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Renewable energy sources in small-scale water pumping systems

Sam Johansson, Roy Nilsson

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RENEWABLE ENERGY SOURCES IN

SMALL-SCALE WATER PUMPING SYSTEMS

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ALLMÄNNA INGENJÖRSBYRÅN AB, CONSULTING ENGINEERS

Stockholm, February 1985

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ABSTRACT

In general, a water supply system consists of a water source, a pipe system and distribution point(s). The water supply can be of the gravity type, but often a pumping unit is required and thus an energy source. Sinceno chain is stronger than its weakest link, all linkshave to be carefully designed, constructed, maintained and operated, separately as well as inpart.

Water supply systems should be designed to match the demand and optimized for investment as well as operation and maintenance costs. Small systems tend to have a higher cost per unit of water produced than larger systems, consequently each system has to be carefully designed and constructed.

For water pumping in rural areas, renewable energy sources such as sun, wind or water offer a competitive alternative to the traditional diesel or petrol. Pumping systems driven by renewable energy normally have a lower operation and maintenance cost than diesel powered systems but require higher investment cost. Reliability depends on the meteorological conditions. Therefore a correct understanding and interpretation of meteorological data is of greatest importance when designing pumping systems.

In some areas solar pumping systems are today the most competitive alternative, despite their relatively high investment costs. However, the prices of equipment tend to decrease and consequently solar pumps will find an increasing number of applications. Windmills for water pumping are a good alternative in coastal and desert areas with strong and regular winds. Some windmills can be locally constructed which normally means a lower cost. The availability expressed as production time strongly depends on the wind speed and the duration of the wind.

Hydro power turbines can be used for direct water pumping, even in small rivers. In suitable rivers these units are the most reliable and economical alternative. Water turbines can also generate electricity for pumping and other purposes. The available energy is generally easy to predict, but the annual variations have to be considered carefully.

Biofuel can be used to run converted diesel engines. This permits replacement of diesel oil with charcoal from farms or waste from timber industry. Biogas generated by animal excreta can also be used as fuel and consequently solve a sanitary problem as well as supply fertilizer.

The characteristics of some common types of pumps are discussed, especially from the aspect of energy, i.e. energy demand and suitable energy sources. The pumps are sensitive to water quality and need correct installation. The need of operation and maintenance input varies. The photovoltaic powered submersible pumping units are virtually operation and maintenance free. The biogas plants need a regular support.

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ACKNOWLEDGEMENTS

The utilization of renewable energy sources in different energy systems is becoming increasingly more widespread all over the world, including developing countries which have a large potential for renewable energy, especially solar energy. This study, sponsored by Swedish International Development Agency (SIDA) and carried out by AIB Consulting Engineers, describes and analyses the possibilities to use renewable energy in water pumping systems. Our intention is to provide information on water pumping systems and to describe their dependence of the renewable energy sources which are used.

The report is based on computer-aided studies of the literature, information from suppliers and experience from a variety of small-scale projects which has been performed by AIB in different countries.

We would also like to express our gratitude to Mrs Karin Wohlin and Mr Rolf Winberg at SIDA and Mr Varis Bokalders at the Beijer Institute for their comments on this study.

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1. RURAL WATER SUPPLY

1.1 Orientation

In many ways water is an essential condition for life, both for human beings, animals and crops. Water can be used for drinking, cooking, washing, irrigation etc. But water may also be a source of or a carrier of diseases. Water supply is therefore a complex problem which has to be studied from several aspects, e.g. cultural, economic, medical, hygienic, sociological and technical.

The purpose of this study is to examine different kinds of water pumping systems suitable for small villages in a developing country. Renewable energy sources for the pumping systems such as the sun, wind, biogas, biofuel and water have been studied. A comparison with conventional energy sources such as gasoline or diesel has also been made.

The study mainly concentrates on the situation in rural parts of some African countries e.g. Ethiopia, Kenya and Tanzania.

The domestic water demand in the rural parts of these countries is about thirty litres per day per person. A village of some thousand inhabitants has a water demand of about one hundred cubic metres a day. The power demand will then be about one to two kilowatt depending on the water pumping head.

Small water pumping systems, that do not rely on imported energy and can perhaps also be manufactured domestically, are very well suited for developing countries. Furthermore, the systems must be reliable and require a minimum of maintenance. The pump and the energy converter must be compatible with and well suited for the actual demands.

Many water pumping systems have been constructed in different countries. Some systems work satisfactorily, whereas others stand abandoned within a few years because of insufficient maintenance or lack of spare parts. One important prerequisite for the success of the by UNDP declared "International Water Supply and Sanitation Decade" is to find low cost, reliable water pumping systems for application in rural areas of developing countries.

1.2 Water sources and water quality

1.2.1 Surface water

In spite of its often low quality, high bacteria count and substantial amount of suspended materials, lakes and rivers are a major source of water. Some tropical diseases are transmitted by water while some are caused by inadequate hygiene, which in turn is a result of insufficient water. Even water of low quality may then have a positive influence for the prevention of some diseases which depend more on water quantity than on water quality. Surface water in general is not suitable for drinking without sterilization by heating, chemical or biological treatment.

Lake water is generally available throughout the year, even if the water level may vary. In a river the flow and water level fluctuate within a wide range throughout the year. Sometimes the river will be dry. A river may be an unreliable water source in respect of quality and availability, a fact that has to be investigated before installation of a pumping system.

1.2.2 Groundwater

In general, groundwater is of high quality. When passing through the soil the groundwater reaches a high rate of purification. Groundwater can normally be used as drinking water without any additional treatment.

However, in certain cases, groundwater may have a high content of dissolved chemicals from the minerals in the soil, which may render it unsuitable for drinking.

The depth to the groundwater table depends on the hydrogeological conditions. In general groundwater can be found at depths of several to a hundred metres. In some areas, only a small quantity of groundwater may be extracted by using traditional methods.

Groundwater can be pressurized, which means that the water level will rise when the aquifer is punctured. The water can then reach above ground level and a spring is created. In such special cases, no additional energy or pumps are needed, only a shelter for the spring (spring catchment) is required in order to keep the water clean. Normally the groundwater has to be pumped from the ground to at least the ground level.

Groundwater can be extracted through different types of wells, as a drilled hole with small diameter (borehole), a drilled or excavated hole with larger diameter (well) or a tube well, which is a perforated pipe with a pointed end. A well with a depth of less than ten metres is called a shallow well, and a well more than ten to fifteen metres deep is called a deep well.

The shallow well is excavated by hand and often lined with e.g. stones. If the well is uncovered leaves, grass, sand, etc. easily fall into the water. This has an adverse effect on water quality and will eventually affect the capacity. The groundwater level varies so that the well can go dry during the dry season. Shallow wells require regular control of the water level and regular cleaning to keep the well deep enough.

A number of drilling methods, primitive as well as highly technical, are available for deep well construction. The traditional way of drilling is vertically down to the groundwater table, but in recent years horizontal drilling has also been introduced. The principle is shown in figure 1-1. In the case of horizontal drilling, no pumping is needed as the water will gravitate through the boreholes. This water flow has to be limited and controlled in order to prevent the borehole from going dry. The method will be an alternative in hilly and mountainous terrains and will have a large potential in areas with favourable geographical and geological conditions.

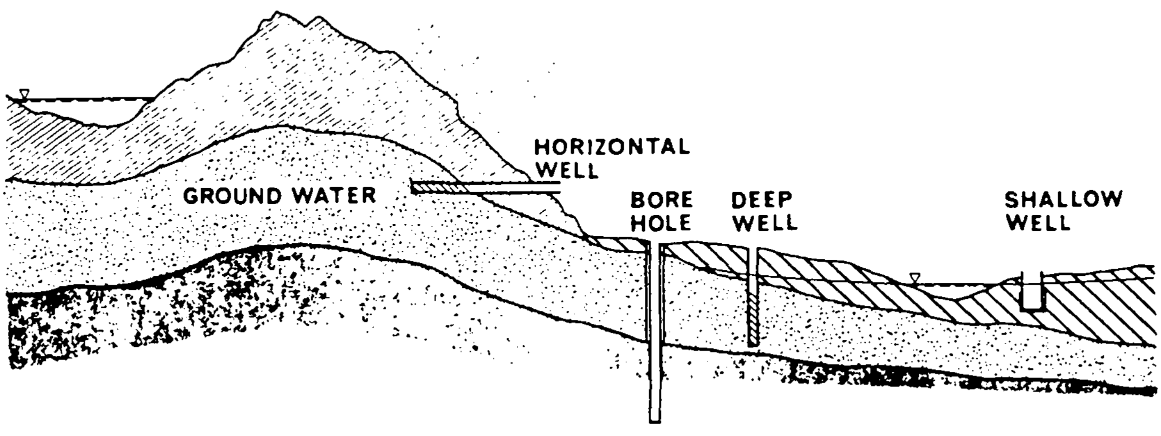


Figure 1-1 Different types of wells for groundwater utilization

At some locations, it is possible to increase the discharge from a groundwater well by infiltration of surface water. The simplest and probably also the best system is to induce surface water to the well by pumping near the river or the lake. The surface water will then be purified when passing through the soil. This method is suitable especially in sandy soil. In clayey soil, only a small amount of water can be induced from the river and the method is therefore less applicable.

1.2.3 Rain catchment

Rain catchment is an old method of collecting water which has been used in different ways in Asia and Europe during the last thousand years. One famous example is in Venice where this principle was used right up to the beginning of the 20th century.

Rain-water is collected from roofs or hard areas and infiltrates artificial, semi-artificial or natural groundwater basins. The basin may partly prevent evaporation and the water will be stored and purified. The amount of water available depends on the volume of the reservoir but especially on the rainfall and the evaporation.

A type of rain catchment reservoir is shown in figure 1-2. A clay barrier is built across the river bed which rests on solid bedrock or another type of dense material as clayey soil.

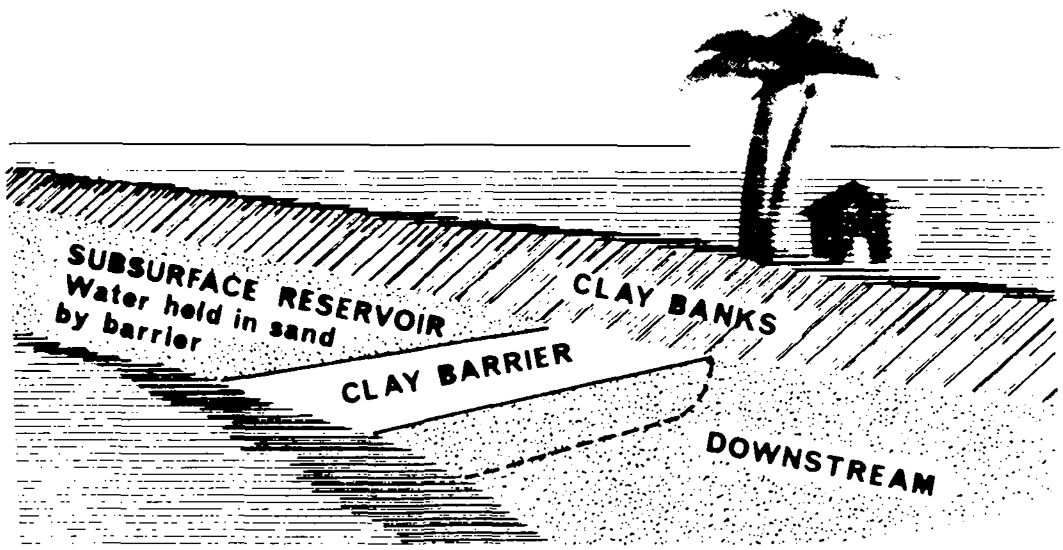


Figure 1-2 Earth subsurface dam for rain catchment /E Nissen-Petersen/

1.3 Water use

1.3.1 Domestic demand

The main purpose of a water supply is to deliver water within an area for the drinking, cleaning and washing needs of the population. The arrangement of distribution points varies according to such factors as the volume of water required, the spacing of the consumers, the degree of service that is wanted and what is affordable. The availability of raw water will in some cases affect the distribution arrangements.

The highest standard normally provided in rural areas is through individual connections (IC). This means a standpipe for one household next to the house. This is required when the consumption is high and when the consumption points are not too scattered, meaning that from an economic point of view this is a possible arrangement.

A group connection, i.e. an individual connection for several households, is sometimes installed. The distance to the water point tends to be longer and the possibility of having to queue at the tap(s) lowers the serviceability. In areas where an IC tends to be too expensive, the system of supplying water through a kiosk is an alternative. As in the case of IC's and group connections, the water is paid for. Another alternative of supplying water is through a water retailer, coming to the consumer and selling.

When the willingness and/or ability to pay for water is very low and where the consumers are very scattered, the water can be supplied through a public standpipe (domestic water point, commercial water point).

The demand for water varies between the different water points.

For IC's, single or as group connections, the demand is normally on the order of 30 - 50 l per capita and day.

For public standpipes the demand is a minimum of 10 - 15 l per capita and day.

The demand increases over time partly due to the increase in the number of consumers using the water supply and partly due to increased per capita consumption.

1.3.2 Livestock demand

For many schemes it is essential to include the livestock demand in the capacity required. The watering points, preferably separate from the domestic water points, are in the form of cattle troughs.

In other areas with only a few sheep, goats and cows it is sufficient to raise the capacity of the domestic water point.

The consumption demand varies from sheep to grade cattle. The range may be as wide as between 5 to 75 liters per unit and day.

1.3.3 Irrigation demand

The volumes of water required for irrigation purposes are of such an order that irrigation supplies have to be separate from the domestic and livestock water supplies. The only exception is that in some cases it is preferable to allow for garden irrigation in the rural water supply, as the water will in any case be used for this purpose.

1.3.4. Institutional demand

Institutions such as dispensaries, hospitals, schools, market centres, etc. require access to water. The demand has to be investigated from case to case regarding both capacity and consumption pattern. Industries and factories are often such large consumption points that they require separate supplies.

1.4 Costs of water

The costs of water supplies consist of investment and recurrent costs.

Investment costs are incurred in the construction of the water supply scheme. Recurrent costs include operating costs, such as costs for chemicals, fuel, direct labour etc. and maintenance costs, such as replacement and labour costs. In addition to these direct costs, there are overhead costs in connection with management, transport and workshops. The costs for both construction, operation and maintenance have increased considerably during the last decade. Apart from inflation, scheme type and scheme size also influence costs.

Recent studies have found the following concerning the investment costs. For small schemes with a capacity of up to 50 m^3/day the unit costs for water are high. For capacities up to 4,000 m^3/day the unit costs seem to be constant and then fall sharply for very large schemes.

Thus, in general, when it comes to very large and very small schemes, there are economics of scale and over a wide range of capacities the unit costs are constant.

Scheme type influence the costs:

- gravity fed schemes are the least costly;
- pumped surface schemes are more expensive than gravity schemes (33 %);
- boreholes are more expensive than gravity schemes (50 %).

From the same studies the following data for operation and maintenance (O&M) costs for different scheme types and sizes are cited. The study was reported in 1981 and the costs are to be read as relative:

Scheme type and size	Relative O&M-costs/m^3
Gravity	1
Pumped	5
Large	1
Medium	15
Small	30
All	2

In other words, pumped schemes are approximately five times more expensive to operate and maintain than gravity schemes. Small schemes are thirty, and medium schemes are fifteen times more expensive than large schemes.

2. ENERGY SOURCES FOR WATER PUMPING

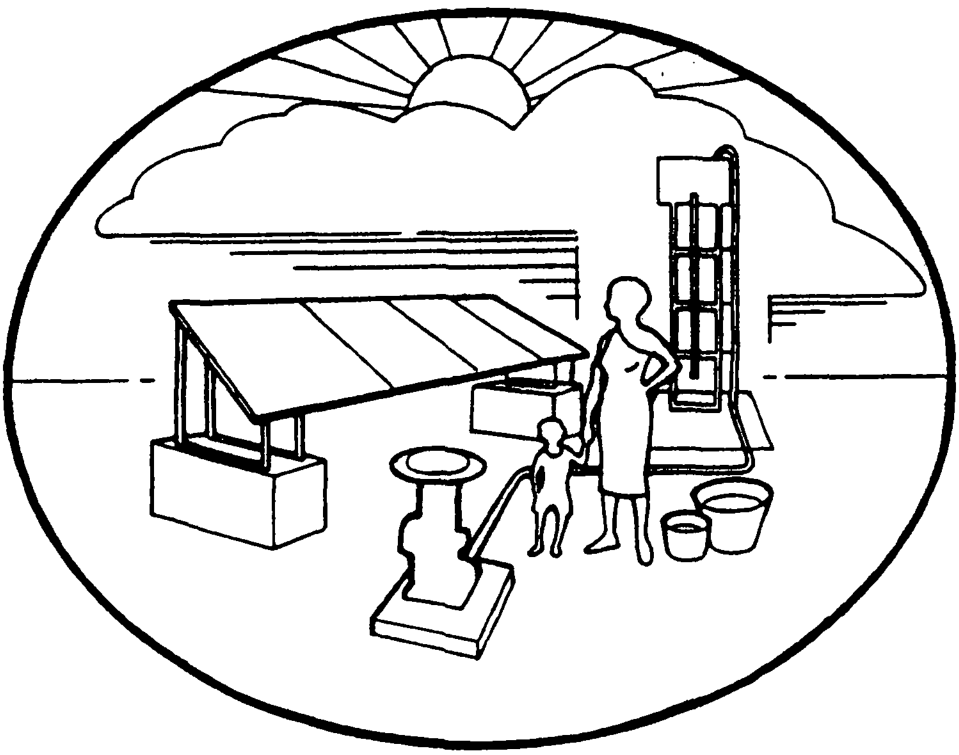
2.1 Solar Energy

2.1.0 Summary

Water pumps can be powered by solar energy in most regions. The solar radiation can be converted to electricity in photovoltaic systems or to heat in thermal systems.

Photovoltaic systems are reliable and inexpensive to run. The relatively high investment costs make these units most suitable for areas with more than five to six daily sun hours or for isolated areas where reliability is imperative. Photovoltaic pumping systems are available for normal flow/head conditions. The power range is between 0.4 and 2 kW. Photovoltaic systems are most economical at low power demand and high solar radiation.

Thermal systems are not available on the market today. Some promising development work is now underway. The costs are assumed to be lower than for photovoltaic systems.



2.1.1 Solar Radiation

The global solar radiation is the sum of direct and diffuse radiation. The annual mean global solar radiation is shown in figure 2-1. The daily global solar radiation in eastern Africa is about 5 - 6 kWh/m^2 (see fig. 2-1).

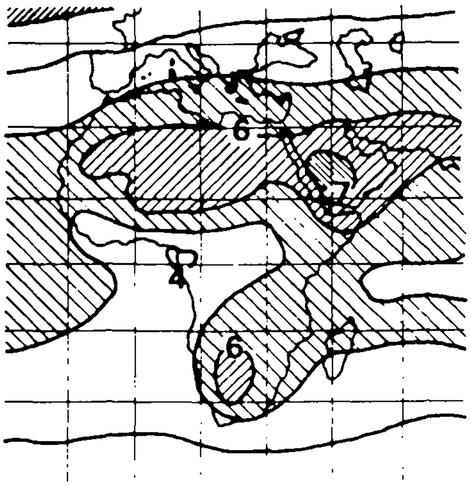


Figure 2-1 Annual mean of daily global solar radiation on ground in kWh/m^2 day /Météorologie Nationale, France/

The annual variations are shown in figure 2-2 and 2-3. In eastern Africa, the daily global solar radiation varies from 4 - 6 kWh/m^2 in January to about 4 - 5 kWh/m^2 in July. Hence, the global radiation is relatively constant during the year.

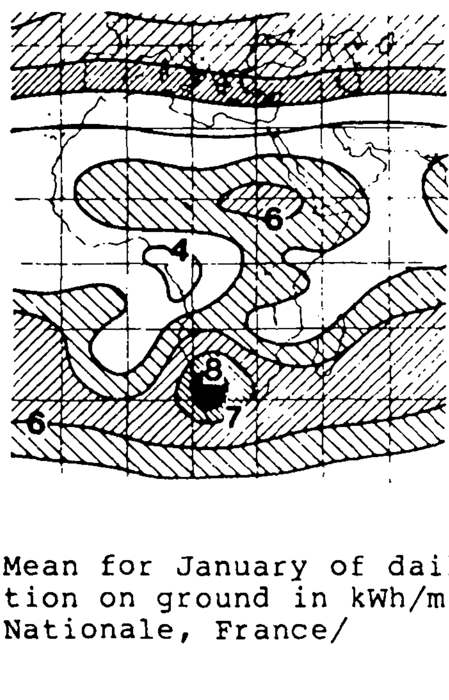


Figure 2-2 Mean for January of daily global solar radiation on ground in kWh/m^2 day /Météorologie Nationale, France/

The situation in southern Africa is different. In Botswana, for instance, the daily mean global radiation in January is about 8 kWh/m^2 and in July only about half of that, i.e. 4 kWh/m^2. This fact indicates that it is important to know whether the main purpose of the water pumping system is irrigation or water supply, and to match the possible production to the consumption of water.

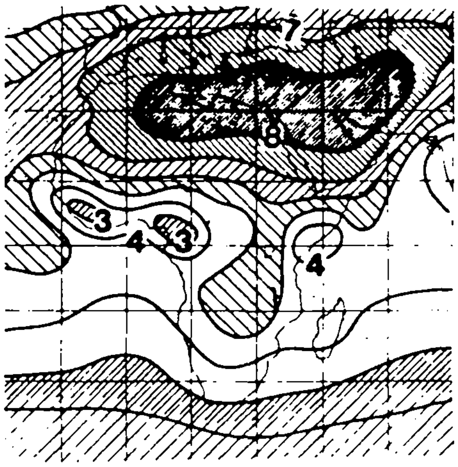


Figure 2-3 Mean for July of daily global solar radiation on ground in kWh/m^2 day /Météorologie Nationale, France/

The diffuse solar radiation is about 1.5 - 2.5 kWh/m^2 per day in the greater part of Africa, which is about 1/3 of the total global radiation, figure 2-4. The intensity of the solar radiation above the atmosphere is 1,377 kW/m^2 and this value is called the solar constant. The rate of diffuse radiation depends on the type of cloud cover which is shown in figure 2-5. Cirrus clouds are thin and high lying clouds which are of the less disturbing kind. The same figure also shows the dependence of the solar angle and the rapid decrease of the radiation when the solar angle is more than $60^{o}C$ from the zenith angle. This means that a solar energy system which will work throughout the day will be very expensive if no energy storage is used.

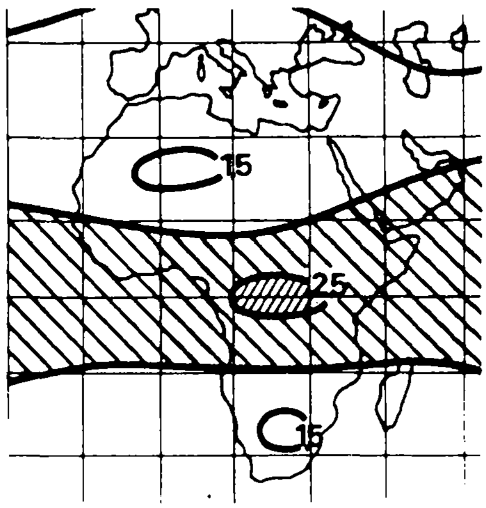


Figure 2-4 Annual mean of the diffuse solar radiation on ground kWh/m^2 day /Météorologie Nationale, France/

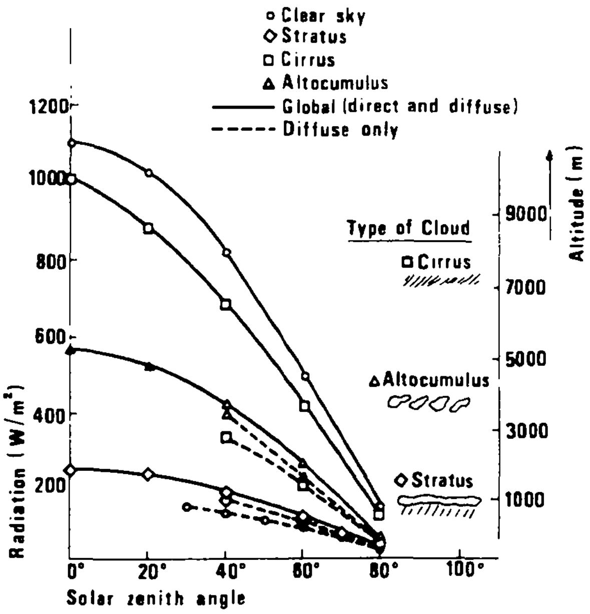


Figure 2-5 Solar radiation on ground at different solar angles and at different types of clouds /W. Palz/

One possibility to raise the efficiency of the solar system is by using sun-tracking solar collectors. This will capture additional solar radiation, especially in mornings and evenings, extending the daily operation period for the system and at the same time maintain the maximal power output, figures 2-6 and 2-7.

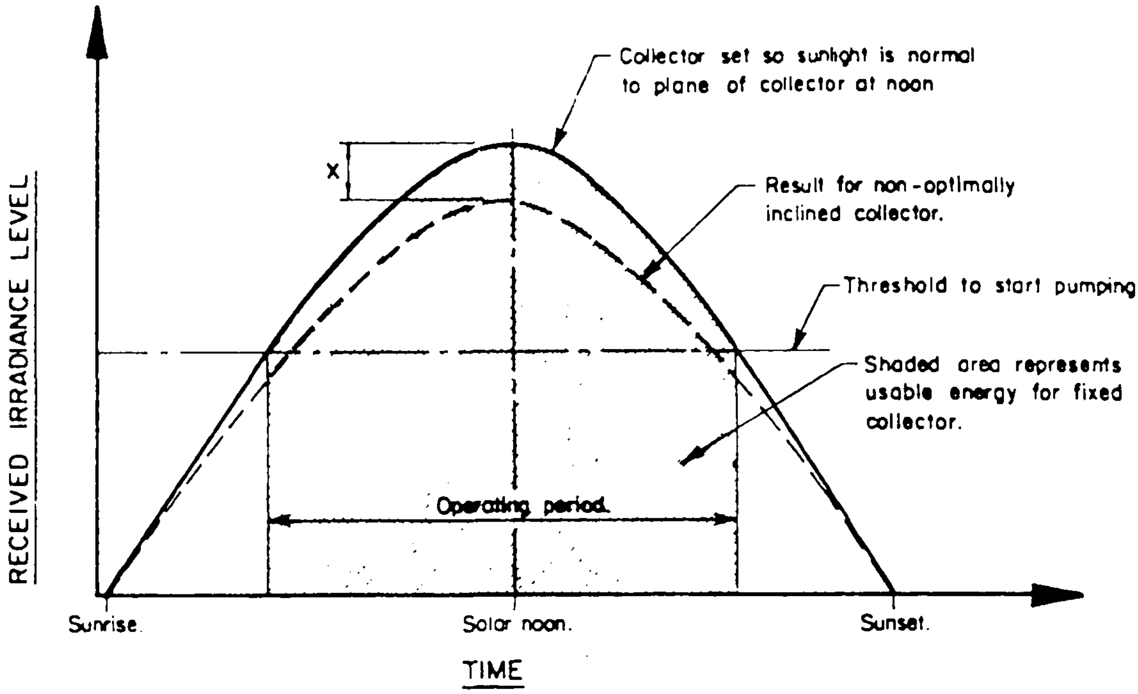


Figure 2-6 Variation of irradiance level received by a fixed collector at optimum inclination /Sir W. Halcrow et al/

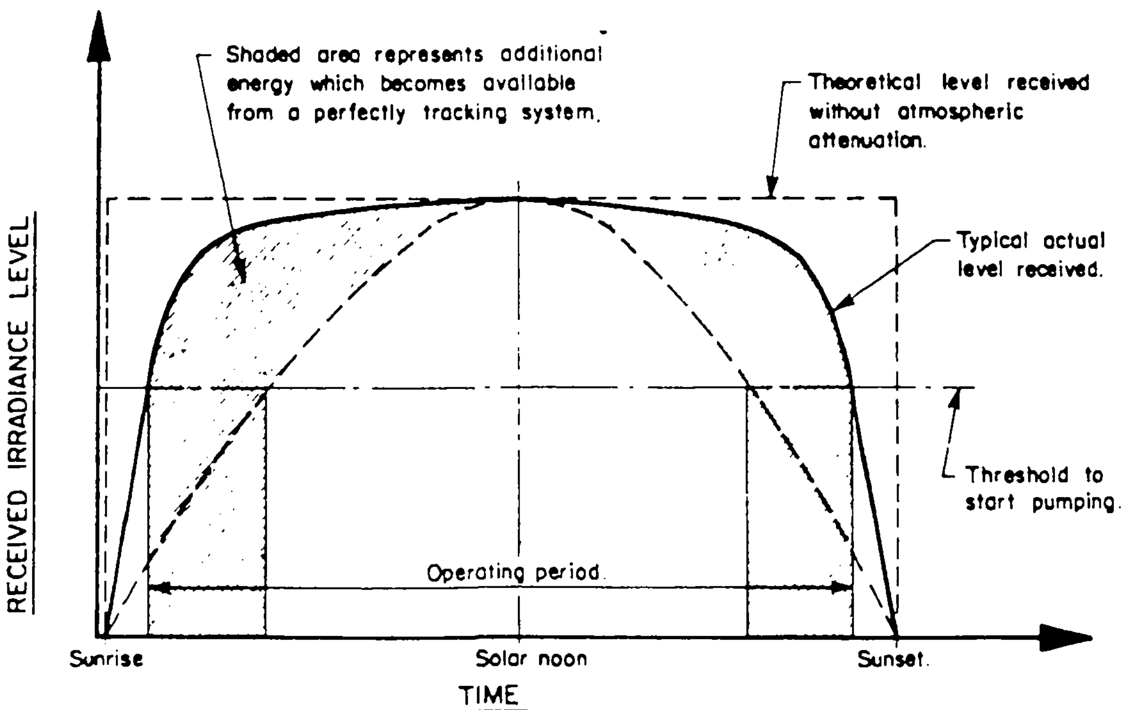


Figure 2-7 Variation of irradiance level received by a sun-tracking collector /Sir W. Halcrow et al/

2.1.2 Thermal solar energy systems

Solar thermal systems collect the heat of solar radiation (infrared light). The main part of this radiation will be absorbed or reflected by the clouds. Therefore, the solar thermal system must be dimensioned for direct solar radiation.

A thermal system for water pumping was developed in France during the 1870's by Mouchot. In this system the solar radiation was concentrated by a conic linear reflector with an area of about 20 m^2 and the solar energy converted to mechanical energy by a steam engine. The capacity of this water pumping system was 1 m^3/h at 1 m head. Other equivalent systems were later developed in USA, some of which also incorporated flat plate solar collectors. The solar steam engines had an output of about 5 to 15 kW. Another big solar powered irrigation system was built in Egypt in 1913. All these systems were later replaced by combustion engines which at that time were becoming cheaper and more convenient.

No development work on solar thermal systems was done until in the 1960's, when especially France and Israel started to work with these systems again. Some systems were built by the French in western Africa. A large system was built in Mali. It had a power output of 70 kW and pumped 1,800 m^3/h of water for irrigation at a waterhead of 8 m.

Thermal water pumping systems are today produced internationally on a limited scale, and substantial development work is underway. Pilot plants are in operation in different countries. The systems work within a temperature range of about 100 to 1,000 °C.

At low temperatures a flat solar collector can be used together with an organic fluid medium. A typical temperature range for these systems is about 50 - 150 °C.

The development work is mainly concentrated on large units with a power output of 10 - 100 kW. Small units seem to be too expensive at present.

Solar energy can also be used as drive energy for engines such as Stirling-engines or gas turbines. These applications require higher temperatures and more advanced solar collectors of the concentrating type. This kind of system often has a power output of 5 - 500 kW and converts the solar energy to electricity. The high power output in combination with the high technology level is too sophisticated to be used for water pumping for rural water supply. However, in the future they may be more interesting for small electric supply networks or small industries.

These types of large thermal systems consist of a considerable number of components which have to be dimensioned for each application. However, some research is underway and perhaps more generally applicable systems will be available for pumping purposes as well. The overall efficiency of the solar powered Stirling-engine with a parabolic dish will be about 30 %, which is rather high compared with other solar systems.

Small lightweight dish solar collectors are also being developed together with a Stirling-engine with a linear generator. Some prototypes have been tested and it seems possible to reach high performance and reliability.

2.1.3 Photovoltaic systems

A solar cell converts the solar energy directly to electric current. Modern commercial cells are generally made of thin layers of mono- or poly-crystalline highly purified silicon, which has been chemically doped. The doping creates one layer with negative electric bias (n-bias, an excess of electrons) and another layer with a positive bias (p-bias, a deficiency of electrons). When exposed to sunlight, electrons will move from the p-type silicon through the junction to the n-type silicon and develop a potential of 0.6 V (at 25 ^{o}C) on open circuit. The cell is able to deliver a current of about 25 mA/cm^2 cell surface under an irradiance of 1 kW/m^2. A number of such cells are connected in series (making the cell voltage additive) and in parallell (making the cell current additive). The desired cell configurations are built into a rectangular module consisting of a glass or plastic window and a rigid back with the cells laminated in between.

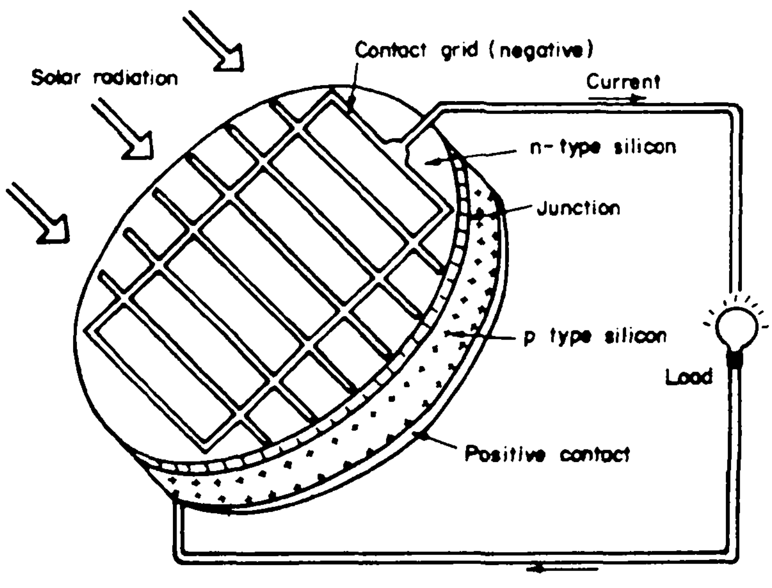


Figure 2-8 Silicon solar cell /Sir W. Halcrow et al/

The cell efficiency varies between 5 and 15 % depending mainly on temperature and irradiance. The polycrystalline cells seem to be less effective at low irradiance than monocrystalline cells.

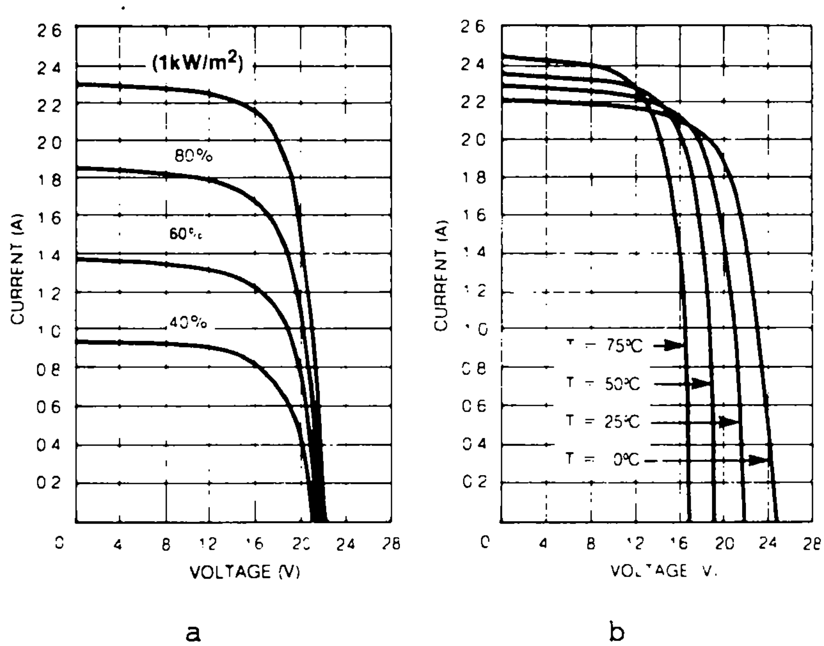


Figure 2-9 a) Example of performance at various light intensities, T = 25 °C
b) Example of performance at various temperatures at an irradiation of 1 kW/m^2 /Solarex data sheet/

A photovoltaic system (PV system) consists of a number of interconnected modules set into a panel. The panels are then connected into an array or sub-array.

The modules, panels or arrays are connected in such a way as to obtain the desired voltage and current. The PV system can easily be adjusted to meet the actual power requirements.

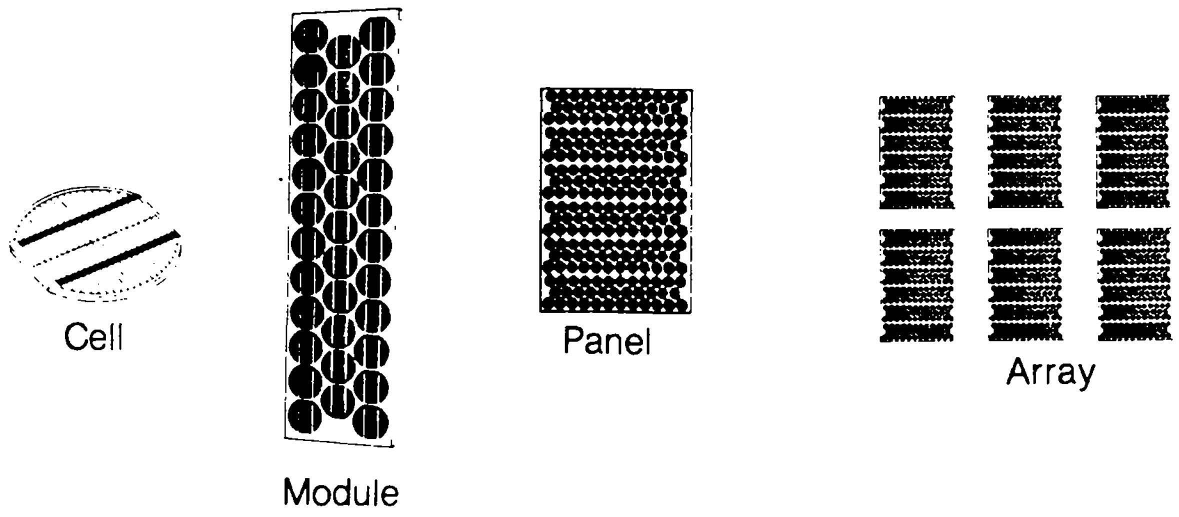


Figure 2-10 Components in a photovoltaic system /Arco data sheet/

There are approximately 60 established solar module manufacturers on the international market today: 12 in Europe, 25 in the United States and 12 in Japan. Many of these companies are large and produce PV modules on an large scale, especially some US firms, whose share of the market was 80 percent in 1980 and 55 percent in 1982. About 10 companies in the Third World - particularly countries like Brazil, Mexico, India and the Philippines - produce PV modules on a small scale, but their competence and production will increase via joint ventures with European and American companies.

Many PV systems for water pumping have been developed and tested. The most common type is the DC system, which requires a minimum of components. The system works in the simplest possible way with only solar modules, connecting wires, junction box and motor/pump. The only form of maintenance needed is cleaning the modules, maybe once a month in dusty areas, and changing brushes in the DC motor once a year. The DC system can be completed with a battery for energy storage but if the system is built for water pumping only, it seems easier to store water in a tank than energy in a battery. A battery may, however, extend the daily operation period by providing more energy for the start-up of the pump. In some systems, a maximum power point tracker (MPPT) is installed for matching the array output to the motor demand. The MPPT will adjust to the maximum power point for the array when irradiance level, array temperatures, the pumping head or any other conditions change. Significant benefits can be gained from a MPPT despite the fact that it is rather energy intensive. A badly designed system with an ill-matched array and sub-system would, however, benefit most. A good system with a well-matched centrifugal pump can be designed for a close match between the maximum power and the efficiency locus of the array, but systems with piston or a positive displacement pump, at a given head, need a MPPT for a good match between the array operating point and the motor demand.

The AC system also has been developed and is commercially available today. ADC/AC converter converts the DC power from the solar array to three-phase AC power, which is transmitted to a submersible pump/motor unit. The pumps maybe standard pumps, which are reliable. The DC/AC converter has an efficiency of 90 - 95 %.

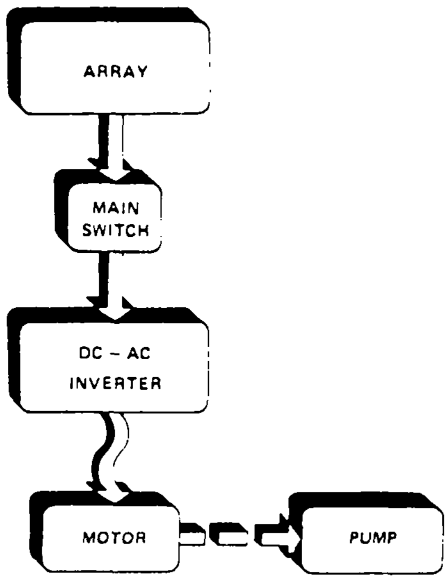


Figure 2-11 Schematic system layout for an AC solar pumping system /Grundfos, leaflet/

2.2 Windpower

2.2.0 Summary

Wind energy's largest potential is in coastal and desert regions, where the wind is strong and regular. Windmills for water pumping require a relatively low investment and in good wind conditions can lift water at a low operating cost. Windmills can pump water directly or produce electricity for a motor and pump.

Windmills are very sensitive to variations in wind speed. The diurnal, monthly and annual variation of wind speed must be measured and considered carefully before construction.

Windmills are available for normal flow/head conditions. Windmills are produced in developing countries (e.g. India and Kenya) as well as in industrialized countries (e.g. Argentina, Australia and US). Some windmills can also be built or produced locally.

2.2.1 Meteorological conditions

The available wind energy for an area is difficult to estimate because of the strong dependence on local meteorological and topographic conditions. High wind energy areas are often associated with:

- long, sloping valleys parallel to prevailing winds
- high elevation plains and plateaux in areas of strong winds
- plains and valleys with persistent downslope winds
- exposed ridge crests and mountain taps
- exposed coastal sites.

Low wind-power areas are often associated with:

- valleys perpendicular to the prevailing wind
- small and/or sheltered basins
- short and/or very narrow valleys or canyons
- areas of high surface roughness.

The dependence on local conditions indicates that an existing wind-map, e.g. fig 2-12, may be used only for general estimation of the potential wind energy. Daily or seasonal variations are not shown on the map. However, the coastal areas in western and eastern Africa seem to have a good potential for wind energy systems, whereas countries like Botswana and Zimbabwe seem to be less favourable for wind energy use.

Of those countries included in the study, Kenya, Ethiopia and Tanzania are in general best suited for the application of wind energy systems. Some areas of Kenya may also be suited for wind energy systems.

The power output is proportional to the cube of the velocity which means that when the velocity is reduced to half, the power will be reduced to an eighth. A more realistic example is that if the velocity is reduced by twenty percent the power will be reduced to half. These examples show the importance of a thorough knowledge of the wind situation at the windmill site.

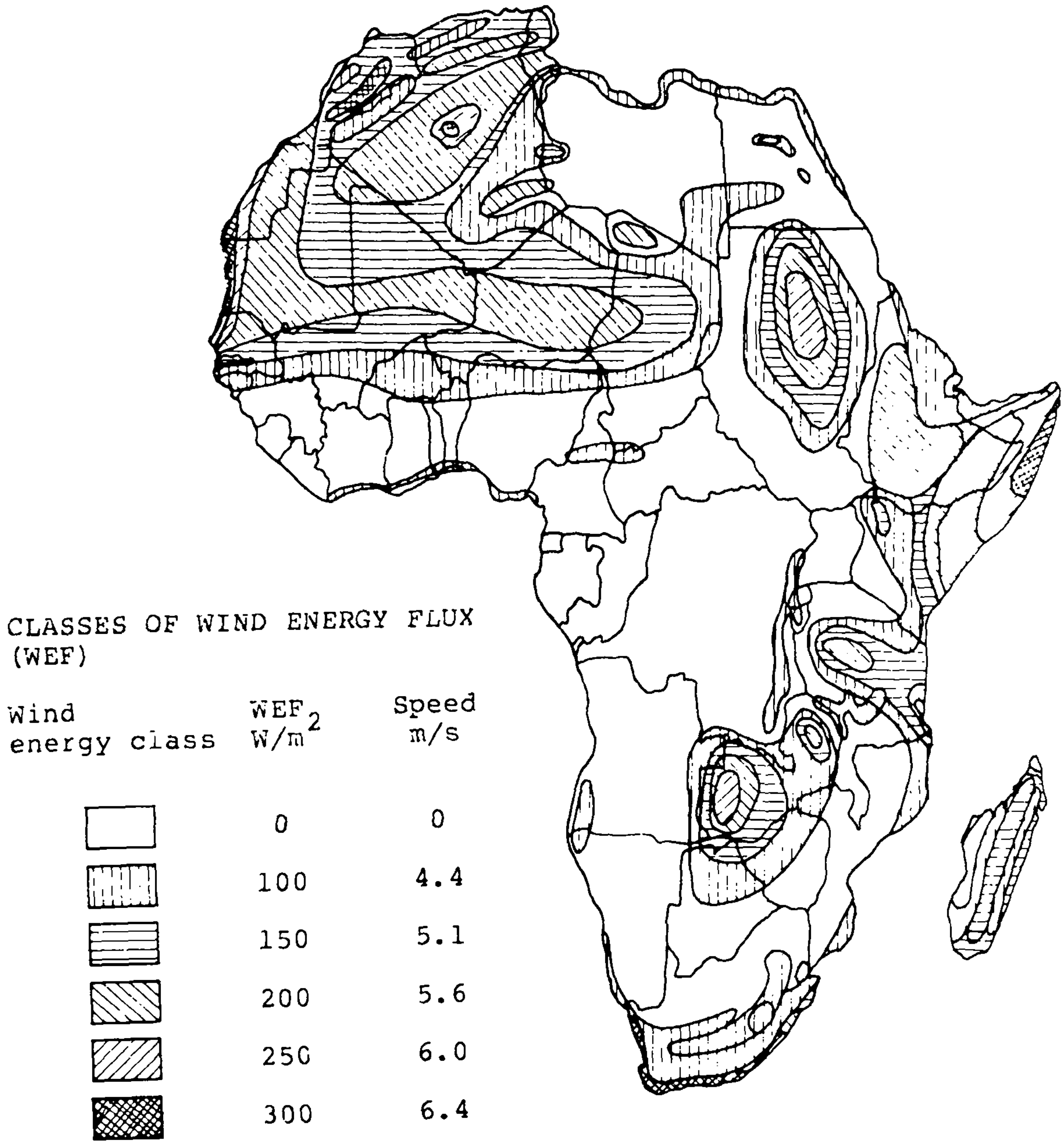


Figure 2-12 Preliminary estimate of the annual mean wind energy available at typical well-exposed locations /Battelle Memorial Institute/

It is important to examine the wind variations during a day. Some areas have high wind velocities in the afternoons and low wind velocities at other times. Measured wind data may then give a wrong value when using the wind data for calculation of the energy content in the wind.

The wind speed is also a function of height which depends on the surface swept over by the wind. The surface is characterized by its so-called roughness height, h_o:

- smooth surface, ocean, sand $h_o = 0.01$ m
- low grass $h_o = 0.03$ m
- high grass $h_o = 0.10$ m
- tall new crops, low woods $h_o = 0.25$ m
- high woods with many trees $h_o = 0.50$ m
- suburbs, small towns $h_o = 1.00$ m

This function is shown graphically in figure 2-13. The graph can be used for flat terrains (elevation difference less than 0.01 and height/length ratio of the largest difference of terrain less than 0.03) and the rotor dish height more than three times the largest difference of terrain for 3 to 5 km in any direction. The graph can, of course, give an approximation of wind speed at different levels even if all the aoove conditions are not completely fulfilled.

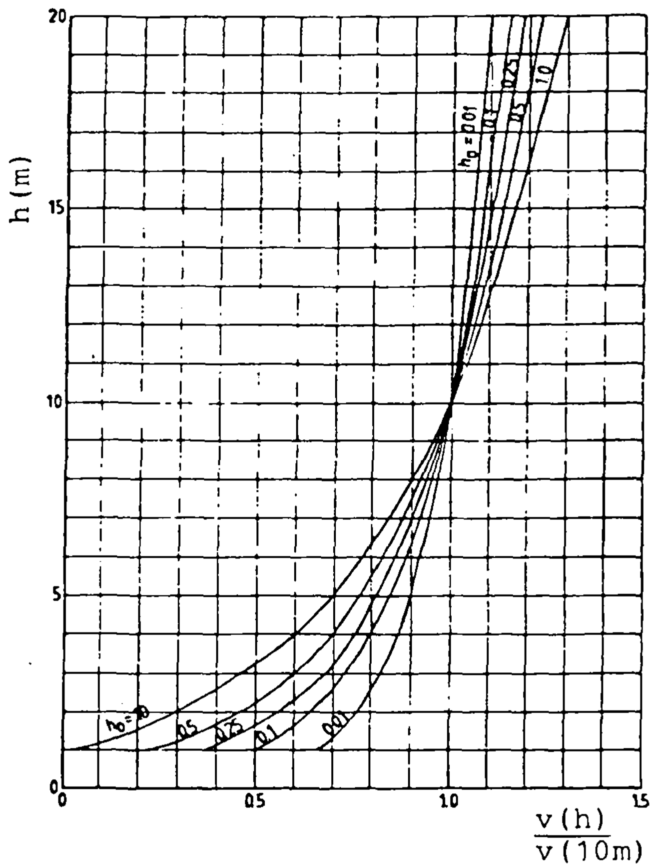
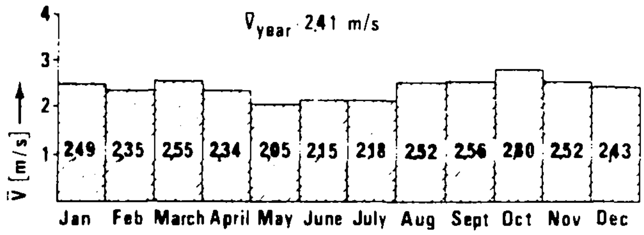


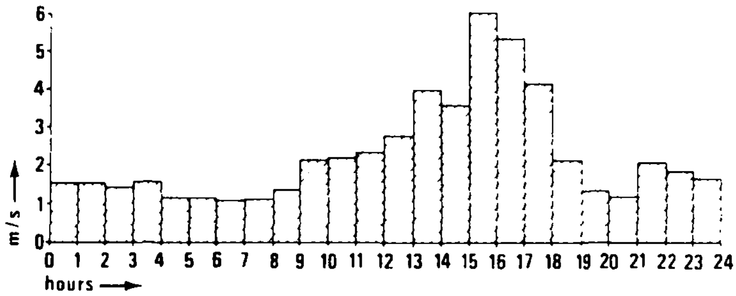
Figure 2-13 Wind speed profiles for different values of the so-called 'roughness height' h_o /WMO/

Some examples are considered as follows. In example 1, a 7 m high windmill with a rotor diameter of 5 m is proposed for a site with an annual mean wind velocity of 2.4 m/s, fig. 2-14 a, measured at 10 m level at noon over a long period, fig. 2-14 b, and a diurnal wind speed pattern measured over a shorter period. There is also the frequency distribution of hourly mean speed, fig. 2-14 c. The windmill will operate at wind speeds between 2.0 m/s and 7 m/s. In example 2 and 3 all data will be the same, except the annual mean wind velocity which is 4 m/s and 6 m/s respectively.

a)



b)



c)

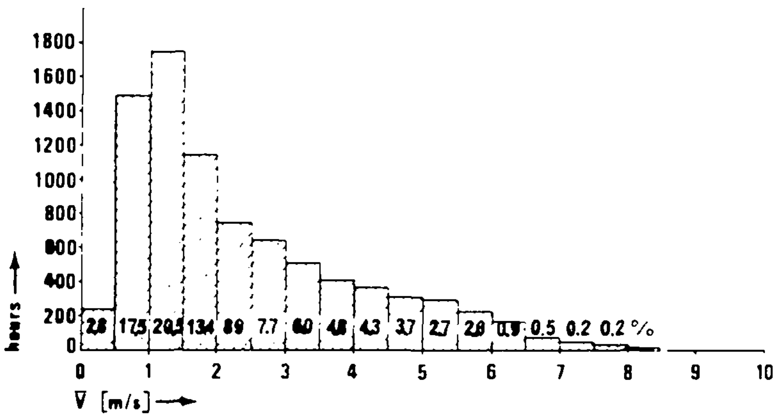


Figure 2-14 Example of wind data, Sudan
a) Yearly wind speed pattern, 1970-1980
b) Diurnal - " - , May 1970
c) Frequency distribution of hourly wind speeds, Jan-March 1970
/Dr. Yahia H. Hamid/

The most accurate way to predict the wind energy flux output is to use the frequency diagram, fig. 2-14 c, and calculate the power output for each wind speed interval and integrate over time. For simplicity, in this example, we will consider only the annual mean wind speed. Fig. 2-14 a shows that the monthly wind speeds vary within about ±15 percent from the annual mean wind speed $\bar{v}_{year}$.

In this example, measuring values at noon are somewhat more optimistic, fig. 2-14 b. It seems realistic to reduce the values with about 10 percent. We also have to reduce for the measuring height by using fig. 2-13. Assume h_o = 0.25 and tower height 7 m and the graph gives v(h)/v(10) = 0.9, fig. 2-14 b. The wind speed at 7 m is then about 90 percent of the speed at 10 m, resulting in a 10 percent reduction.

The power output, P, from a windpower system can be calculated for a given wind speed, v, and swept area, A ($A = \pi d^2/4$), by the formula:

$$P = \rho \times C_p \times v^3 \times A$$

where ρ = the density of ambient air = 1.2 kg/m^3 at 25 °C and efficiency or power coefficient C_p = 0.1 to 0.25 in wind pumping systems. The calculations are shown in table 2-1.

Calculation and data	Unit	Ex 1	Ex 2	Ex 3
Annual mean wind velocity, $\bar{v}_{year}$	m/s	2.41	4.0	6.0
Annual variation, percentage		±10	±10	±10
Correction, measuring value, percentage				
time, c_t		-10	-10	-10
tower height, c_h		-10	-10	-10
Corrected wind velocity $v_c = \bar{v}_{year}(1+c_t+c_h)$	m/s	1.95*	3.2	4.8
Swept area $A = \pi d^2/4$, d = 5m	m^2	20	20	20
Power calculated without corrections for the wind speed (C_p = 0.2)	W	65	310	1040
Power calculated with corrections for the wind speed (C_p = 0.2)	W	0*	155	530
Annual variation limits	W	0-40	110-210	390-710

* v_c is less than the start up speed

Table 2-1 Calculation of wind energy output

These examples show the importance of correct data for siting a windmill and indicate that such low wind velocities as 2-3 m/s are not very useful for the purpose of water pumping. Wind driven water pumping systems have to be sited at locations with wind speeds of at least 3-5 m/s to be an economical alternative.

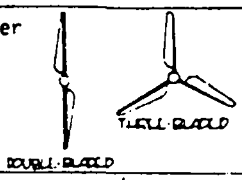
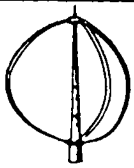
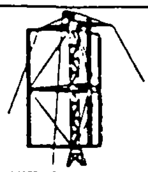
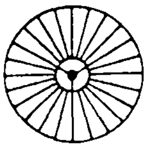
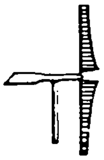
Wind variations during a year are in general small when comparing annual with monthly mean wind velocity. These variations seem to be of lesser importance especially when the water demand is relatively constant througout the year as is the case of drinking water supply. For irrigation purposes these variations may even be favourable since both the wind velocities and the irrigation water demand will be low during the rain season.

Wind energy can be an economical and reliable energy source for water pumping in some countries in Africa if windmills are located and constructed taking into account the prevailing wind situation. This may be a problem in some cases where the water source is located at a site with insufficient wind conditions. A number of windmills are, however, developed for low wind velocities but the swept area of this kind of wind turbine has to be large to obtain the desired energy output.

2.2.2 Rotor configurations

About one hundred wind turbines with different rotor configurations have been tested. Lift- and drag-type rotors are the two major classes used to describe their function.

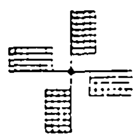
In general, lift-type rotors are low torque and high speed which makes it possible to reach a high power coefficient. Lift-type rotors are sensitive to wind-speed changes which in combination with their low torque makes them less suitable for direct water pumping. Some types, however, have a lower speed which makes them more suitable for direct connection to a water pump.

Rotor Type	Tip/Speed Ratio Range	C_p*	RPM	Torque	Typical Load
Propeller (lift) 	6 to 10 (up to 20)	0.42	High	Low	Electrical Generator
Darrieus (lift) 	5 to 6	0.40	High	Low	Electrical Generator
Cyclogiro (lift) 	3 to 4	0.45	Moderate	Moderate	Electrical Generator or Pump
Chalk Multi-Blade (lift) 	3 to 4	0.35	Moderate	Moderate	Electrical Generator or Pump
Sailwing (lift) 	4	0.35	Moderate	Moderate	Electrical Generator or Pump

* C_p = power coefficient

Figure 2-15 Some examples of lift-type rotors and some operating characteristics

Drag-type rotors have a lower speed and a higher torque and are often used for water pumping purposes. The old Dutch windmill is a good example for water pumping.

Rotor Type	Tip/Speed Ratio Range	C_p*	RPM	Torque	Typical Load
Fan-Type (drag) 	1	0.30	Low	High	Pump
Savonius (drag) 	1	0.15	Low	High	Pump
Dutch-Type (drag) 	2 to 3	0.17	Low	High	Pump or Mill Stone

* C_p = power coefficient

Figure 2-16 Some examples of drag-type rotors and their operating characteristics /WMO/

To raise the efficiency of a water pumping system, a gear-box or a beltdrive is connected between the windmill and the pump. The gearboxes cause an energy loss and make the systems more complicated. The tendency today is to try to find more suitable pumps which can be coupled directly to the windmill and work with a high efficiency.

It is important to know the start-up speed for a windmill. Most windmills do not start up when the wind velocity is lower than 2-4 m/s. Since areas of Africa usually have a lower wind speed than 5 m/s it may be difficult to find a windmill which can work continuously througout the whole year.

2.2.3 Construction materials

Wind pumps can either be constructed domestically of indigenous materials such as wood, bamboo and sail, or constructed of metal in factories. It is difficult to draw a line between these technologies which however represent two main approaches to the application of windpower.

Small-scale wind pumping systems have been constructed of local materials in many countries around the world. In Crete, windmills have been used for water pumping during hundreds of years. The Cretan windmill is built as a tower of wood and a rotor of sail and wood. The windmills have been used for water pumping at low head in good wind conditions.

Classic concepts have lately been developed and a number of low-cost windmills constructed by such organizations as ITDG (Intermediate Technology Development Group, UK), VITA (Volunteers in Technical Assistance, USA), SWD (Steering Committee Wind Energy Developing Countries, the Netherlands) and Centro de Desarollo Integrado Los Gaviotas, Colombia. These organizations have published construction manuals for windmills which can be built and repaired in the developing country. These wind mills are usually connected directly to a water pump so that the number of moving parts are limited. The maintenance needed is regular check-ups and lubrication services, of course some moving parts might wear out and have to be replaced. The life-span of these windmills seems to be about 10 - 15 years with regular maintenance.

In countries like the Netherlands, USA, Australia and Argentina, windmills for water pumping were common at the beginning of this century. These wind pumps were mainly used by farmers for supply of drinking water. This kind of windmill has developed right up to World War II. Many of these wind pumps became very reliable and efficient, resulting, however, in high investment costs. They are still commonly available in countries like Australia, South Africa, USA and Argentina. Their useful life often extends over 15 years. The market for this kind of wind pump has increased since the early seventies and some development work is now underway. Some of these windmills are also available for electric production which makes them more useful in good wind conditions.

2.2.4 Conversion of wind energy

Many water pumping locations often require electricity. A good choice can then be a windmill with an electric output that can meet both the electric and water pump demand. At such conditions, it may also be interesting to search for a site with better wind conditions than may be the case at the site of the water source.

The efficiency or power coefficient (C_p) is around 0.10 - 0.25 for direct water pumping system while many wind-electric generators can achieve C_p values of between 0.3 - 0.4. A wind electric system, in combination with a suitable electric pump, can then be more useful yielding a higher energy output than a direct wind pump system. Electrical systems are, however, more complicated, which may be a problem in some areas.

A wind-electric system can support a water pump during the daytime and lighting during nighttime. The diurnal wind flow pattern, fig. 2.17, shows that in general the maximum wind energy is available during the afternoon. During evenings and nights, wind speeds are lower. Windmills for electric production can operate at low wind speeds and some systems can therefore produce electricity for lighting purposes during evenings when the pump is shut down. Of course, it is possible to store electricity in a battery, but this adds complexity and components like AC/DC converter, battery protector, etc.

Instead of being converted to electric energy, wind energy can be converted to hydraulic energy with a compressor. Windmills with hydraulic conversion also have the advantage that they can be sited some hundred meters away from the well. The compressor is coupled in-line with the windmill and is connected to the pump by a small pipe. The system is reliable but requires regular control of the compressor unit.

2.3 Hydro power

2.3.0 Summary

If hydro power is available on site, it is generally the most preferable source of energy because of good reliability and low running costs. It is generally easier to predict the available hydroelectric energy than, for example, the wind energy. Annual variations are significant, however. Most streams in arid areas have a peak flow once a year. During the rest of the year low flow conditions prevail or the streams can sometimes be dry. Building large dams and reservoirs for collecting the peak flow is not advisable for that small scale water power stations. It is easier to use only a portion of the water flow which is relatively constant during the year. Since the energy in flowing water is almost bigger than the power demand for the water pump a hydroelectric set is often installed to produce electricity for the water pump and for other purposes.

2.3.1 Hydromechanical systems

A hydromechanical system transforms energy from a high flow and low head to low flow and high head or the reverse. Different systems are developed and in general they are highly reliable but moderately efficient. In general, this system pumps the same water as used for driving the pump, thus the water source usually has to be the surface water.

Figure 2-17 shows a suitable system for using the energy in a stream. The turbine/pump can be made of items that are almost scrap, e.g. oil barrels, inner tubes and standard components of cars. At a mean flow in the stream of 0.8 m/s, the pump head is about 10 m and the discharge flow about 4 l/s.

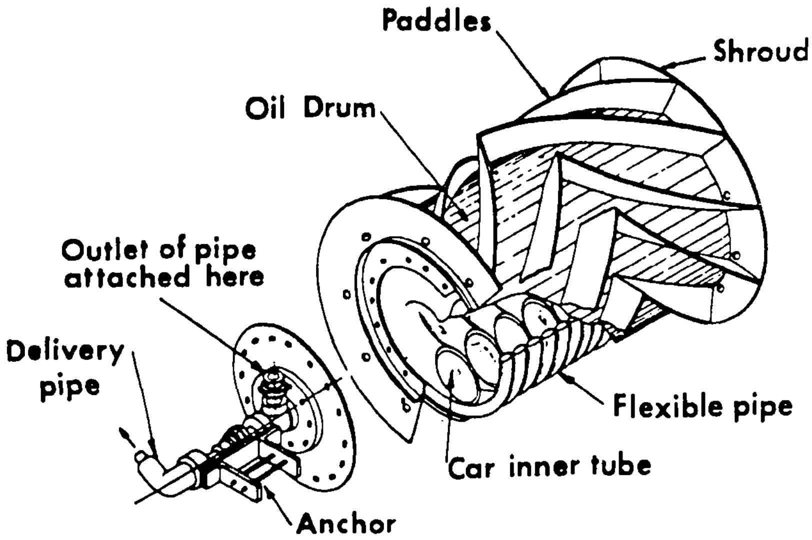


Figure 2-17 Stream-powered rotating coil pump /Consulting Engineer, April 1981/

The pump has no valves. As it rotates in the stream, plugs of water and air are alternately forced into the inlet of the pipe coil. Each revolution of the pump forces the plugs of water to rotate around the coil once. This increases the static head acting on them by an amount proportional to the diameter of the drum.

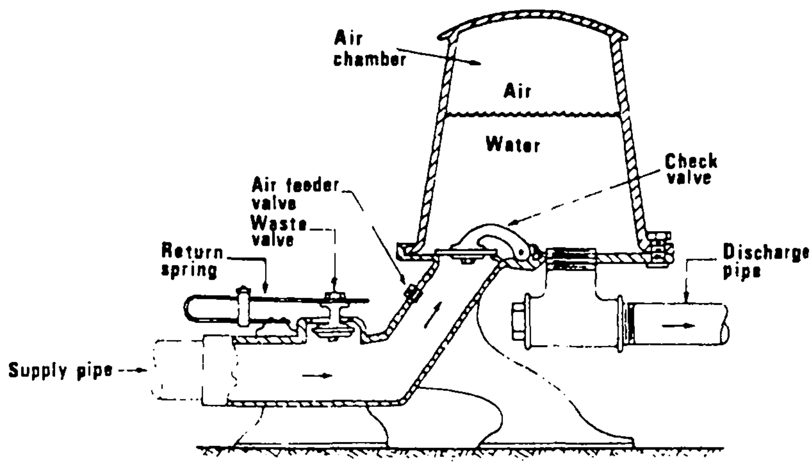


Figure 2-18 Sketch of a hydraulic ram /Wood/

The working cycle of a hydraulic ram begins, see fig. 2-18, with a waste valve which has just been opened, and a closed check valve. Water accelerates in the supply pipe through the waste valve almost instantaneously. The water hammer effect opens the check valve and water flows in to the air chamber. The flow continues through the check valve until the original kinetic energy of the water column in the supply pipe is exhausted. The momentary pressure drop in the valve chamber results in the closure of the check valve and the waste valve is opened and the cycle repeated.

A hydraulic ram can be installed when the drive head exceeds 1.0 m and a driving water flow exceeds 0.1 l/s. The ram is available up to driving flow around 20 l/s and can deliver water at a head of about twenty times the drive head.

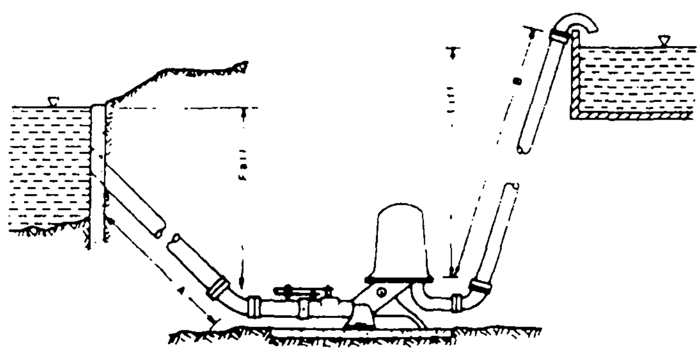


Figure 2-19 Example of a hydraulic ram installation /Wood/

The performance of the ram will decrease with decreasing ratio between driving and delivery head. Normally the performance is about 60 percent with a ratio of 1:3 and about 20 percent with a ratio of 1:20.

In order to illustrate how the capacity of the ram is calculated, an example is constructed with the following data. The water flow is at least 10 l/s throughout the entire year. The driving head is 2.0 m and the desired delivery head is 10 m. How much water can then be delivered?

The driving flow Q_{dr} times the driving head H_{dr} is equal to the delivered flow Q_{de} times the delivery head H_{de} times the performance. Assume the performance C_p = 50 percent since the ratio H_{dr}/H_{de} is 2:10 (equal to 1:5). Hence,

$$Q_{dr} \times H_{dr} = C_p \times Q_{de} \times H_{de} \quad \text{or}$$

$$Q = \frac{Q_{dr} \times H_{dr}}{C_p \times H_{de}} = \frac{10 \times 2}{0.5 \times 10} = 4 \text{ l/s}$$

Since the ram works 24 hours a day, delivered flow is about 350 m^3/day in this example.

Commercially available hydraulic rams are not expensive, but they can also be home-made of commonly used materials such as galvanized pipes or the equivalent. Construction manuals for selfmade rams are included in the reference list of this report.

Another type of hydro-mechanical system is the turbine pump. The passing water drives a water turbine which is directly coupled to a water pump which in turn pumps a smaller amount of water to a higher level. Such pumps have successfully been used in China where more than 100,000 units have been installed during the last 20 years.

Turbine pumps are safe and reliable in operation, simple in design and construction with seemingly low maintenance costs.

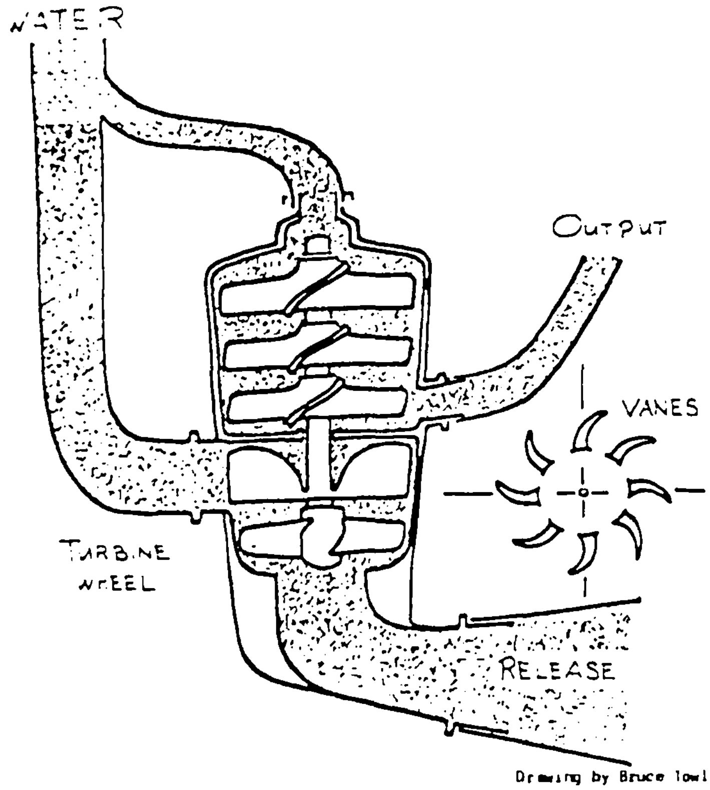


Figure 2-20 Section through a Chinese turbine pump

The Chinese turbine pump can operate with a head exceeding 10 m and lift capability of 200 m.

The few rivers which exist in arid zones are rather large with a high flow and a low head. The systems described above are not well-suited for such conditions, since they work with head exceeding several meters. Different turbines for extracting energy in flowing water with low head have been developed. Considerable research is also being done on these turbines' potential for extracting tidal power.

These turbines operate on principles comparable to wind turbines. For low head applications, a type of Darrieu's turbines is often used. The energy output can also be calculated in the same way as for wind turbines. The only factor which is changed is the density, where water (1,000 kg/m^3) instead of air density i used. The energy flux in flowing water is then about 800 times larger than the wind energy flux if the rotor area and speeds (wind and water) are equal. However, in practice it is not advisable to construct water turbines with the same area as wind turbines. In addition, water speed almost always is lower than the wind speed. The velocity is here as sensitive as it is for wind turbines, which means that estimates of the energy flux in water have to be cautious.

A river turbine can be suspended by a floating pontoon which is moored in the river current by means of a steel cable. A floating installation has the advantage that water level fluctuations have a minor effect on the unit. The range of water level fluctuations is difficult to estimate which is why fixed installations at the riverside have to be very large and safe. Floating installations are therefore generally preferable.

The power output from a river turbine is about 1 - 5 kW. This can be used for direct water pumping or for generating electricity. A prototype has been tested in the White Nile in Sudan as of January 1981. The vertical rotor has a sweep area of 3.75 m^2. Its axis is via a belt drive coupled to a centrifugal pump. The power output is about 170 W where the river speed is 1.2 m/s. The manufacturer claims that the turbine can convert 25 percent of the energy which flows through its sweep area.

Overshot water wheel is also an old well known technique which can be used when the head exceeds several meters. The water wheel can be made of local low-cost material and constructed locally. When selecting a site for the water wheel, flow variations must be considered and the the construction designed to withstand peak flows. In most cases, it is necessary to build a dam and a small intake channel.

Low-cost water wheels are about 10 percent efficient depending on design and natural conditions. Their power output can be in the range of about one to two kW which makes them suitable for water supply to villages.

Since the water wheels usually are directly coupled to the pump, they will as a rule pump water from the river.

If water from a river has to be lifted it may be possible to find a suitable system which can work using the energy in the flowing water. These systems seem to be very reliable with low maintenance demand. Hydropower is in general more economical compared to other energy sources.

2.3.2 Hydroelectric systems

Most water turbines for electric generation have a power output exceeding 10 kW, which is high compared with the water pumping power demand in this study. However, a number of small water turbines are available with an output suitable for water pumping.

A number of small turbines have been developed for production of electricity. Complete systems are available with turbine, generator and electric equipment for a low voltage output. These complete units are often very compact and designed for simple connection with standard plastic pipelines.

The head for this kind of system is in the range 2 - 100 m and the flow range is about 1 - 15 l/s. Its power output is from about 50 W to 2,000 W.

Even if the power output range seems to be well suited for water pumping purposes, it may be difficult to find suitable sites for such systems in many parts of Africa.

The water turbines are well suited for areas with a humid climate, where rivers and small streams have a regular flow. On the other hand, the water demand is less in a humid climate and perhaps water can be directly led into pipes. The system can in some cases be of interest since the electricity can be used for other purposes, e.g. lighting and refrigeration.

In arid zones, the flow in the rivers varies widely, with no flow during the dry period and very high flow during the rain period. Rivers in arid zones with a regular flow during the year are rare. However, they are often large with a high flow and usually a small head. Systems shown in chapter 2.3.1 above seem therefore to be better suited for water pumping in arid zones.

2.4 Bioconversion

2.4.0 Summary

Bioconversion is the general term applied to techniques which make use of biological processes to transform biological material to energy. The best known form of using biofuel is the burning of wood. The bioenergy is mostly transformed into heat for cooking, but it can also be used in engines, e.g. steam engines, stirling engines, gas turbines or in internal combustion engines by gasification.

Another form of bioenergy is biogas, which is produced by microbes when organic material is fermented in a certain range of temperature, moisture contents and acidities and lack of air.

A general potential for bioconversion is difficult to estimate since it mostly depends on the local situation. Long transport distances for the biomass make the costs too high. Biofuel for gasification is an alternative in the case of an excess of wood. In Africa the lack of wood for cooking purposes is a great problem with grave ecological consequences. Use of wood for large scale energy production must therefore be carefully planned and controlled. For water pumping purposes biofuel is mainly suitable in the neighbourhood of wood-industries or similar conditions, where it is possible to use waste material.

Biogas generally has a larger technical potential, since it makes use of manure and such biological waste products as straw, stalks or leaves. The main problems here are of social and cultural nature. The technique for biogas production is "appropriate". Utilization, however, is more advanced.

The bioconversion systems available today are in general more complicated than conventional diesel systems. Hence, maintenance problems will be more pronounced.

2.4.1 Biogas

Biogas plants can in many countries be an alternative, both for fuel production and for treatment of waste disposal. The biogas slurry can after some months also be used as fertilizer. The greatest problems resulting from the introduction of biogas plants are mostly of social and cultural character.

Biogas is a mixture, consisting mainly of methane and carbon dioxide. It can be extracted from different kinds of organic material such as grass, leaves, garbage and human or animal manure.

Biogas can be used as cooking and lighting fuel, as well as replace diesel in an engine. The energy content of one cubic metre of biogas is about 1.5 - 2 kWh, the same amount as in about 4 kg of general stable manure from livestock, table 2-2. The real biogas production may be lower than the values in table 2-2. When the temperature in the biogas plant decreases, biogas production also decreases. Practical problems as, for example leaking plants, may also reduce biogas production.

Material	*Amount of gas produced per tonne of dried material in cubic metres*	*Percentage content of methane*
General stable manure from livestock	260-280	50-60
Pig manure	561	
Horse manure	200-300	
Rice husks	615	
Fresh grass	630	70
Flax stalks or hemp	359	59
Straw	342	59
Leaves from trees	210-294	58
Potato plant leaves and vine etc.	260-280	
Sunflower leaves and stalks	300	58
Sludge	640	50
Waste water from wine or spirit making factories	300-600	58

Table 2-2 Gas yield of some common fermentation materials /A Chinese Biogas manual edited by A. von Buren/

Biogas can be a realistic energy source for village water pumping purposes. As a rule of thumb, manure from one cow can provide about 1 kWh daily, which corresponds to 10 m^3 water lifted 10 m.

A pumping unit driven by biogas may consist of a biogas plant, an engine and a pump. It is also possible to produce electricity by connecting a generator to the motor and use electric pumps.

There are many designs of biogas plants, more or less complicated. One type is the Chinese model, figure 2-21. An alternative type, the Indian model, is illustrated in figure 2-22.

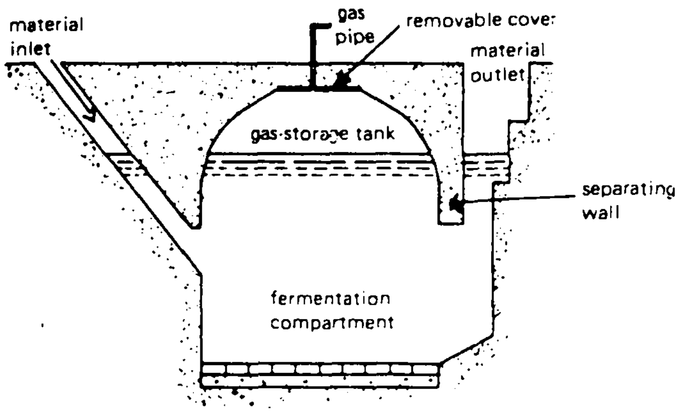


Figure 2-21 A Chinese circular biogas pit. /A Chinese Biogas manual, edited by A von Buren/

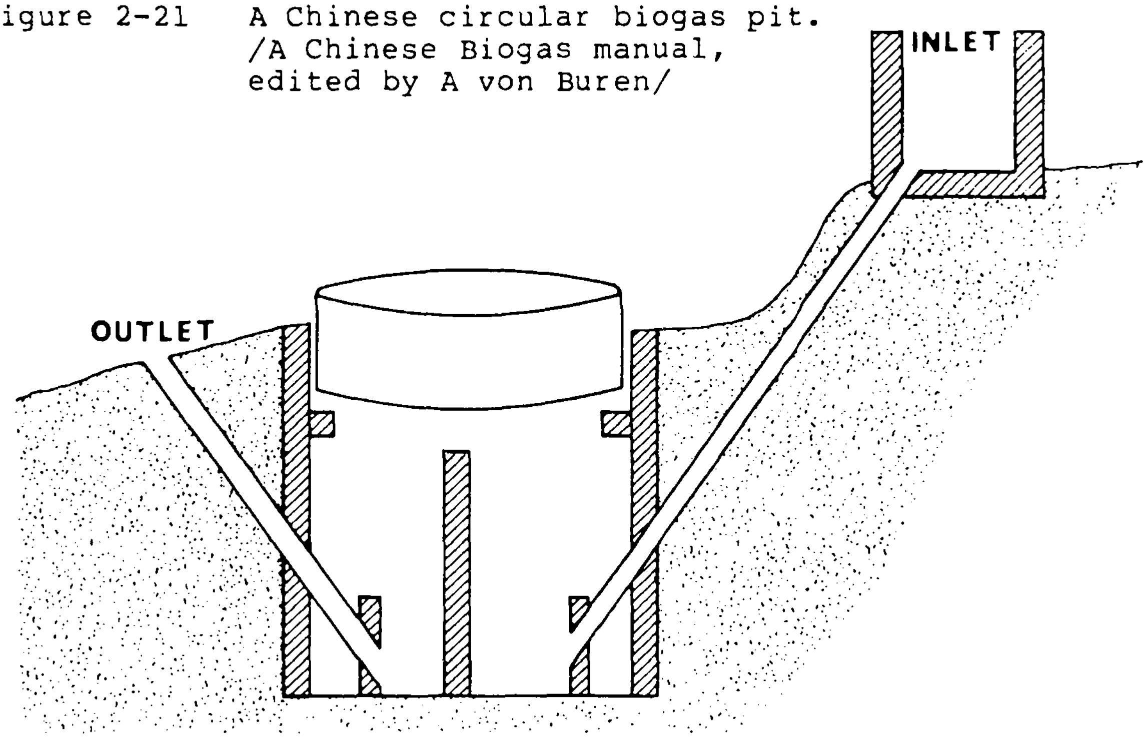


Figure 2-22 Indian-type digester /BIOGAS - not just a technology, Metangruppen, Gothenburg/

Biogas plants require regular maintenance. Suitable material has to be filled in and taken away, the pH level has to be checked and the liquid fertilizer stirred frequently. The cultural and social aspects of this work are very significant.

Biogas engines are available for direct connection. Such systems may consist of modified petrol or diesel engines.

However, with small modifications diesel engines can also work with a mixture of diesel and biogas. It should be observed that biogas often has small quantities of hydrogen sulphide. This causes an acid condition in the engine requiring careful maintenance. The use of filters which reduce the acidity may decrease the adverse effects.

Any pump which can be connected to a diesel engine can also be connected to a biogas driven engine.

2.4.2 Gasification and biofuel

Different kinds of biomass may be used for gasification. Dominating sources today are wood and charcoal, which have been used since World War I. During World War II theywere further developed and gasification played an important role replacing petrol and diesel. Other possible biomasses, such as rice-hulls, corn cubs and straw of different kinds, have been tested in laboratory and in field experiments. Cocoanut shells e.g. have been used in Tanzania.

All kinds of dry wood may be used for gasification. The wood is cut to pieces at small sawmills. Charcoal can be used directly and is easier to handle.

Gasification plants seem to be rather big and complicated units. The size of the systems is about 5 to 10 kW or more. This makes them more attractive for rural electrification in places where skilled people can maintain the units.

Steam may also be produced when burning biomass. The steam can be used in a turbine producing electricity. Such systems have been tested in a field experiment and may be commercially produced. All kinds of biogas may be used in the burner enabling the use of different kinds of waste materials. Because the units are complicated, the maintenance seems to be of great importance.

2.5 Muscular energy

2.5.1 Animal driven pumps

Animals are the traditional power source in all agricultural cultures in the world. They are mainly used for work in the fields and for transportation, but also for low-lift waterpumping. In general, animals walk around an axis to which some kind of waterwheel is connected.

In Egypt water for irrigation has for centuries been lifted 1-2 metres with a kind of waterwheel, sakia, and in Iran and Pakistan the persian wheel has been used. It can raise water up to a height of 9 metres at a rate of 8-10 cubic meters per hour. These kinds of pumps are made of wood and other local material. The construction and driving equipment are based on a long tradition and craftsmanship. This combined with the fact that the pump head is in general higher in East Africa makes it difficult to introduce animal driven pumps in this region.

The potential for using draught animals for water pumping depends, of course, on the number and kind of animals and the available amount of animal feed. The food situation and the animal population may change rapidly. About one hectare of land is required to provide fodder enough for a cow to grow, to produce milk and draft power.

Animal	Weight (kg)	Power (W)
Heavy horse	680 - 1200	350 - 1500
Light horse	400 - 700	370 - 1080
Mule	350 - 500	450 - 600
Donkey	200 - 300	250
Cow	400 - 600	350
Bullock	500 - 900	360 - 640

Table 2-3 Power output for different animals /D.R. Birch and I.R. Rydzewski/

Since it may be difficult to construct reliable pumps locally it may be better to buy them from abroad. A few pumps are suitable for animal power supply. Probably the rotary pump, see chapter 3.4.2, is the kind of pump that is best suited. It can be used for both low and high heads. The primary advantage is that the rotary motion from the animals can be used directly in the pump without conversion from rotary motion to a reciprocating motion. However, it is advantageous to use a simple gearbox to speed up the rotation of the pump. This can be made locally or purchased abroad.

In general, it is more difficult to use reciprocating displacement pumps, which is the most common model. Models equipped with a flywheel can be used more easily. In that case some kind of right-angle-gear must be used. Such technical solutions are possible, but animal powered pumps unfortunately seem to be less promising in developing countries than more sophisticated techniques. One reason for this can be the cultural situation and the lack of tradition of using animals for lifting water.

2.5.2 Manually driven pumps

The use of human labour for water pumping is well known. Where the water output is low, the daily time to fetch water is often considerably reducing the time for more productive activities.

Hand pumps are most applicable for shallow wells and other low lift heights. Since the investment costs for each unit are low, these often are the only realistic alternative. The real costs, including operation and maintenance costs are usually high, since service life is only a few years. Many pump manufacturers are therefore working on the V.L.O.M hand pumps (Village Level Operation and Maintenance).

3. PUMP TYPES

3.1 General

As this study deals with energy sources and pumps, the pumps described below have been divided into two major categories from the point of view of energy use:

1) dynamic pumps in which energy is continuously added to increase the fluid velocity and to produce a pressure increase

2) displacement pumps in which energy is periodically added to an enclosed fluid-containing volume resulting in a direct pressure increase.

Dynamic pumps have rotating parts which have to rotate at high speed. Flowing energy sources cannot in general provide this high speed directly. When using dynamic pumps in combination with these energy sources, it is necessary to use gear-boxes or to convert the energy to electricity which can provide the desired speed.

Displacement pumps usually have slow cycles since the water has to fill up the containing volume and then be pressed out. Their slow cycles make them suitable for most flowing energy sources and muscle force. Most hand pumps today are displacement pumps. The pumps are often connected to a fly-wheel or equal, where energy can be stored to be used at peak cycle periods.

A number of pump types has been developed for industrial purposes. Some of these pumps are not applicable in rural areas in developing countries since the water often has a high content of suspended material etc. The pumps briefly described below are more or less adapted to meet this situation.

3.2 Useful terms and definitions

The power P needed for lifting a discharge q to a height h_{stat} can be expressed by

$$P = \frac{1}{\eta} \cdot \rho \cdot g(h_{stat} + h_f)q \quad (m^3/kg \times m/s^2 \times m \times m^3/s = W)$$

where η is the efficiency of the pump, ρ is the density of the fluid, g is the gravitation constant and h_f is the friction losses in the pipe system. The friction losses will be low in a well designed pumping system and can be neglected if the delivery pipe is short and the diameter of the pipe large. Figure 3-2 can be used for calculation of the friction losses in the pipes.

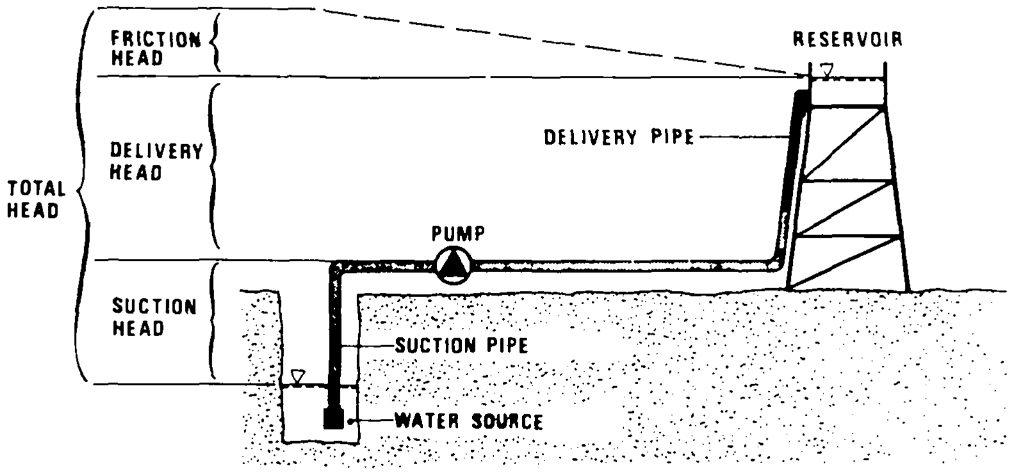


Figure 3-1 Schematic diagram of a pumping system

In practice the suction height can be maximized to about 5 m. If the water level is lower, the pump has to be installed at a greater depth or submerged altogether. The pump motor/engine can still be installed at a dry site.

"Priming" is a useful term to understand. A self priming pump is a pump which can start to pump water without manual refilling of the suction pipe.

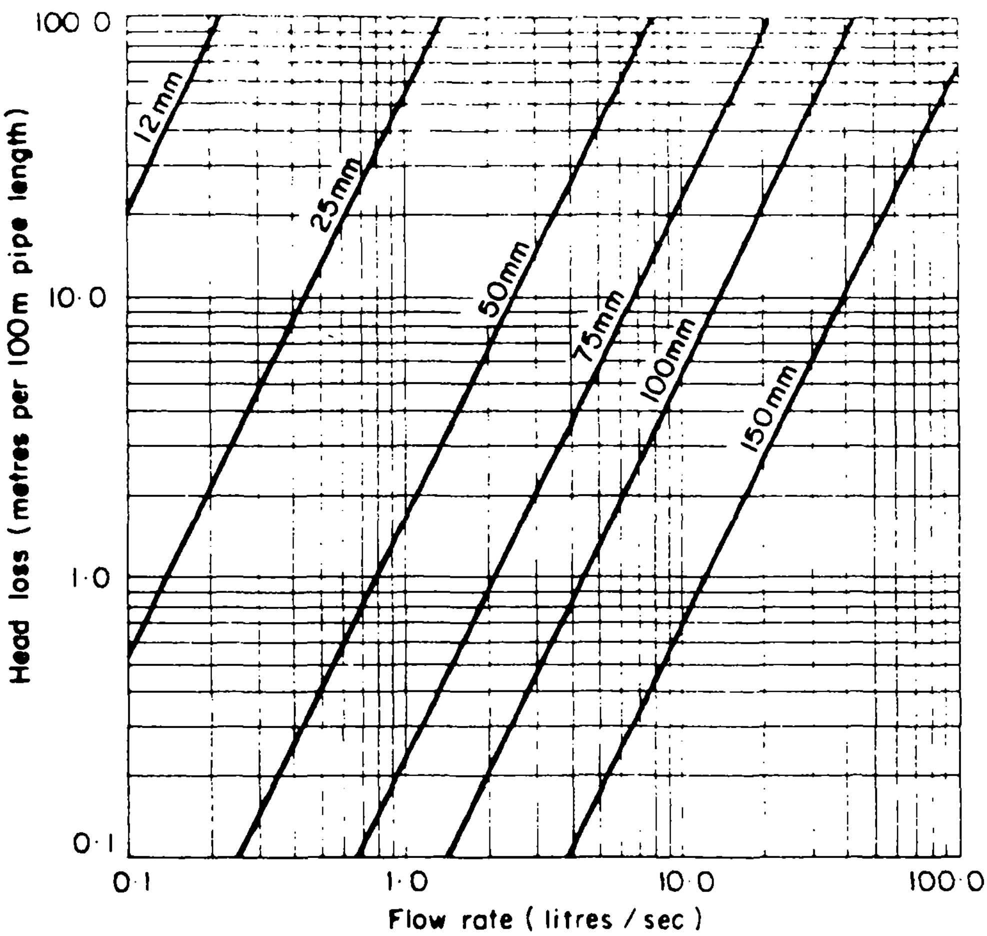


Figure 3-2 Head losses in smooth pipes with different internal diameters

3.3 Dynamic pumps

3.3.1 Centrifugal pumps

Centrifugal pumps can be constructed in a wide range of flow and head situations. Flexibility is achieved by using different types of pump wheel and variable speed.

In a centrifugal pump, the water enters in the center of the pump wheel and is forced outwards by the rotation of the wheel. The pressure rise depends on the design of the pump wheel (impeller).

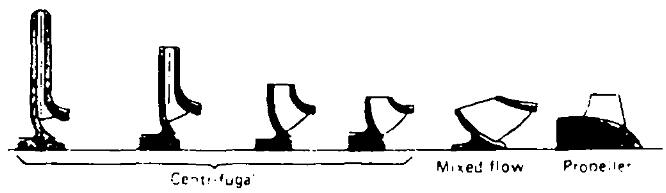


Figure 3-3 Different kinds of pump wheels for various heads
/Chemical Engineering, October 4, 1982/

For high head applications some impellers can be assembled in series. These multi-stage pumps are often submerged and used especially in deep wells or boreholes.

The efficiency of the pumps is as high as 0.8 for large systems. For pumps with a power demand below 5 kW, the efficiency is about 0.5 - 0.7.

Centrifugal pumps require a relatively high speed. Therefore, the dominating energy sources are electricity or diesel. Other energy sources which can be used are biogas or biofuel.

Centrifugal pumps generally require a low frequency of maintenance. If the pump is well suited for the water demand, it will have a service life of about 5 - 10 years. However, the water quality can be important if it has a high content of suspended material. This can cause rapid wear which decreases both durability and efficiency. Occasional small particles with a diameter of a few millimeters seldom cause serious pump damages.

3.3.2 Jet pumps

In a jet pump (or ejector pump), water at high pressure passes through a nozzle giving the water a high velocity. The resultant jet creates a low-pressure area causing water to flow in from the suction entrance. This water is then mixed with the water from the nozzle. A jet pump has no moving parts and can be built compactly. However, jet pumps need a pump to give the driving fluid its high pressure. In many cases a centrifugal pump can be used for this purpose.

A jet pump system is a good alternative when the suction height exceeds 5 - 8 m or when the borehole has a small diameter. The efficiency is lower than the centrifugal pump and the jet pump is also more sensitive to water with a high content of suspended material.

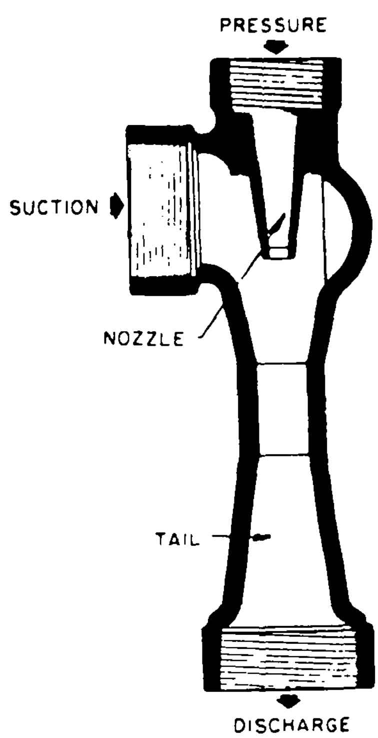


Figure 3-4 Principal sketch of a jet pump /I.J. Karassik et al, Pump Handbook/

Jet pumps can also work with gases as the driving fluid. One variant on this theme is the air-lift pump, fig. 3-5.

Air-lift pumps consist basically of a vertical pipe submerged in the well and an air-supply tube enabling compressed air to be fed to the pipe at a considerable distance below the water level. The mixture of air and water in the pipe is lighter in weight than the water outside so the mixture in the pipe will rise. The pump can be used in water with a high content of sand, etc.

The disadvantages of the pump are a low efficiency (less than 0.4) and the need of substantial submergence depth as compared with conventional pumps. The pump is simple and easy to construct and can be built by the user himself.

One suitable energy source for this pump is wind. Systems applicable at low head conditions are available.

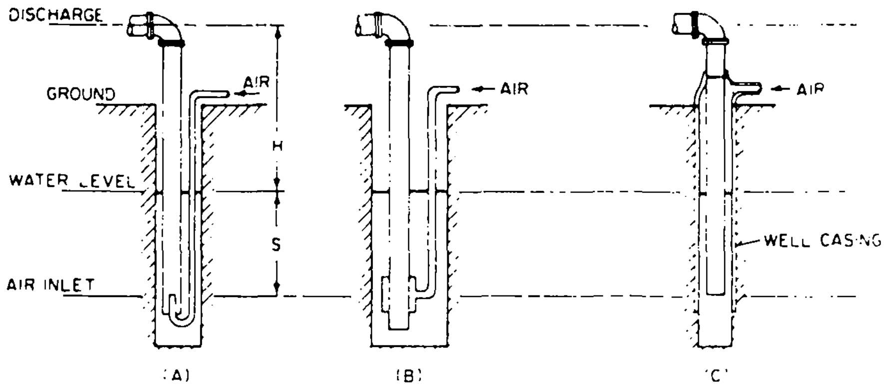


Figure 3-5 Air-lift pump
(A) bottom inlet, (B) side inlet (Pohle) type,
(C) Sauders system cased well
/Pump Handbook, Karassik et al/

3.4 Displacement pumps

3.4.1 Piston, plunger and diaphragm pumps

Displacement pumps are a classic method of pumping water and the most frequently used as regards hand- and wind-pumps.

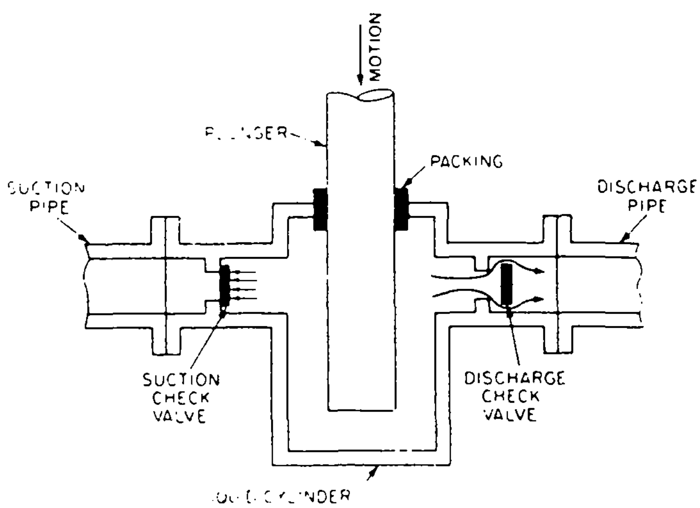


Figure 3-6 Scheme of a reciprocating pump liquid end during discharge stroke
/Pump Handbook, Karassik et al/

The basic principle of a positive displacement pump is that a solid will displace an equal volume of liquid. The solid can be a piston, a plunger or a diaphragm and the liquid is moved through the pump by moving the solid. A simple plunger-pump scheme is shown in fig 3-6. Before pumping, the liquid cylinder has to be filled with water (primed). When the plunger moves out of the liquid cylinder (suction stroke) the suction check valve will open and the liquid will flow in and fill the volume being vacated by withdrawal of the plunger. The plunger movement is then reversed and the plunger moves into the cylinder (discharge stroke). The suction check valve will then close, the discharge check valve will open and the liquid will flow into the discharge pipe. This pumping cycle is that of a single-acting pump. The efficiency of displacement pumps can be up to 0.8 if the packing and valves are in good condition. With leaking packing or check valves the efficiency will decrease rapidly. This is, unfortunately, often the case when the water has a high particle content.

Maximum suction height for reciprocating pumps is about 6 - 7 m, giving a practical limit of about 5 m (c.p. 3.2.). When the water table is lower, the pump cylinder can be submerged and connected to the driving parts with a crank. Submergeable pumps are often made of brass or equal inoxidable material.

Displacement pumps work well both at low and high speed. The upper speed limit depends on the capacity of the check valves. Hence, the flow is a function of the speed. This gives displacement pumps a great advantage when using energy sources with varying power, for example wind.

The delivery head can also vary within a wide range, even if displacement pumps are best suited for high-head and low-flow conditions. An optimal combination of piston/ /plunger diameter and stroke length can be calculated for each head. At low head the stake length shall be short and the diameter large. The diaphragm pump is therefore suitable at low head and the plunger pump at high head conditions.

Displacement pumps are produced in some developing countries, mostly for hand pump applications. The technological level can be appropriate or advanced.

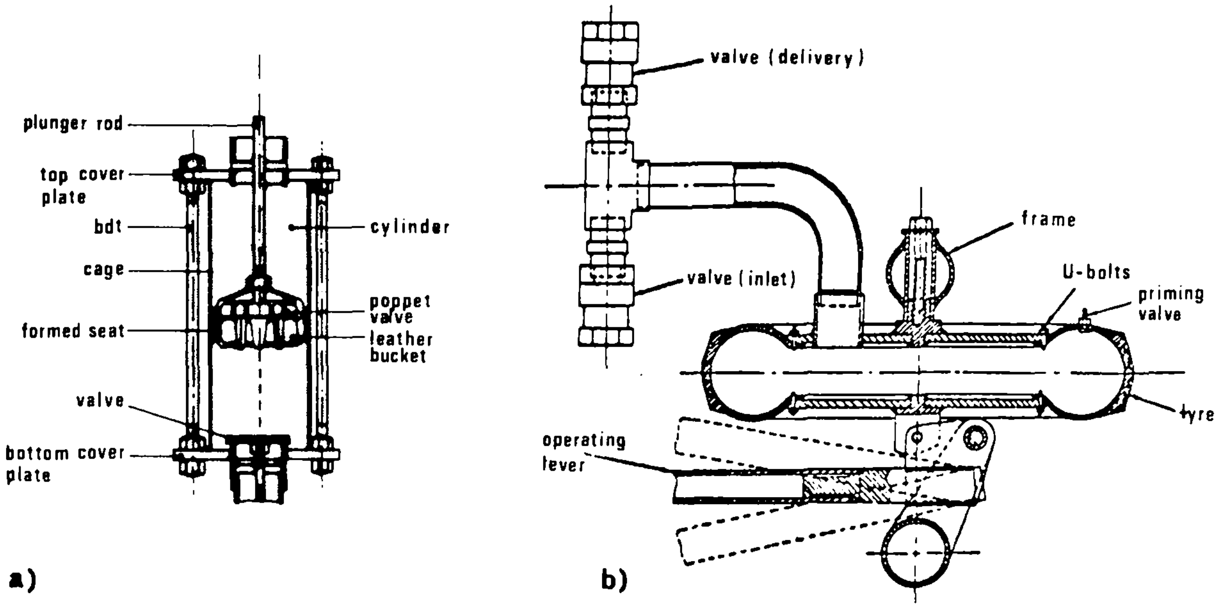


Figure 3-7 Example of reciprocating pump used for windmills in India.
a) Single-acting plunger pump with brass cylinder
b) Diaphragm pump made of tyre
/Windpump Handbook, Rastogi/

The main problem with reciprocating pumps is that they are maintenance intensive. Packings have to be replaced regularly and the function of the check valves controlled. This has been recognized when installing hand-pumps, but the maintenance problem is more important when the pump is connected to a non human energy source. Small damage to the pump can cause serious damage to the driving equipment.

The most common form of damage in pumps is a leaking suction, check valve or foot valve. This makes it difficult to get the pump primed, which in turn makes it impossible for the pump to lift the water. The pump will then only blow air, and in some cases also damage the packing. Leaking foot valves can be caused by sand particles between the seat and the valve, by old untight packings or by oxidation that prevents movement of the valve.

Special types of displacement pumps are the Petro-pump and the Vergnet hydro pump. These pumps work with an elastic medium instead of a moving solid. This eliminates the need of packings.

3.4.2 Rotary pumps

The classical rotary pump is the Archimedean screw which has been used in Egypt for a long time. The pump consists of a screw which rotates inside a drum. Water then moves upwards in the drum. The pump can be used to lift water only a few meters depending on the length and angle of the screw. The traditional energy sources of this pump is manual or animal force.

Archimedean screw pumps are insensitive to water with a high foreign particle content and are therefore well suited for lifting water from a river. Since the pump can be made of local materials the efficiency may vary from about 0.3 to 0.7.

A number of screw pumps and rotary pumps has been developed for industrial purposes. Most of them are not suitable for water pumping. Some exceptions can be found, and one of them is the helical rotor pump, see figure 3-8. The pump consists of a rotor turning within a double thread stator. The pump is self priming and requires no valves because the rotor to stator contact provides an effective continuous seal. The pump consists of a screw which rotates inside a drum. Water then moves upwards in the drum.

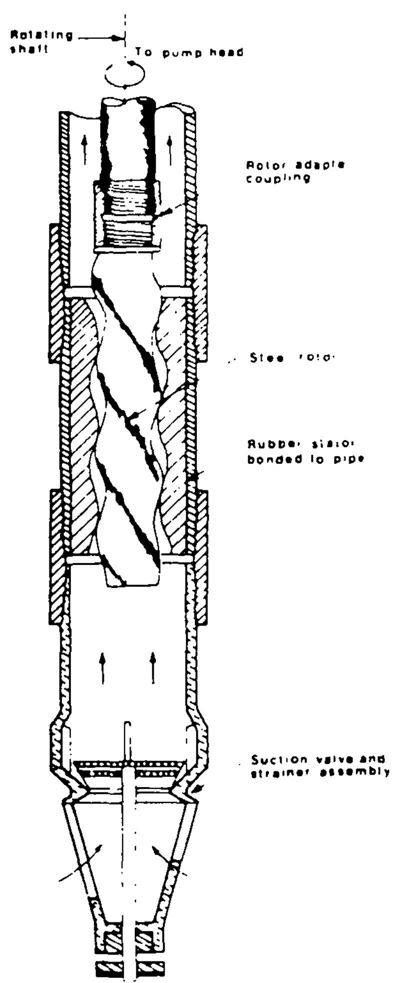


Figure 3-8 Cross section of a helical rotor pump /Handpumps, F. E. McJunkin/

Helical rotor pumps are reliable but rather expensive as the rotor and stator must be made with high quality demand.

The pump can be used in combination with most energy sources which can give at least 60 revs/min. The torque will be high for installation in very deep boreholes.

4. GUIDELINES FOR SYSTEM SELECTION

4.1 General

Some general guidelines for choosing a water pumping system at a specific site are given below. The guidelines can be used to get an indication of the most suitable system and a rough cost estimate.

A number of different factors has to be taken into account when choosing a system. Sociological factors can sometimes be more important than technical and economic factors. Another important factor is, of course, the use of the pump and its technological level and the possibility to carry out the necessary maintenance work. Questions like "Who should be the owner(s)", "Who will be responsible for the system" and "Shall the water be free" are relevant and have to be carefully considered. Answers to these questions can not be given in a general way since they depend on local conditions.

The evaluation of a suitable system can be done as follows:

1. Try to use a water source which can provide the desired amount and quality of water.

2. Calculate the power required at the desired flow and estimated head.

   N.B. For long pipelines, do not forget to calculate the friction losses in the pipe.

3. Try to collect meteorological data.

4. Make a comparison between the different energy sources available.

5. Choose a suitable pump.

6. If the combination energy source - pump is suitable, analyse the choice from a non-technical point of view. If the combination is not suitable, try a new one.

The following pages show some diagrams which may be used to obtain the results in a fairly simple manner.

An alternative is the use of the decision charts for an appraisal of solar pumps for rural water supply or for irrigation. Charts of this type are published in the report of the UNPD project GLO/80/003, carried out by the World Bank. C.p. Appendix C. The chart gives an initial appraisal of the feasibilitity of using a solar pump.

4.2 Calculation of power

In figure 4-1 the theoretical power input, P_t, is shown for different values of water flow and head. The value of power in this figure has to be corrected for the actual efficiency of the pump, η_{pump} and for the daily running time, t_{run}, in hours. This correction is made by the following formula:

$$P_{real} = \frac{P_t}{\eta_{pump}\ \eta_{motor}} \cdot \frac{24}{t_{run}}$$

where P_{real} is the real power needed and η_{motor} will be used if the system includes a motor.

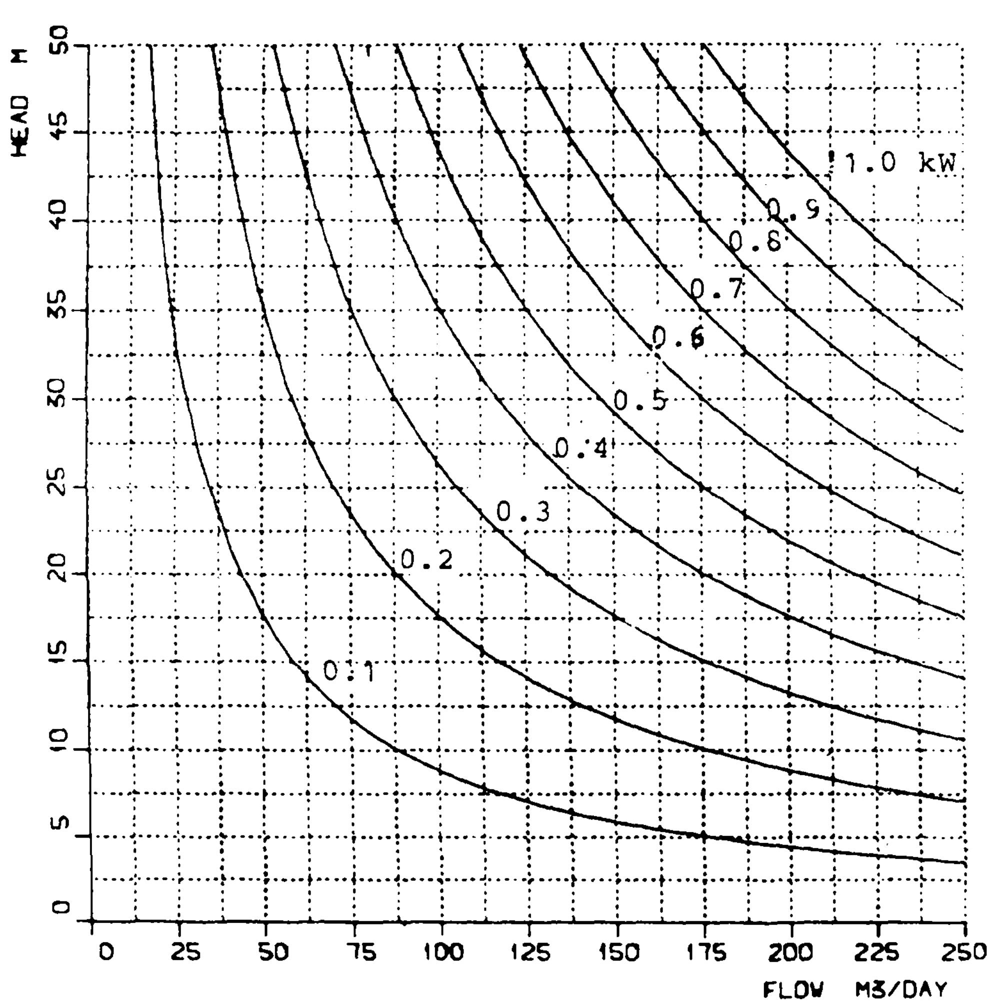


Figure 4-1 Flow-head diagram for power output requirements, P_t in kW

Let us take an example. Our water demand is 75 m^3/day and the head is 15 m. Figure 4-1 gives a theoretical power, P_t = 0.13 kW. The system may work 10 h/day. The pump and motor efficiency is η_{pump} = 0.4 respectively η_{motor} = 0.85.

$$P_{real} = \frac{0.13}{0.4 \cdot 0.85} \cdot \frac{24}{10} = 0.92 \text{ kW}$$

The diagram above can also be used for calculating the energycontent in a stream with a certain flow and head. See the following example.

A hydraulic ram with an efficiency of η = 0.6 will be installed in a river with the flow of 0.002 m^3/s (173 m^3/day) and a head of 10 m. Figure 4-1 gives P_t = 0.2 kW. The ram will be used for lifting water at a head of 50 m. The real output P_{real} power is 60 % of this value (since η = 0.6). The output power is then 0.6 · 0.2 = 0.12 kW, which can lift about 30 m^3/day to the desired head 50 m (see figure 4-1).

4.3 Estimate of available energy and cost

4.3.1 Solar energy

The largest application of solar energy in water pumping seems to be conversion to electric energy in solar cells. Present-day thermal systems are too complicated for general introduction in developing countries.

A first estimate of available solar energy can be made by observing the number of sun hours per day. The solar radiation in cloudy weather can be neglected in this first estimate. The mean value of the solar radiation is around 600 - 1000 W/m^2 at clear sky, depending on time and location, see figure 2-5. The available energy can then be estimated and the needed solar module area can be calculated for the actual power demand. If water will be used during a special season, that season will be studied carefully.

The investment cost today (1983) is about 10 USD/Wp for commercial solar modules, where Wp is the notation for peak watt which means the power generated at a radiation of 1,000 W/m^2. Prices have been falling over the last years, but not as dramatically as expected.

The life-span of the system is an important variable when calculating the total cost. Photovoltaic pumping systems seem to have a life-span of 10 - 20 years. The pump may be replaced 2 - 3 times during that period, but is relatively cheap in comparison with the solar modules. In figure 4-2 the production costs per kWh are shown for different values of solar radiation, the daily number of sun hours and different life-spans. The costs do not include replacement of pumps. Other operation and maintenance costs are minimal and have been neglected.

The diagram in figure 4-2 shows a relatively high system cost and if the prices remain on the same level, the photovoltiac system seems to be too expensive for a wide application in developing countries. Today they can be economical in some special cases. However, the photovoltaic system can be the only realistic system in isolated locations depending on the extent of reliability and need of maintenance. Also, they are not affected by fuel transports or fuel shortages.

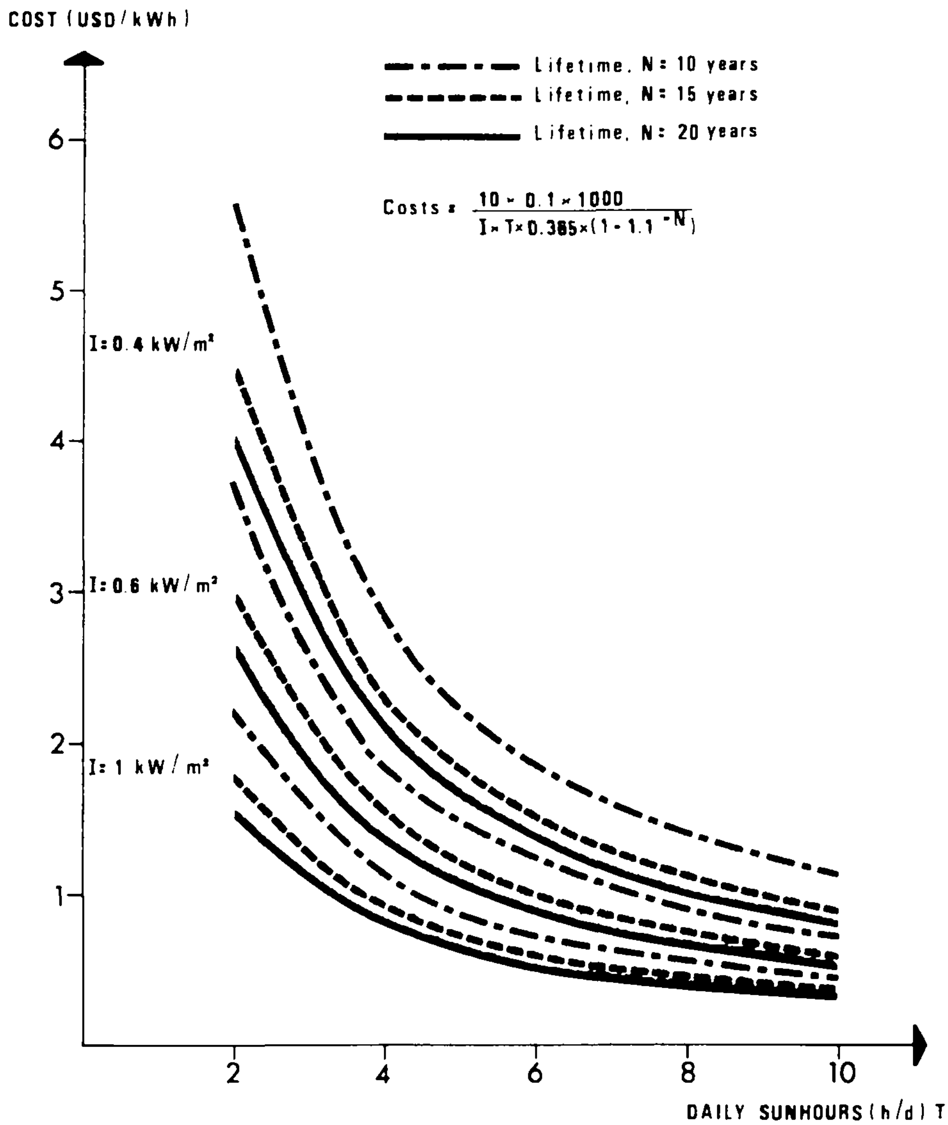


Figure 4-2 Energy costs of photovoltaic systems at various sun conditions. The investment cost is 12 USD/Wp and the discount rate is 10 percent.

4.3.2 Wind energy

The most important consideration when using wind energy is to choose a suitable site for the windmill. Many windmills are abandoned because of insufficient wind speed. The actual wind speed and the duration of the wind also have a great influence on the economy of the windmill.

The cost of a windmill constructed in an industrialized country is between USD 500 and 1000 per m^2 rotor area. Local windmills can be constructed at a material cost of USD 40 - 50 per m^2 rotor area. The construction time is about 200 - 300 hours, depending on the size of the windmill. The cost of a locally built windmill seems to be about one tenth of the cost of a windmill constructed in industrial countries. No investment costs for a factory are included in this comparison. However, a great part of the locally built windmills can be paid for in local currency, which is a great advantage. The cost relation therefore seems to be 1:10.

Since the commercially available windmills are more or less based on the technology of the beginning of this century, some projects have been started to develop windmills with modern materials and more advanced technical designs. This will reduce the weight and also the production costs and will enable to manufacture the windmills in small industries in developing countries.

The Intermediate Technology Development Group has developed a modern windmill which is now in preliminary production in Kenya, Pakistan and India. The capital cost of this windmill in Kenya is about 200 USD/m^2 of rotor area or about 1/4 of the cost of a windmill produced in an industrial country.

The efficiency of the locally produced low-cost windmill is lower than that of the more sophisticated types. It is estimated that the low-cost windmill yields about 50 percent of the power produced by the modern type. Figure 4-3 shows the energy costs of these types of windmills. In the calculation, a value of 50 per cent has been used for correcting the lower power output of the low-cost windmill. The discount rate is 10 percent.

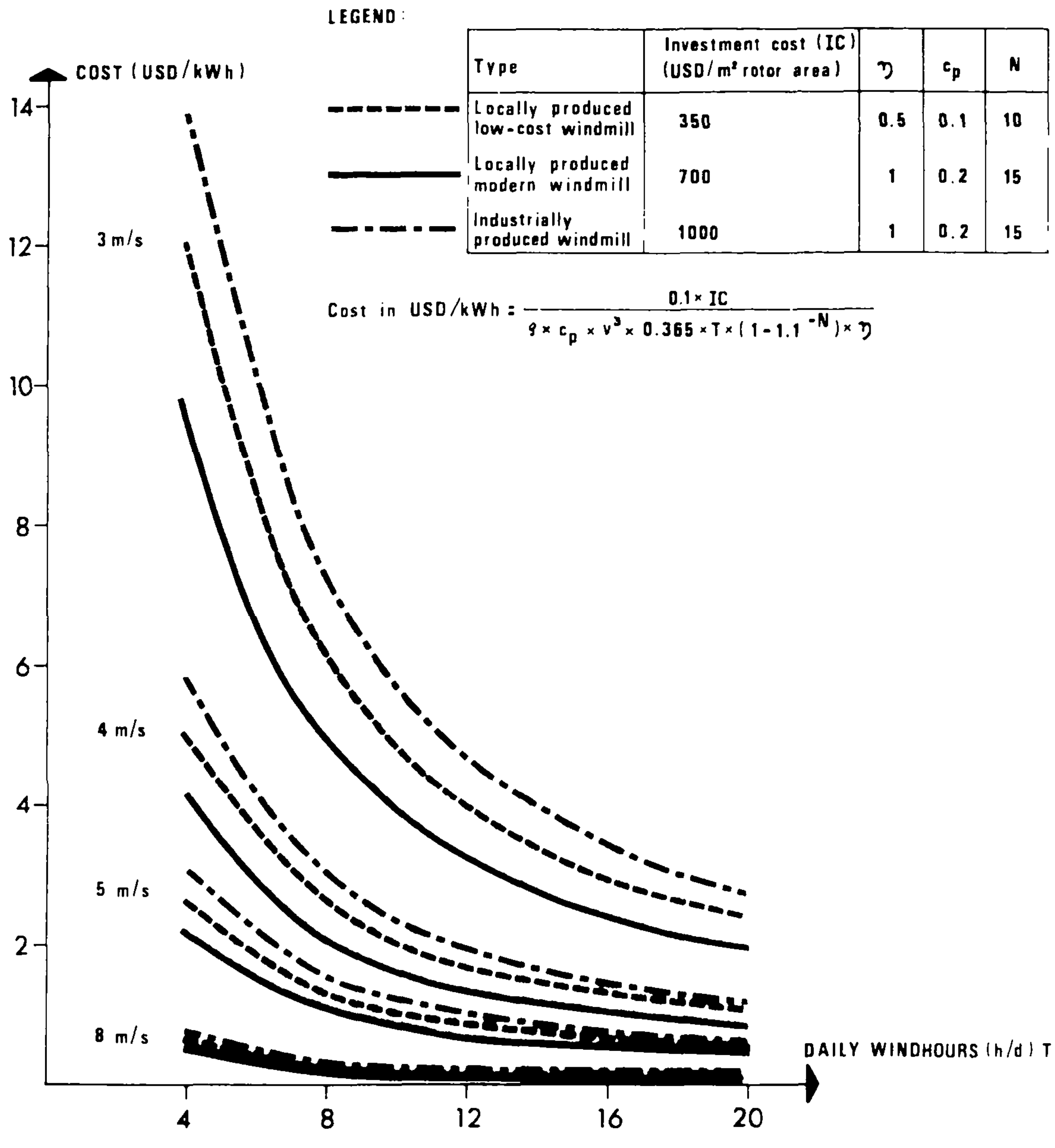


Figure 4-3 Energy costs of different wind driven systems at various wind conditions. Input data are described in the text above.

4.3.3 Biofuel and diesel power

Diesel engines can be converted for use of biofuel and the energy costs are therefore comparable.

A conventional diesel engine has a life-span of about ten years. A biofuel driven engine has a somewhat shorter life-span. In most countries conventional diesel engines seem to be cheaper in spite of the need for using foreign currency. If biofuel systems are introduced, the biofuel will have to be much cheaper than diesel in order to be competitive.

The energy cost mainly depends on the actual fuel price. The diesel consumption is about 0.3 l/kWh, which gives anoperating cost of 0.1 - 0.2 USD/kWh, see figure 4-4.

The investment cost of small (less than 10 kW) diesel units is about 500 USD/kW. The life-span is about 5,000 - 10,000 h, depending on the frequency of maintenance. A daily running time of 3 hours a day will correspond to a life-span of 5 - 10 years.

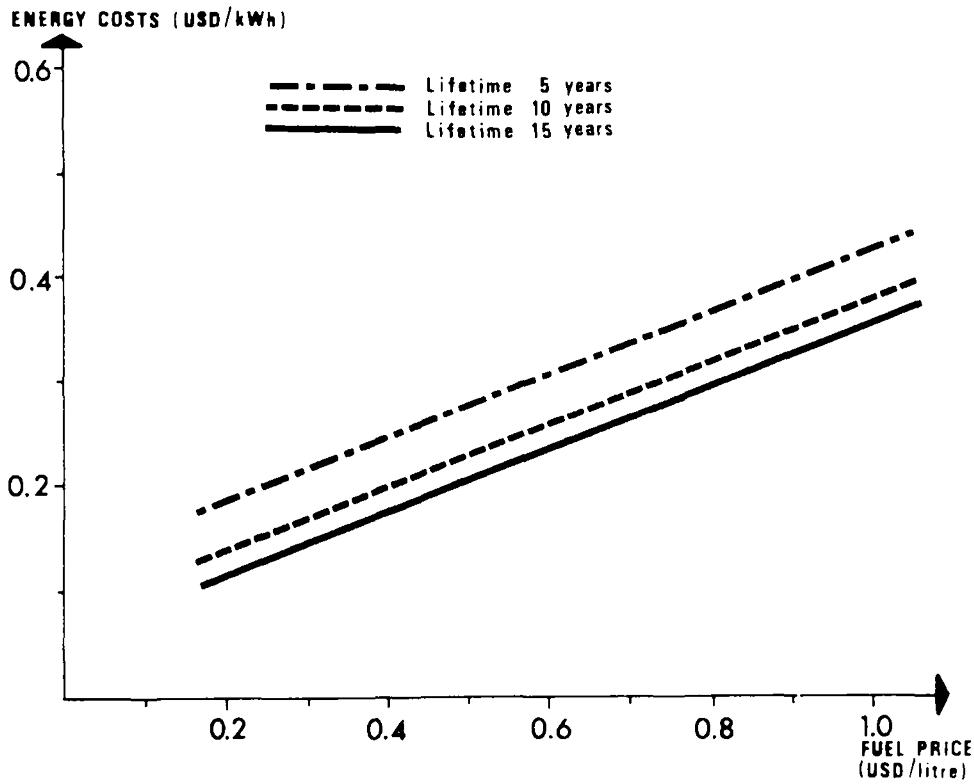


Figure 4-4 Energy cost of diesel engines at varying fuel prices. Investment cost is 500 USD and the discount rate is 10 percent.

4.3.4 Muscular energy

The cost of energy produced by human labour is high. The power output in daily pumping work is about 100 W, which yields approximately 1 kWh per day per person. Depending on the actual salary, the energy cost is on the order of a few USD/kWh. This cost is acceptable for rural water supplies when people are pumping their own water, but the cost tends to be too high for irrigation purposes, etc.

Animal power is about five to ten times cheaper than manual power (hired labour). Before deciding on using animals for water pumping it is important to study the demand for fodder. If the potentially cultivated area is utilized for food production, the fodder has to be bought. The energy costs for animal driven pumps will then be considerable.

4.4 Maintenance requirements

A high reliability or a good service programme is necessary for well functioning water supply systems. Someone has to be responsible for the operation and maintenance. The maintenance demand of the system has to be adopted to the cultural and technological level of the user. This balance is difficult to attain and some education is often necessary when installing a new water pumping system.

Water turbines are very reliable and have a long lifetime and moderate maintenance needs. If the site conditions are favourable, it is possible to get a safe water supply.

Photovoltaic systems also seem to be very reliable, especially the systems without batteries and complicated electronic equipment. Modern wind pumps also are quite reliable and easier to repair locally than photovoltaic panels.

Diesel and biogas pumps require a more or less regular maintenance. The lack of spare units is often a problem which shortens the useful life of the system. As a rule, it is possible to repair the engines locally.

4.5 Aspects of pump selection

As a general rule in small pump applications, the displacement pump should be used at high head and the centrifugal pump at low head.

For each installation, it is important to estimate the suction and static head, and sometimes to calculate the friction losses at various discharges. These data give the system head curve, figure 4-5. Each pump has a characteristic curve which is drawn in a flow-head diagram. In a well designed system the rating point will be at efficiency optimum of the pump and the rating flow and headwill be approximately the desired flow and head. A goodpump choice results in the lowest energy demand and costs.

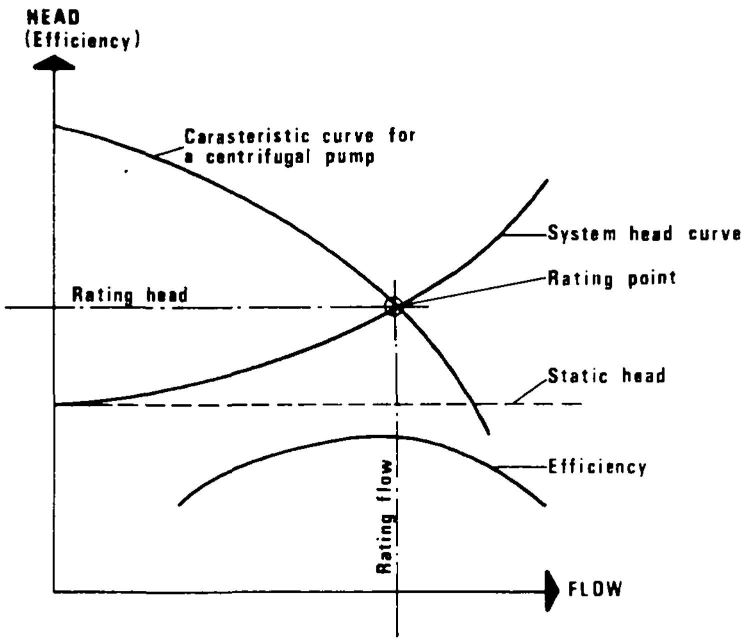


Figure 4-5   Flow-head diagram for a pumping system

It is important to check the maximum suction head of the pump. If this is less than actual suction head, the pump has to be installed lower than planned or to be exchanged. Generally, it is favourable to minimize the suction head.

The water quality may also have an influence on the choice of pump and decides the rate of maintenance.

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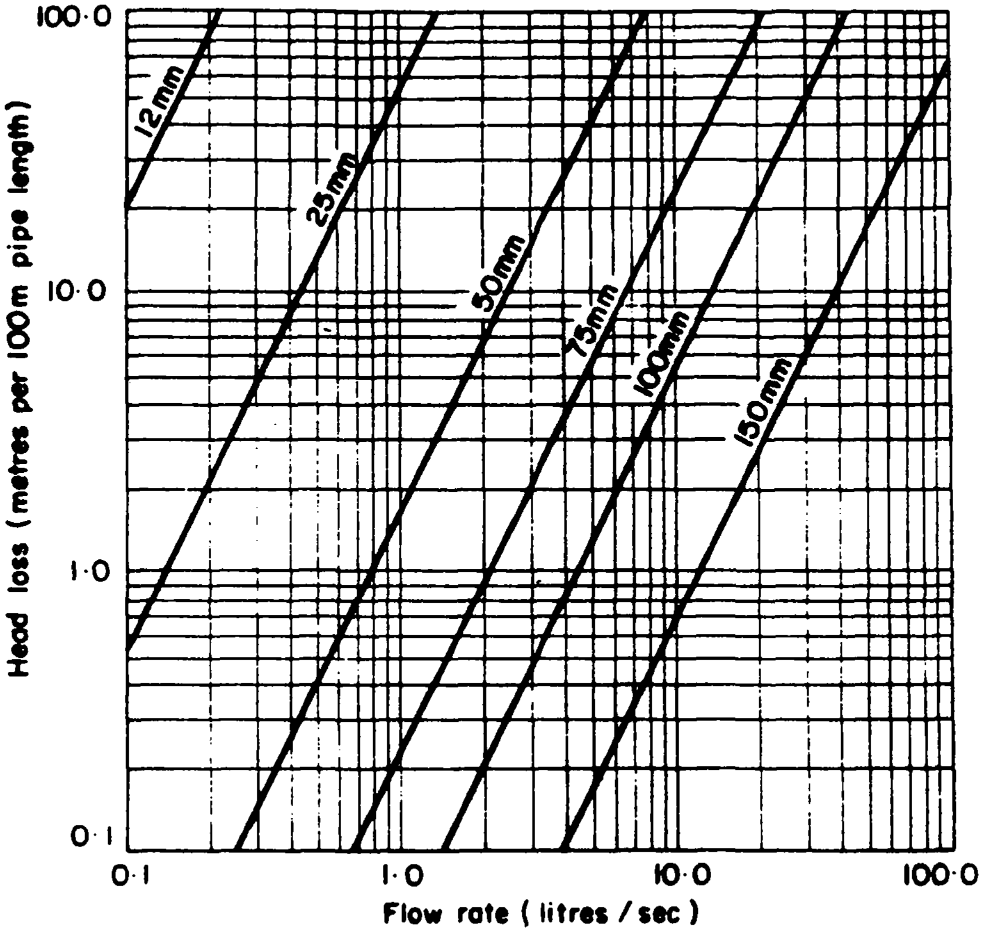
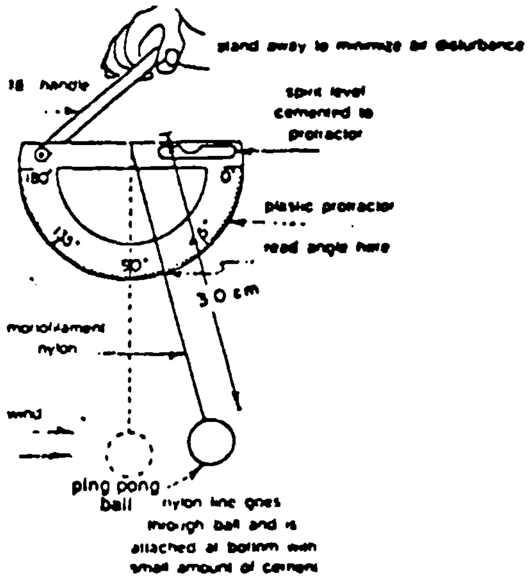
FRICTION LOSSES IN PIPES



Head losses in pipes of different internal diameter and a roughness of about k = 5 mm

SIMPLE METHODS FOR ESTIMATING THE WIND POTENTIAL

Windpump Handbook, page 3



Calibration data

angle	m/s
90	0
85	1.7
80	3.7
75	4.5
70	5.3
65	6.0
60	6.7
55	7.3
50	8.0
45	8.8
40	9.6
35	10.5
30	11.5
25	12.8
20	14.5

WMO - No. 575, page 83 - 86

In remote forested areas, vegetation indicators may be useful in estimating wind-energy potential. The flagging of trees offers perhaps the easiest method of using vegetation to infer wind speed. (A flagged tree is one in which the growth of branches produces an asymmetrical crown.) Figure 4.2.2 depicts flagged trees from the side and top ans numerically classifies the degree of flagging using the Griggs-Putnam index. Different species of trees may be flagged to different extents by the same winds. however classification of flagging by tree type has demonstrated that this method can be used to obtain rough estimates of the annual average wind speed. Some results of using the Griggs-Putnam index to estimate the average annual winds are shown in Figure 4.2.3. The mean speed prediction error for this technique is ± 15% of the true mean wind speed

The deformation ratio shown in Figure 4.2.4 ranks second to the Griggs-Putnam index in accuracy Linear regression of the deformation ratio with mean wind speed produced the results shown in Figure 4.2.5. These results represent approximately a ± 18% mean error in estimating annual average winds.

When using vegetative indicators of wind, there are certain drawbacks which must be considered. The degree of flagging is a species-dependent phenomenon and may be biased toward winds occurring during the growing season (spring and summer). Past or present growing conditions, diseases, trees that once grew nearby, and ice storms may also cause deformation of the tree crown. Although trees provide only rough estimates of wind-power potential, continued research in this area involving more species of trees and the analysis of large data samples should yield vegetation indicators that provide a useful means of estimating the wind resource in forested data-sparse areas.

Aeolian land forms are another type of supplemental wind information that may be useful in data-sparse regions. Aeolian indicators of wind are most likely to be present in sparsely vegetated arid and semi-arid lands. Surface features indicative of areas of strong wind are sand dunes, playas (i.e. shallow desert basins where water gathers after rains and then evaporates) and scour features produced by wind erosion. Mapping of such features from satellite imagery or aerial photography can be used to locate regions of possibly high wind-energy potential. However, quantitative techniques for estimating wind speeds from an analysis of aeolian land forms are still in the developmental stage

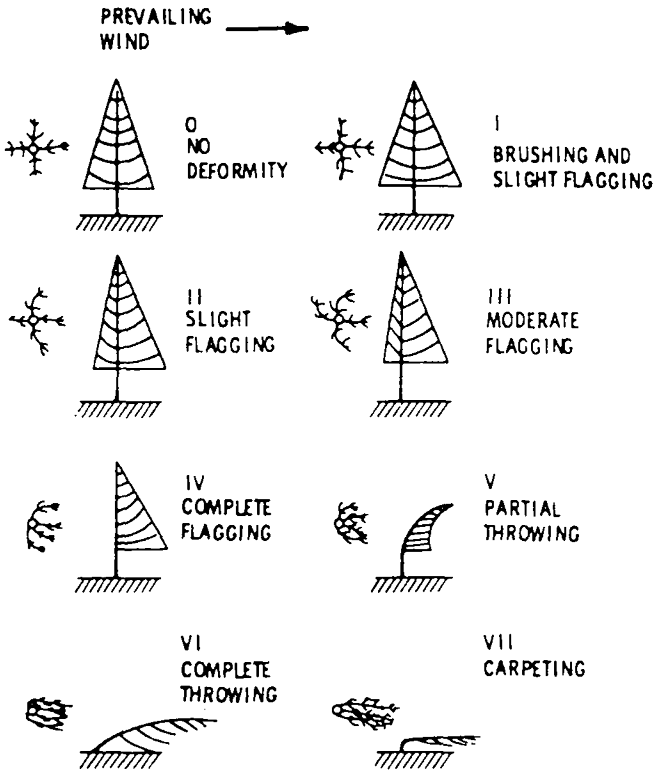


Figure 4.2.2 – Classification of tree flagging by the Griggs-Putnam index (*From Hewson* et al., *1979*)

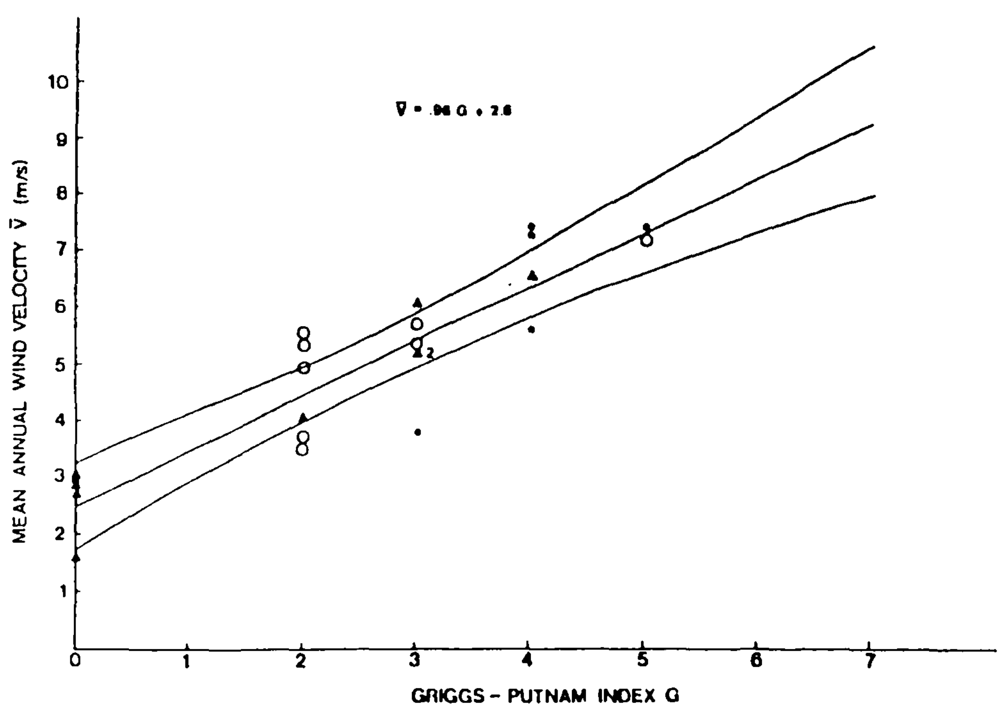


Figure 4.2.3 – The relationship between the Griggs-Putnam index and mean annual wind speed for a data set containing both Douglas-fir and Ponderosa pine. The 99% estimation limits are given for the regression equation (*From Hewson* et al., *1979*)

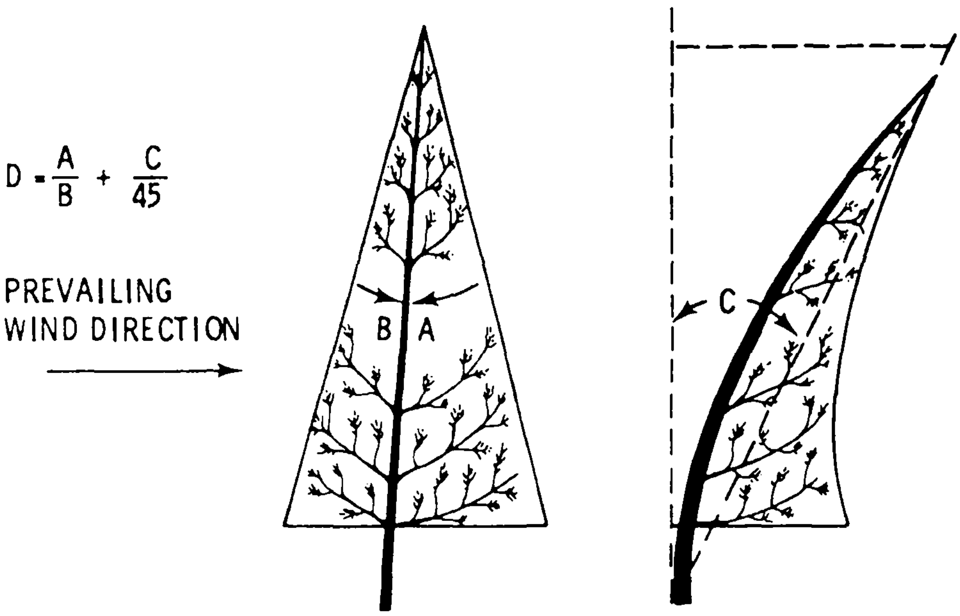


Figure 4.2.4 – Classification of tree flagging by the deformation ratio (*From Hewson* et al., *1979*)

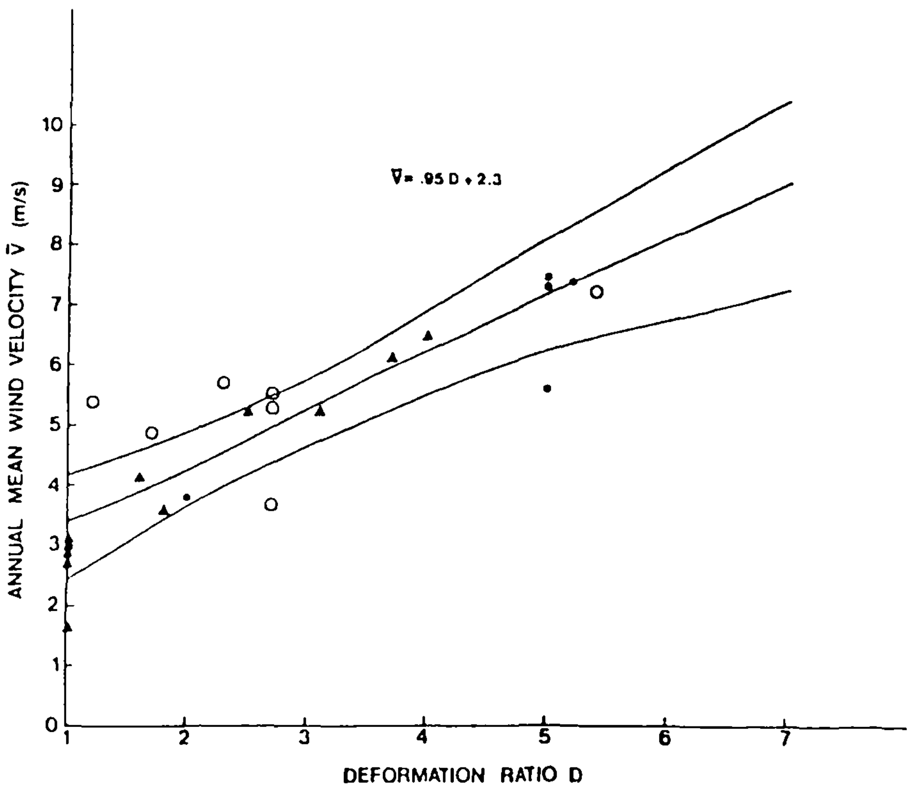
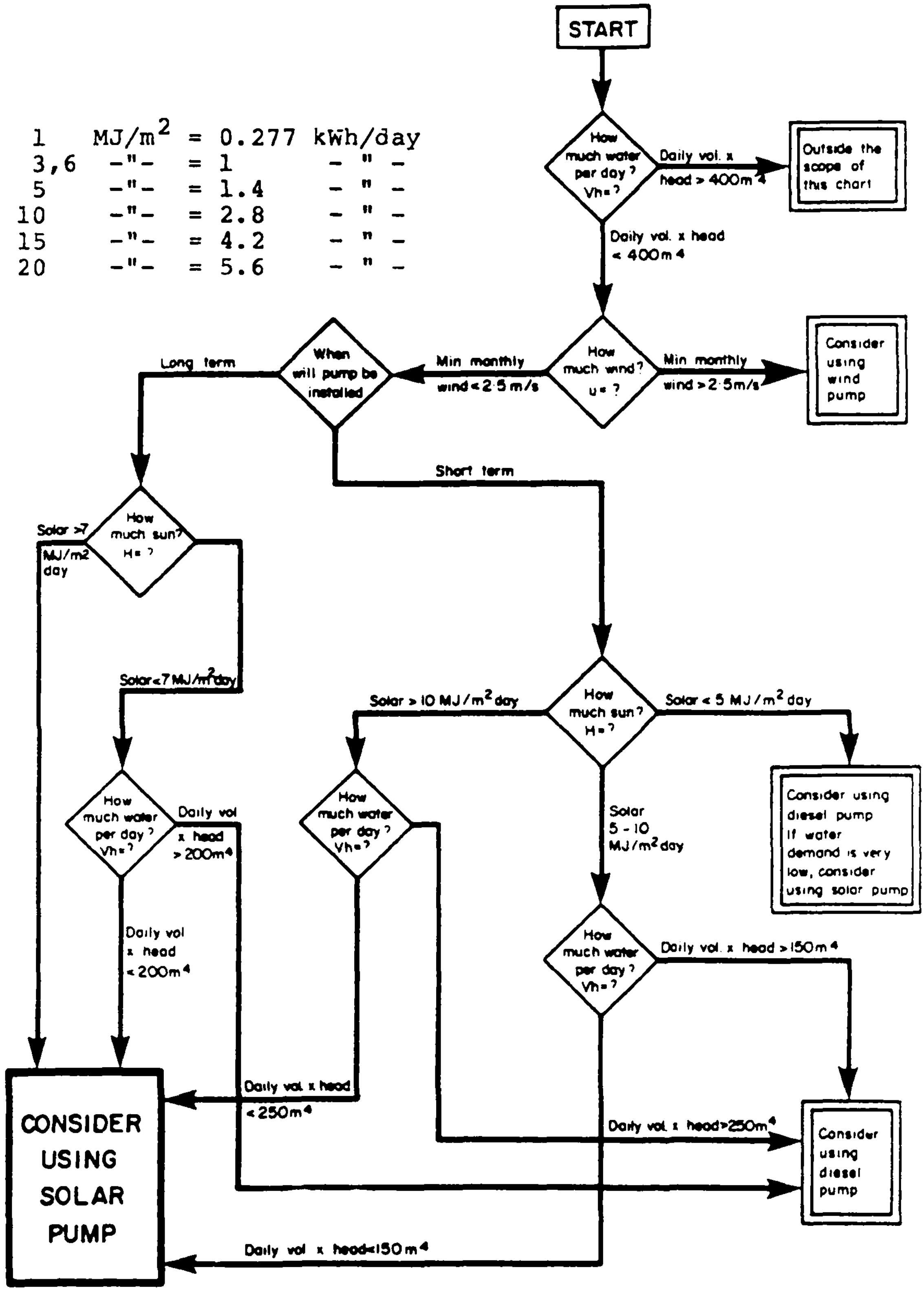


Figure 4.2.5 – The relationship between the deformation ratio and mean annual wind speed for a data set containing both Douglas-fir and Ponderosa pine. The 99%estimation limits are given for the regression equation (*From Hewson* et al., *1979*)

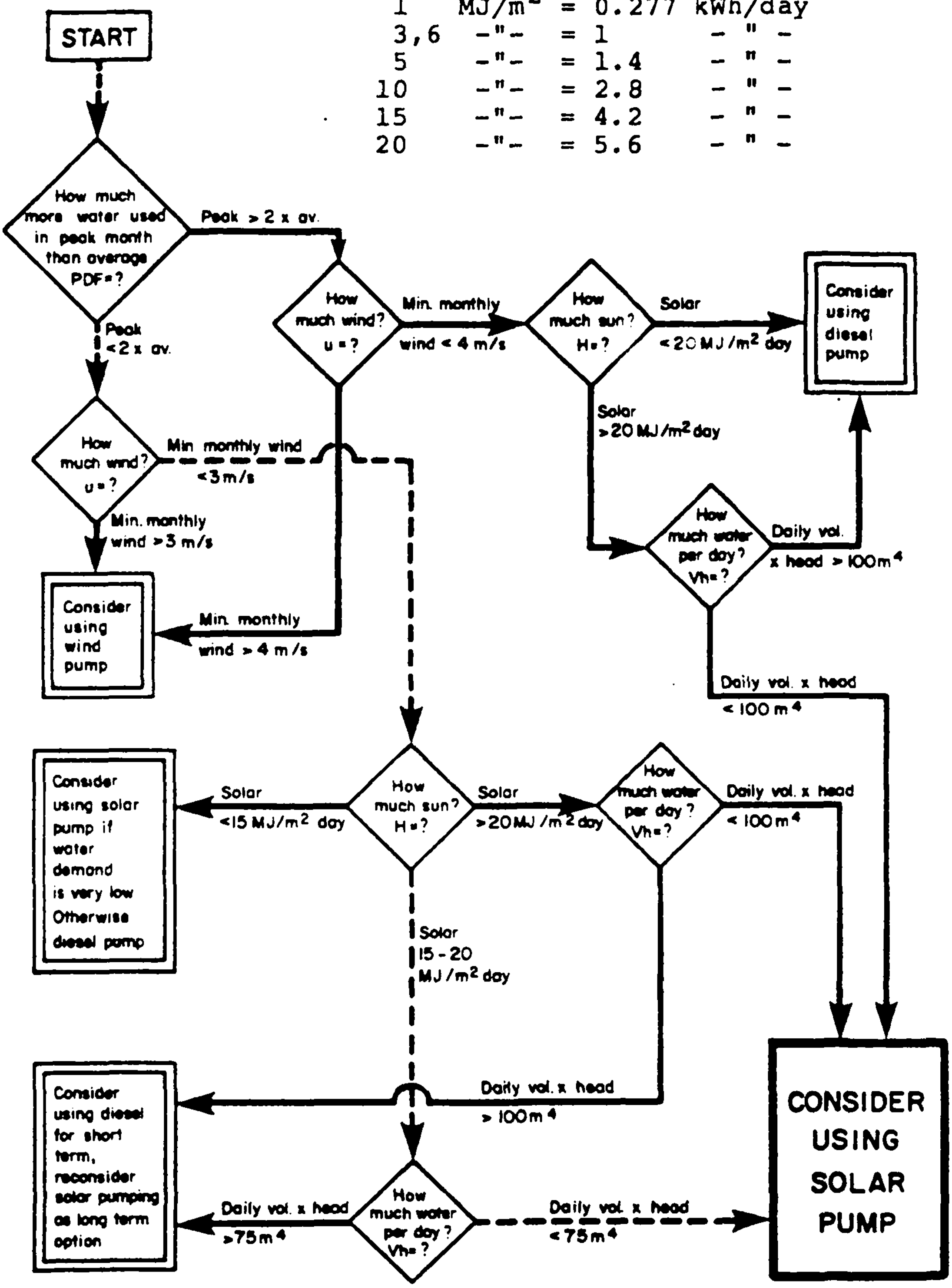
DECISION CHARTS FOR APPRAISAL OF SOLAR PUMPS

1	MJ/m^2	= 0.277	kWh/day
3,6	-"-	= 1	-"-
5	-"-	= 1.4	-"-
10	-"-	= 2.8	-"-
15	-"-	= 4.2	-"-
20	-"-	= 5.6	-"-



Decision chart for rural water supply
/Sir William Halcrow et al/

1	MJ/m^2	=	0.277	kWh/day
3,6	-"-	=	1	- " -
5	-"-	=	1.4	- " -
10	-"-	=	2.8	- " -
15	-"-	=	4.2	- " -
20	-"-	=	5.6	- " -



Decision chart for irrigation
/Sir William Halcrow et al/