 7505 per year.

1. 5 HP Diesel engine matched with centrifugal pump @ 44135/-; piping @ 1200/- (5m @ 240/- per meter); includes sales tax. Overhaul of diesel engine in eleventh year @ 15500/-
2. Replacements of pump every fifth year @ 5000/- each.
3. Initial installation labor costs @ 2100; transport @ 2400/- (400 km @ 6/- per km); subsequent labor in eleventh year @ 2000/-; transport in eleventh year @ 2000/- (400 km @ 5/- per km).

Fuel costs can be determined using the relationship :

$$E = [H][Q][9.81]/[N][3600]$$

where E is in kWh, H is the head in meters, Q is the output in cubic meters, and N is the pumping efficiency (assumed in this analysis to be around 0.25), and 9.81 is the gravitational constant. One liter of diesel can produce 3.36 kWh, so, the number of liters of diesel that would be required per year can be determined from the equation :

$$\text{liters per year} = 0.0032\,[H][Q][365]$$

where Q is output in cubic meters per day.

The cost per liter of diesel in Nairobi is around KSh 5.95 per liter. Average Annualized Costs for diesel, over a 20 year project period can be determined from the equation :

$$C_{aa} = [C_p][(1 + R)^z - 1]/[z][R]$$

where C_{aa} is the average annualized cost, C_p is the present cost, R is the rate of inflation, and z is the number of years over which the costs are annualized (20 in this case). Annual OMR costs are calculated to be 25 percent of average annualized fuel costs.

8 HP DIESEL ENGINE PUMPSET ANNUAL COST FLOWS EXCLUDING FUEL AND OMR COSTS

Costs are in Kenyan Shillings
U.S. Dollar exchange rate is approximately
KSh 14.7 per dollar

Year	Pump[1]	Piping	Replacements[2]	Transport/ Installation[3]	Total Cost
0	60526	3600	..	5590	64126 [4]
	60526	6000	..	5590	66526 [5]
1	..	..	..	..	..
2	..	..	..	..	..
3	..	..	..	..	..
4	..	..	..	..	..
5	..	..	..	..	..
6	..	..	6000	2000	8000
7	..	..	..	..	..
8	..	..	..	..	..
9	..	..	..	..	..
10	..	..	..	..	..
11	20000	..	6000	5000	31000
12	..	..	..	..	..
13	..	..	..	..	..
14	..	..	..	..	..
15	..	..	..	..	..
16	..	..	6000	2000	8000
17	..	..	..	..	..
18	..	..	..	..	..
19	..	..	..	..	..
20	..	..	..	..	..

At a 10 percent rate of discount, the Net Present Cost of this system, installed at a head of 15 meters, is KSh 81248. At a 10 percent rate of interest, Average Annualized Costs are KSh 9543 per year. The Net Present Cost of this system, installed at a head of 25 meters, is KSh 83648. At a 10 percent rate of interest, Average Annualized Costs are KSh 9825 per year.

1. 8 HP Diesel engine matched with vertical turbine pump @ 60526/-; includes sales tax. Overhaul of diesel engine in eleventh year @ 20000/-
2. Replacements of pump every fifth year @ 6000/- each.
3. Initial installation labor costs @ 2650; transport @ 2940/- (400 km @ 7/35 per km); subsequent labor in eleventh year @ 3000/-; transport in eleventh year @ 2000/- (400 km @ 5/- per km).
4. Pump installed at head of 15 meters; cost of piping @ 3600/- (240/- per meter).
5. Pump installed at head of 25 meters; cost of piping @ 6000/- (240/- per meter).

Total annualized costs for each pumping configuration can be determined from the equations :

$$C_{aa}[5] = 73[Q] + 7505$$
$$C_{aa}[15] = 218[Q] + 9543$$
$$C_{aa}[25] = 364[Q] + 9825$$

where $C_{aa}[z]$ are the average annualized costs of a diesel pumpset operating at a head of z, and where Q is the daily water output in cubic meters. The effect of increasing the price of diesel on C_{aa} can be determined by increasing the slope by the required percent.