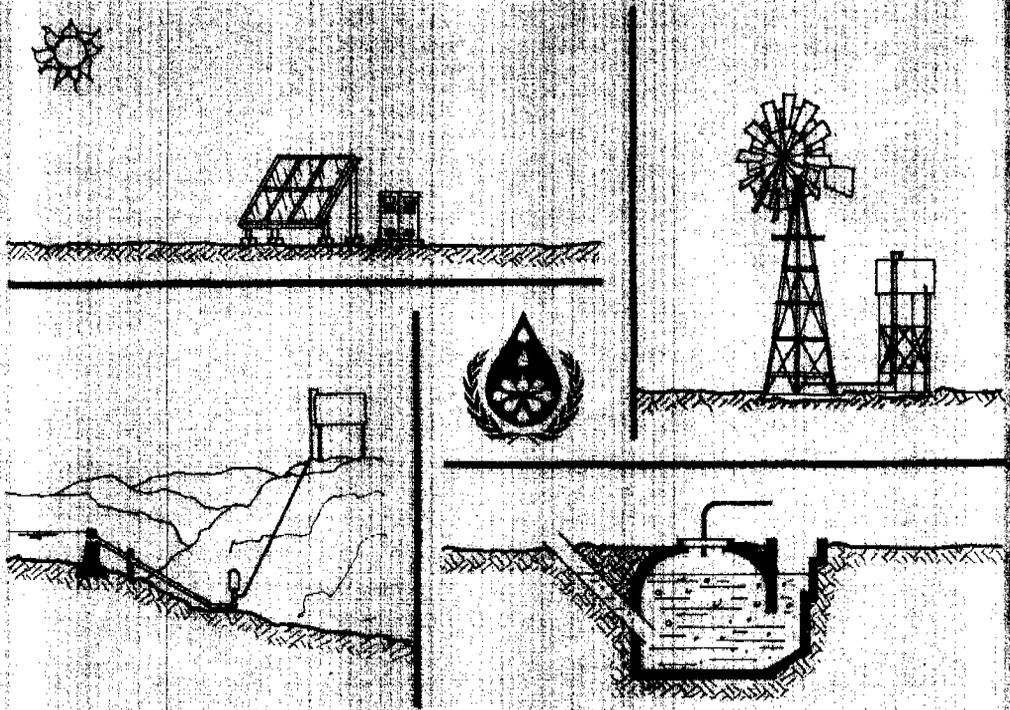


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Renewable Energy Sources for Rural Water Supply



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*Renewable Energy Sources
for Rural Water Supply*

RENEWABLE ENERGY SOURCES FOR RURAL WATER SUPPLY

E.H. Hofkes and J.T. Visscher

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Abstract

The potential of using renewable energy sources (solar energy, wind energy, hydropower, biomass energy) to power water pumping systems for rural water supply is receiving increased attention. Assessment and selection of these energy sources and pumping systems require careful analysis of a wide range of factors. This book provides guidance and information to support the systematic consideration of renewable energy sources and devices for rural supply pumping. In Part I (Chapters 1-3), the various factors to be considered and the selection methodology to be followed in energy sources assessment and pumping system selection are discussed. In Part II (Chapters 4-8), state-of-the-art information on the technology of solar pumps, wind pumps, hydro-powered pumps, and pumping systems using biomass energy are presented.

Keywords: water lifting devices / rural supply systems / energy / feasibility studies / comparative analyses / costs / solar energy / wind-powered pumps / hydropower / biomass / selection criteria.

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Preface

In larger communities, the water requirement is greater than a hand pump water supply can provide. In these cases, pumping systems based on diesel or electric pumps are most commonly used. However, particularly in remote rural areas of developing countries, the use of diesel or electric pumps meets with considerable difficulties, including high costs in securing regular supplies of fuel or power, inadequate infrastructure and skills for operation and maintenance, and organizational limitations. As a result, increasing attention is directed to the potential of using alternative power sources for medium-size rural water supplies.

These energy sources, which are collectively referred to as renewable energy sources, are solar energy, wind energy, hydropower, and biomass fuels. Research and development, supported by field trials, have advanced pumping systems using these energy sources to a stage where they are competitive with the conventional diesel and electric pumping devices.

However, lack of practical information is a serious limitation for decision-makers, planners, and engineers, in the assessment of pumping systems using renewable energy sources for large-scale application in national water supply programmes. Therefore, this book has been produced for the guidance of renewable energy pumping devices. The book is divided in two parts. The first part deals with the systematic pre-selection of the most appropriate pumping systems for a particular country or region. The considerations covered include environmental, technical, social, and economic feasibility. Comparative cost analysis is presented as a useful tool in the pre-selection process. The second part of the book provides detailed information to support further consideration of the pumping systems pre-selected using procedure given in the first part.

At the end of each chapter the reader can find a bibliography. This is a combination of references and further reading, selected from a wealth of sources.

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Mr. S. Venstra assisted in the selection and evaluation of source materials, and contributed to the writing of several sections; Ms. Christine van Wijk-Sijbesma reviewed the draft and contributed specifically to the sections on planning, community involvement, and health education; Dr. A.T. White contributed material for various sections, specifically on the selection process for renewable energy pumping devices.

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1. Energy sources for small community water supplies

In developing countries, sources of energy commonly used for community water supplies are human muscle, diesel fuel, and electricity. Hand pumps may be used in small rural communities, but in larger communities the water requirement is usually far beyond the capacity of a single hand pump. In such cases, additional hand pumps may be provided, but one larger pumping system based on a diesel pump or electric pump may be more attractive. However, the high costs, difficulties of ensuring regular fuel supplies and meeting the operation and maintenance requirements, make the use of these pumps less attractive for communities in remote areas.

Thus, interest in renewable sources of energy, such as solar energy, wind energy, hydropower and biomass fuels has increased. Pumping systems based on these energy sources have become technically reliable and economically attractive, particularly for small water supply systems with a capacity of up to about 250 m³/d. The number of people to be served by a pumping system of this size varies, depending on climate, water use practices and convenience of supply. Usually, water use is between 20 and 100 litres per person per day, but may be higher if the system is also used for watering livestock or for small-plot irrigation.

1.1 ENERGY REQUIREMENT

To lift water from its source to a higher elevation requires a source of energy, a device for energy conversion, and a water pumping device. For example, to convert wind energy to a form suitable for the pump, a rotor is used to produce mechanical shaft power which can be transmitted to the pump. In solar-powered, photovoltaic pumping systems, the electricity generated by the solar cells is transmitted to an electric motor which drives the pump. An overview of energy sources used for water pumping and devices for energy conversion is presented in Figure 1.1.

human energy	HANDLE MECHANISM
animal energy	TRANSMISSION RACK
fossil fuel	COMBUSTION ENGINE
electricity (grid)	ELECTRIC MOTOR
hydropower	HYDRAULIC RAM PUMP
	TURBINE OR RIVER - CURRENT ROTOR
wind energy	LOW SPEED MULTI-BLADE WIND ROTOR
	HIGH SPEED ELECTRICITY GENERATING WIND ROTOR + ELECTRIC MOTOR
solar energy	PHOTOVOLTAIC ARRAY + ELECTRIC MOTOR
	DIGESTER + COMBUSTION ENGINE
biomass energy	GASIFIER + COMBUSTION ENGINE
	ALCOHOL FERMENTER + COMBUSTION ENGINE

Figure 1.1: Overview of energy sources and conversion devices for water pumping systems

The energy requirement for water pumping is determined by the quantity of water to be lifted, the head over which it is to be lifted, and the overall energy conversion efficiency of the pumping system. The energy requirement is proportional to the first two factors, and inversely related to conversion efficiency, which indicates how much of the energy input is actually used to lift the water (Figure 1.2).

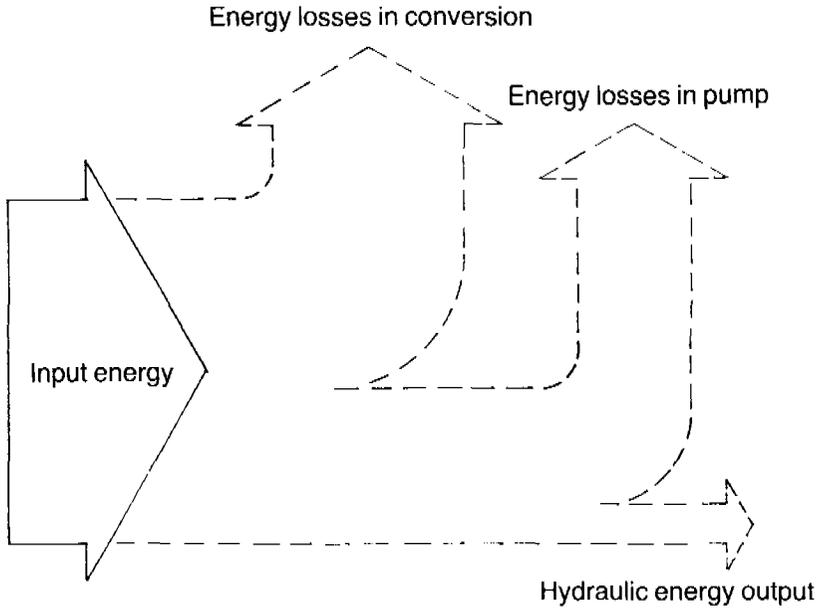


Figure 1.2: Indication of energy losses in the water pumping system (Kenna, 1985)

The energy requirement per second, that is the power required for pumping water, can be calculated with the following equation:

$$P = \frac{Q_w \cdot g \cdot Q \cdot H}{\eta}$$

where:

P = power requirement (watt)

Q_w = specific weight of water (kg/l)

g = gravity acceleration factor (m/s^2)

Q = output rate (l/s)

H = pumping head (m)

η = overall efficiency of pumping system (%)

For example, to pump water having a specific weight of 1 kg/l, at a rate of one litre per second through a head of 10 m, using a pumping system of 20% overall efficiency, at a location where the gravity acceleration factor is 9.8 m/s^2 , would require a power input of 500 watt (W), or 0.5 kilowatt (kW). If this pumping system operates eight hours a day, the daily water output would be $8 \times 3600 = 28\,800 \text{ l/d} = 28.8 \text{ m}^3/\text{d}$ against a head of 10 m, for an energy requirement of $8 \times 0.5 = 4$ kilowatt-hour (kWh).

1.2 CONVENTIONAL ENERGY SOURCES

Human energy

The use of hand pumps or foot-operated pumps is limited to where the water requirement, and thus the energy requirement for pumping, is fairly low.

Little information is available on human energy output for work, such as water pumping. This will depend on the strength and age of the pump user, the duration of the task, and the ambient conditions. At a comfortable level, the human power output over a prolonged period may be estimated to be 50-75 W. Thus, individuals can produce an energy output of 0.4-0.6 kWh in eight hours. With this energy output, about 8-12 m^3 of water can be pumped against a pumping head of 10 m, assuming the mechanical efficiency of the pump to be 50%. As the muscles of the legs are more powerful, foot pumps can produce more water than hand pumps. However, these pumps are not very popular with women and children, and because of the mode of operation, their reliability is limited.

Field experience indicates that hand pumps are being operated up to 12, or even 16, hours per day, but because they are not used continuously, the effective pumping time is about half. Using the maximum of eight hours effective pumping as the criterion, one hand pump on a well 20-30 m deep could supply between 4 and 5 m^3 water, serving 150-200 people with 25 litres per person per day (Table 1.1).

Animal energy

Over a period of eight to ten hours per day, the average energy output of a draught animal is generally five to ten times greater than that of a man. An animal of 500 kg body weight, driving a suitable pumping device, can thus lift 25-50 m^3 of water against a head of 10 m in eight to ten hours, assuming an

Table 1.1: Time required for water pumping*

Pumping depth (m)	Pumping time (hours) to supply 20 litres/person/day			
	2m ³	3m ³	4m ³	5m ³
5	0.7	1.1	1.5	1.8
10	1.5	2.2	2.9	3.7
20	2.9	4.5	5.9	7.4
30	4.5	6.7	8.9	
40	5.9	8.6		
50	7.4			

* Power output of pump users: 50 W (average)
 Efficiency of pumping: 50%
 Number of effective hours operation per day: 8

efficiency of 20%. Animals are used mostly with slow-moving pumping devices to lift water for irrigation, for example, water wheels, chain pumps, and bucket and rope devices. Animal power is not used very often for community drinking water supplies, possibly because animals are owned by individuals. Therefore, animal power is not considered further.

Diesel fuel

In small-scale pumping systems, low-speed diesel engines are used. A suitable power transmission, such as a gearbox or belt drive, and a clutch mechanism are required to connect the engine to the pump. Small diesel engines have an efficiency of about 10-15%. Because of additional power losses in power transmission and in the pump, the conversion efficiency is normally 5-10%, but actual efficiency under field conditions depends heavily on the level of maintenance of the engine. Diesel engines require extensive maintenance and a regular supply of fuel and spare parts, which small communities have difficulties in meeting. Moreover, the lifetime of diesel pumps is limited. Diesel powered pumps also have the disadvantage that the power output is relatively high for small community water supplies, since engines of less than 3 kW rated power output are not available. Petrol and kerosene engines are less efficient and more expensive to operate than diesel engines, and therefore are rarely used for community water supply.

Electricity

Electric motors are produced in various sizes and to a wide range of specifications. The energy conversion efficiency, that is "wire-to-water", of an electric motor pump is about 30-40%. Electricity as a source of energy for water pumping is only economical if a reliable power supply from the mains grid is available close to the pump installation, say within one kilometre. In most developing countries this is rarely the case, and electricity is not a very attractive energy source because of frequent interruptions to the supply, and large voltage fluctuations. Therefore, its use for small-scale water pumping is generally limited, mostly to small communities in close proximity to larger towns.

1.3 RENEWABLE ENERGY SOURCES

The technical reliability, performance, and cost of pumping systems using renewable sources of energy has now reached the point of being competitive with pumping systems using conventional sources. This is particularly the case in small-scale water supplies with a capacity of less than 250 m³/d. The capital cost of renewable energy pumping devices is relatively high, but they can be cost-effective because of their low running costs. There are no costs for fuel supply, and the recurrent costs for operation and maintenance are limited. Local manufacture within the country or region could reduce the capital cost, and in many situations would then make these pumping systems cost-effective in comparison with conventional systems. However, most renewable energy devices require a high level of production technology for their manufacture, and skilled technicians for maintenance and servicing.

Hydropower

A wide range of water pumping devices have been developed which use the energy of flowing water. Here, attention is focused on small hydro-powered pumping devices which convert the energy of flowing water directly into mechanical power to drive a pump. These systems pump water from surface sources, and can operate continuously. There are three main types of hydro-powered pumps for small community water supply:

- hydraulic ram pumps;
- turbine pumps;
- river-current pumps.

Hydraulic ram pumps use the kinetic energy of water running through a drive pipe to lift a small proportion of that water to a higher level than the supply source (Figure 1.3). They can operate reliably where there is a steady and continuous supply of water with a fall of 0.8 m or more. Ram pumps have considerable potential to lift water for small community supplies from unpolluted streams or springs in hilly or mountainous areas.

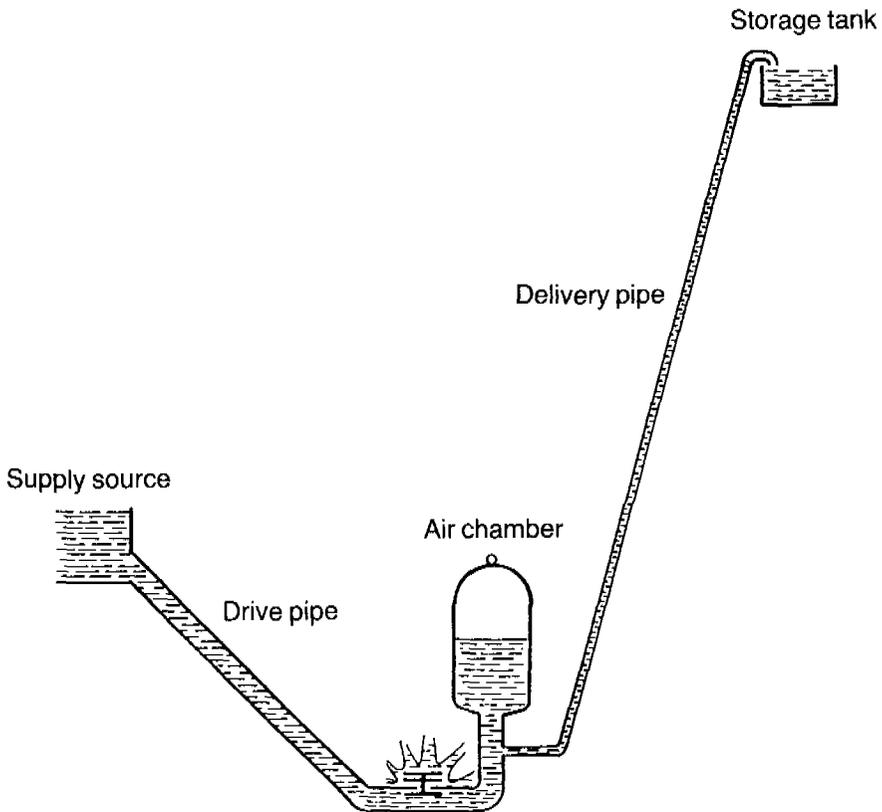


Figure 1.3: Main features of a hydraulic ram pump installation (Watt, 1975)

Turbine pumps have a submerged runner coupled to a pump on the same shaft so that the rotational power is directly transmitted to the pump. In contrast to slow-moving water wheels, they operate at relatively high speeds, and can work satisfactorily under a head as low as 0.5 m, for example, at a weir in a river.

River-current pumps are mounted on a floating platform. They have a partly submersed rotor which rotates by the force of the river current. The rotor shaft power is transmitted to the pump by a transmission mechanism, such as gears or a drive belt, which also multiplies the rotational speed to the required level for efficient pumping.

Wind energy

Wind energy has been used for various purposes for more than 2000 years, and is widely used today in many countries for irrigation and drainage. Since the early 19th century, the windmill with four large blades has been used in the Netherlands for drainage. The potential for using wind power to pump water in small-scale systems is greatly affected by the local wind speeds and the wind regime. For example, at a wind speed of 5 m/s, a power output double that at a

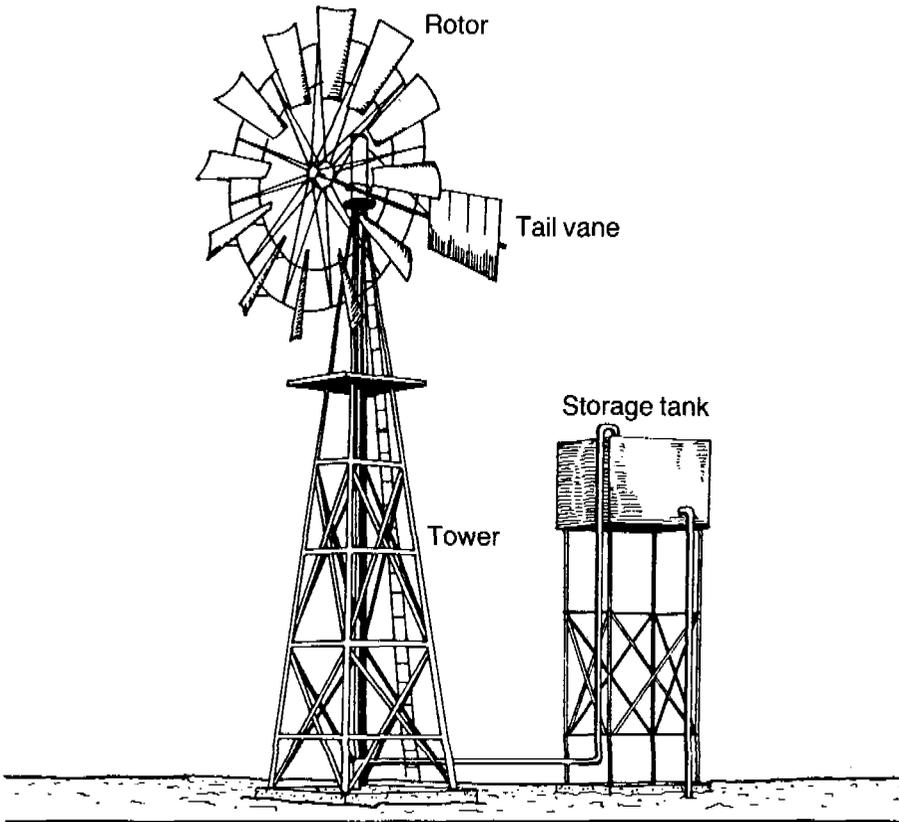


Figure 1.4: Wind pump with multi-blade rotor (Brown, 1978)

wind speed of 4 m/s can be generated. A wind-powered pumping system, or wind pump, consists of a rotor, a pump, and a power transmission mechanism connecting the rotor to the pump. The most common type of wind pump has a multi-bladed rotor mounted on a horizontal axis which transmits the power to the pump through a rod (Figure 1.4). Most wind pumps of this type operate "up wind", that is facing the wind. Generally, they have a control system to protect the rotor against overspeeding, that is, rotating too fast in high winds. The control system either stops the rotor or turns it out of the wind when wind speeds become excessive.

The best known types of vertical-axis wind rotors are the Darrieus and Savonius rotors. As these rotors are not self-starting, they are not particularly suitable for unattended water pumping installations (Figure 1.5). Wind-driven *electro-generators* may be used to supply power to electric pumps. These units operate at higher rotational speeds and have rotors of two or three blades, instead of the multi-bladed rotors in mechanically coupled pumps. A control device is required to stabilize the voltage and current for efficient operation of the electric motor pump.

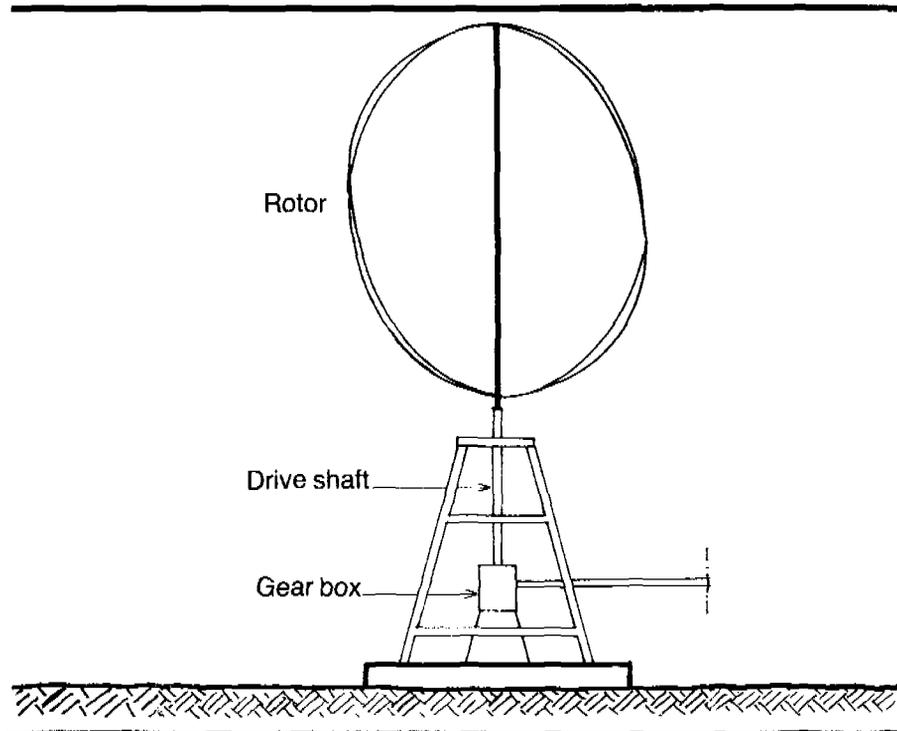


Figure 1.5: Vertical-axis wind rotor (Park, 1981)

Although the capital costs of wind pumps are higher than for diesel pumps or electric pumps of the same output capacity, lower running costs and longer service life can make wind pumps economically attractive in areas of sufficient wind and suitable wind regime. In areas with relatively long windless periods, large water storage tanks are required and wind pumps are then unlikely to be economical.

Solar energy

There are two fundamentally different devices to use solar energy for water pumping, namely thermodynamic devices and photovoltaic systems. For thermodynamic conversion of solar energy, several types of heat engines can be used to produce mechanical energy to drive a pump, the most well-known being the steam engine and Rankine engine. However, small thermodynamic pumping systems generally have a low efficiency, are quite complicated, and to date, have not performed adequately under field conditions.

In photovoltaic pumping systems, solar radiation energy is converted into electricity by solar cells which are interconnected in modules placed in an array.

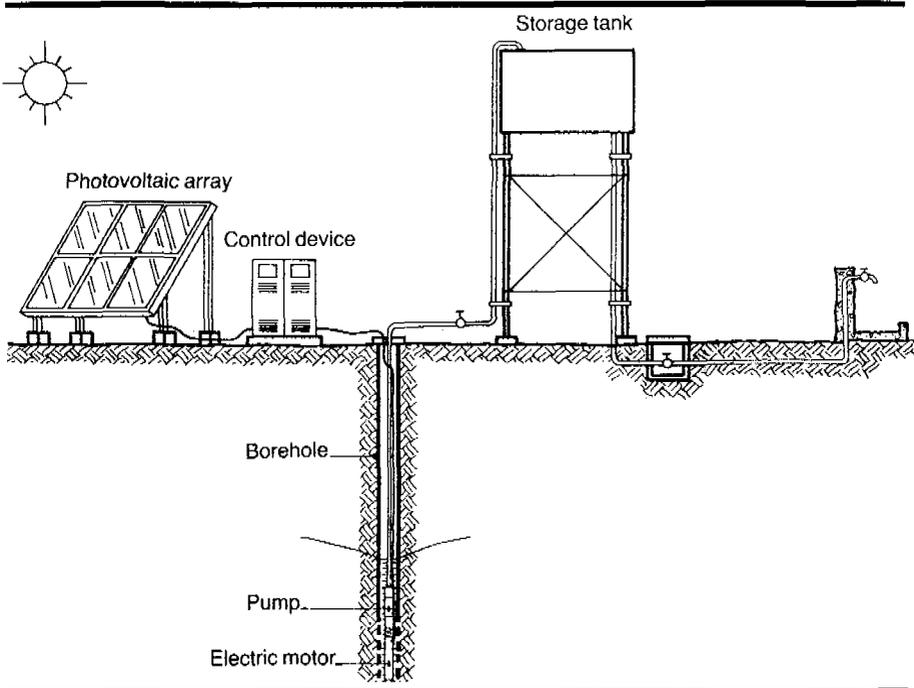


Figure 1.6: Solar photovoltaic water pumping system (Kenna, 1985)

A number of these systems are commercially available, technically reliable, and have performed well under field conditions. A control device is usually, but not always, incorporated to stabilize the fluctuating voltage and current of the energy output of the array. If the electric motor used is designed for alternating current, then an inverter is required to convert the direct current supplied by the array into alternating current (Figure 1.6). The modularity of photovoltaic pumping systems is a distinct advantage. If more power is required, the solar array can be easily expanded by adding more modules. By contrast, a larger diesel engine would have to be installed for greater output if this was the power source. Photovoltaic pumps have considerable potential for remote areas where solar conditions are favourable.

Energy from biomass

Biomass is widely used as a source of energy, mainly for cooking and heating, in many developing countries, especially in rural areas. Human and animal excreta, household waste, wood, crop residues, or aquatic weeds, can be processed to combustible gases, such as biogas and producer gas, or combustible liquids, such as alcohol, methanol or vegetable oil. These gases and liquids can be used as fuel for small engines to drive water pumps.

Biogas is produced in a digester, a specially constructed tank in which a slurry of biomass mixed with water reacts. The biogas produced consists mainly of methane (50-60%) and carbon dioxide (40-50%). The main features of a

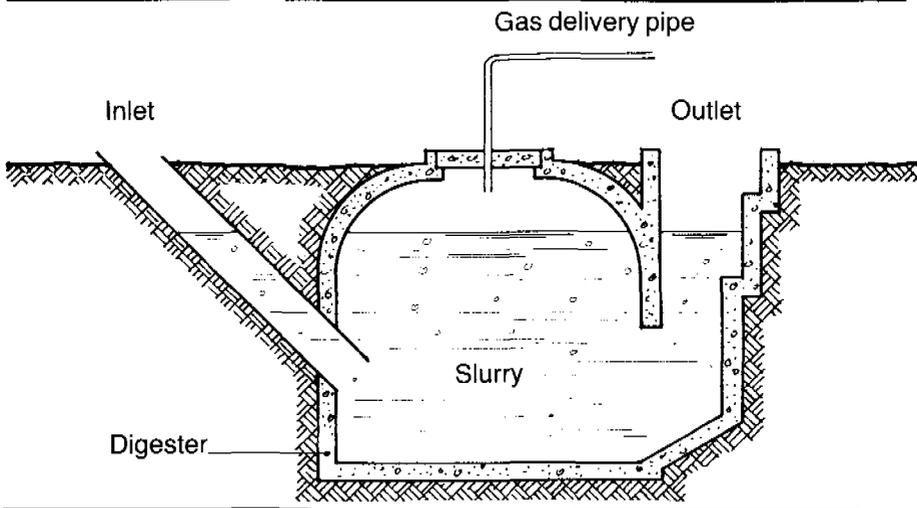


Figure 1.7: Main features of biogas digester (Hall, 1982)

digester are shown in Figure 1.7. The feasibility of biogas production depends on the ambient temperature, the regular supply of suitable biomass throughout the year, and the availability of skilled manpower to operate and maintain the plant. Often, the main barriers to the use of biogas systems are socio-cultural and organizational.

The process of gasification involves the partial burning of solid biomass, such as wood, charcoal, coal, coconut husks or maize cobs, to produce a combustible gas, known as producer gas. Alcohol can be produced from plants with a high content of sugars or starches, such as sugar-cane, sorghum and cassava, and may be used directly, or after mixing with gasoline, as fuel to drive an engine. Vegetable oils, such as sunflower oil, can also be processed to produce fuel for use in engines.

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2. Considerations for selection of energy source

In selecting the most appropriate renewable energy source for small water pumping systems, environmental, social, technical, and economic factors are to be considered. Environmental conditions in the area may reduce the feasibility of certain renewable energy sources, for example, the average wind speed may be less than required for economic use of wind pumps. The social organization, available skills, and infrastructure may not be adequate to cope with the technical requirements of certain pumping systems. In large-scale national programmes, organizational, technical, and economic limitations are not necessarily decisive because many of these can be overcome. If a large number of pumping systems are to be installed, then lack of trained manpower, weakness in organizations, or inadequate maintenance facilities, are no final constraints. If a national government is interested in introducing renewable energy pumping systems, then large-scale application can be prepared through training programmes and the development of infrastructures for the functioning and maintenance of these pumping devices. For a large number of units, it may also be feasible to initiate local production of renewable energy pumping devices.

For small local projects concerned with installation of one or a few pumping systems at individual locations, selection is restricted by the limitations of local infrastructure, technical capabilities, skills and materials. The installation of a pumping device which has operation and maintenance requirements beyond these limitations, would inevitably lead to failure and wastage of funds, or alternatively make the community dependent on external support.

Systematic assessment of all relevant factors should be made in the selection of appropriate energy sources for water pumping (see Figure 2.1). In this way, one or more renewable energy sources can be pre-selected. However, available data are often neither adequate nor reliable, and a pilot project may be required to study and test the feasibility of the pre-selected energy sources and pumping systems. These projects are of particular relevance for rural water supply programmes in countries having little experience with the use of renewable energy devices. On the basis of the present state-of-the-art and cost data from 1985, the general order of preference for selection is hydropower, wind energy, solar energy, and biomass energy.

Factors	Selection criteria	Information required
Environmental feasibility	Availability of energy sources	<ul style="list-style-type: none"> – data on energy sources – hydrology – climate – topography
Technical feasibility	Existing level of technological infrastructure	<ul style="list-style-type: none"> – design – manufacture – installation – operation – maintenance
Social feasibility	Social acceptability of energy source and pumping device	<ul style="list-style-type: none"> – social structure – organization – potential for productive water use – willingness and – capacity to pay
Economic feasibility	Cost-effectiveness of energy device	<ul style="list-style-type: none"> – cost data – time profile of costs – economies of scale – local manufacture

Figure 2.1: Systematic assessment of relevant factors in selection of energy sources for water pumping

2.1 ENVIRONMENTAL FEASIBILITY

Data base

A first indication of the availability of renewable energy sources in the study area may be obtained from maps showing the world distribution of these sources. There is a general relationship between availability of renewable energy and climate (Barnett, 1982). In arid tropical zones encompassing the Sahel region, Saudi Arabia, Iran and Pakistan, Peru and Chile, and most of Australia, solar energy is abundant, whereas the scope for hydropower and biomass energy is limited. In humid tropical zones, such as the Amazon and Congo river basins, the southern part of west Africa, central Africa, parts of

Kenya and Tanzania, Madagascar, most of Malaysia, parts of Thailand, Indonesia and Papua New Guinea, hydropower and biomass energy are likely to be promising, but solar energy is less attractive because of the relatively long cloudy periods during the rainy season. Where there is a distinct wet and dry season, such as in central Africa around the equator, southern Venezuela and eastern Brazil, a detailed analysis of the seasonal variation is required to assess the potential of renewable energy sources throughout the year. Good wind regimes are found mostly in coastal areas where the winds are relatively strong and regular throughout the year. For example, in the coastal areas of South America, the Atlantic coast of west Africa, the plains of northern Africa, and also in Malaysia, Indonesia, the Philippines, and most of the Pacific islands, there is potential for wind power. The minimum requirements for environmental feasibility of pumping devices using renewable energy are given in Table 2.1.

Table 2.1: Indication of minimum requirements for environmental feasibility of renewable energy sources

Renewable energy source	Minimum requirements for environmental feasibility
Micro-hydropower	
hydraulic ram pumps	average monthly flow rate of at least 3-5 l/s in combination with a hydraulic head of at least 1 m
river-current pumps	minimum current speed of 1 m/s
Wind energy	
wind pumps	average annual wind speed greater than 3.5 m/s average wind speed in least windy month more than 2.5 m/s
Solar energy	
photovoltaic pumps	average annual solar irradiation at least 15 MJ/m ² /d (4.0 kWh/m ² /d) solar irradiation in least sunny month more than 12.5 MJ/m ² /d (3.5 kWh/m ² /d) clearness factor (lack of clouds) at least 60%
Biomass energy	
biogas production	humid climate, annual average temperature higher than 15°C
gasification	50-100 kg of dry wood or crop waste of 10-20 ha per day
alcohol production	200-400 ha of land for energy crop production

The initial assessment of the potential of the various energy sources must be followed by more detailed study to determine the potential within the particular country or region. This can be done on the basis of available or collected data, such as wind regime, ambient temperature and solar irradiation. Such information is sometimes available from national institutions and meteorological stations, or from the World Meteorological Organization, Geneva, Switzerland. Preferably, the data should cover a period of five or more years to establish, to a reasonable degree of accuracy, the annual and monthly average values for the particular area.

If sufficient, reliable data are not readily available, data will have to be collected. At least one year's record of essential data is required, from which a sufficient indication of monthly and seasonal variation can be obtained. In some cases, it may be possible to extrapolate to a reasonable degree of accuracy using data from other locations. For example, an estimate of the monthly average solar irradiation may be derived from data for neighbouring countries. Wind speed values cannot be extrapolated from data for other regions however, because they are greatly affected by local topography and are therefore likely to show considerable variation. Because of the cost, data collection should be restricted to the essential. In some areas, the general conditions may strongly favour a particular renewable energy source, and data collection may then be restricted to that option.

Hydropower

The number of locations suitable for the use of hydropowered pumping systems is limited in most countries and regions. The main requirement is a continuous and adequate flow of water of sufficient fall, throughout the year. For most small streams, rivers and springs, flow data for long periods are not available and thus, local measurements must often be made. Further, because hydropowered pumps draw water from surface water sources or spring-fed streams, the suitability of the water for drinking and domestic use must be assessed.

Wind energy

In locations where the average wind speed is higher than 3.5 m/s, and the mean wind speed in the least windy month greater than 2.5 m/s, wind can be an adequate and reliable source of energy for water pumping. A record of average hourly wind speeds over a period of at least one year, and preferably over one-and-a-half years, is required to determine whether wind-powered pumping systems are feasible. Wind speed data for the least windy month are necessary to

assess whether wind pumps are economically feasible, because the length of windless periods determine the storage capacity required to ensure a reasonably reliable water supply, and thus to a large extent the cost of wind-powered pumping systems.

Solar energy

Areas with solar irradiation levels and a clearness factor which meet the requirements given in Table 2.1 for solar photovoltaic pumping systems, are found mostly between the Tropics of Cancer and Capricorn.

In arid tropical zones, average daily irradiation is often as high as 15-20 MJ/m²/d (4.0-5.5 kWh/m²/d), which is quite sufficient for solar pumping systems. Irradiation levels are generally less in humid tropical areas, but may still be sufficient for operation of solar pumps. Photovoltaic pumping systems are considered to be environmentally feasible in areas with an average daily irradiation greater than 12 MJ/m²/d. Thermodynamic pumping systems have not as yet been developed sufficiently to warrant consideration as a feasible and viable option for small-scale water pumping systems.

Biomass energy

Generally, biomass energy is environmentally feasible in humid tropical areas where ambient temperatures throughout the year are above 15°C, and where there is sufficient rainfall and sunshine, and favourable soil conditions, to ensure a continuous and generous supply of suitable biomass. Because of the minimum size of a biomass processing plant and the concomitant economics, biomass energy is only worth considering for water pumping duties above 150 m³/d.

Biomass conversion is regarded principally as an energy production technology, but has additional environmental benefits because it can improve waste disposal and produce fertilizer for agricultural production. Where biomass energy for water pumping is considered, due attention needs to be given to safeguarding the supply of suitable biomass in the long term.

2.2 TECHNICAL AND SOCIAL FEASIBILITY

Water pumping devices using renewable energy sources vary considerably in technical complexity, and thus in operational and maintenance requirements. In general, complex pumping systems, often imported, require more qualified

attention than simple locally manufactured equipment, but less frequently. For example, maintenance of photovoltaic pumping systems requires a visit by a mobile team of qualified technicians once or twice a year. By contrast, hydropowered pumps and wind pumps can be maintained on a regular basis by local mechanics. Engine pumps running on a mixture of diesel and biomass fuel require extensive maintenance and frequent servicing, generally about once every two to three months. Most renewable energy pumping systems require a well-established back-up support for maintenance (Table 2.2).

Table 2.2: Frequency of maintenance attention and level of technical skills required for various types of pumping devices

Energy source	Type of pumping device	Frequency of maintenance attention ¹	Technical skills ²
Renewable			
micro-hydropower	hydraulic ram	low	low
	turbine pump	low	medium
	river-current pump	low	low
wind energy	commercially manufactured	low	medium
	intermediate technology	medium	medium
	village level product	high	low
solar energy	solar photovoltaic	low	high
biomass energy	biogas digester	high	medium
	gasification unit	high	high
	alcohol fermenter	high	high
Conventional			
human energy	hand pump	medium	low
diesel fuel	diesel engine	medium	medium
electricity	electric motor	low	medium

¹ Low, once a month; medium, once a week; high, daily

² Low, locally trained villagers; medium, trained operators (local mechanics, carpenters, blacksmiths); high, qualified technicians

Provision for operation and maintenance must be made before pumping equipment is installed. Arrangements should be made so that the user community, the water supply agency, and the local authorities each have clearly defined responsibilities for management, operation and maintenance of the pumping system. These arrangements must be made in consultations with the

user communities so that they are fully informed of, and agree with, their responsibilities and rights in each stage of the project.

The back-up service for maintenance and repair may be either centralized or decentralized, depending on the complexity and frequency of maintenance requirements. The technical and organizational capacity of user communities is one of the determining factors in the choice of pumping system. Other factors are the available infrastructure, the social organization of the user communities, transport facilities and costs, and any existing maintenance structure. A general indication of back-up service requirements is given in Table 2.3.

Table 2.3: Indication of back-up service requirements for various types of pumping systems

Energy source	Type of pumping device	Frequency of back-up support required ¹	Level of back-up service required ²
Renewable			
micro-hydropower	hydraulic ram	low	low
	turbine pump	low	medium
	river-current pump	low	medium
wind energy	commercially manufactured	low	high
	intermediate technology	medium	medium
	village level product	low	low
solar energy	photovoltaic	low	high
biomass energy	biogas digester	medium	medium
	gasification unit	medium	high
	alcohol fermenter	high	high
Conventional			
human energy	hand pump	low	medium
diesel fuel	diesel engine	medium	high
electricity	electric motor	medium	high

¹ Low, once a year; medium, once every 3-4 months; high, once a month

² Low, local mechanic; medium, specially trained mechanic; high, qualified technician

Construction and installation of the pumping systems may require special expertise, which is often not readily available within the national organization or water supply agency. Therefore, training will be needed to develop the capacity to ensure quality of construction and reliability of installation.

A guiding principle for rural water supply programmes is that every community involved should participate actively in the choice of pumping system, so that local needs and preferences are taken into account, and the consequences of the various options are known to the users. The impact of the new pumping system on the local situation needs to be assessed and this may require extensive discussions with future users, particularly women. Some groups within the community may benefit more than others if, prior to installation, agreement is not reached on the use of water for small-plot irrigation, livestock watering and similar productive uses. For example, systems requiring large-scale collection of biomass may disadvantage the poor. In many societies, women of poorer groups have the right to collect organic waste, such as cow dung; they may well lose this benefit if it becomes financially attractive for other groups to collect this biomass.

It is often necessary to establish some form of local organization, such as a water committee, to participate in the selection and supervision of local pump caretakers, and to arrange for collection of water charges and provision of labour support. The importance of the development of a suitable organization, and of upgrading local skills, is often underestimated. A minimum level of organization and skills is required at the local level to ensure proper use and maintenance of pumping systems, and to establish the regular collection of water charges. For biomass collection and use, local organization is especially important, and includes the need to ensure payment to the suppliers of biomass. Pilot projects provide a useful opportunity to experiment with, and establish, the most appropriate ways of involving the community.

Hydropower

Hydropowered pumping devices require only limited maintenance, such as occasional checks on the moving parts, cleaning the water intake, and routine work, including greasing and bolt tightening. The supply of spare parts for imported hydropowered pumps may be quite difficult to arrange unless guaranteed by the back-up service organization. In general, these pumping devices do not require a full-time operator; an attendant may be appointed to check the pump occasionally and to carry out routine maintenance. However, water treatment will often have to be provided because surface water is pumped and supplied directly, and users are thus exposed to pollution hazards.

Civil works are required to install hydropowered pumping devices, for example, a small dam or weir to control the flow of water to the pumping device. The extent of the civil works depends on the site, but if building materials are available locally, these works can usually be constructed by local labour or contractors.

Hydraulic ram pumps may require the diversion of a considerable proportion of the water from the source. This may lead to conflicts over water use with communities downstream. Therefore, the possible consequences of ram pumps must be discussed with various communities, and agreement reached before implementation.

Sturdy ram pumps are commercially available from manufacturers in Europe, North America, India, Japan and Taiwan. However, small industries or local workshops in many developing countries should also be able to manufacture simple ram pumps, or assemble them from locally available parts. Some simple ram pumps are actually being manufactured in India, Kenya, Tanzania and Zambia.

Turbine pumps are currently manufactured only in the People's Republic of China, where they have established a record of proven design and performance. River-current pumps are of relatively simple design and may be suitable for local manufacture from available parts and materials.

Wind energy

At present, most commercially available wind pumps are manufactured in industrialized countries and shipped to developing countries. These pumps are generally well-designed, efficient, and sturdy, but expensive, and maintenance and repair are difficult because spare parts have to be imported. Wind pumps of relatively simple design can be manufactured locally and more cheaply, but require more maintenance and repair. If complex parts, such as gears or other transmission mechanisms are used, these may have to be imported.

Wind turbulence and changing wind speeds produce a fluctuating load on the tower, which can cause fatigue failure of inadequately constructed parts and materials. Therefore, proper design and construction of the tower and foundation, and careful alignment of the transmission mechanism, are essential for reliable operation of wind pumps.

The moving parts of wind-powered pumping systems are subjected to varying loads, fatigue, corrosion and dust, and therefore, regular servicing and maintenance are required to ensure reliable performance. A local caretaker must be available to carry out routine maintenance, such as bolt tightening, greasing and lubrication. Locally manufactured wind pumps often require frequent maintenance attention. For major repairs, back-up support is required from a service organization or a local workshop.

Installation of a wind pump sometimes requires the removal of trees around the wind rotor. It may be necessary to compensate those who lose the benefit of using these trees by allowing them, for example, to use the excess water produced in periods of high wind for small-plot irrigation, livestock watering, or similar productive uses.

Solar energy

At present, photovoltaic solar pumping systems are only available from manufacturers in industrialized countries. These systems are offered as a package consisting of the solar array, the motor-and-pump subsystem, and ancillary equipment. In a number of developing countries, there appears to be scope for local assembly, and in some countries it may be possible to establish local manufacture. Photovoltaic pumping systems should be installed by skilled technicians, according to the manufacturers' instructions.

Maintenance requirements of these systems are limited. Regular cleaning of the transparent surface of the solar array, and checking the electric controls, may be all that is required on a routine basis. In addition, periodic replacement of the brushes is required for brushed motors. Arrangements for reporting faults or breakdown to the back-up service should be made, because all major repairs can only be carried out by trained mechanics. As the number of photovoltaic solar pumping systems in operation for domestic water supply increases, more data on field performance will become available, thus permitting more accurate assessment of the maintenance and servicing requirements.

Biomass energy

Biogas production plants are used in many developing countries, particularly in China and India. The major components of the plants can be manufactured locally, but some of the more complex parts are only produced in small industries. Gasifiers and alcohol fermentation plants are mostly available from industrialized countries, but can be manufactured in developing countries. In the Philippines, gasifiers are manufactured commercially with government support, and there is considerable experience in Brazil in the manufacture of alcohol fermentation plant. Installation of gasifiers and fermentation units is relatively easy, but careful attention must be given to site selection to avoid problems of smell, smoke and dust.

In general, a biomass processing plant requires a trained operator and a considerable amount of unskilled labour to collect the biomass. In rural areas of most developing countries, biomass is a source of fuel for many purposes, including cooking and heating. Therefore, introduction of biomass energy production for water pumping may only be feasible if a generous supply of biomass is available to avoid creating a scarcity for traditional uses. The use of biomass to produce fuel for water pumping must be discussed with the community, to avoid conflicts about present collection and use, often by the poorest sections. The regular supply of biomass required for water pumping can rarely be assured on a voluntary basis at no cost.

The maintenance requirements of pumping systems running on biogas, producer gas, or alcohol, are similar to those of small engines and fuel production plant generally.

2.3 ECONOMIC FEASIBILITY

Cost analysis

Cost analysis is a useful tool to support selection of the renewable energy source to be used for water pumping systems in the study area. Since both the capital and the recurrent costs must be assessed, it is necessary to use discounting techniques because the various types of pumping systems under consideration have different time profiles of costs. For example, for solar pumps, the capital cost is relatively high and may represent more than 70-75% of total lifetime costs, while for diesel pumps, the capital cost is relatively small and may be no more than 25-30% of total lifetime costs (see Figure 2.2).

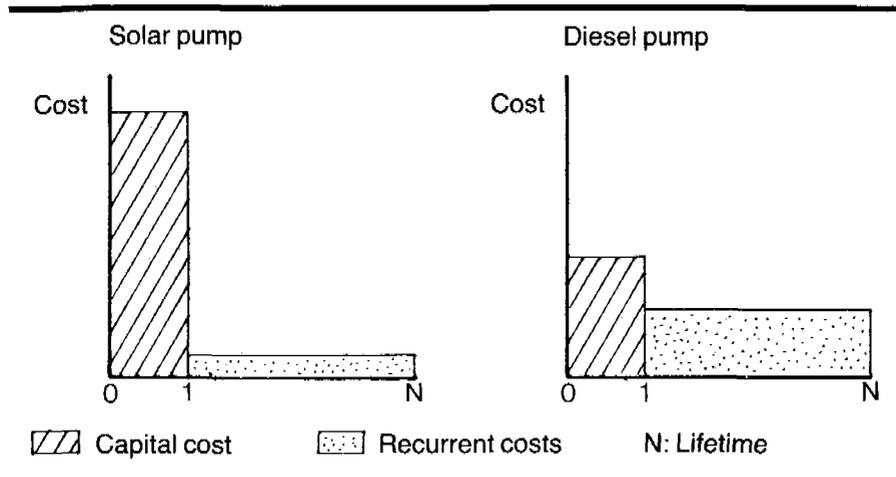


Figure 2.2: Comparison of time profile of costs for solar pump and diesel pump

The distribution of capital and recurrent costs can affect the level of the financial contribution to be charged to the users. In rural water supply programmes, capital expenditure is often financed from government or donor funds, while recurrent costs are paid fully or largely by the users. Thus, user communities may expect to be charged less for a capital-intensive, low recurrent cost pumping system than for a system with high recurrent costs. An indication of the distribution of capital and recurrent costs for various pumping systems is given in Table 2.4.

Table 2.4: Level of capital and recurrent costs of various types of pumping systems

Energy source	Type of pumping device	Capital cost	Recurrent costs
Renewable			
micro-hydropower	hydraulic ram	low	low
	turbine pump	low	low
	river-current pump	low	low
wind energy	commercially manufactured	high	low
	intermediate technology	medium	medium
	village level product	low	medium
solar energy	photovoltaic pumping system	high	low
biomass energy	biogas digester engine	medium	medium
	gasification unit engine	medium	medium
	alcohol fermenter engine	medium	medium
Conventional			
Human energy	hand pump	medium	low
diesel fuel	diesel engine	medium	high
electricity	electric motor	medium	low

Effect of local manufacture

The capital cost of pumping systems powered from renewable energy sources could be reduced in large-scale production for national rural water supply programmes. The minimum number of units required to initiate local manufacture will vary from country to country. To stimulate local production, research and development of renewable energy technology needs to be promoted. If research and development capabilities are not available in local industries, local manufacture may be promoted by involving government research institutions or technical universities. While it is highly desirable to increase self-reliance at both national and local level, at present, local manufacture is often hampered by lack of suitable materials, essential components, and expertise, and initially the market may be too small to justify local production. Therefore, as an intermediate solution, consideration may be given to local assembly of imported equipment, to reduce shipping and inland transport costs.

General indication of economic feasibility ranges

As yet, few systematically-collected cost data, based on field experience, are available to assess the economic feasibility of water pumping systems using renewable energy sources. Nevertheless, the general level of costs of the various types of pumping systems has been calculated from global cost data, and on this basis, the economic feasibility ranges for the various energy sources have been estimated (Figure 2.3). It must be emphasized that these ranges are indicative only, and that local cost data may give quite a different result. Thus, the economic feasibility of a particular pumping system can only be determined reliably from local cost data. If several types of pumping systems appear to be economically feasible, comparison of unit output costs is important in the final selection process. These unit costs are calculated per kWh of hydraulic energy output, or per cubic metre of water pumped (see Chapter 3).

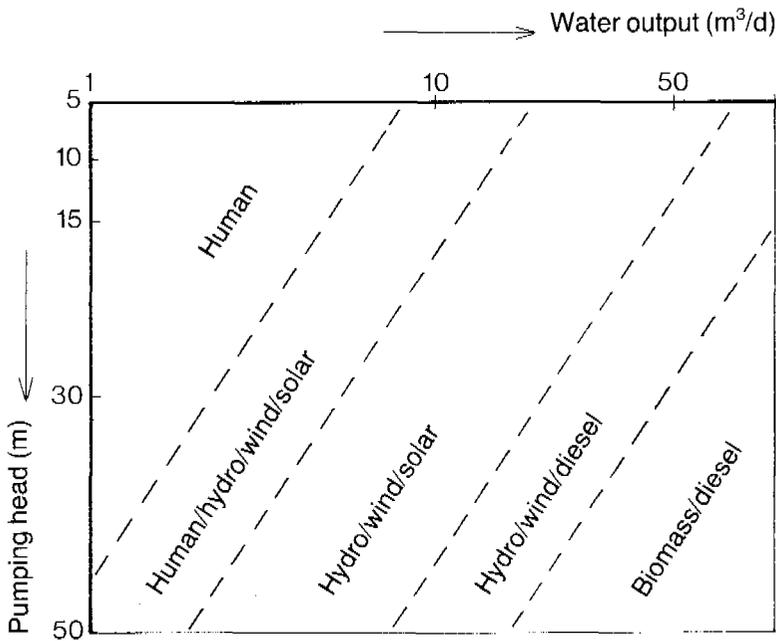


Figure 2.3: Estimated range of economic feasibility of energy sources for a particular water pumping duty

2.4 PILOT PLANT STUDIES

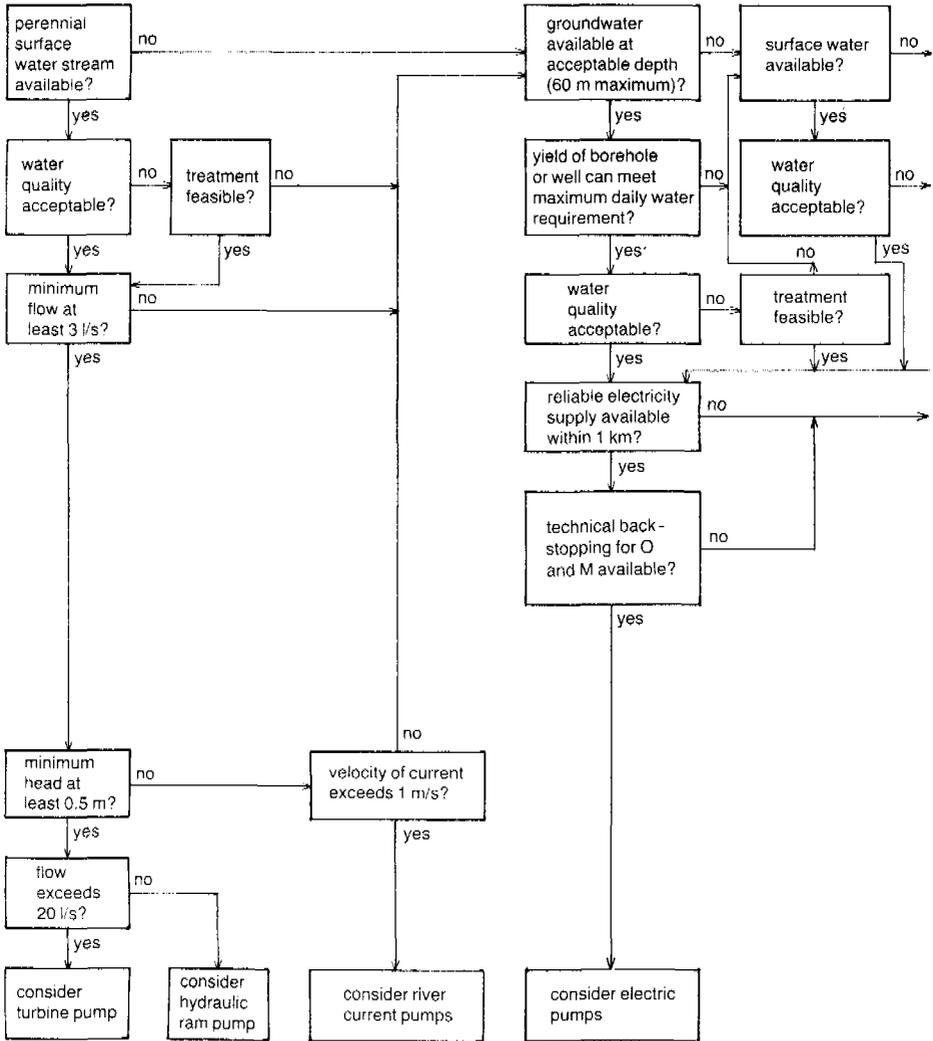
Usually, the selection process will indicate one or two types of pumping systems having potential for use in the area or rural water supply programme under study. Pilot projects are then essential to assess the performance of these devices under field conditions, to adapt technology to local conditions, to support the economic appraisal, and to experiment with methods of involving the communities.

Testing and monitoring of prototype pumping systems at universities or research institutes should be used primarily to gain experience and to improve designs. Pilot plants are useful to familiarize national authorities and engineers with the new types of pumping systems, and to facilitate training of technical field-staff. The results of pilot plant studies must be checked by periodic evaluation, at least in the initial stage of full-scale implementation.

2.5 LOCAL SELECTION

If pumping devices powered from renewable energy sources are selected on a local basis for one or a few locations, then the limitations posed by the technical, social and organizational constraints are much stricter than in large programmes. The type of pumping device to be selected will have to fit into the existing situation, that is, must be suitable for the available technical skills, workshop facilities, equipment, and capabilities for operation and maintenance. Usually, for these few installations it is neither economical nor possible to initiate a training programme, or to establish a back-up service system. These constraints are likely to limit severely the technical feasibility of most of the pumping devices under consideration. However, it is preferable to accept this limitation rather than to install pumping equipment which will break down after a short period of time. At an early stage, the feasibility of options should be discussed with the community or its leaders, and they should be involved in the decision-making.

The flow chart in Figure 2.4 can be used to check the feasibility of energy sources for water pumping at a specific location. The entry point to the selection chart is the available water source. The various sources of energy should be considered in the order in which they are generally rated as technically feasible and economically attractive. Through this step-by-step process, the most promising type of pumping system is identified. If several energy sources appear to be feasible, a comparison of the costs per unit of water output should be made (see Chapter 3).



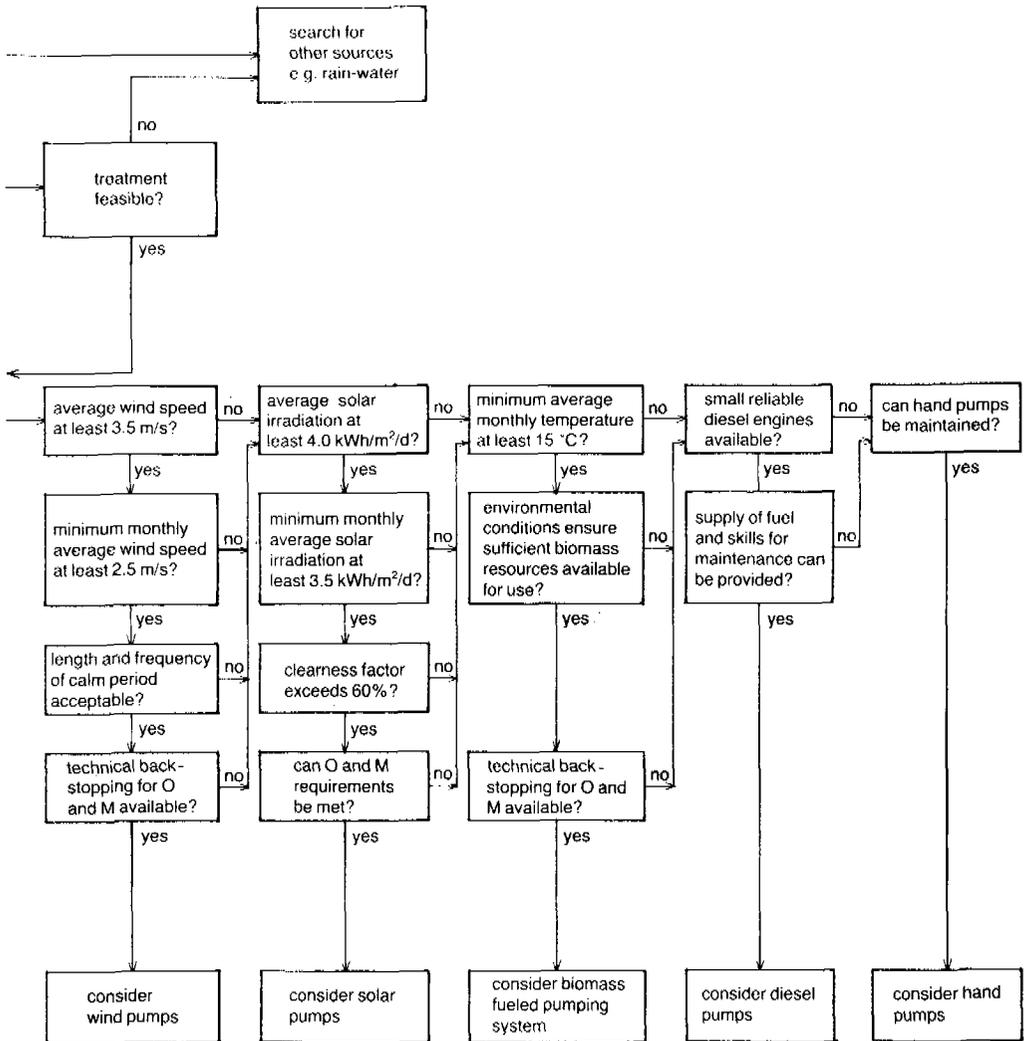


Figure 2.4: Selection chart for determination of energy source(s) and pumping system(s) to be considered for a particular location

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3. Comparative cost analysis

The purpose of comparative cost analysis as presented in this chapter, is to assess the cost-effectiveness of the pumping systems which have emerged in the pre-selection process. The cost analysis should be specific to the particular country or region and findings should not be extrapolated to other countries or regions.

3.1 COST CATEGORIES

Basically, two cost categories are distinguished: capital costs and recurrent costs. Capital costs are all costs incurred when the pumping equipment is purchased and installed. Recurrent costs are incurred for operation, maintenance and repair throughout the lifetime of the pumping system and include the cost of fuel, replacement parts, wages and transport. The various costs in these two categories are listed in Table 3.1.

Cost comparison of various pumping devices need not necessarily take into account all the components of the water supply system. The first step is to identify those components common to the systems being compared, for example, the distribution system or the borehole. These costs will be the same for all types of water pumping systems, and therefore can be excluded from the comparative cost analysis. However, it is useful to estimate the general level of

Table 3.1: Capital and recurrent costs of a water pumping system

Capital costs:	land site preparation foundations pumping equipment storage tank power supply equipment prime mover (e.g., diesel engine, electric motor) pipework and appurtenances installation and mounting (e.g., transport, labour)
Recurrent costs:	consumables (e.g., fuel, lubricants) salaries and wages spare parts and replacements

these costs when deciding on the type of pumping device. For example, if the construction cost of the distribution system and the borehole represent 85% of the total capital cost, then a cost difference in two pumping devices of 20% represents only 3% of the overall capital cost of the system.

3.2 CALCULATION OF COMPARABLE COSTS

For a valid comparative cost analysis, the capital costs and recurrent costs have to be converted into comparable units. Two methods can be used for this purpose:

- present value;
- equivalent annual cost.

Present value method

The "present value" of future recurrent costs can be calculated by discounting them at an appropriate rate, the discount rate. If there is no price inflation, the prevailing interest rate, if not regulated by governmental control measures, may be used as the discount rate. For example, to cover a cost of US \$ 99 for maintenance in the following year, it is sufficient to set aside US \$ 90 invested at an interest rate of 10%; and if the expenditure of US \$ 99 is required after three years, US \$ 74 invested at 10% would be adequate. Present value calculations are more complicated where price inflation occurs, because then it is necessary to adjust the prevailing interest rate for inflation in order to arrive at a realistic discount rate.

The present value of a cost (C), incurred in the year (n) from the present, can be calculated with the equation:

$$PV = \frac{C}{(1+r)^n}$$

where:

- PV = present value of cost
- C = nominal amount of cost incurred
n years from present
- n = number of years
- r = discount rate

The present values of all recurrent costs to be incurred over the expected lifetime are added to the initial capital cost to obtain a total figure, which can be compared for various types of pumping systems.

Method of equivalent annual cost

The capital cost is converted in a series of equivalent annual costs over the total lifetime of the pumping system. The sum of the annual equivalents will be greater than the initial capital cost of the system, because interest over the remaining debt is included in each annual instalment. The equivalent annual cost of a capital investment (C), over an expected lifetime of (n) years, can be calculated with the equation:

$$EAC = C \times \frac{r(1+r)^n}{(1+r)^n - 1}$$

where:

EAC = equivalent annual cost

C = initial capital cost

n = expected lifetime

r = discount rate

The total annual cost is obtained by adding the annual recurrent costs to the equivalent annual capital cost, to give a figure which can be compared for various pumping systems. This method is recommended for comparative cost analysis of pumping systems for the following reasons. Recurrent costs are difficult to estimate accurately, and it may well be necessary to adjust the cost calculations from time to time. This is more easily done in this method than for the discounted amounts in present value calculations. Another advantage is that the total equivalent annual cost divided by 365 gives the daily cost of the pumping system which, divided by the daily water output, yields the unit cost per cubic metre of water pumped. This unit cost figure is particularly useful in the cost comparison of water pumping systems.

Discount rate selection

The discount rate to be used differs from country to country. In general, the World Bank applies discount rates in the range of 8 to 15% for developing countries. When sufficient data are not available, it is advisable to make calculations for several discount rates to get an indication of the effect of the selected discount rate on the results of the comparative cost analysis.

Lifetime estimation

It is difficult to estimate the lifetime of renewable energy pumping devices because very few extended field tests have been carried out. More is known about the lifetime of other components, such as pipes and tanks. It is recommended that the pumping equipment be reviewed and those components be identified, the lifetime of which can be reasonably estimated. For the lifetime of the other components, a rough estimate of ten years can be used. It may be advisable to make additional cost calculations, using lifetime estimates of eight and 15 years, to assess the sensitivity of the analysis results for these changes.

Capital recovery factor

The equivalent annual cost can be readily calculated using an appropriate capital recovery factor, which represents the amount per invested dollar to be paid annually for full repayment. Capital recovery factors for various combinations of lifetime and discount rate are given in Table 3.2.

Table 3.2: Capital recovery factors for various combinations of discount rate and lifetime

Lifetime (years)	Discount rate (%)				
	5	8	10	12	15
5	0.23	0.25	0.26	0.28	0.30
10	0.13	0.15	0.16	0.18	0.20
15	0.09	0.12	0.13	0.15	0.17
20	0.08	0.10	0.12	0.13	0.16

Example:	Investment	\$ 1000
	Lifetime	10 years
	Discount rate	10%
	Capital recovery factor	0.16
	Equivalent annual cost	\$ 160

3.3 COST ANALYSIS USING ADJUSTED COST DATA

If the comparative cost analysis is made to support selection of the pumping system for one or a few local projects, it is justifiable to base the cost analysis on actual prices or costs in order to avoid complicated calculations. The market prices of local construction materials, local wages, and the current interest rate may then be used.

However, when comparative cost analyses are made to support national authorities or a rural water supply programme in the selection of pumping systems for large-scale use, then market prices or observed costs should be adjusted to reflect the real scarcity and cost of resources. For example, the real cost of skilled staff is related to their actual capacity to contribute to the national economy, which is often higher than reflected by their salary. Thus, to find the real cost of using the scarce resource of skilled staff, the financial cost, that is the salary, should be adjusted for the country concerned.

In some countries, the foreign exchange rate for the national currency is regulated by the authorities and kept artificially high, at an unrealistic level. The real cost of purchasing foreign products will then be higher than reflected in the financial cost, that is, the local currency amount quoted by the bank.

A set of adjustment factors based on actual cost data obtained in a water supply project in the Morogoro region of Tanzania, to convert market prices to real costs, is given in Table 3.3.

Table 3.3: Adjustment factors used to convert market prices to real costs for the Morogoro region of Tanzania

Cost category	Adjustment factor
Unskilled labour	0.5
Skilled staff	1.5
Foreign exchange	2.0
Local materials	1.0
Diesel fuel	4.0
Transport vehicles	2.5

3.4 ESTIMATION OF RECURRENT COSTS

The recurrent costs have to be estimated in order to make valid cost comparisons. Some annual recurrent costs are fixed amounts, for example, the wages of caretakers, whereas other costs are related to the period of time that the pumping equipment runs and thus to the water output, for example, fuel consumption, spare part requirements, and repairs. It is generally best to calculate the recurrent costs of various pumping systems per kWh hydraulic water output, or per m³ of water output. For cost comparison purposes, the cost per kWh hydraulic water output is preferable because it takes into account both water output and pumping head.

3.5 PUMPING SYSTEMS USING CONVENTIONAL ENERGY SOURCES

In this section, general cost data in US dollars (1985) are presented for conventional pumping systems. The cost data are only indicative, because accurate and reliable cost data are scarce.

Hand pumps

The capital cost of hand pumps varies considerably, depending on size, type, and quality of construction materials. Suppliers' catalogues can be consulted for current prices. The capital cost of a hand pump may be roughly estimated to be in the range \$ 300 to \$ 500, the annual costs of maintenance and repair vary considerably, but may be assumed to be between \$ 80 and \$ 150 per pump. When more than one hand pump is required to provide the same water output as a single more powerful pumping system using a renewable energy source, the construction cost of additional wells or boreholes has to be taken into account in the cost comparison. These costs may be estimated to be between \$ 150 and \$ 250 per metre depth of the well or borehole.

Diesel engines

The capital cost of diesel engines is generally estimated to be in the range of \$ 500 to \$ 1200 per kW rated power. Costs of inland transport, foundation construction, and installation are additional. Reliable diesel engines for small community water supplies are available from 3kW rated power. The life

expectancy of a diesel engine depends on the quality of manufacture and maintenance, and the number of hours of operation. If field data are not available, the useful life of a diesel engine may be taken to be 8000-15 000 hours, or about 4-5 years. However, inadequate maintenance may reduce the useful lifetime by about half. The cost of diesel fuel is a high proportion of the overall running costs, and varies widely from country to country, and even within one country. National taxes and additional charges for transport generally bring the price of diesel fuel in the range of \$ 0.40 to \$ 0.80 per litre. Maintenance and servicing costs may be estimated to be about 20-25% of the fuel costs, or \$ 200-400 per 1000 hours of operation.

Electric motors

The capital cost of electric engines for small water supplies ranges from \$ 400 to \$ 1000 per kW rated power. These motors usually have a lifetime of some 20 000-50 000 hours of operation. Maintenance and repairs need to be carried out by trained caretakers, which may present a problem in many developing countries.

Running costs include the wages of caretakers and the charges made by the electric power company, which may be about \$ 0.07 per kWh but are likely to vary considerably for different regions. In many countries, the costs of using electric power in rural areas is prohibitive. However, on-site generation of electricity by solar photovoltaic or wind-electric generators may increase the scope for electric motors.

3.6 PUMPING SYSTEMS USING RENEWABLE ENERGY SOURCES

Because of the limited data from field experience and trials, cost data on pumping devices using renewable energy sources vary even more than data for conventional power pumps.

Hydropower

The pumping equipment in hydropowered pumping systems accounts for only a small proportion, usually 25-30%, of the initial capital investment because this includes the cost of civil works, such as dams, weirs, pipelines, platforms and foundations. These costs vary greatly according to site conditions. Current prices for foundry-made hydraulic ram pumps start at \$ 700, and generally are

sales volumes, and lower production costs of solar cells. Local manufacture or assembly may also reduce costs in some countries. From the limited data on field performance, it is difficult to estimate recurrent costs of solar pumps, for the guard or attendant, for minor routine maintenance, for occasional visits of a mobile maintenance team for servicing, and for major repairs. The World Bank/ UNDP project on solar-powered pumps estimates these costs to be \$ 50/year for maintenance of the array system, and \$ 12 per 1000 hours operation for the motor-pump set.

Table 3.4: Indication of capital cost for solar photovoltaic pumps

	Size of pumping system, array rating (Wp)	Cost range (\$ per Wp)
Small	less than 500	20 – 25
Medium	500 – 3000	15 – 20
Large	more than 3000	10 – 15

Biomass energy

Fuel produced by biomass conversion can be used to replace 60-70% of the diesel fuel requirement of engine-driven pumping systems. The capital cost of digesters for biogas production ranges from \$ 30-45 per m³ digester volume for commercial plant, to \$ 15-30 per m³ for locally constructed digesters, but may vary according to local costs and conditions. Additional equipment for gas cleaning and storage, piping and appurtenances, may add 10-15% to the digester costs. Recurrent costs are site-specific, and mainly consist of costs for labour and biomass resources. Annual costs for repair and maintenance may be estimated at 5-10% of capital costs.

A number of other factors complicate the cost analysis for pumping systems using biomass energy. Considerable community involvement in terms of time and effort is required, the cost of which is difficult to estimate. Benefits, such as prevention of parasitic and microbial diseases, production of fertilizer for crop production, and the productive use of local labour are also not easily reflected in the cost analysis.

The capital cost dominates the economics of using gasifiers for fuel production. Where gasifiers can be supplied at less than \$ 200 per kW rated power, as is now the case in Brazil and in the Philippines, they are competitive with conventional diesel engines. Gasifiers costing more than \$ 400 per kW rated power, as is the case with systems imported from Europe or North

America, are rarely economical. Other factors affecting the cost analysis are the cost of the diesel fuel being replaced, the operating load, the lifetime of the equipment, and the costs of acquiring suitable dry biomass. Costs of operation and maintenance are relatively high, but cannot be specified because of lack of data.

It is generally accepted that at present, ethanol production is not a cost-effective substitute for diesel fuel. The unit cost of ethanol is often substantially higher than that of diesel, depending on local costs, such as crop yield per hectare, and process conditions in the distillery. The costs of establishing distilleries are far beyond the capacity of rural communities and require financing at the national level. Cost calculations for distilleries in Brazil show that the cost of both cassava and sugar-cane alcohol is in the range of \$ 0.35 to \$ 0.45 per litre, which is higher than the current price of diesel fuel in that country. When subsidized in national programmes, alcohol production may become marginally cheaper.

3.7 STORAGE TANKS

Because of the daily and seasonal variation in availability of renewable energy sources, provision for water storage is necessary in order to ensure a continuous and reliable water supply by pumping systems using these energy sources. Storage of pumped water is almost always cheaper than storage of the equivalent amount of electric energy in batteries. An indication of the storage capacity required for various types of pumping systems is given in Table 3.5, and costs for types of tanks are given in Table 3.6.

Table 3.5: Indication of water storage requirements for various types of pumping systems

Type of pumping system	Storage (days)
Hydropowered pumps	1-2
Wind pumps	5-7
Solar photovoltaic pumps	2-4
Biomass-fueled pumps	1-2
Diesel pumps	1-2
Electrical pumps	1-2
Hand pumps	0

Table 3.6: Cost indication of various types of water storage tanks

Type of storage tank	Cost per m ³ capacity (US \$)
Lined earth bound	5 – 10
Compacted soil with cement lining	8 – 20
Brickwork with cement lining	12 – 25
Ferrocement	15 – 30
Concrete	20 – 30
Steel	60 – 80

3.8 COST COMPARISON

Calculation of cost ranges

On the basis of the cost data presented, cost ranges have been calculated for various types of pumping systems, for the following output capacities and pumping heads:

- 10 m³/day at a pumping head of 15 m
- 50 m³/day at a pumping head of 15 m
- 10 m³/day at a pumping head of 50 m
- 50 m³/day at a pumping head of 50 m

The general results of these cost calculations have been presented in Chapter 2. Details of the calculations are given in Appendix B.

Example of cost comparison

A cost comparison is made for a wind pump, a solar pump, and a diesel pump, at a specific location for which the basic environmental data and other conditions have been assumed as in Table 3.7. The renewable energy pumping systems are compared with a diesel pump because much of the current interest in renewable energy systems stems from the high cost and logistic problems of diesel fuel. It must be stressed that results are greatly affected by the values assumed for the key parameters.

Table 3.7: Cost comparison of wind pump, solar pump and diesel pump for a particular location

Location data:	
Water requirement	27 m ³ /d
Pumping head	30 m
Annual average wind speed	4 m/s
Critical length of calm periods	5 days
Monthly average irradiation (in critical month)	14 MJ/m ² /d (4 kWh/m ² /d)
Critical length of cloudy periods	3 days
Smallest size of diesel engine available	3 kW rated power
Cost of 3kW rated diesel pump	\$ 4500
Price of diesel fuel	\$ 0.50/litre
Cost of wind pump	\$ 350/m ² of swept rotor area
Cost of solar photovoltaic pumping system	\$ 22/Wp installed
Unit cost of water storage tank	\$ 30/m ³
Discount rate	8%
Cost calculation: diesel pump	
Hydraulic energy output requirement	2.25 kWh/d
Size of diesel engine	(smallest available engine) 3 kW rated power
Capital cost of diesel pump (3 kW rated power)	\$ 4500
Nominal power output	2 kW
Efficiency of pump	40%
Hydraulic power output of engine	0.8 kW
Water output	4.1 l/s
Hours of operation required per day	1.83 hours
Efficiency of engine	15%
Fuel consumption per hour operation	1.34 litres of diesel/hour
Fuel consumption per year	895 litres of diesel/year
Capacity of storage tank	1 day's supply = 27 m ³
Capital cost of tank	\$ 810
Lifetime of tank	20 years
Lifetime of engine	5 years
Lifetime of pump	10 years
Capital cost on annual basis:	
engine and pump	\$ 960
tank	\$ 95
Annual fuel costs 895 litres at \$ 0.50/litre	\$ 450
Annual costs of operation and maintenance:	
engine and pump (5% of capital cost)	\$ 225
tank (2% of capital cost)	\$ 15
Annual cost of operator	<u>\$ 500</u>
Total annual costs	\$ 2240
Water output per year	9850 m ³
Unit cost per m ³	\$ 0.23/m ³

 Cost calculation: wind pump

Hydraulic energy output requirement	2.25 kWh/d = 821 kWh/year
Swept rotor area	$821 : 0.9 V^3$
E hydr : $0.9 V^3$	= 14.25 m ²
Capital cost of wind pump	14.25 x 350 = \$ 5,000
Lifetime of wind pump	15 years
Capacity of tank required	5+1 = 6 days supply = 160 m ³
Capital cost of tank	\$ 4800
Lifetime of tank	20 years
Capital cost on an annual basis:	
wind pump	\$ 650
tank	\$ 560
Annual costs of operation and maintenance:	
wind pump (5% of capital cost)	\$ 250
tank and piping (2% of capital cost)	<u>\$ 100</u>
Total annual costs	\$ 1560
Useful water output per year	9850 m ³
Unit cost per m ³ pumped	\$ 0.16/m ³

 Cost calculation: photovoltaic pump

Hydraulic energy output requirement	2.25 kWh/d
Efficiency of motor and pump	40%
Electrical energy output requirement	5.63 kWh/d
Peak watt rating of system	1700 Wp
Installed cost of solar pumping system	1700 x \$ 22/Wp = \$ 15,400
Lifetime of solar pump	15 years
Capacity of storage tank required	3+1 = 4 days supply = 110 m ³
Capital cost of tank	\$ 3300
Lifetime of tank	20 years
Capital cost on annual basis:	
solar pump	\$ 2010
tank	\$ 390
Annual costs of operation and maintenance:	
solar pump (2% of capital cost)	\$ 310
tank and piping (2% of capital cost)	<u>\$ 65</u>
Total annual costs	\$ 2775
Water output per year	9850 m ³
Unit cost per m ³ pumped	\$ 0.28/m ³

3.9 EFFECT OF ASSUMPTIONS MADE ON COST CALCULATION RESULTS

When making a comparative cost analysis, the assumptions made affect the results considerably. Examples of assumptions which need to be checked before use in comparative cost analysis are, the price of diesel fuel, the price of solar pumping equipment, the average annual wind speed, and transport costs.

If values are difficult to obtain, or a particular value is not certain, then cost analyses are often made using different values to show how sensitive the calculated unit output costs are to changes in the assumptions. This is called sensitivity analysis. To illustrate this, the assumptions for the cost of diesel fuel and the average annual wind speed in the example presented in Table 3.7 have been varied. If the diesel fuel price is increased from \$ 0.50/litre to \$ 0.85/litre, the unit output cost per m^3 of water for a diesel pump is increased slightly from \$ 0.23 to \$ 0.27. A considerable change in the diesel fuel price thus has a relatively minor effect on the unit output cost in the example. However, if the annual wind speed is not 4 m/s but 3 m/s, a much larger wind rotor would be required, and thus the capital cost of the wind pump would be increased considerably. The rotor-swept area required would be about $34 m^2$ greater and capital costs about \$ 12 000 more. The equivalent annual costs would rise by \$ 1420, and operation and maintenance costs by \$ 590. The unit costs per m^3 of water pumped would increase from \$ 0.16/ m^3 to \$ 0.27/ m^3 .

These sensitivity analyses are complicated, in particular when many variables are involved, and computerized data processing may be required. It is recommended that a specialist be consulted, should a complete sensitivity analysis be required.

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4. *Basics of water pumping and pump selection*

The most commonly used pumps in rural water supply systems are positive-displacement pumps such as plunger pumps, and rotodynamic pumps such as centrifugal pumps. The type of pump needs to be selected carefully to match the energy device. Therefore, selection should be based on consideration of:

- pumping duty required;
- characteristics of the water source;
- power requirement and pumping efficiency;
- maintenance and repair requirements.

4.1 SPECIFICATION OF PUMPING DUTY

The first step in selection of the type of pump is to specify the pumping duty required in terms of the output capacity and pumping head.

Output capacity

In this book, pumping systems of output capacities of up to 250 m³/d are considered. The required output of the pump, in m³/h, is calculated on the basis of the maximum daily water requirement and the number of hours daily operation.

The maximum daily water requirement is not the same as the water demand of the community. For example, for a wind-powered pumping system at a location where periods of insufficient wind for three subsequent days occur, a storage reservoir of at least three times the daily water demand is required. To refill this reservoir after a windless period, more water than the daily water demand will have to be pumped. This is the maximum daily requirement, and the pump should be of sufficient capacity to supply water at that rate.

Some types of pumping systems are designed to operate continuously, other types can provide the required amounts of water in a few hours daily. Factors which determine the number of hours of daily operation include the type of energy supply, the maintenance requirements, and the minimum size available for the selected type of pumping system. For example, the output capacity of even the smallest diesel pump is so great that it can supply the daily water

requirement of most rural communities in a few hours of operation. For electrical pumps, the required output capacity will depend on the number of hours per day during which electricity is available, which in many countries is limited, sometimes to a few hours in the evening. Hydropowered pumps can operate continuously, and the required hourly output capacity can be calculated by dividing the maximum daily requirement by 24. However, it is wise to select a slightly larger pump, as the actual number of hours of daily operation may be less because of operational limitations. In principle, wind pumps can also operate continuously, but because of the variation in wind speed from day-to-day, the output capacity should be sufficient to pump enough water on windy days to provide for periods of insufficient wind. Solar pumps can operate during most daylight hours, so the output capacity should be sufficient to supply the maximum daily water requirement in six to eight hours.

Example:

The daily water demand of a rural community is estimated to be $48 \text{ m}^3/\text{d}$, and the maximum daily water requirement of this community $60 \text{ m}^3/\text{d}$. Thus, a solar pumping system designed for six hours operation per day, would have to have an output capacity of $10 \text{ m}^3/\text{h}$. For a hydropowered pump designed for 20 hours operation per day, the average output capacity required would be $3 \text{ m}^3/\text{h}$.

Pumping head

The total pumping head for which the pumping system has to be designed comprises the following components (Figure 4.1):

- static lift, that is, the vertical distance between the static water level of the source (for example, a well) and the level at which the water is delivered in free discharge (for example, in an elevated tank);
- friction head, that is, the head losses caused by friction and turbulence of the water flowing through pipes, valves and fittings;
- drawdown, that is, the lowering of the water level in the source resulting from the withdrawal of water;
- additional head allowance, to allow for possible increase of friction head over the years, or a decline of the groundwater level.

Most types of pumps are designed for lift operation and must be in the well or borehole so that they operate submerged in the water, even when the level of the water in the source is at its lowest. Suction pumps are to be used only when they can be set within 6 m of the lowest possible water level in the source, because they cannot work reliably at a greater suction head. Most suction pumps need to

be primed, that is, the pump body has to be filled with water before the pump can be operated.

The total pumping head under operating conditions is often called the dynamic head. When water is pumped at a very low rate, the total pumping head may be assumed to be the same as the static lift. At higher output rates, the head

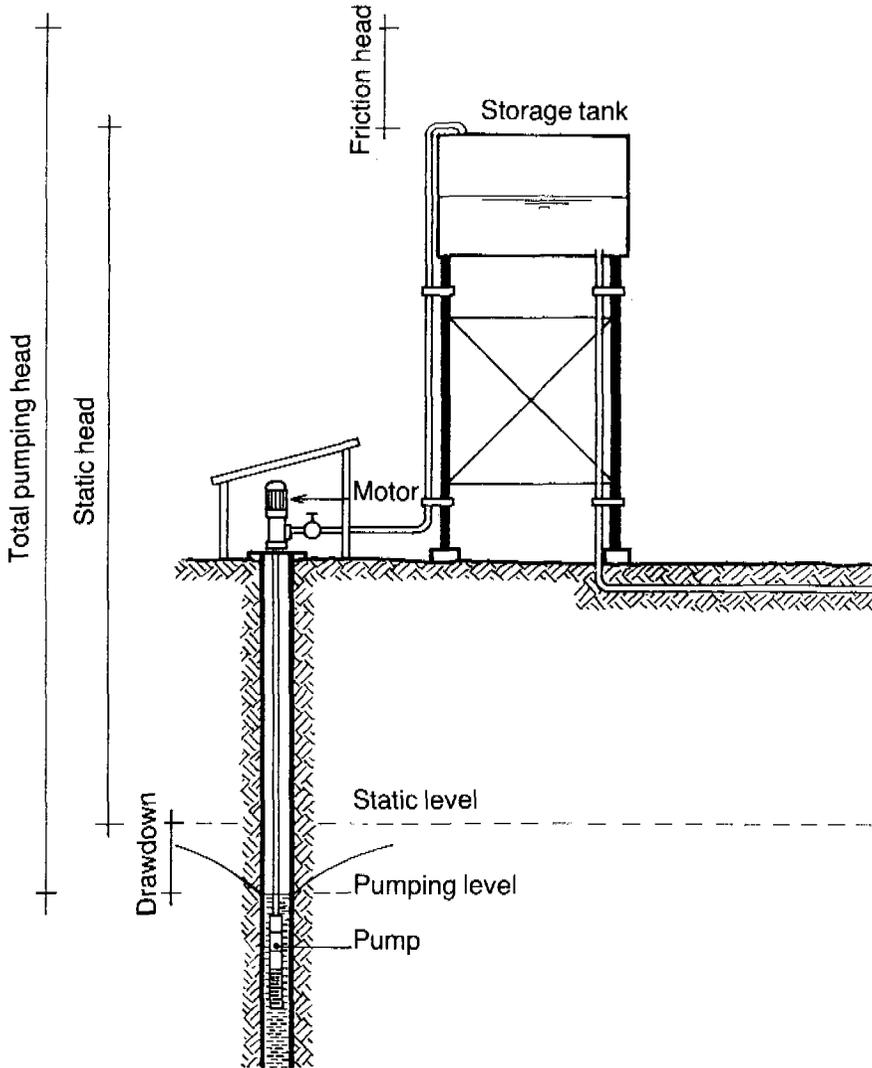


Figure 4.1: Components of total pumping head

losses caused by friction and turbulence of flow will increase and add to the pumping head. As stated above, it is prudent for design purposes to include in the total pumping head an allowance for greater friction head and decline of the groundwater table.

4.2 CHARACTERISTICS OF WATER SOURCE

Sustainable yield and drawdown

The sustainable yield of the water source is an essential factor in pump selection, because it is closely related to the drawdown during pumping (see Figure 4.2). If the yield of the water-bearing formation is small, a pump of high output capacity can cause excessive drawdown, or may even pump the borehole dry. Pumping tests should be carried out to determine the sustainable yield of the aquifer. If the yield appears to be small, a pump of limited output capacity will have to be selected.

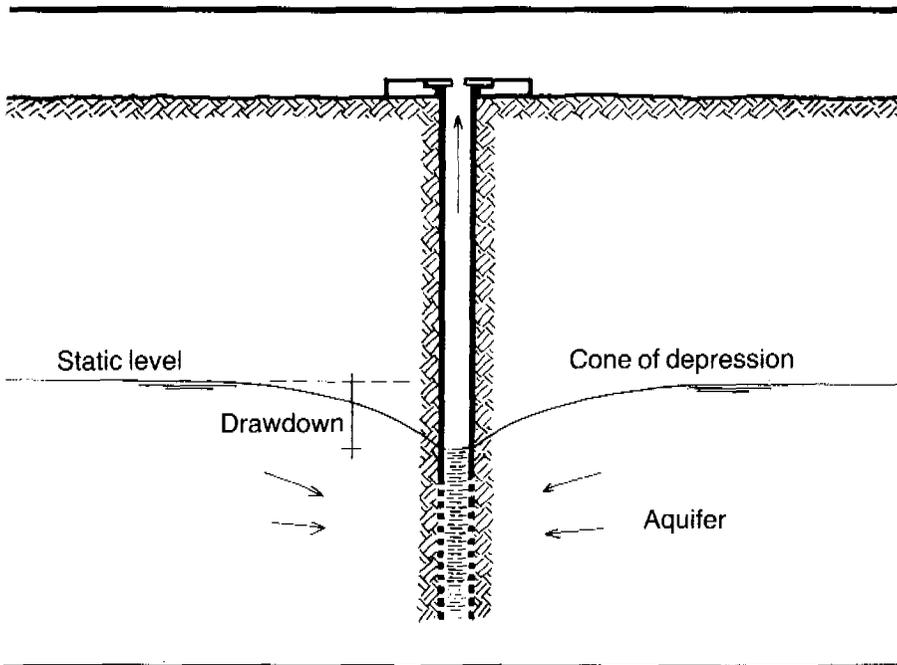


Figure 4.2: Drawdown effect caused by abstraction of water from borehole (AWWA, 1984)

Water quality

The water quality should also be considered in pump selection. If the groundwater is corrosive, then pumps constructed of corrosion-resistant materials must be selected. If the water pumped has a high content of iron and manganese, precipitates may be deposited in the inlet openings and also on the internal parts of the pump, and pumps that are little affected by these deposits should be chosen. Calcium and magnesium carbonates can precipitate out of the water, and cause clogging of the pump inlet openings and interior. Regular inspection and cleaning of a pump's internal parts, therefore, are required in conditions where these precipitates and thus clogging of the pump, are likely to occur.

4.3 POWER REQUIREMENT AND PUMPING EFFICIENCY

The effective power output or hydraulic power output for water pumping at a given rate (Q) and pumping head (H) equals $Q_w \cdot g \cdot Q \cdot H$. The effective power output of a water pumping system will be less than the power input because of power losses occurring in power conversion in the prime mover, in power transmission, and in the pump itself. The ratio between power output and power input is called the efficiency (η) of the pumping system. Thus, the power requirement (P) for water pumping can be calculated:

$$P = \frac{Q_w \cdot g \cdot Q \cdot H}{\eta}$$

For a specific weight of water (Q_w) of 1 kg/l and a gravitational constant (g) of 9.8 m/s², this can be simplified to:

$$P = \frac{9.8 \cdot Q \cdot H}{\eta}$$

where:

P = power requirement (W)

Q = output rate (l/s)

H = total pumping head (m)

η = overall efficiency (%)

Example:

A pumping system is designed for a water output capacity of $60 \text{ m}^3/\text{d}$ at a total pumping head of 10 m , and for six hours operation per day. The hourly output capacity required is $10 \text{ m}^3/\text{h}$, or 2.78 l/s . The hydraulic power requirement for this pumping duty is calculated to be $9.81 \times 2.78 \times 10 = 272 \text{ W}$. If the efficiency of the pump is 60% , then the input power requirement for the pump is $272 : 0.6 = 453 \text{ W}$. If the pump is driven by a motor of an average efficiency of 70% in the operating range, then the input power to be supplied to the motor should be $453 : 0.7 = 647 \text{ W}$. The overall efficiency of this system is $272/647 = 42\%$.

The efficiency with which a pump converts the transmitted mechanical power into hydraulic output depends on its design and configuration, and the conditions under which it operates. For reciprocating pumps, the efficiency of operation is little affected by output rate and pumping head, and is usually in the range of 60 to 75% . With centrifugal pumps, efficiency depends heavily on the combination of output rate and pumping head under which it operates, and may vary widely, from 25 - 85% . The operating efficiency of centrifugal pumps for each combination of output and head can be measured and plotted on a pump performance curve. Such graphs are provided by most manufacturers, as for example that presented in Figure 4.3.

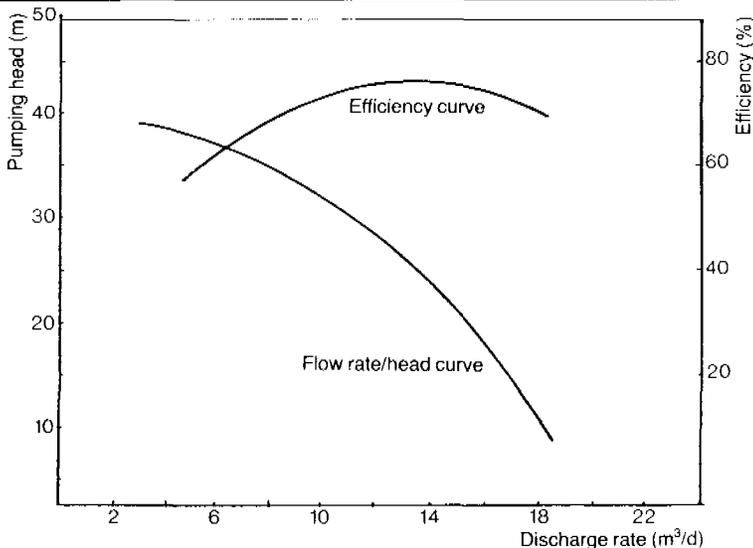


Figure 4.3: Pump performance curves for centrifugal pump

The downward slope of the output rate/head curve from left to right, indicates that the output is greater for lower pumping heads. As shown, pumping efficiency varies considerably at different water output rates. A high efficiency is achieved only in the relatively narrow range of 12 to 16 m³/h output. At output rates of less than 12 m³/h, or higher than 16 m³/h, efficiency is considerably less. For reasonable efficiency, it is necessary to select a centrifugal pump specifically for the pumping head and output rate under which it will operate.

4.4 MAINTENANCE AND REPAIR REQUIREMENTS

Maintenance and repair requirements are important considerations in pump selection. Factors to consider include the frequency of servicing, and the skills, tools and spare parts required. Experience shows that water pumping systems often fail because of inadequate maintenance and lack of spare parts. Often, it takes a long time before repairs are done, and as a result, pumping systems may be completely abandoned by the user community. Back-up service is always needed and includes spare part supply, training of pump attendants, and technical support.

All pumps wear with time, but if silt or sand is present in the water pumped, the durability and useful life of most pumps is shortened considerably. Excessive wear of pumps is often more an indication of inappropriate design of the well or borehole than of faulty construction of the pump.

4.5 TYPES OF PUMPS

The main types of pumps used in small-scale pumping systems fall roughly into two main categories: positive-displacement pumps, and rotodynamic (impeller) pumps.

Positive-displacement pumps

Reciprocating-plunger pumps. These pumps have a plunger (piston) which moves back and forth within a closed cylinder. When the plunger moves upwards, it lifts water, and at the same time, due to pressure reduction below the plunger, water is drawn in through the inlet valve. When the plunger moves downwards, the inlet valve closes and water is forced out through the outlet valve (Figure 4.4).

Plunger pumps are self-priming when the cylinder is located near or below the water level in the source. The same amount of water is displaced with each stroke. Thus, the water output rate is largely governed by the running speed, that is, the number of strokes per minute at which the pump operates. The pumping head has little effect on the output rate of these pumps. Single-acting plunger pumps produce output only during the up-stroke, and double-acting plunger pumps during both the up-stroke and the down-stroke.

Reciprocating-plunger pumps should be especially considered for pumping water from medium-depth and deep boreholes with the dynamic water level at a depth of 30-40 m, or if necessary, up to 60 m. They can give reliable performance at efficiencies of 60-75%, which is little affected by variations in the pumping head. The use of these pumps is limited to 60 m, because pump rods of greater length are susceptible to flexing and breakage.

Plunger pumps require a relatively high force to start. To overcome this problem, a clutch mechanism may be incorporated which allows the motor to gain speed and power while free-running until it has developed the required starting force for the pump. This reduces the starting torque to be provided by the prime mover, and thus has design implications. For example, equipped with a clutch, a rotor with six blades may be adequate for a wind pump, which without a clutch would probably need a 16 or 24-bladed rotor. An alternative method to

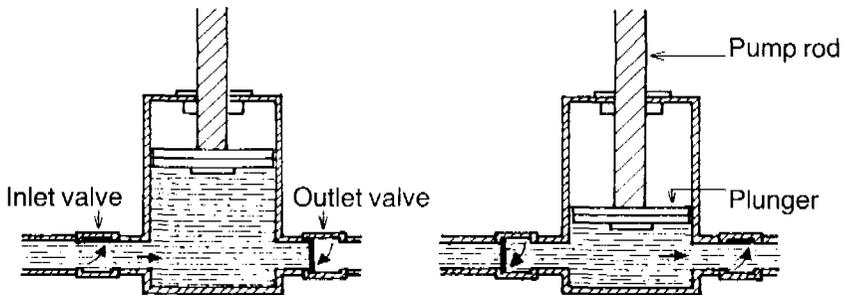


Figure 4.4: Principle of operation of reciprocating-plunger pump

reduce the starting force of plunger pumps, is to make a small hole in the plunger. The variable loading which the reciprocating-plunger exerts on the drive mechanism and prime mover, is another problem. The speed of operation of these pumps must be kept low, rarely more than 50 strokes per minute, to limit the frequency and effect of load reversals in the pumping system.

Diaphragm pumps. The essential part of this type of pump is the diaphragm, made of strong rubber, metal sheet, or a similar flexible material. The diaphragm is fixed to the edges of the pump chamber (Figure 4.5). Non-return valves are fitted at the inlet and outlet of the pump chamber. As the diaphragm is lifted, water is drawn in, and when the diaphragm is pushed down, water is forced out of the pump chamber.

Diaphragm pumps are self-priming if located near or below the water level in the source. They have the advantage that internal friction is low because there is no sliding plunger seal rubbing against the pump chamber wall, as in the cylinder of a reciprocating-plunger pump. Sand particles can pass through the pump in the water pumped without causing damage.

Because of their simple design, diaphragm pumps were expected to gain popularity in small-scale pumping systems, but to date, have had only limited use.

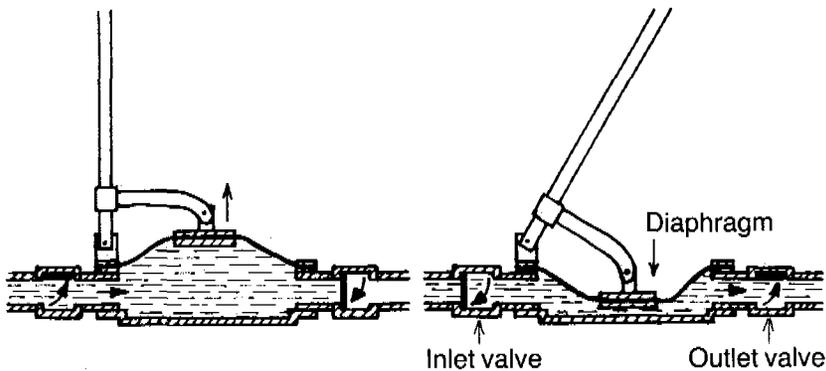


Figure 4.5: Principle of operation of diaphragm pump

Helical-rotary pumps. These pumps have a helical (spiral) rotor, generally made of stainless steel, which rotates inside a helical stator made of wear-resistant rubber. As the rotor is rotated, the meshing helical surfaces force the water up by positive displacement in a steady flow. The water output rate is proportional to the speed of rotation, and thus can be easily varied. No valves are required in this type of pump, because the rotor and stator provide a continuous seal against backflow (Figure 4.6).

Helical-rotary pumps are self-priming when operating under water. They can work against a wide range of pumping heads, but their efficiency is limited at greater heads. These pumps can tolerate small amounts of silt or fine sand in the water pumped without appreciable wear or damage.

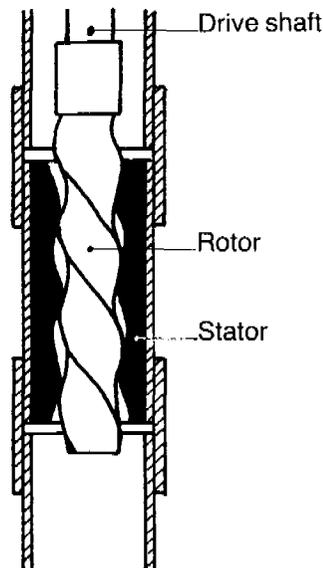


Figure 4.6: Main features of helical-rotary pump

Rotodynamic (impeller) pumps

Centrifugal pumps. These pumps operate on the principle of imparting kinetic energy to the water, and thus do not work by positive displacement of the water. They have one or more impellers, which rotate within a casing of a special shape. Each impeller and its matching casing is called a stage (Figure 4.7). The impeller has a number of vanes radiating from the centre to the periphery, which at high-speed rotation throw the water radially out by centrifugal force, thus imparting kinetic energy to it. The casing is so shaped that most of the kinetic energy is converted into useful pressure, which then lifts the water against head. The pumped water is replaced by water which is drawn in at the centre (eye) of the impeller.

If more pressure is required than a single stage can produce, additional stages can be placed in series to form a multi-stage pump. All impellers are mounted on a common shaft and thus rotate at the same speed. As the water passes through successive stages, pressure is built up to give the required pumping head.

Submersible pumps. These pumps are multi-stage centrifugal pumps which are built together with a close-coupled electric motor as one unit. The motor-and-pump unit is of slim construction so that it can be lowered in a borehole for submerged operation (Figure 4.8). These pumps are often a "tight fit" in the

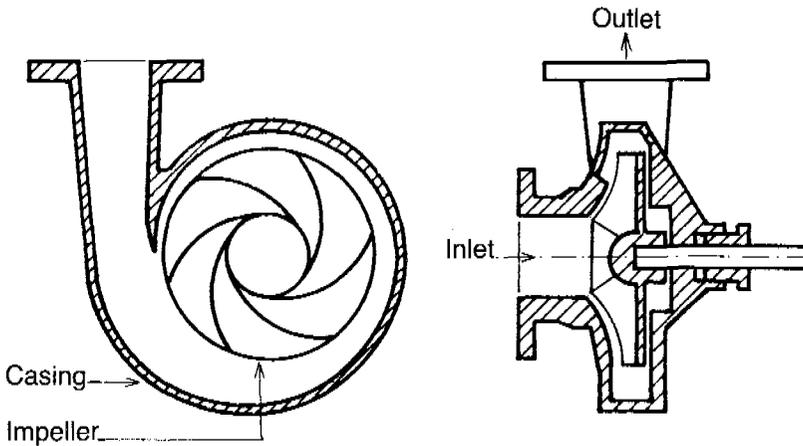


Figure 4.7: Stage of centrifugal pump

borehole, their diameter being only 1-2 cm less than the internal bore of the well casing. Thus, considerable care is needed when installing or removing this type of pump.

With submersible pumps, the motor receives electric power through a power cable from the power source. Because they have to be slim, these motor-pump sets are generally less efficient than surface-mounted motors. However, their overall power efficiency is often higher than that of pumps driven by a surface-mounted engine because there are not the considerable power losses of the drive shaft. Maintenance and repair is costly, especially in deep boreholes, because the entire length of riser pipe has to be dismantled to haul the motor-and-pump unit to the surface.

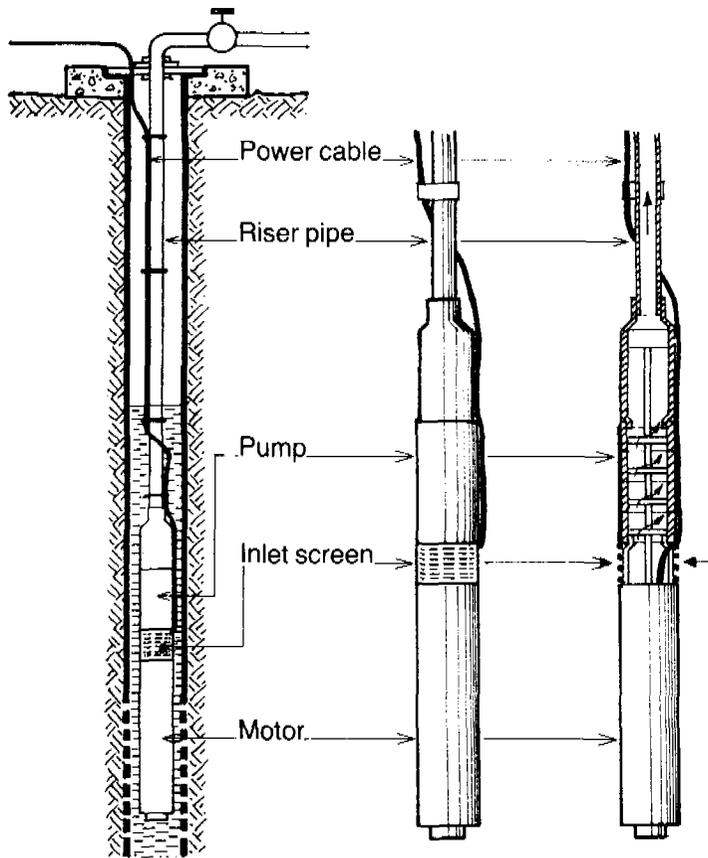


Figure 4.8: Submersible pump

Deep well turbine pumps. Although usually considered to be a type of centrifugal pump, their mode of operation is slightly different, the water being lifted by a combination of positive displacement and centrifugal action. These pumps can easily be recognized by their distinctive bowl units with long tapered passages (see Figure 4.9).

Deep well turbine pumps are self-priming, and usually driven by a surface-mounted electric motor or diesel engine using a long drive shaft. The shaft may need supporting by special stabilizers or spacers set at regular intervals. Correct

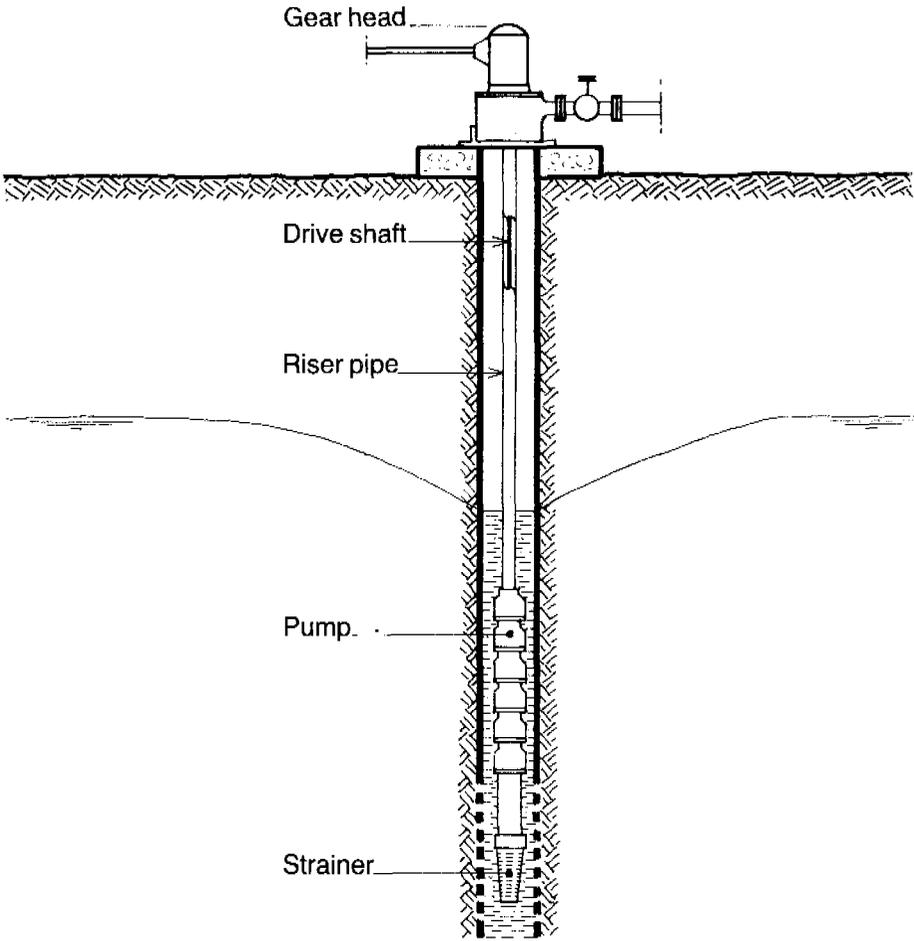


Figure 4.9: Deep well turbine pump

alignment of motor, shaft, and pump is essential for reliable performance and long useful life. The water output can be varied by adjusting the rotational speed. Most of these pumps are designed for high output capacities and generally, are more suitable for pumping large quantities of water for irrigation than the relatively small amounts required for domestic water supply.

Axial-flow (or propeller) pumps

Axial-flow pumps have a propeller with radial fins or blades which rotate inside a straight turbine casing. The propeller produces axial water flow. Fixed guide blades are mounted inside the turbine casing to prevent the water developing "whirl" flow when pumped (Figure 4.10). As these pumps are best suited to lifting water at high output rates against low pumping heads, they are mostly used for irrigation.

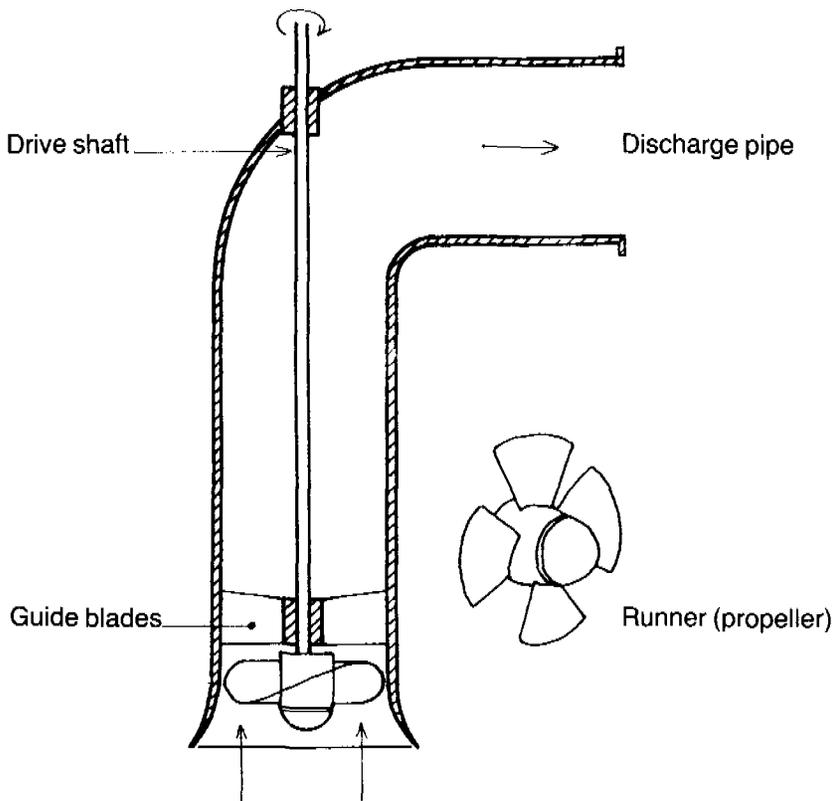


Figure 4.10: Main features of axial-flow pump

4.6 MAIN CHARACTERISTICS OF VARIOUS TYPES OF PUMPS

A general indication of the most suitable application for various types of pumps is given in Figure 4.11. Reciprocating-plunger pumps are to be considered particularly for applications where the pumping head is high and the required flow rate relatively small. Helical-rotary pumps are mainly suitable for low to medium pumping heads and limited flow rates. Centrifugal pumps can be used, depending on their design, for medium to high pumping lifts and a wide range of flow rates. The use of shaft-driven centrifugal pumps is subject to depth restriction, because of the need to ensure proper alignment and support of the drive shaft. Submersible pumps are, in general, applied for medium to large pumping lifts with flow rates ranging from small to medium. Deepwell turbine pumps, because of their large output capacity, are generally restricted to those few applications in rural water supply where the required flow rate is large enough to justify this type of pump. In Tables 4.1 and 4.2, the main characteristics, and the advantages and disadvantages, of different types of pumps are set out.

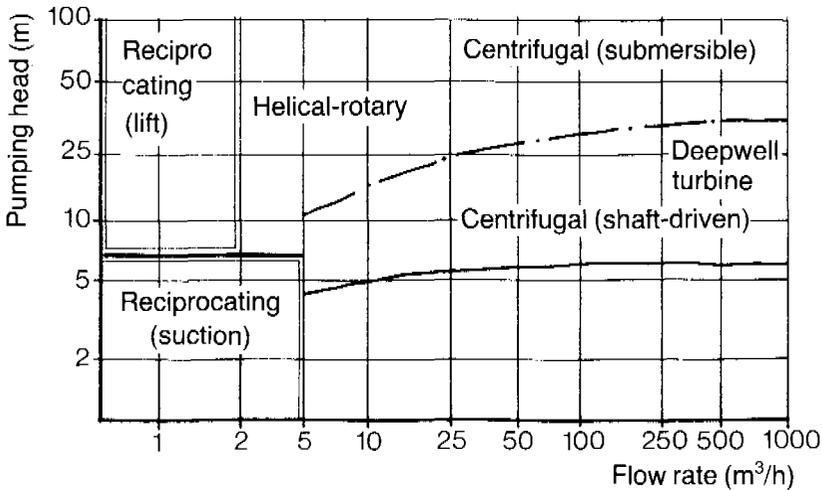


Figure 4.11: General indication of application for various types of pumps

Table 4.1: Characteristics of various types of pumps

Type of pump	Practical depth range (m)	Capacity range (l/min)	Power source
Reciprocating-plunger pumps			
shallow well	5- 15	30- 50	human wind
deep well	15- 18	40-100	human motor wind
Chain pumps	2- 12	5- 30	human wind
Bucket pumps	5- 40	10-100	human animal wind
Diaphragm pumps	5- 30	20- 50	human motor wind
Axial-flow (propeller) pumps	5- 30	large	motor
Centrifugal pumps			
single stage	15- 50	variable	motor solar
multi-stage shaft-driven	20- 40	variable	motor wind
multi-stage submersible	50-500	variable	electro-generator solar
Deep well turbine pumps	15- 50	variable (100-20 000)	motor

Table 4.2: Advantages and disadvantages of various types of pumps

Type of pump	Advantages	Disadvantages
Reciprocating plunger pumps	<ul style="list-style-type: none"> - Low speed of operation - Simple design and construction - Efficiency little affected by variation in pumping head - Suitable for relatively high pumping heads 	<ul style="list-style-type: none"> - Below-ground components (e.g. cup seals, valves) subject to sliding friction - Regular maintenance and replacements required - Discharge pulsates, subject to vibration
Chain pumps	<ul style="list-style-type: none"> - Simple design and construction 	<ul style="list-style-type: none"> - Low efficiency - Suitable for low pumping heads only
Bucket pumps	<ul style="list-style-type: none"> - Simple design and construction 	<ul style="list-style-type: none"> - Low efficiency - Suitable for low pumping heads only
Helical-rotary pumps	<ul style="list-style-type: none"> - Speed of operation can be varied over wide range, and adjusted to output requirement - Only one moving part in well - Steady discharge 	<ul style="list-style-type: none"> - Suitable for small output capacities only - Gearing required - Subject to abrasion when sand or silt present in the water pumped - Not satisfactory in deep wells
Diaphragm pumps	<ul style="list-style-type: none"> - Little internal friction - Few moving parts - Water containing particles smaller than the valve openings, may be pumped without causing wear or damage to the pump 	<ul style="list-style-type: none"> - Relatively low capacity - Not satisfactory in deep wells - Diaphragm subject to wear because of continuous flexing
Deep well turbine pumps	<ul style="list-style-type: none"> - Wide range of capacities and heads - Steady discharge can tolerate small amounts of sand or silt in the water pumped 	<ul style="list-style-type: none"> - Speed of operation must be relatively constant for satisfactory efficiency - Expensive maintenance and repair require skilled technicians and pump must be removed from the well

Table 4.2: Advantages and disadvantages of various types of pumps
(cont'd)

Type of pump	Advantages	Disadvantages
Centrifugal pumps	<ul style="list-style-type: none"> - Quiet operation - Wide range of capacities - Steady discharge - Satisfactory only when working at, or near, design output rate and head 	<ul style="list-style-type: none"> - High speed of operation - Maintenance and repair require extensive skills - Output and efficiency are greatly affected by variations in pumping head
shaft driven	<ul style="list-style-type: none"> - Motor accessible above ground 	<ul style="list-style-type: none"> - Alignment of shaft critical for reliable and efficient operation
submersible	<ul style="list-style-type: none"> - Straightness of well not critical 	<ul style="list-style-type: none"> - Maintenance and repair require that motor and pump unit be removed from well
Axial-flow pumps	<ul style="list-style-type: none"> - Suitable for large- capacity pumping through limited heads 	<ul style="list-style-type: none"> - Expensive - Not suitable for hand operation or coupling to wind rotor

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5. Solar energy

The sun emits radiant energy at a rate of 3.8×10^{20} MW, of which a very small proportion is intercepted by the earth. Yet, a vast amount of solar radiation reaches the earth, equivalent to 1.2×10^{11} MW (WMO, 1981). This is the capacity of over one hundred million large power stations, each of 1000 MW. The amount of solar radiation at the outer limit of the earth's atmosphere is equivalent to 1353 W/m^2 and is known as the extraterrestrial solar constant. Some solar radiation is absorbed by the atmosphere, and some is reflected back into space. The remainder is transmitted to the earth's surface as either direct or diffuse radiation (see Figure 5.1).

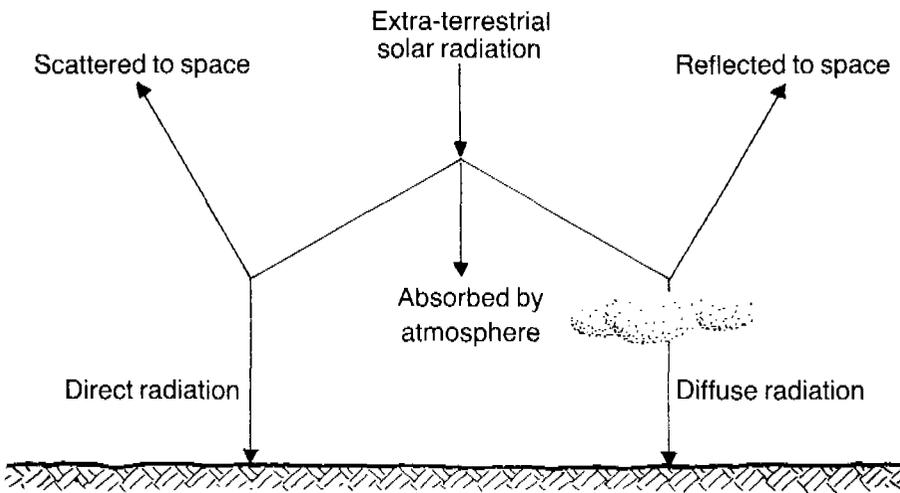


Figure 5.1: The paths of solar radiation

The total daily amount of solar irradiation, direct and diffuse, at ground level is called the daily global irradiation (or insolation) of the location concerned, and is measured as energy ($\text{MJ/m}^2/\text{d}$, or $\text{kWh/m}^2/\text{d}$). The rate at which solar irradiation reaches the ground is called the global irradiance, and is measured as power (W/m^2). Global irradiance varies, depending on the hour of the day, the

season, location (latitude), and cloudiness. In tropical zones, it can reach a maximum of about 1000 W/m^2 at noon on a clear day, but when heavily overcast may be as low as 100 W/m^2 . The average daily global irradiation on a horizontal plane varies from $7 \text{ MJ/m}^2/\text{d}$ ($2 \text{ kWh/m}^2/\text{d}$) in most parts of northern Europe, to $22 \text{ MJ/m}^2/\text{d}$ ($6 \text{ kWh/m}^2/\text{d}$) in some arid tropical regions (see Figure 5.2).

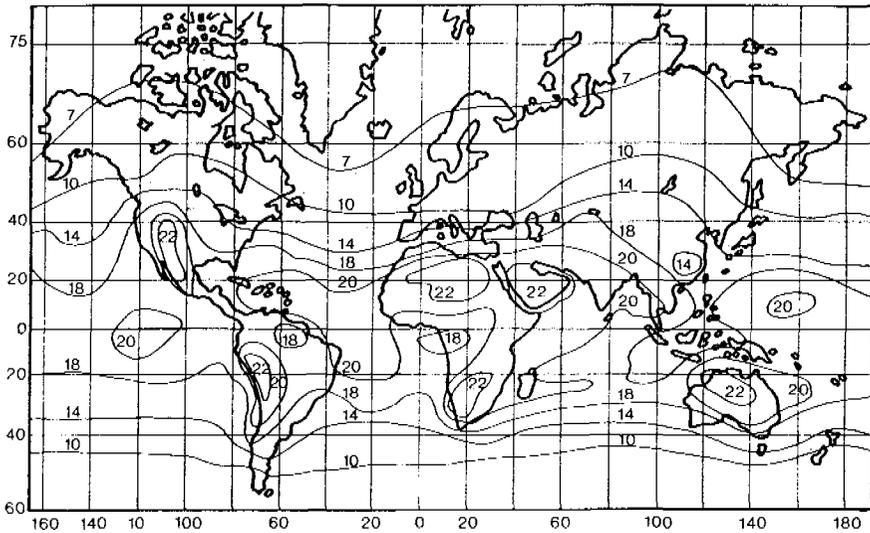


Figure 5.2: Average daily global irradiation ($\text{MJ/m}^2/\text{d}$) on the horizontal plane (WMO, 1981)

To assess whether a location is suitable for solar pumps, a record of daily irradiation over at least one, and preferably two years, is required. The design of a solar pump system cannot be based on average daily irradiation, because insufficient water would then be pumped in months of below-average solar irradiation. Therefore, the month of the lowest irradiation is usually selected as the basis for sizing solar pump installations, and allowance must be made for cloudy periods in which irradiation may be much lower than the average. Local variations for an arid and humid tropical location are shown in Figure 5.3.

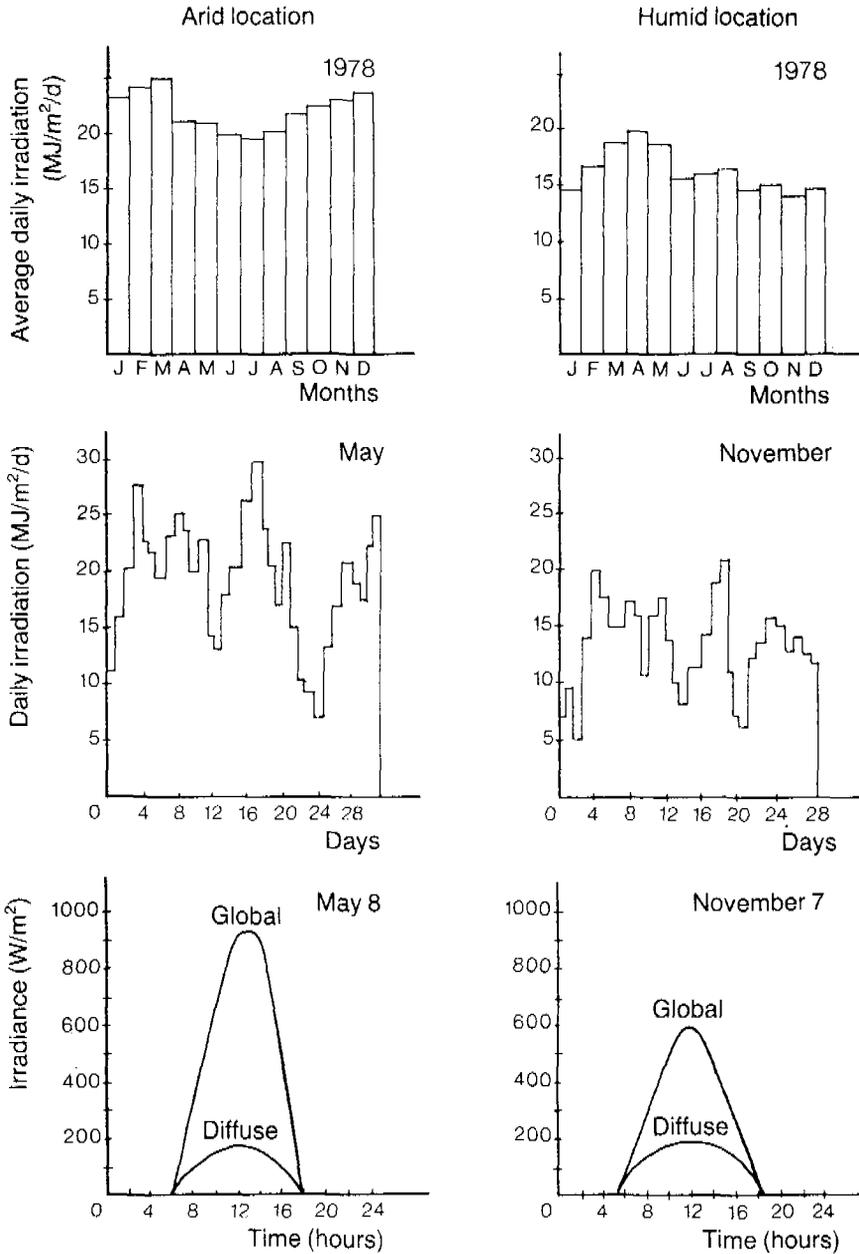


Figure 5.3: Annual, monthly, and daily variation in solar irradiation at an arid and a humid tropical location (Halcrow & Partners and IT Power, 1982)

Global irradiation on a solar array or heat collector tilted towards the equator is higher than that on the horizontal plane. It is the irradiation on a tilted surface which should be the basis for the design of a solar pumping system. This can be calculated using conversion tables for irradiation data on the horizontal plane. The optimal tilt of an array or heat collector is about the degree of latitude of the location; for example, an angle of 25° may be used for a place at latitude 25° . Theoretically, this would enable the maximum amount of global irradiation to fall on the array or collector. In practice, the selected angle is often somewhat greater ($5-15^\circ$) in order to collect as much as possible of the lower irradiation in the cooler season.

5.1 SOLAR-POWERED WATER PUMPING SYSTEMS

In solar pumping systems, solar irradiation is converted to useful mechanical power for pumping water. This can be done in two ways, using fundamentally different technologies:

- photovoltaic cells producing electricity which is then used to produce mechanical power;
- thermodynamic conversion of solar heat into mechanical power.

Photovoltaic pumping systems use photovoltaic cells which convert the irradiation directly into electricity, which in turn is used to run an electric motor to drive the pump (see Figure 5.4). Several pumping systems of this type are technically proven, and available from a number of manufacturers. It is estimated that, at present, about 2000 have been installed in various areas throughout the world.

The main constraint to wider use is probably the relatively high capital cost. However, analysis of both capital and recurrent costs indicates that photovoltaic pumps are likely to be cost-effective in areas of high levels of solar irradiation, and they are likely to become more attractive as increased production of photovoltaic cells results in reduced costs.

In thermodynamic solar pumping systems, irradiation is used to produce heat energy in a solar collector, and this heat is converted by a heat engine to mechanical power to drive the pump. Solar thermodynamic pumps were first demonstrated in the late 19th century, and since then a number of prototype pumps have been designed, built, installed and operated. However, various technical problems have prevented them from working reliably and

continuously, and further, the operating costs are high. In spite of all efforts to develop solar thermodynamic pumps, no field-proven pumping systems of this type are available commercially at present.

5.2 PHOTOVOLTAIC PUMPING SYSTEMS

Components, configuration and principle of operation

The main components of a photovoltaic pumping system are:

- photovoltaic array to convert solar irradiation into direct-current (dc) electricity;
- motor-and-pump subsystem to convert electricity to mechanical power for pumping water;
- control equipment;
- water storage and distribution system.

There are various configurations for photovoltaic pumping systems, depending on the water source and type of pump used (see Figure 5.4).

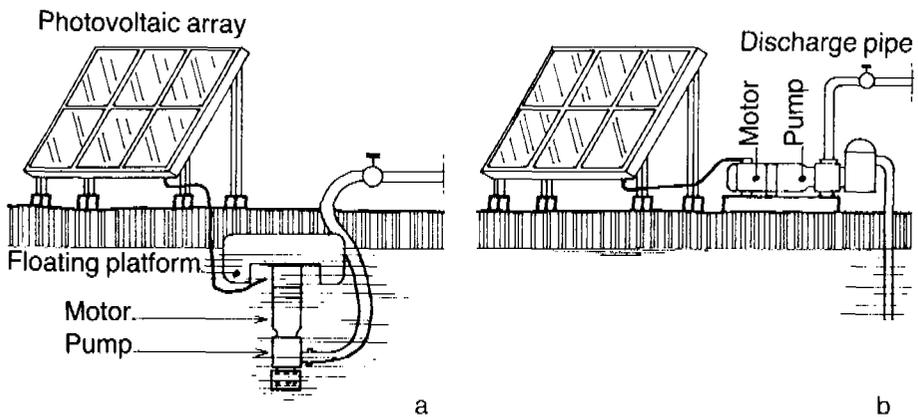


Figure 5.4A: Configurations for photovoltaic pumping systems: (a) floating motor/pump set; (b) surface motor with surface-mounted suction pump (Kenna, 1985)

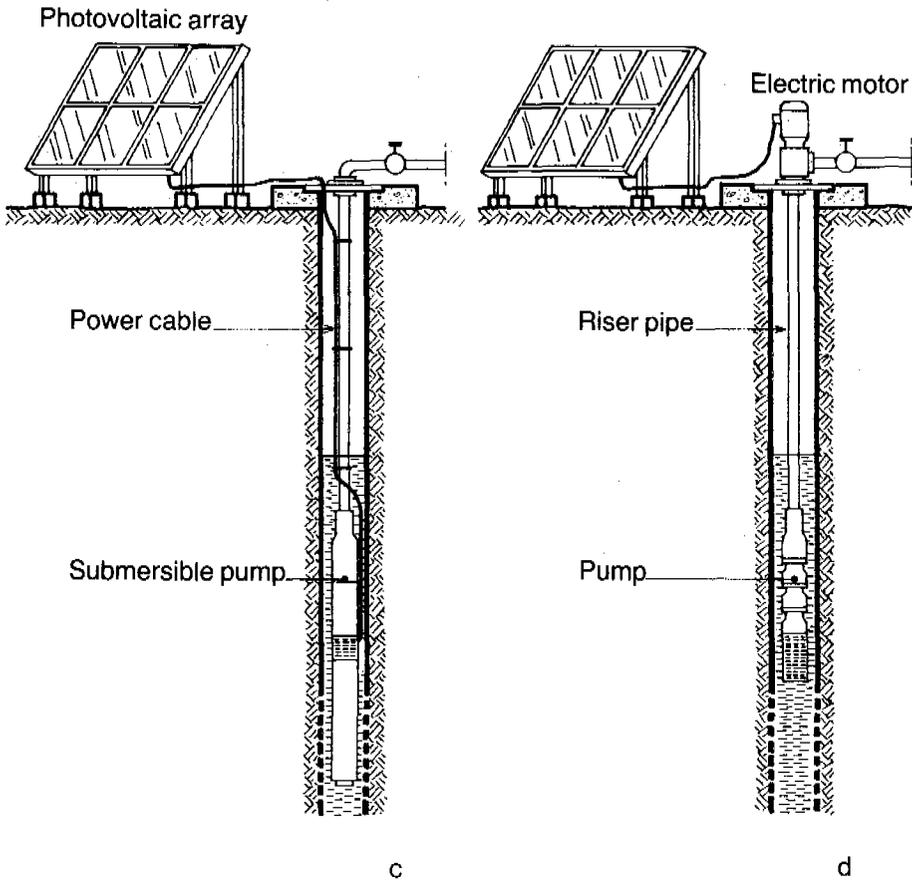


Figure 5.4B: Configurations for photovoltaic pumping systems: (c) submersible motor/pump set; (d) submerged pump with surface motor

The water output rate and pumping head determine the load on the electric motor, for which the array must provide the required power in the form of electrical voltage and current. The power conversion in a photovoltaic pumping system and the concomitant power losses are shown in Figure 5.5.

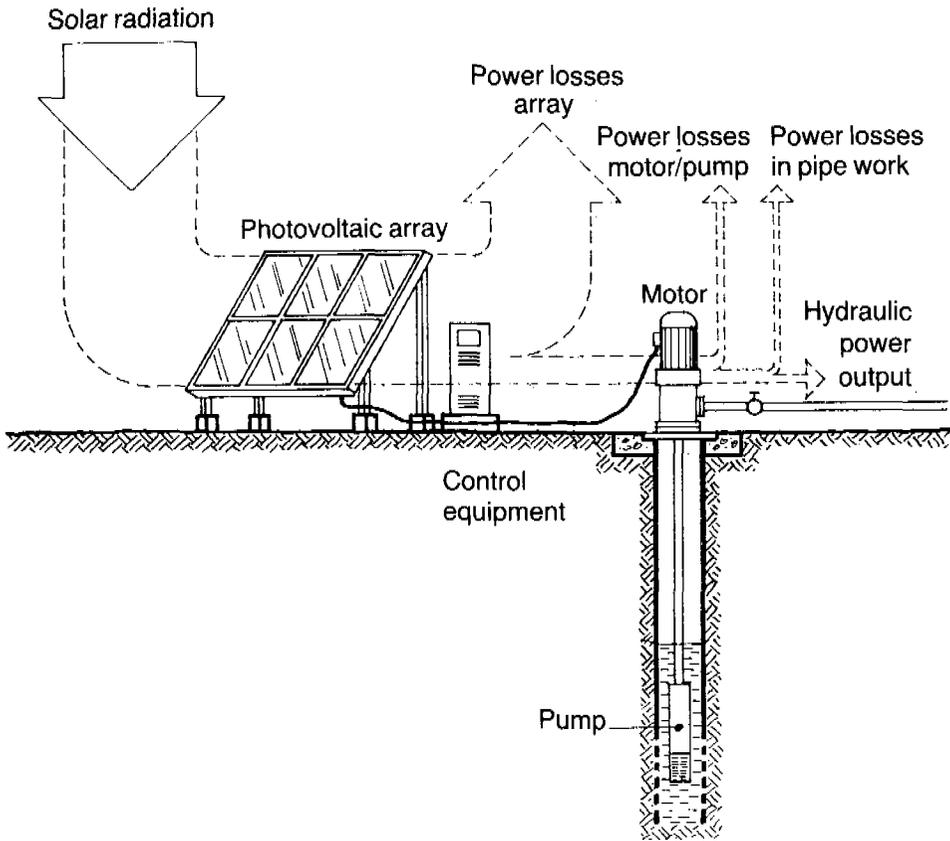


Figure 5.5: Power conversion in a solar photovoltaic pumping system

The general relationship between the solar irradiance, the power supply from the array, and the hydraulic power output, is shown in Figure 5.6. The electric power supply from the array varies with the irradiance received, and the efficiency of the motor is affected by the voltage and current produced by the array, which in turn is reflected in the water output pattern.

A photovoltaic pumping system starts to pump water when the solar irradiance rises above the system's "cut in" threshold which may be, for example, 300 W/m^2 . The water output rate then increases as the irradiance continues to rise. As the motor-and-pump subsystem approaches its optimal operating point, the efficiency improves so that the water output increases more rapidly than does the irradiance. In the afternoon, when the array heats up, the

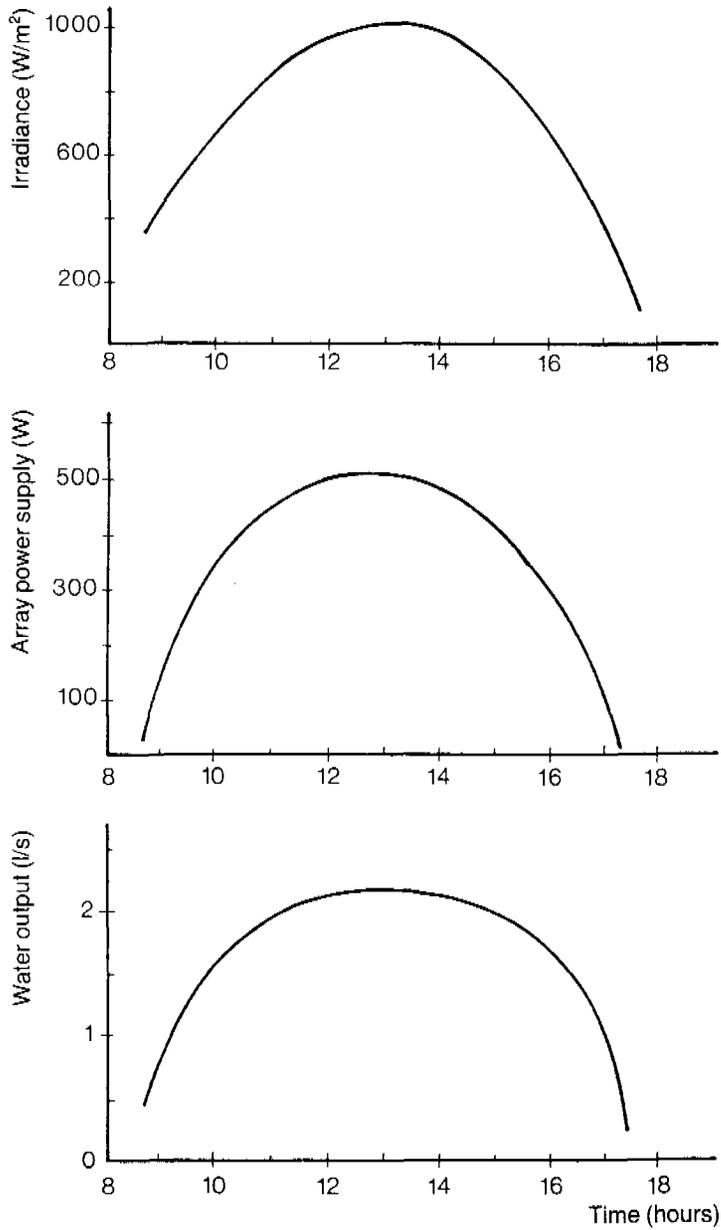


Figure 5.6: Relationship between irradiance, array power output, and water output, for photovoltaic solar pump (Halcrow & Partners and IT Power, 1981)

efficiency of the photovoltaic process reduces, and thus the electric power output is also reduced. Later in the afternoon, as the array cools down, photovoltaic efficiency increases again, but then irradiance is falling off. When solar irradiance drops below the threshold, insufficient electric power is generated for the pumping system to produce water output.

5.3 PHOTOVOLTAIC CELLS, MODULES AND ARRAYS

The first photovoltaic cells were installed by Bell Laboratories in 1955 in a solar-powered rural telephone carrier system in Georgia, USA. In 1958, photovoltaic cells were used to power a communication satellite, and since then, great advances in the technology and production of photovoltaic cells have been made. The most common type of photovoltaic cell is the monocrystalline silicon cell, but polycrystalline silicon cells are becoming increasingly popular. Silicon is a highly purified form of one of the most abundant elements in common sand. To make photovoltaic cells, large silicon crystals "doped" with other additives are grown, and this material is sliced into thin wafers. There are also several types of photovoltaic cells made from various materials other than silicon, but either these are not yet commercially available, or their performance is so unreliable that in terms of real use they are still in the development stage.

When solar radiation strikes the surface of a photovoltaic cell, an electrical potential is generated. Metal contacts attached in a grid to the front and back of the cell enable electric current to run. The general configuration of a silicon photovoltaic cell is shown in Figure 5.7.

Multiples of photovoltaic cells are connected electrically to form a "module". The more cells connected in series, the higher the voltage available; the more cells in parallel, the higher the current. The cells are usually laminated in a rectangular panel between a transparent window and a rigid back. Formerly, plain tempered glass was used for the transparent surface, but field experience has shown glass to be too vulnerable to breakage. Polycarbonate plastics and polymerized resins have been tested, but were found to deteriorate under moisture, dust and ultraviolet light. Currently, multi-layer laminated glass and high-impact plastics are preferred for the transparent face.

The packing factor for round cells, that is the ratio of cell area to the surface area of the module, is about 75%. Modules composed of square cells are becoming available, and these have a packing factor of almost 100%.

The power output capacity of a photovoltaic module is rated in peak watts (Wp). This is the value of the maximum power output from a module, when

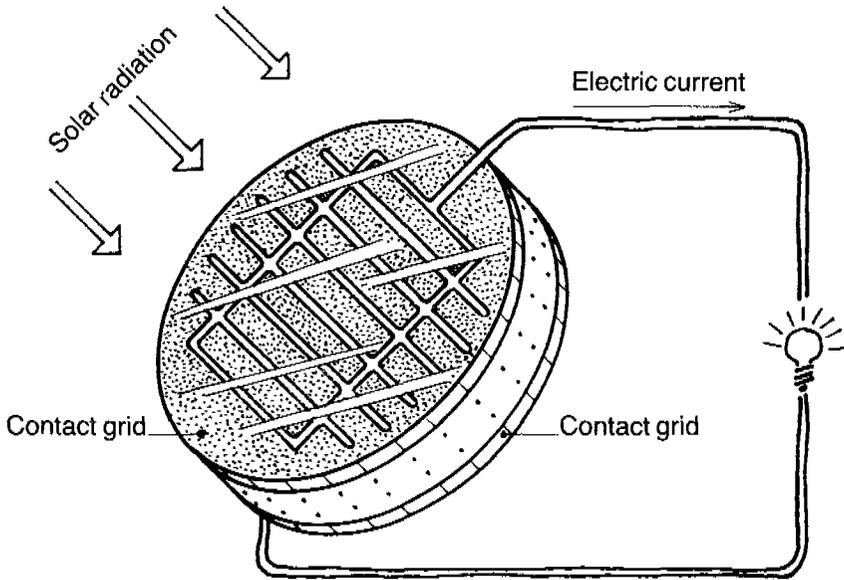


Figure 5.7: Configuration of a silicon photovoltaic cell (Halcrow & Partners and IT Power, 1982)

operating under a solar irradiance of 1000 W/m^2 at a reference cell temperature of 25°C . Cell temperatures under operating conditions are often much higher, between 50 and 70°C . An approximate correction can be obtained by reducing the array power output by 0.5% for each degree centigrade above the reference temperature 28°C . For example, at a cell temperature of 60°C the expected reduction in power output is about 16% .

Photovoltaic arrays

A photovoltaic array consists of a number of modules mounted in a framework of galvanized steel or aluminium alloy extruded profiles (Figure 5.8). The modules forming the array are connected electrically, so that the current and voltage produced by all the modules add up to give the total array current and voltage output. Current-voltage (I/V) curves can be plotted for various levels of irradiance and array temperature (Figure 5.9).

The operating point of the array depends on the combination of current and voltage required to operate the motor-and-pump subsystem. If the motor-and-

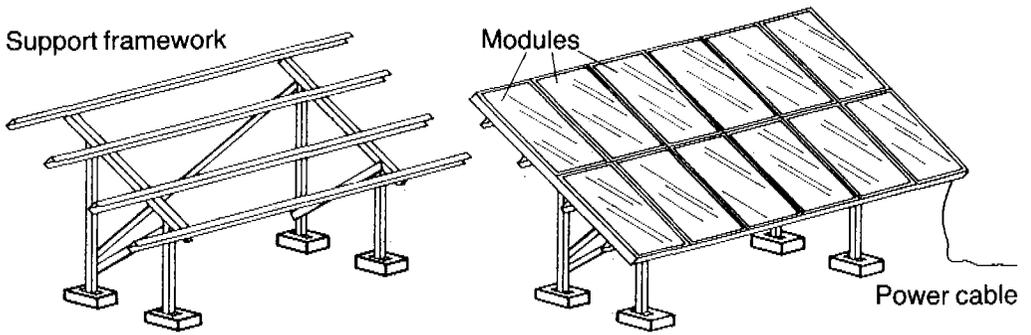


Figure 5.8: Mounting framework of photovoltaic array

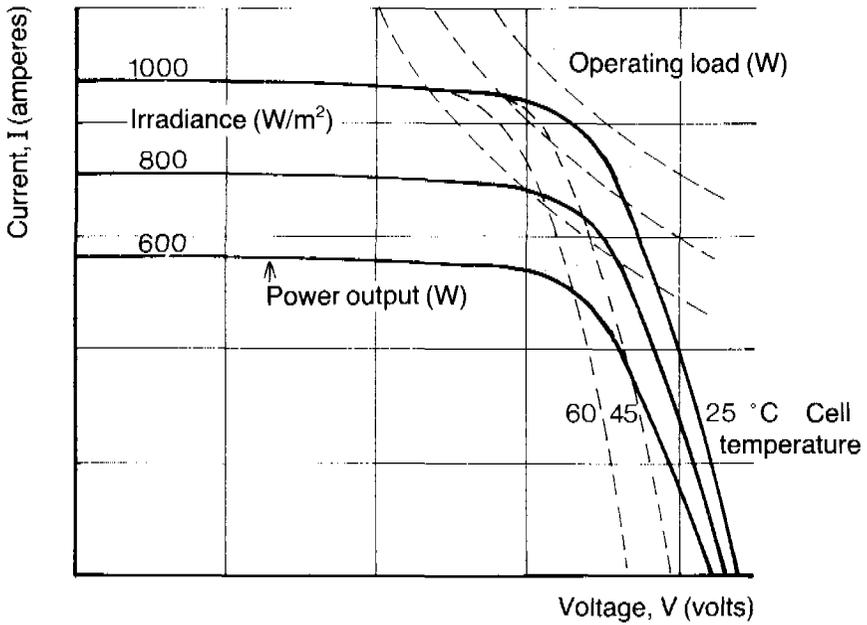


Figure 5.9: Current/voltage curves for a photovoltaic array (Grundfos, 1985)

pump is disconnected, the array operates under open-circuit conditions and produces only voltage, no current. If placed in short circuit, there is only current, no voltage. Under both conditions, the power output to the subsystem is zero. Maximum power output from the array is obtained when it operates on the knee of the current-voltage curve, for the irradiation level and array temperature that apply (see Figure 5.9). The maximum power output is about 0.7 of the product of short circuit current and open circuit voltage.

If the electric motor is coupled directly to the array, the system will operate at the point where the current-voltage curve of the motor intersects with the current-voltage curve of the array for the prevailing irradiance level and array temperature. Because this is not the maximum power operating point, electronic power conditioners can be used to control the operating conditions and keep the power output as close as possible to the maximum value. Early photovoltaic pumping systems only used very basic control equipment, but increasing requirements for optimal efficiency have prompted the development of fairly sophisticated electronic equipment for conditioning.

The power output capacity of an array may be reduced by 5-10% when the array surface becomes less transparent, as a result of ageing or dirt accumulation.

5.4 MOTOR-AND-PUMP SUBSYSTEM

It is important to match the operating characteristics of the motor to those of the pump by selecting an appropriate coupling and power transmission. The incorporation of a flywheel may have advantages, when a reciprocating-plunger pump is used. Currently, photovoltaic water pumping systems use the following types of electric motor:

- brushed permanent magnet direct-current (dc) motors;
- brushless direct-current motors;
- alternating-current motors.

Brushed motors require replacement of the brushes at regular intervals. For conventional brushes, these intervals are 2000-4000 hours, which is equivalent to one to two years use in a solar pumping system. Special highly wear-resistant brushes have been developed which may last up to 10 000 hours operation.

There are also brushless dc motors with a permanent magnet rotor and electronically switched field windings. These brushless motors, designed for use with solar pumps, are a relatively new development and problems with the electronics have yet to be overcome. Nevertheless, the potential for brushless dc motors in water pumping systems is increasing, as their reliability is improved.

Direct-current motors are generally attractive in photovoltaic pumping systems because the array provides dc power supply, so that the electric motor can be coupled directly. However, the available range of alternating-current (ac) motors is far greater because they are manufactured standard for mains power supply, and the prices are generally lower than those of dc motors. Using a cheaper motor in a solar pumping system may be a false economy, if a larger and thus more expensive array is required to compensate for the lower efficiency of the motor.

Development work on electric motors by a number of manufacturers aims to reduce maintenance requirements, to increase durability of bearings, and to increase the service life of brushes if these are used. A particularly important development is the production of reliable brushless motors.

If an alternating-current motor is used in a solar pumping system, an inverter is required to convert the dc power output from the array into ac electricity. This involves additional expenditure and some energy losses. For this reason, ac motors have so far not been considered seriously, because this additional cost would increase the overall cost of the pumping system considerably, especially for small-scale applications. Further, ac motors are less efficient and have a much higher starting current requirement than dc motors. However, new types of ac motors are being developed which have higher efficiency and these could become attractive for solar pumping systems. The present trend is to use either brushless motors or specially-designed ac motors with an efficient and reliable inverter.

Pumps

The choice of pump for a photovoltaic pumping system depends on the water output capacity required, the pumping head, whether it is driven by a close-coupled submersible motor or shaft-driven by a surface-mounted motor, and many other factors. Selection of pumps is discussed in Chapter 4.

5.5 ANCILLARY EQUIPMENT

Tracking mechanisms

Most arrays are placed in a fixed position for simplicity, and to reduce costs. However, movable arrays are sometimes used, which can be oriented to track the apparent movement of the sun. This adds considerably to the complexity of

the installation, but has the advantage of a substantial increase, about 30%, in array power output throughout the day. Alternatively, if the array is movable, the required array area may be reduced by about 20% for a given hydraulic output.

Manually-operated tracking mechanisms can be cost-effective, if an operator is available to adjust the array orientation during the day. At present, automatic tracking mechanisms are expensive and complex. Generally, the costs are higher than can be justified by the increased power output or reduced array area, and the greater complexity of the array installation with tracking mechanism is a distinct disadvantage.

Solar concentrating devices

Increasing the intensity of solar radiation falling onto the cells will increase their power output. Therefore, the cell area could be reduced by concentrating the solar radiation with special devices, such as focusing mirrors or Fresnel lenses moulded in a plastic holder. The solar cells can also be surrounded by reflecting surfaces forming a parabolic reflector.

While solar concentrating devices may reduce the cell area required for a given power output, they have a number of drawbacks. The cells will be heated to high temperatures, and therefore will require cooling. For low solar concentration rates, air-cooled fins may be adequate, but for higher concentration rates, water cooling is needed. If the cooling system fails, there is likely to be serious damage of the cells. Moreover, most types of solar concentrators need tracking to keep them focused efficiently on the sun, and any tracking mechanism makes a solar water pumping system considerably more complex. The use of solar concentrating devices in a photovoltaic pumping system is only advantageous if the cost reduction for the smaller cell area required, outweighs the costs of the solar concentrating equipment. In most cases, it is doubtful whether concentrators are economically justifiable, and as the cost of solar cells decreases, arrays without solar concentrating equipment will become increasingly attractive, particularly in small installations. However, it may be cost-effective to place small reflectors at the periphery of a flat plate array, because this would increase the power output sufficiently to justify the small additional cost.

Batteries

In some photovoltaic pumping systems, batteries are incorporated for energy storage. The advantage of using batteries is that a steady supply of electricity can

be provided from the varying electricity supply of the photovoltaic array. The batteries can also accumulate electrical energy for use during periods when more energy is required than produced by the array. However, the disadvantages of using batteries are considerable:

- they are expensive;
- regular topping up with distilled water is required, unless specially sealed batteries are used, but these are extremely expensive;
- the energy loss involved in the charge-discharge cycle of the batteries reduces the overall efficiency of the pumping system;
- batteries have a relatively short life, for example, conventional lead/acid batteries may last only five years or less under field conditions.

It is possible to use oversized battery storage capacity, or better quality batteries, but this is very costly. Solar pumping systems without batteries are favoured because of their cost advantage, simplicity, and greater reliability.

5.6 CONVERSION EFFICIENCIES

The motor-and-pump subsystem of a photovoltaic solar pump operates under different conditions from the steady-voltage power supply for which conventional electric motor pumps are designed, because the power produced from the available solar irradiance varies considerably. Therefore, the subsystem of a photovoltaic pump should operate efficiently over a range of combinations of voltage and current. Two types of efficiency can be distinguished:

- the power conversion efficiency: that is, the ratio of hydraulic power output to the electrical power input, which will be highest when the subsystem operates at or near its design point;
- the daily energy conversion efficiency: that is, the ratio of the hydraulic energy output to the electrical energy output of the array over the whole day; it is the average of the varying power efficiencies achieved during the day, under the daily variation in solar irradiance and other operating conditions.

The daily energy conversion efficiency is the most important parameter, because it determines the size of array required for a particular water output, and the array is by far the largest cost item of photovoltaic pumping systems. In a well-designed system, a daily energy conversion efficiency of 4.5% should be attainable with present technology, but in practice, 2.0-3.5% is more usual.

5.7 MATCHING MOTOR/PUMP AND ARRAY POWER OUTPUT CHARACTERISTICS

To start operation, the motor-and-pump subsystem requires a certain power to overcome the starting torque. The irradiance required to produce the starting torque is the threshold level for the solar pumping system. If reciprocating-plunger pumps are used, the threshold irradiance is fairly high, because of high starting resistance of this type of pump. Therefore, if a plunger pump is used in a photovoltaic pumping system, then a fairly high irradiation level or battery storage of electric energy is required to start the pump. The characteristics of dc motor-driven centrifugal pumps are well matched to the power output characteristic of a photovoltaic array. These motor/pump sets can therefore be coupled directly to the array. A centrifugal pump has a relatively low starting torque, and will readily start to rotate slowly even if irradiance is limited, but there is no water output until irradiance has increased to the level where sufficient power is produced to develop the rotational speed required for pumping.

If the threshold irradiance for a photovoltaic pumping system is high, incorporation of a special power conditioning device, known as a Maximum Power Point Tracker, may be considered. This is an electronic device which controls the release of power to the motor, so that the power produced at low irradiance levels can be maximized to obtain the threshold power required to start the pump. As a result, photovoltaic pumps equipped with this device can start earlier and stop later, and so give a higher water output. The use of power conditioning equipment implies additional cost and power loss, and an extra source of potential failure. To be economical, the benefit of the water output must outweigh the additional power loss, costs, and failure risks.

An alternative, simpler method of matching the motor-and-pump characteristic and the array power output, is to control the voltage produced by the photovoltaic array at a fixed value. The array will then work fairly close to its maximum efficiency at most, but not all irradiance levels, and consequently the operation of the pumping system will be fairly optimal.

Inverters are electronic devices that convert the direct current supplied by the array to single or three-phase alternating current, to run motor-and-pump sets driven by an ac motor. To maximize their benefit, electronic control can be incorporated to provide impedance matching. The inverter will then automatically increase the voltage and frequency of the ac current, and so enable the pumping system to deliver water under low irradiance levels. Peak efficiencies of some commercially available inverters are claimed to be as high as

85%, but most inverters are very inefficient under part-load. Therefore, only specially designed inverters should be used for solar pumping systems.

Batteries also provide impedance matching, because they allow the electric motor to start at low irradiance levels. However, batteries also have several disadvantages, such as considerable power loss, lack of reliability, need for regular maintenance, and a limited life which is shorter than the rest of the solar pumping system.

5.8 WATER STORAGE REQUIREMENT

Solar pumping systems require a storage tank of sufficient capacity, usually two to three days' supply, in order to ensure the continuous availability of water. An elevated storage tank is required to provide sufficient head for piped distribution of the water.

The storage tank capacity required to guarantee the supply of water at a required level of certainty can be calculated from data on solar irradiation at the location concerned. For example, storage of two days' supply may give 80% certainty of water being available, while storage of three days' supply may give a certainty of 90%.

5.9 APPROXIMATE SIZING OF PHOTOVOLTAIC PUMPING SYSTEMS

The photovoltaic array should be as small as possible for the power output requirement, in order to design the most cost-effective system. The cost of the array is approximately proportional to the peak power capacity installed, and represents a considerable proportion of the total capital cost of the pumping system.

The average daily solar irradiation available in the least sunny month of the year, and the maximum daily water requirement determine the array size required. For fully accurate sizing, all manufacturers of solar photovoltaic pumps have computer models available to determine the minimum size of array. However, a simplified procedure can be used to obtain the approximate size of the array:

(1) The hydraulic energy demand of the pumping system can be estimated as:

$$E_{\text{hydr}} = \frac{Q \cdot H}{100} \quad \text{where: } E_{\text{hydr}} = \text{hydraulic energy demand (MJ/d)}$$

$Q = \text{pumping rate (m}^3\text{/d)}$
 $H = \text{pumping head (m)}$

For example, a pumping system of 10 m³/d rated capacity operating against 20 m pumping head, has an estimated hydraulic energy demand of 2 MJ/d.

(2) The average daily efficiency of the pumping system is also estimated. For pumping systems operating against low heads of 2-5 m, an efficiency of 30% may be a good approximation; for systems operating against pumping heads of 10-30 m, an efficiency of 40% may be assumed.

(3) The hydraulic energy demand is divided by the daily energy efficiency of the subsystem, to give the daily energy output required from the array, in the example: 2 MJ/d : 0.4 = 5 MJ/d.

(4) Reference to Figure 5.2 indicates the average daily irradiation for the area in question; for example, in the area around Dakar, Senegal, about 20 MJ/m².

(5) To estimate the average daily irradiation available in the least sunny month, the value found in (4) is reduced by 20%, in the example: 20 x 80% = 16 MJ/m²/d. If monthly average solar irradiation figures are available from meteorological stations, it is more accurate to use the daily average irradiation in the least sunny month from these records.

(6) The daily energy output requirement as calculated in (3) is divided by the average daily irradiation in the design month, as found in (5), and the result multiplied by 1200 to obtain the approximate peak watt rating required for the array; in the example: (5 : 16) x 1200 = 375 Wp.

(7) Solar arrays are available in modules rated at 35-45 Wp. Therefore, the result found in (6) should be divided by the appropriate module rating, as appropriate. The result is rounded up to an integer to give the number of modules required, in the example: 375 : 35 = 11 or 375 : 40 = 10.

The simplified sizing procedure can also be carried out graphically, using Figure 5.10.

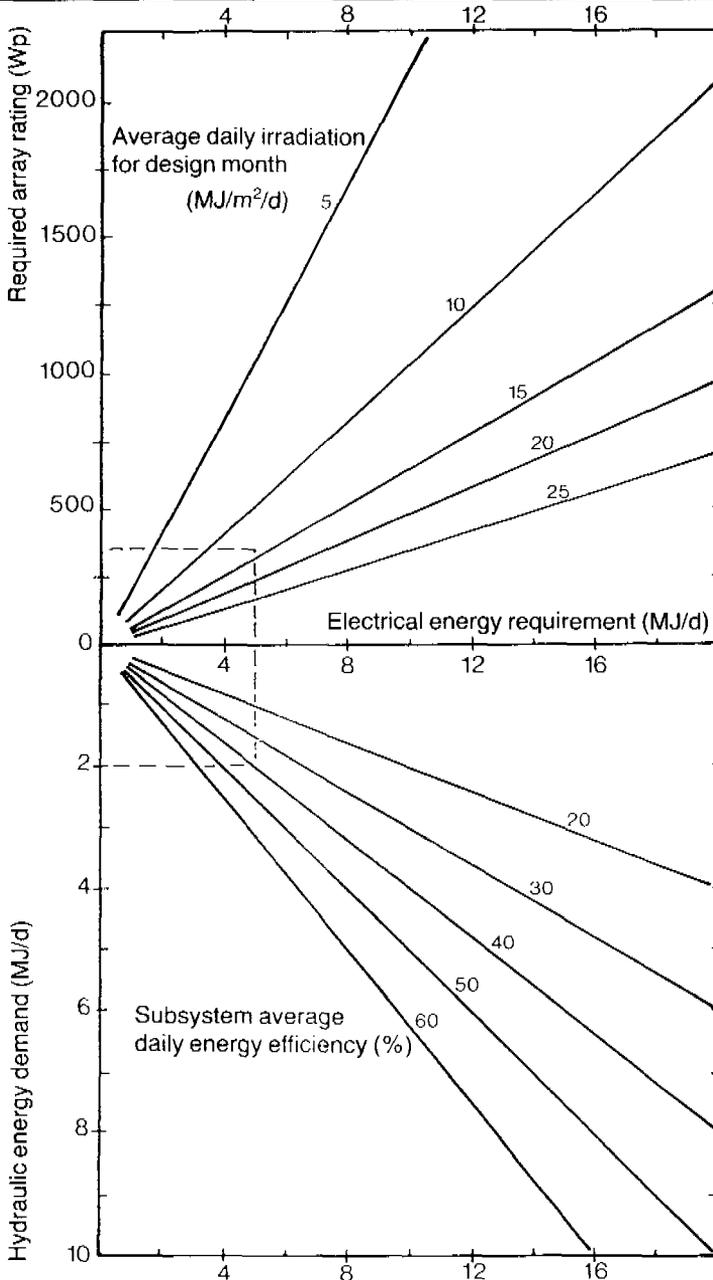


Figure 5.10: Approximate sizing of photovoltaic pumping system (Halcrow & Partners and IT Power, 1983)

5.10 THERMODYNAMIC PUMPING SYSTEMS

At present, solar thermodynamic water pumping systems have not been proven in the field, but for completeness, a brief description of these systems is given.

The basic configuration and components (Figure 5.11) are:

- solar collector converting solar irradiation into heat energy;
- heat engine which uses a thermodynamic cycle to convert heat into mechanical energy;
- pump;
- water storage and distribution system.

About 60 solar thermodynamic pumps produced in France have been installed in developing countries. The energy conversion efficiency of these pumps under field conditions was about 1%, but because of their complexity, few have operated for any length of time.

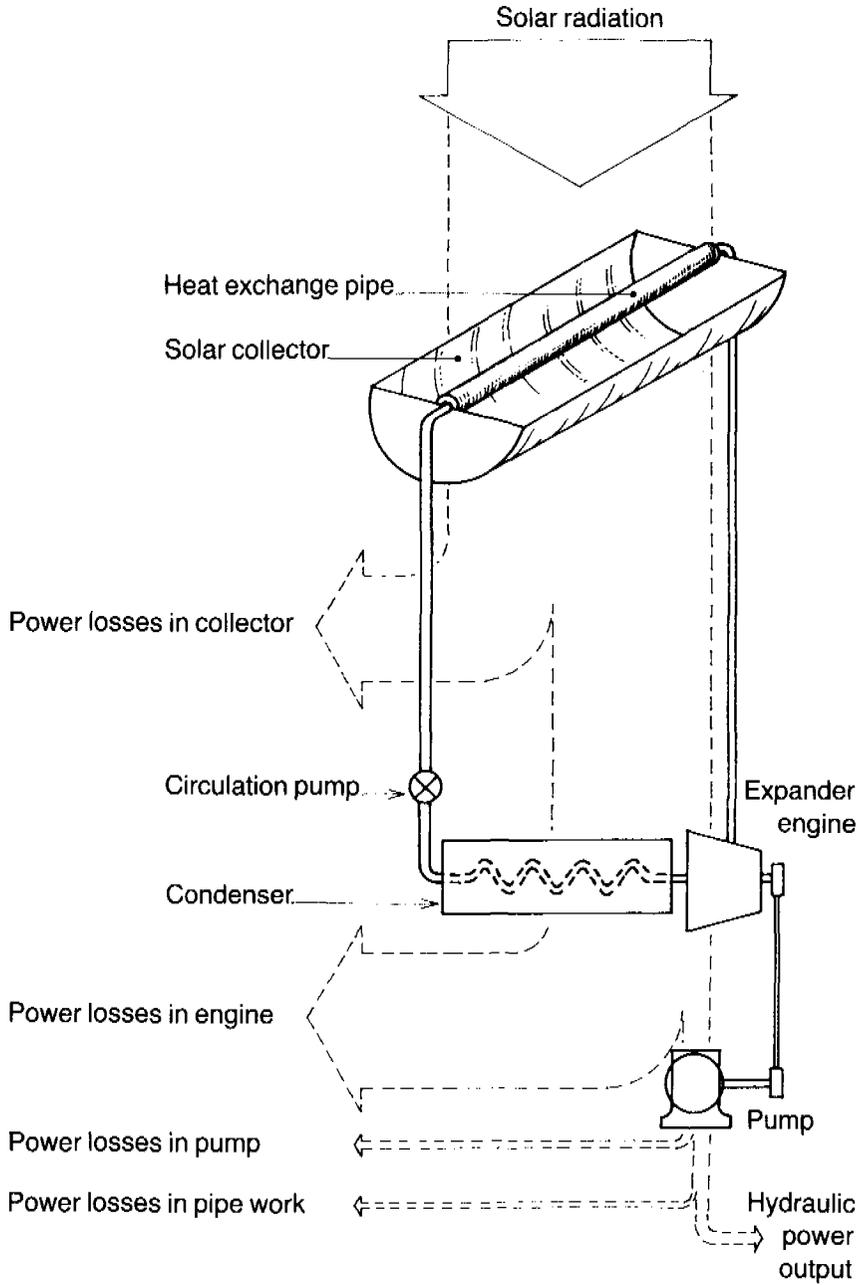


Figure 5.11: Basic configuration of a solar thermodynamic pumping system (Halcrow & Partners and IT Power, 1981)

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6. Wind energy

The winds over the earth are a vast energy source estimated to yield an average 2700 million MW (WMO, 1978). However, only a small proportion is over the land areas and close enough to the surface to be captured by wind rotors. Nevertheless, the potential production of useful power is very great, estimated roughly to be 2-10 million MW (Park, 1981). At present, wind power provides as little as 0.04% of the total energy consumption, but by the year 2000 this may have increased to 2%, and perhaps more (UNESCO, 1981). A World Bank study has identified 20 developing countries with more than 40% of their land area having average annual wind speeds greater than 3.5 m/s (Blake, 1978). At

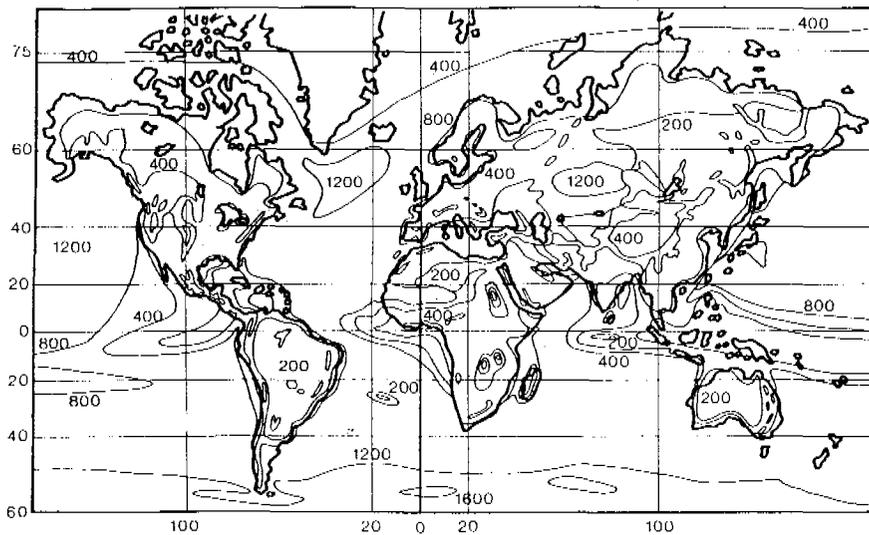


Figure 6.1: World wind power distribution (mean wind power flux through unit vertical area perpendicular to wind direction, measured at 10 m above ground level, W/m^2). Estimates for large areas which are relatively free of obstructions (WMO, 1978)

this level of wind speed, wind-powered water pumping systems or wind pumps may well be cost-effective. The world distribution of wind power at 10 m above ground level is shown in Figure 6.1.

By the fourth century, wind pumps were widely used in the Middle East, and their application spread throughout central and east Asia, and into China. From the sixth century, wind pumps were being used increasingly in Europe, and by the 19th century they were used on a large scale for water pumping, particularly in the Netherlands, Denmark and in northern Germany. Wind pumps also had a major role in the early development of North America and Australia, and are still used in large numbers. This is also the case in Argentina, South Africa and the Soviet Union, where wind pumps are used primarily for watering livestock. About one million wind pumps are in regular use throughout the world today. In recent years, interest has been renewed in developing low-cost, reliable wind pumps for developing countries, both for drinking water supply and for irrigation purposes.

6.1 WIND-POWERED WATER PUMPING SYSTEMS

A relatively large rotor is required to capture sufficient wind to produce useful power. In mechanically coupled wind pumps, the wind rotor is directly coupled to the pump (Figure 6.2). A crankshaft coupling is often used for a reciprocating-plunger pump, while for rotary pumps, the most common coupling is by gears or pulley. Generally, a rotary pump will give a more favourable operating load on the wind rotor than a plunger pump, because the power required to operate a plunger pump changes continuously during the pumping cycle. In contrast, a rotary pump imposes a relatively constant and continuous operating load on the rotor.

Electrically coupled wind pumps use an electric cable for power transmission from the wind-driven electro-generator to an electric motor driving the pump (Figure 6.3). This type of wind-powered pumping system is sometimes referred to as "wind-electric pumping" or "remote pumping". Power transmission by cable allows the wind rotor to be placed some distance from the well or borehole at a favourable site, such as on a hill top, to capture more wind and produce more power than would be possible at the site of the well or borehole, which is often in a valley or low-lying area.

A two or three-bladed rotor is used to drive the electro-generator through a step-up gear unit to obtain the required high rotational speed. A slip ring assembly connects the generator poles to the power cable. If the generator

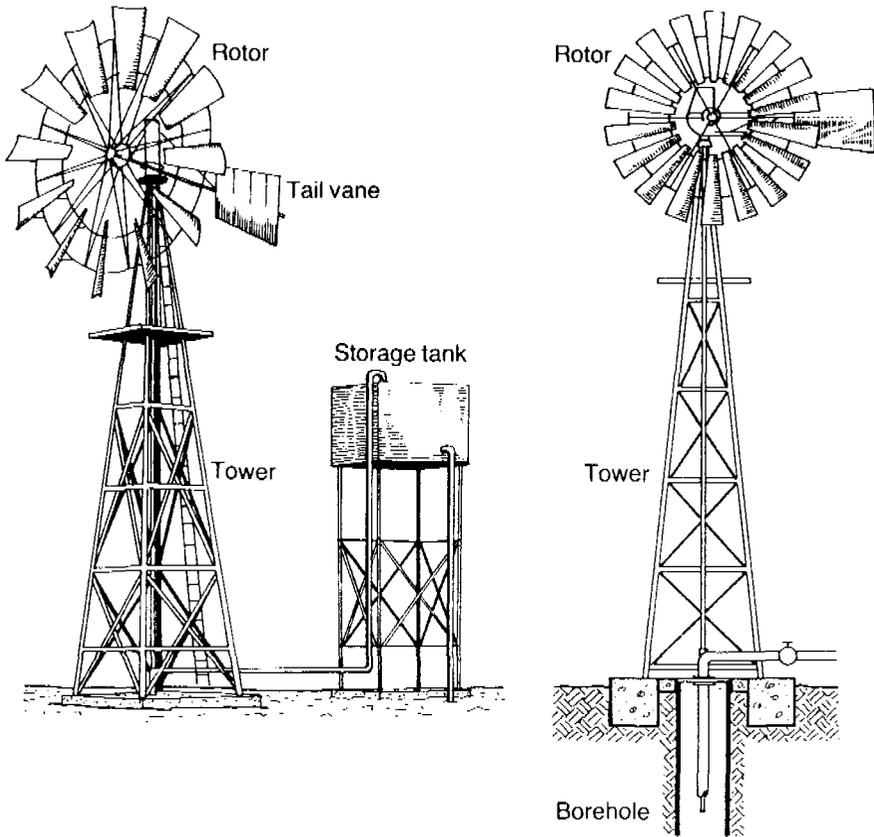


Figure 6.2: Main features of mechanically coupled wind pump

produces three-phase alternating current, this power can be supplied directly to a standard submersible motor/pump set with a three-phase induction motor. The maximum power rating of the electric motor should not be more than about 40% of the generator rating.

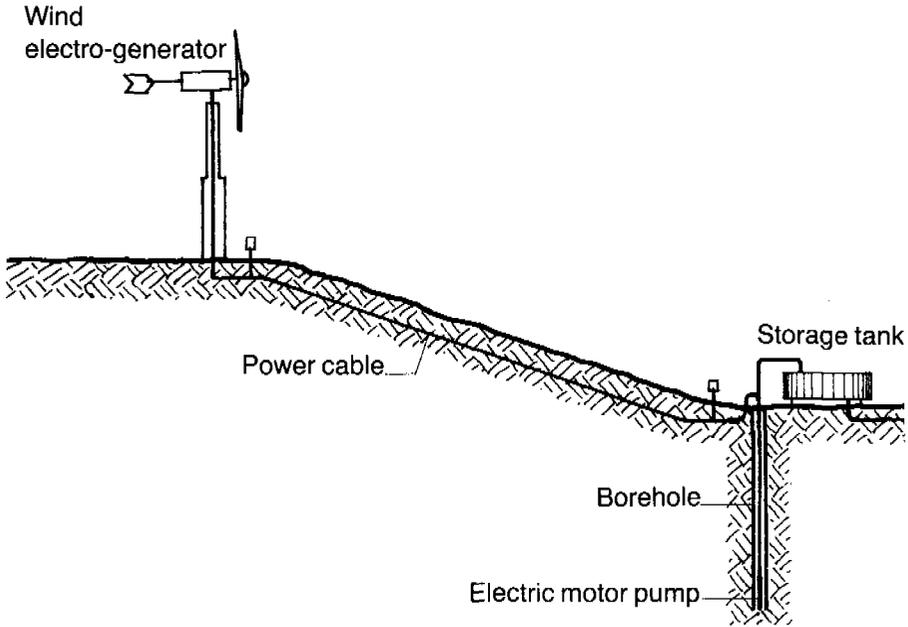


Figure 6.3: Main features of electrically coupled wind pump

6.2 WIND ROTORS

Horizontal-axis wind rotors are equipped with two or more blades. Multi-bladed rotors are designed for relatively slow rotational speeds, between 30 and 80 revolutions per minute, and produce a relatively high torque, making them suitable for driving mechanically coupled pumps. Fast-running rotors having two or three blades are more suitable for driving an electro-generator at high rotational speed, for electrically powered pumps. A slow-running, multi-bladed rotor has to be of sturdy construction because of the considerable load and torque exerted by the rotor (Figure 6.4). With a fast-running rotor, alignment and blade profile design are critical because of the greater aerodynamic forces on the rotor blades ("blade friction"), the considerable centrifugal forces, and the greater risk of vibrations.

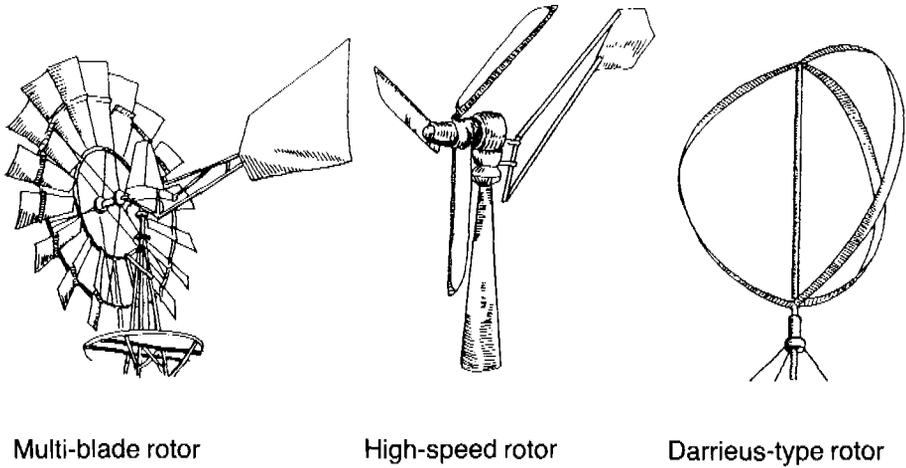


Figure 6.4: Types of rotors used in wind pumps

There are two main types of vertical-axis wind rotors, the "lift" and "drag". Drag is the wind force on the rotor pointing downwind, parallel to the air flow. Lift is the force on the rotor pointing perpendicular to the wind. The Darrieus rotor (see Figure 6.4), consisting of a number of curved blades of aerofoil-shape, is an example of the lift type of rotor. This type of rotor can produce as much power as horizontal-axis rotors, but is not self-starting. An example of the drag type rotor is the Savonius wind rotor, which has S-shaped blades. This type of rotor has a limited power output, and is difficult to protect against strong winds.

6.3 TOWERS

The tower should be sturdy enough to withstand the considerable forces exerted on it by the rotating rotor, especially in high winds. Being normally 6-15 m high, the tower needs to be of strong construction. Therefore, it is not recommended that it be constructed exclusively from local materials. Failure or misalignment of the tower can wreck the whole wind pump. Moreover, use of a locally constructed tower for an imported wind rotor is likely to negate the manufacturer's warranty.

6.4 TRANSMISSION SYSTEMS

In a wind pump system using a plunger pump, power is often transmitted by a crankshaft which reciprocates the pump rod to drive the pump (Figure 6.5).

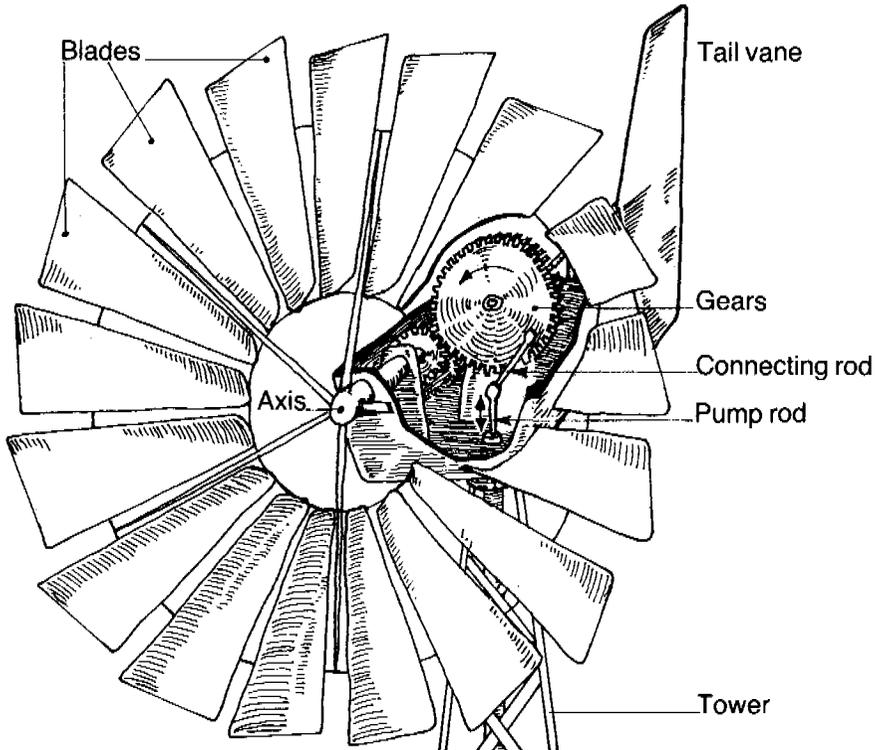


Figure 6.5: Transmission mechanism for wind pump using plunger pump (Park, 1981)

Another type of transmission system for plunger pumps is an overhead rocker which reciprocates the pump rod directly. The swept arch of the rocker controls the stroke length of the pump.

In some commercially available transmission systems, extensive gearing with a roller-and-sleeve coupling is used to produce the reciprocating motion of the pump rod. A clutch mechanism may be incorporated to allow free rotation of the rotor until sufficient speed and power is attained to start the pump by engaging the clutch (Figure 6.6).

If the transmission mechanism incorporates a provision to vary the stroke length, the torque required to start the pump can be adjusted for weak and strong winds. This arrangement is similar to the transmission gears used in bicycles, by which the operating torque can be adjusted to reduce the leg power required. With a variable stroke provision, the wind pump can thus start at lower wind speeds, and a considerable increase in water output can be obtained.

A simpler way to reduce the starting torque of a wind-driven plunger pump is to make a small hole in the plunger. The starting resistance is then less, and the

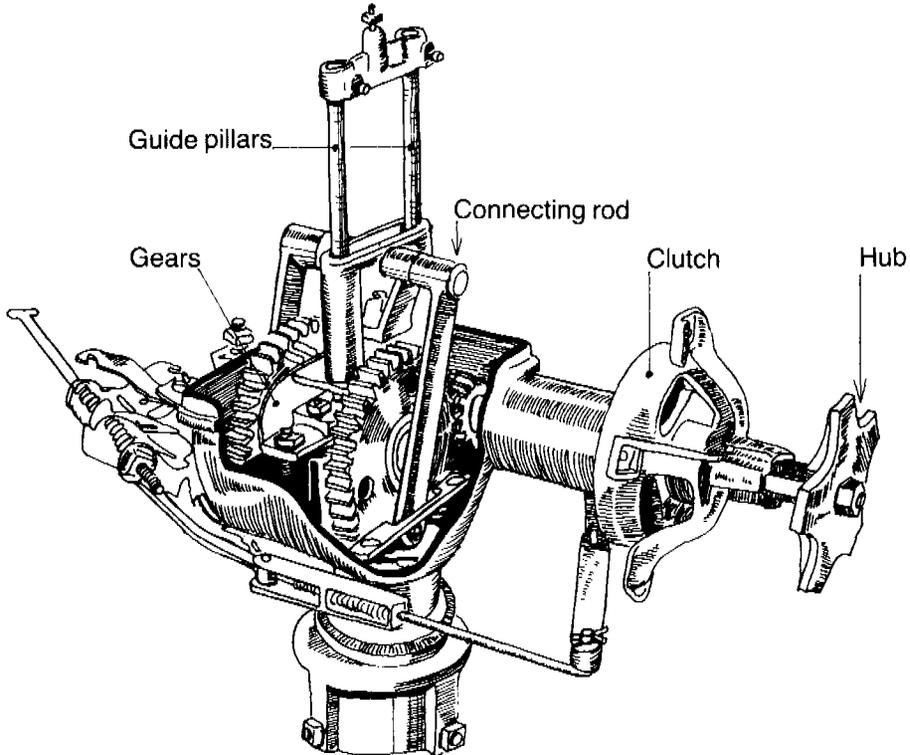


Figure 6.6: Transmission mechanism equipped with a clutch (Dempster Industries)

wind pump can start to operate at lower wind speeds. In stronger winds, the hole will cause some loss of water output, but this is usually not important and readily compensated for by the output gained in low wind speeds.

Rotary pumps can be coupled to the wind rotor by gears, a pulley or belt drive. Wind rotors and centrifugal pumps have similar torque and speed characteristics

that both vary with the square power of rotational speed. The loading of the transmission mechanism is thus favourable. With vertical-axis rotors, the rotor can be coupled to the pump by a simple belt drive system. Pulleys of different diameter may be fitted to adjust the rotational speed of the pump, and thus pump operation can be matched to the wind speed regime in different seasons.

6.5 CONTROL MECHANISMS

Every wind pump should have a control mechanism to protect it from rotating too fast and being damaged in high winds. Modern wind pumps are equipped with control mechanisms of various types, all of which limit the rotational speed of the rotor, or stop it in excessive winds. In some designs, a brake mechanism is incorporated which is actuated automatically if the rotor speed exceeds the set maximum, or if blade imbalance occurs. It is also possible to use a "pull-out" mechanism by which the rotor is automatically turned from the wind by a vane, when the wind speed becomes greater than the allowable maximum for the rotor. Under normal operating conditions, the vane is perpendicular to the wind direction, but in high winds the force on it makes the rotor turn away from the wind. Another control mechanism comprises a device to disturb the air stream on the rotor, when the wind speed increases beyond the allowable maximum level. The aerodynamic pressure exerted by a disturbed air stream is much less than that of the undisturbed wind, and thus the speed of the rotor will be reduced to within safe limits.

6.6 BASIC THEORY OF WIND-POWERED PUMPING

Wind flowing at a speed (V), through an area (A), represents an air mass flow, which can be calculated (Figure 6.7):

$$m = \rho_a \cdot A \cdot V$$

where:

m = air mass flow (kg/s)

ρ_a = density of air (kg/m³)

A = area swept by rotor (m²)

V = wind speed (m/s)

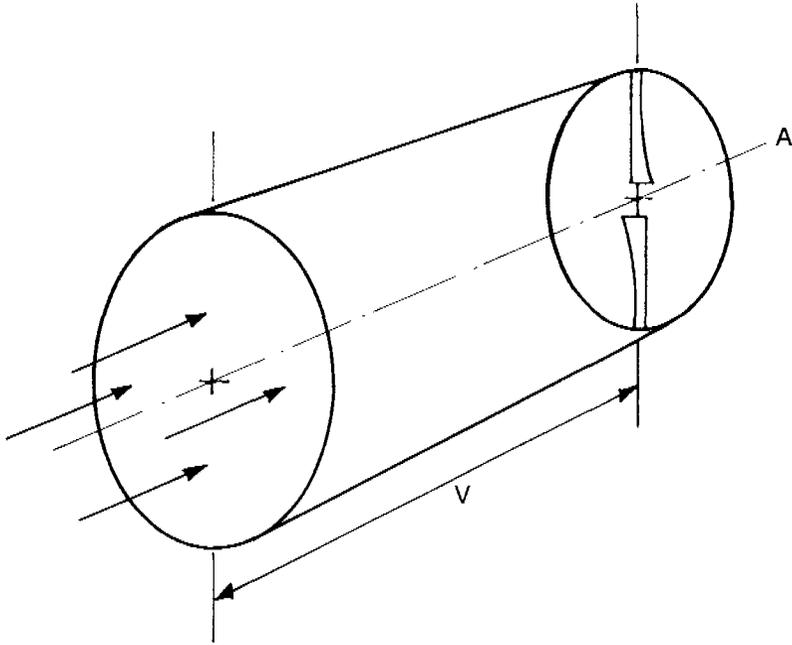


Figure 6.7: Air mass flow

The kinetic power in the wind can be calculated:

$$P_{\text{kin}} = \frac{1}{2} \rho_a \cdot A \cdot V^3$$

where:

- P_{kin} = kinetic power (W)
- ρ_a = density of air (kg/m^3)
- A = area swept by rotor (m^2)
- V = wind speed (m/s)

Two important points are reflected in this equation:

- Wind power is proportional to the third power (cube) of wind speed. It thus varies greatly. For example, at a wind speed of 3 m/s, the power available in the wind is 16 Watt per m^2 of swept rotor area; at 6 m/s, it is about 130 W; at 10 m/s, about 600 W.

- Wind power is proportional to the area swept by the rotor, and thus is proportional to the square of the diameter of the rotor.

For physical reasons, the power that a rotor can extract from the wind is only a part of the kinetic energy in the wind. This proportion is known as the power coefficient, C_p . Its theoretical maximum is approximately 60%, but the practical C_p of rotors is in the range of 10 to 40%.

The hydraulic power output of a wind pump is determined by the wind speed, the area swept by the rotor, the C_p of the rotor, the efficiency of the power transmission, and the efficiency with which the pump uses the mechanical power input to produce hydraulic output. This is expressed in the following equation:

$$P = \frac{1}{2} \rho_a \cdot C_p \cdot q \cdot A \cdot V^3$$

where:

- P = hydraulic power output (W)
- C_p = power coefficient (%)
- q = power conversion efficiency (%)
- ρ_a = air density (kg/m^3)
- A = area swept by rotor (m^2)
- V = wind speed (m/s)

The C_p of the rotor depends on aerodynamic design and rotational speed, and is not constant but varies with wind speed. The rotor should be selected or designed so that the power coefficient is maximum for the prevailing wind speed at the particular location. This is called the design wind speed, and is not the same as the average wind speed. A wind pump of a low design wind speed does not require much wind to start, and will have a relatively high power output in weak winds. However, in higher wind speeds its power conversion efficiency will be less, and the total power output for the prevailing wind speeds will be relatively small, because the greater power in stronger winds is not used efficiently.

Power conversion and power losses in a wind pump installation are shown in Figure 6.8. Power losses are incurred in the rotor, the electro-generator (if used), the transmission mechanism, and in the pump itself. Indicative values of these power losses are given in Table 6.1.

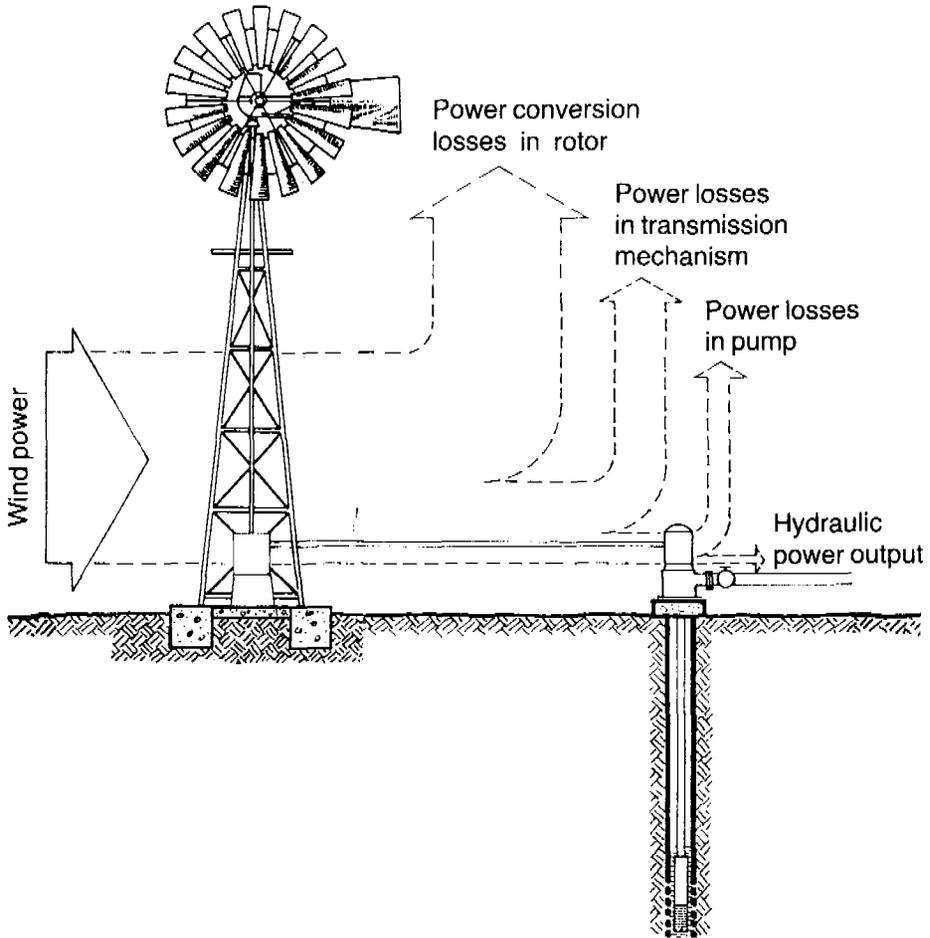


Figure 6.8: Power conversion in a wind pump installation

Table 6.1: Indication of power losses in wind pump systems

Component	Range of power loss (%)
Electro-generator	10-20
Power cable	5-10
Electric motor	20-30
Centrifugal pump	30-50
Plunger pump	40-50

6.7 DATA COLLECTION AND WIND REGIME

As wind regimes differ considerably from place to place, data from global or regional surveys can only be used to give an indication. Ideally, the wind potential at each location should be assessed on the basis of long-term wind speed records, but extensive records are rarely available. Usually, measurements of wind speed will need to be taken at the location where the wind pump is to be installed. Hourly records of wind speed are required for a period of at least one year, and preferably one-and-a-half years. Studies in North America have shown that the average wind speed determined on this basis is within 10% of the long-term average, at a confidence level of 90%.

The most widely used wind-speed measuring device is the anemometer. It is essential that each anemometer, and the method used for reading and recording data, is checked to ensure which unit of measurement (m/s, knots, miles/hour) has been used in the record.

From the data collected, the wind regime needs to be analysed in order to assess the suitability of a particular location for a wind pump system. This may be done on the basis of time distribution, for example, the average wind speed for each individual hour of the day. The frequency distribution gives the frequency of occurrence of wind speed in each specific interval, for example, the number of hours during which the wind speed is 3-4 m/s.

6.8 SITE SELECTION

Site selection is not critical in flat terrain, but in hilly or mountainous areas there are considerable variations in wind availability, and allowance for this should be made when selecting the site for a wind pump. Belts of trees, buildings, and other obstructions greatly reduce the wind speed available on the leeward side. The effect of various obstructions and topographical features is shown in Figure 6.9.

Near the earth's surface, the wind stream is disturbed. Wind blowing around buildings or over rough surfaces is likely to have a turbulent pattern, which considerably reduces the power a rotor can extract from the wind. On the leeward side of tree belts or similar obstructions, turbulences occur over a distance of 10-20 times the height of these obstructions (Figure 6.10).

The output capacity of the wind pump should be matched to the yield of the water source. Basically, the capacity should be less than the safe yield of the source from which the water is pumped. If the capacity of the wind pump is greater, the source may be pumped dry, and the pump will wear quickly.

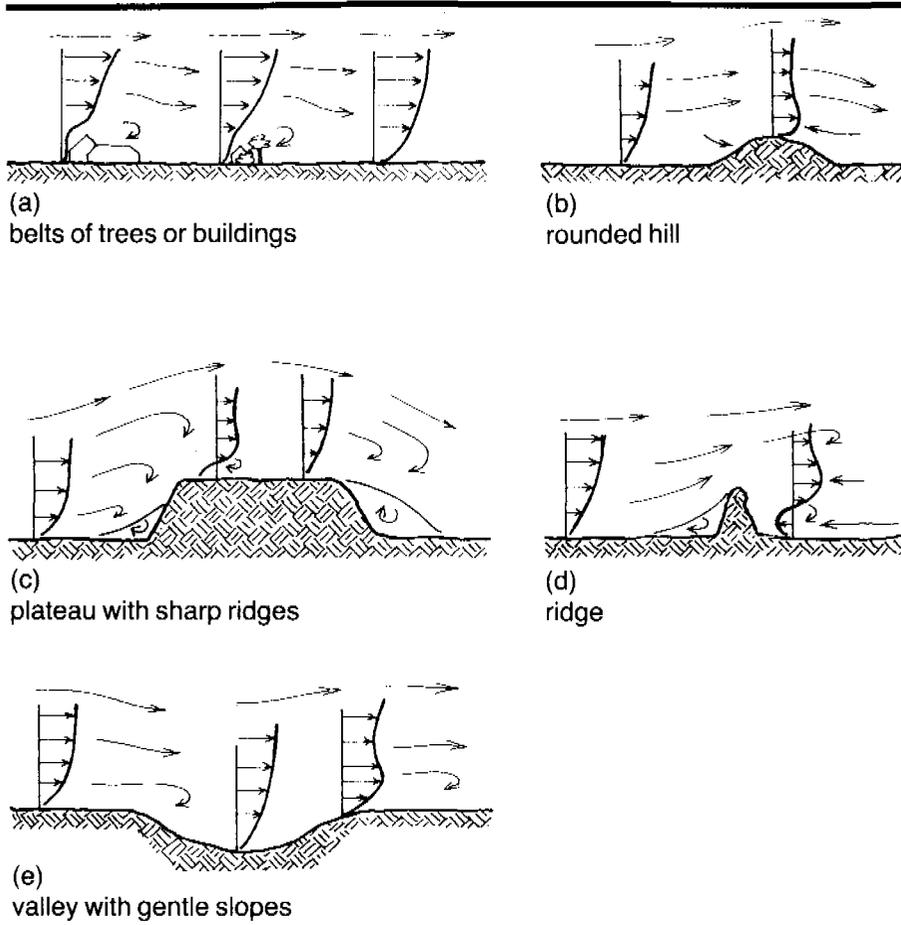


Figure 6.9: Effect of various obstructions and topographical features on wind speeds

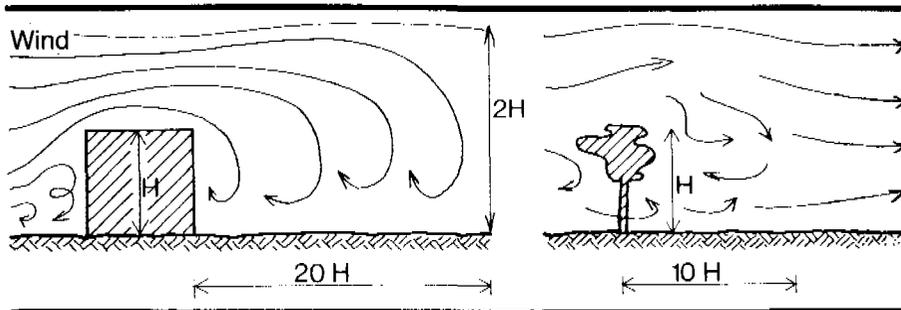


Figure 6.10: Zone of turbulence behind an obstruction

6.9 DESIGN

The power output of a wind pump is usually presented diagrammatically in a power curve, which shows the relationship between hydraulic power output and wind speed (Figure 6.11). The wind pump starts operation at the "cut-in" wind speed (V_{in}). At greater wind speeds, the hydraulic power output increases until at the "rated" wind speed (V_r), the maximum power output is obtained. In most wind-powered pumping systems, a control device will then be activated, which limits the rotational speed of rotor and pump. At limited rotor speed, the wind pump can continue to operate until the "cut-out" wind speed (V_{out}) is reached. The rotor is then stopped or turned away from the wind to prevent damage.

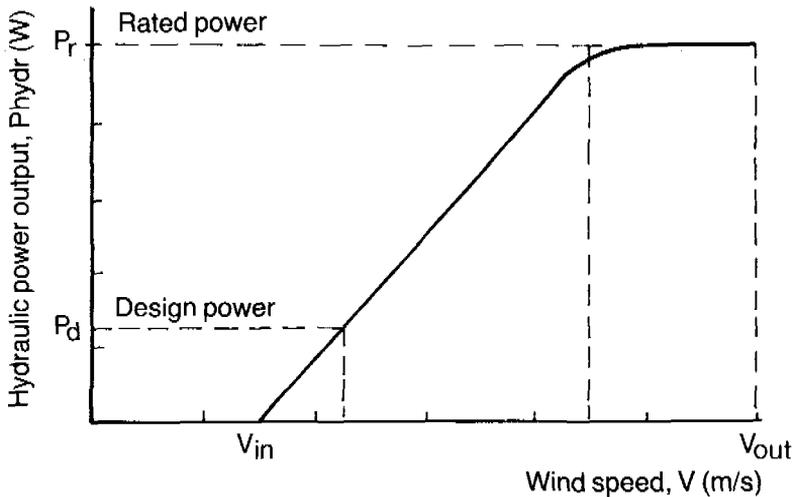


Figure 6.11: Power curve of wind pump

To work efficiently, the wind pump should be designed for maximum power output in the prevailing range of wind speeds. The power output at the design wind speed (V_d) is called design power (P_d). The design wind speed is generally in the range of 0.8 to 1.3 times the annual average wind speed.

Values for the power curve are generally in the following ranges:

$$V_{in} = \text{approximately } 2/3 V_{design}$$

$$V_{design} = 3 - 5 \text{ m/s}$$

$$V_{rated} = 8 - 10 \text{ m/s}$$

$$V_{out} = 12 - 16 \text{ m/s}$$

For a wind pump to start operation, the wind speed has to be high enough to produce the necessary starting ("break-away") torque. Once started, the pump will need less wind power to run. The starting torque is an important consideration in the choice of pump. For example, a plunger pump normally has a starting torque of about three times the mean torque required when running, whereas the starting torque of a rotary pump is only about 1.5 times the mean torque. Thus, the type of pump selected has considerable influence on the "cut-in" wind speed at which the wind pump starts operation.

6.10 ESTIMATION OF HYDRAULIC OUTPUT

A rough estimate of the average hydraulic power output of a wind pump may be made with the following "rule of thumb" equation:

$$\bar{P} = 0.1 A \cdot \bar{V}^3$$

where:

\bar{P} = average hydraulic power output (W)

A = area swept by rotor (m^2)

\bar{V} = average wind speed (m/s)

In this equation, the dimensions do not tally and the equation is only valid for wind pumps of which the wind rotor and pump are well matched, and at sites where the average wind speed does not differ very much from the design wind speed.

Example:

A wind pump with a rotor of 5 m diameter at a site with an average wind speed of 5 m/s, may be expected to produce an average hydraulic power output of about 245 W. Thus, operating 24 hours per day, this wind pump could produce about 6 kWh hydraulic energy output per day. This corresponds, for example, to about 50 m^3/d against a pumping head of 40 m, or 200 m^3/d through 10 m head.

The diagram presented in Figure 6.12 can be used to estimate the average hydraulic power output for wind pumps of varying rotor size and operating under various combinations of average wind speed and pumping head.

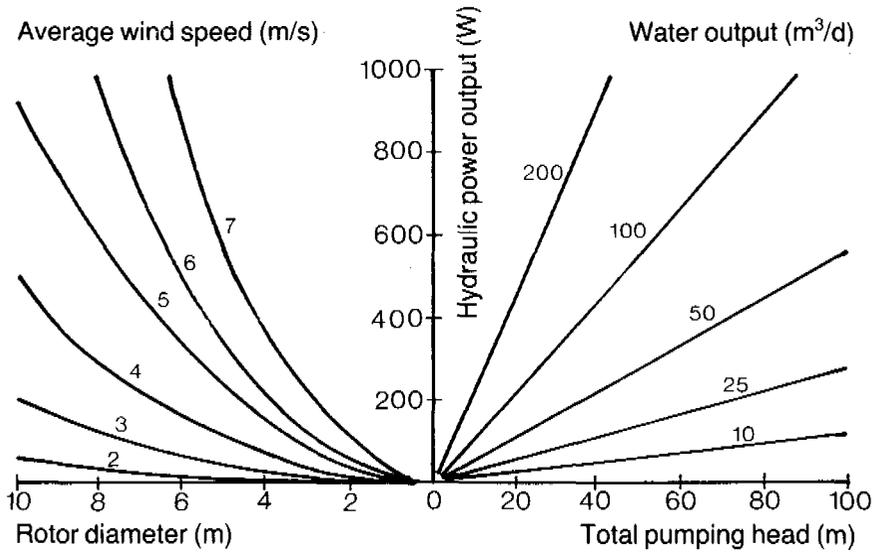


Figure 6.12: Estimation of average hydraulic power output of wind pump (Rastogi, 1982a)

The following method may be used to determine accurately the hydraulic energy output of a wind pump. A frequency distribution histogram is prepared and multiplied by the power curve for the wind pump to give the hydraulic energy output histogram (see Figure 6.13). The total energy output over the period of analysis can then be determined by adding up all columns in the histogram.

The annual hydraulic energy output of a wind pump can also be estimated roughly using the following equation:

$$\bar{E}_{\text{hydr}} = 0.9 \bar{V}^3 \cdot A$$

where:

- \bar{E}_{hydr} = annual hydraulic energy output (kWh/year)
- \bar{V} = average wind speed (m/s)
- A = rotor swept area (m^2)

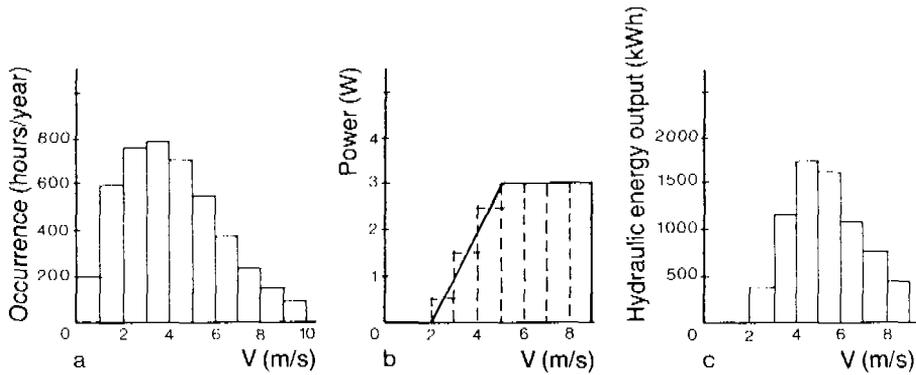


Figure 6.13: Determination of hydraulic energy output of wind pump (Rastogi, 1982b)

6.11 MAINTENANCE

Occasionally, lubrication of the bearings, bolt tightening, minor adjustments, and repairs need to be made. A complete overhaul and service will probably be required once every two or three years. Depending on the quality of the water pumped, cup seals and other moving parts of the pumps are likely to need more frequent maintenance. If the wind pump is equipped with a stuffing box, then this box should be inspected regularly, say every two months.

These maintenance provisions are all that well-designed wind pumps require. If there is no gearing, there will be no need to change the oil. If conventional bearings are used on the rotor axis, regular greasing or lubrication is required, which can be organized by the user community. However, permanently lubricated bearings do not require any maintenance; inspection and servicing once a year should be sufficient.

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7. Hydropower

Hydropower is the energy in flowing water. The amount of hydropower available depends on the fall and flow rate. The main types of hydropowered pumping devices used in small community water supplies are: hydraulic ram pumps; water turbines; and river-current pumps. These pumps can operate continuously without a supply of fuel but require civil works, such as dams, weirs, intake structures, and pipelines, the scale and costs of which depend on conditions at each individual location.

7.1 HYDRAULIC RAM PUMPS

Throughout the world, hydraulic ram pumps have been installed to supply water to villages and farms and this type of pump has given long and reliable service. These pumps operate on the principle of creating a pressure surge, or water hammer, in the drive pipe by the sudden stoppage of water flowing through it. (Figure 7.1).

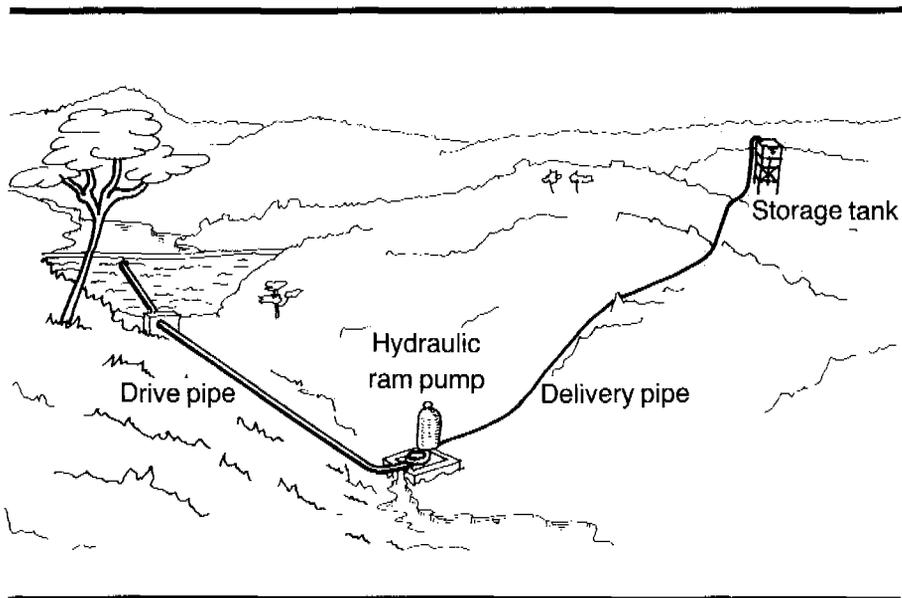


Figure 7.1: Hydraulic ram pump installation

The supply of water from the source must be steady and continuous to operate the hydraulic ram pump. Hilly or mountainous areas with a good supply of flowing water are suitable locations. These pumps can be operated by a flow of as little as 4 l/min, provided there is sufficient fall. Alternatively, if the water flow is fairly great, a fall of 0.8 m is adequate to operate a ram pump.

The inclined pipe feeding the water from the source to the ram pipe is called the drive pipe. The essential moving part of the pump is the impulse valve, which, when opened, allows the flow in the drive pipe to gain speed and power. Sudden closure of the valve causes the flow to stop, and thus creates the pressure surge in the drive pipe which is converted into power for water pumping.

Foundry-made hydraulic ram pumps are strongly built of rigid materials (Figure 7.2). When correctly installed, these pumps are very reliable and can lift water against considerable pumping heads. They can work satisfactorily for many years and need only limited maintenance.

A number of low-cost hydraulic ram pumps are made from locally available materials. Some of these designs use components which are obtainable "off-the-shelf", as shown in Figures 7.3 and 7.4.

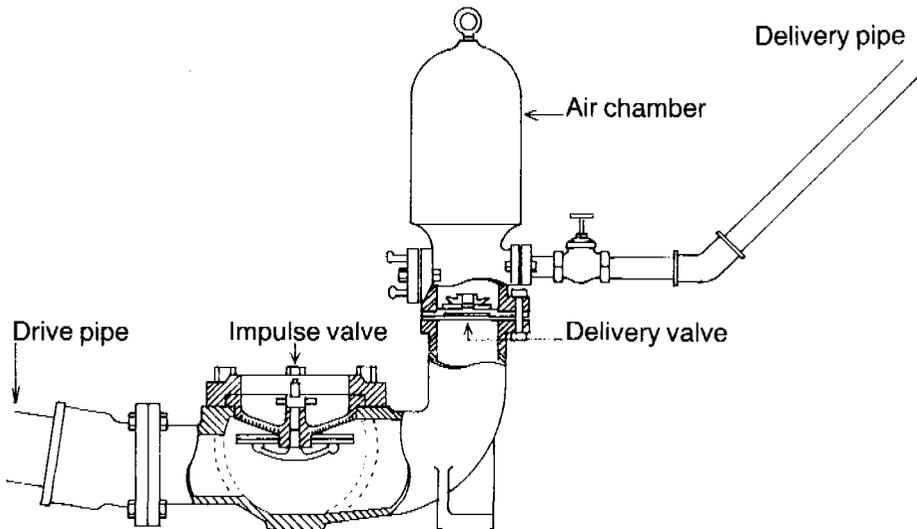


Figure 7.2: Example of hydraulic ram pump (John Blake Ltd.)

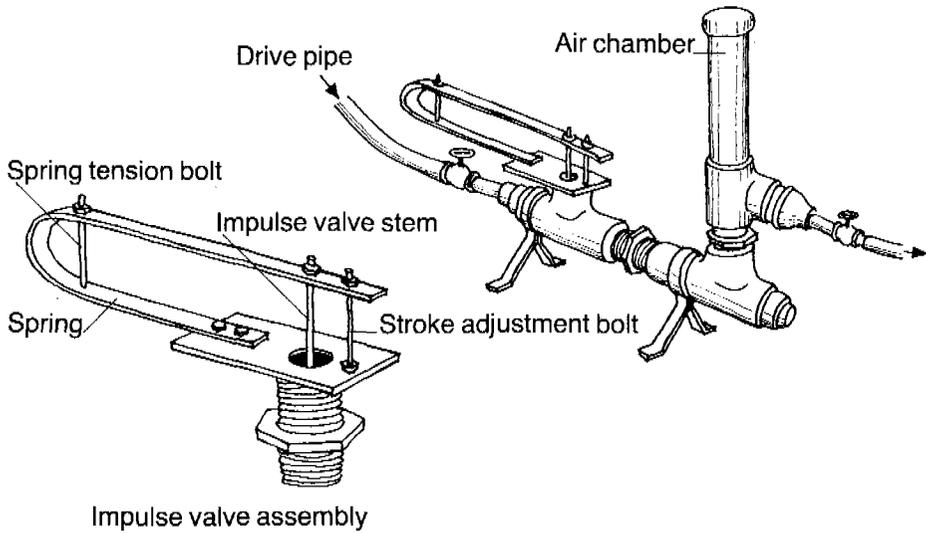


Figure 7.3: Example of low-cost hydraulic ram pump (Watt, 1975)

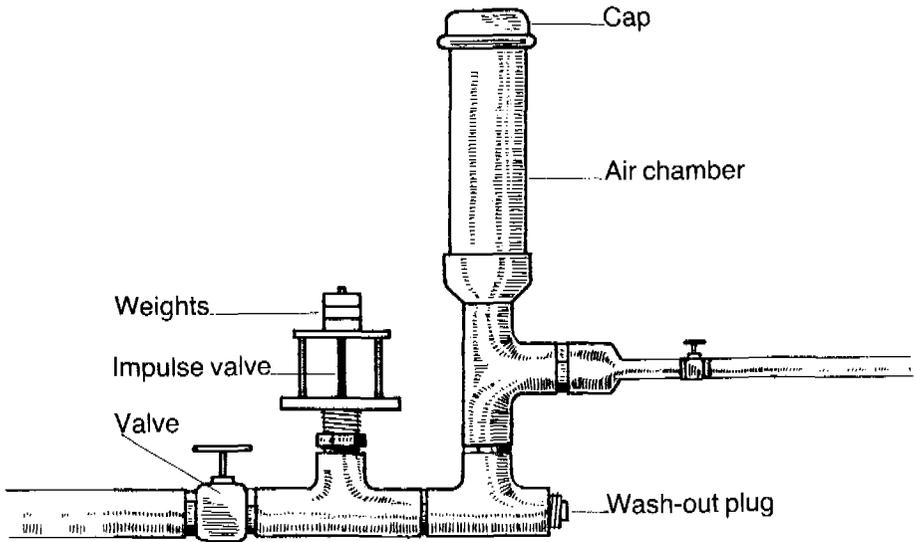


Figure 7.4: Example of hydraulic ram pump made from off-the-shelf components (Watt, 1975)

Locally manufactured hydraulic ram pumps are generally much cheaper than imported, foundry-made ram pumps. However, the cost saving with these pumps is not very great, because the cost of the ram pump is only a small proportion of the total cost of the total installation.

Operation

At the start of the pumping cycle, water from the source runs down the drive pipe, gaining speed and power, and then through the pump body, finally escaping through the impulse valve (Figure 7.5A). As the flow through the impulse valve speeds up, the hydraulic pressure on the valve increases until it exceeds the weight of the valve, or the spring load at which the valve is set, and the valve is then forced to close suddenly. The moving column of water is halted instantly, and a pressure surge is created in the drive pipe. The delivery valve is forced to open and water flows through the opened valve into the air chamber (Figure 7.5B). This will continue until the energy of the pressure surge is exhausted. The impulse valve then opens by its own weight, or by its spring load, and water from the source starts running again through the drive pipe and a new pumping cycle begins (Figure 7.5A). Most hydraulic ram pumps operate at 30-100 pumping cycles per minute, depending on the weight or spring tension setting of its impulse valve.

The air chamber cushions the pressure pulses of the water surges entering it, and so ensures that there is a fairly continuous flow through the delivery pipe (Figure 7.5C). A small air valve is fitted to the pump chamber. During each pumping cycle, a small amount of air is drawn in. This is essential because some air dissolves in the water and leaves the air chamber with the pumped water. If the lost air is not replaced, the air chamber will become full of water and the hydraulic ram will cease to operate.

Hydraulic ram pumps are not self-starting. Usually, the impulse valve is operated by hand until the pump begins to operate by the impulse action.

The requirements for operation and maintenance of hydraulic ram pumps are limited to:

- occasional adjustment of the impulse valve;
- regular check on functioning of delivery valve;
- occasional replacement of the valve rubbers;
- occasional tightening of bolts.

Occasionally, a ram pump may have to be dismantled for cleaning because of sand and silt deposited in the pump chambers and in the impulse and delivery valves. To prevent debris from entering the drive pipe, a grate or strainer is usually fitted at the intake.

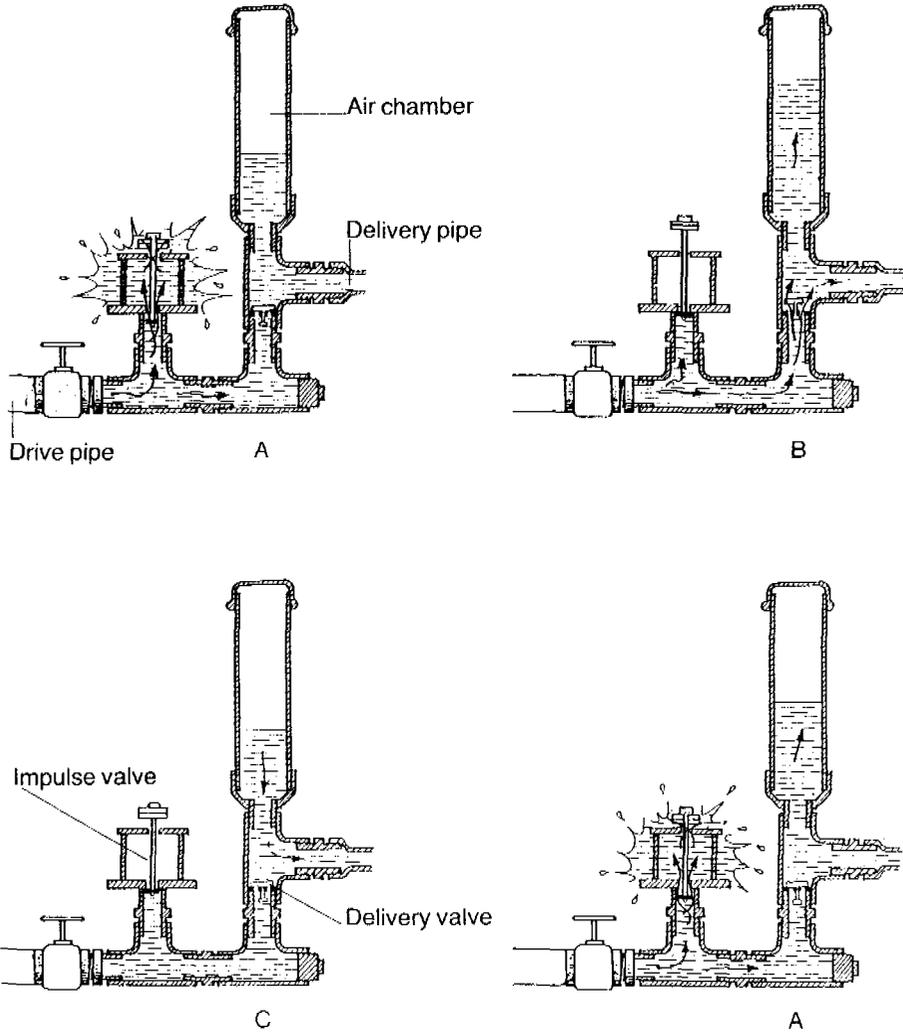


Figure 7.5: Operation of hydraulic ram pump

Design

The design parameters for hydraulic ram pump installations are shown in Figure 7.6. The water flow (Q) from the source and the supply head (H), determine the combination of delivery flow (q) and delivery head (h) that the ram pump can produce. This is indicated in Table 7.1.

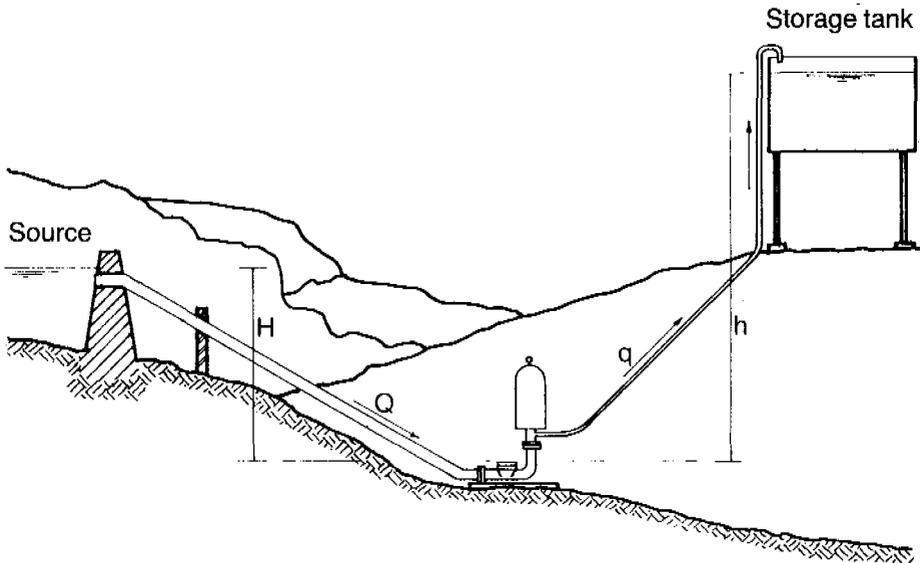


Figure 7.6: Design parameters of hydraulic ram pump installation

Table 7.1 Water delivery (q) as a proportion of supply flow (Q) for hydraulic ram pumps operating under various combinations of supply head (H) and delivery head (h)

h	H	2	3	4	5	6	7	8	9	10
q	Q	40	26	18	13	11	085	07	06	05

Example:

Supply head $H = 5$ m
Delivery head $h = 45$ m
Supply flow rate $Q = 100$ l/min

The ratio of delivery head to supply head (h/H) is 9. From Table 7.1, the output flow rate will be about 0.06×100 l/min, or 6 l/min, which is 8.6 m³/day in continuous operation.

The hydropower available in the supply flow of water can be calculated with the equation:

$$P_{\text{input}} = \rho_w \cdot g \cdot Q \cdot H$$

The hydraulic power output produced by the hydraulic ram pump is calculated as:

$$P_{\text{output}} = \rho_w \cdot g \cdot q \cdot (h-H)$$

Therefore, the operating efficiency (Rankine efficiency) of a hydraulic ram pump is:

$$\eta = \frac{q(h-H)}{Q \cdot H}$$

where:

η = operating efficiency (%)
 h = delivery head (m)
 H = supply head (m)
 q = delivery flow rate (l/min)
 Q = supply flow rate (l/min)

Example:

Supply head $H = 5$ m
Delivery head $h = 45$ m
Supply flow rate $Q = 100$ l/min
Output flow rate $q = 6$ l/min

The operating (Rankine) efficiency of this ram pump is:

$$\eta = \frac{6 \cdot (45-5)}{100 \cdot 5} = 48\%$$

Frequently, manufacturers calculate the efficiency with the equation:

$$e = \frac{q \cdot h}{Q \cdot H}$$

This gives a slightly higher efficiency value than the Rankine efficiency; in the example it would be 54%.

If the required delivery flow rate is greater than one hydraulic ram pump can supply under the given conditions, a number of pumps may be installed in parallel, provided the supply flow from the source is sufficient to drive all the pumps. Each pump unit must have its own drive pipe, but the water can be delivered through a common delivery pipe (Figure 7.7).

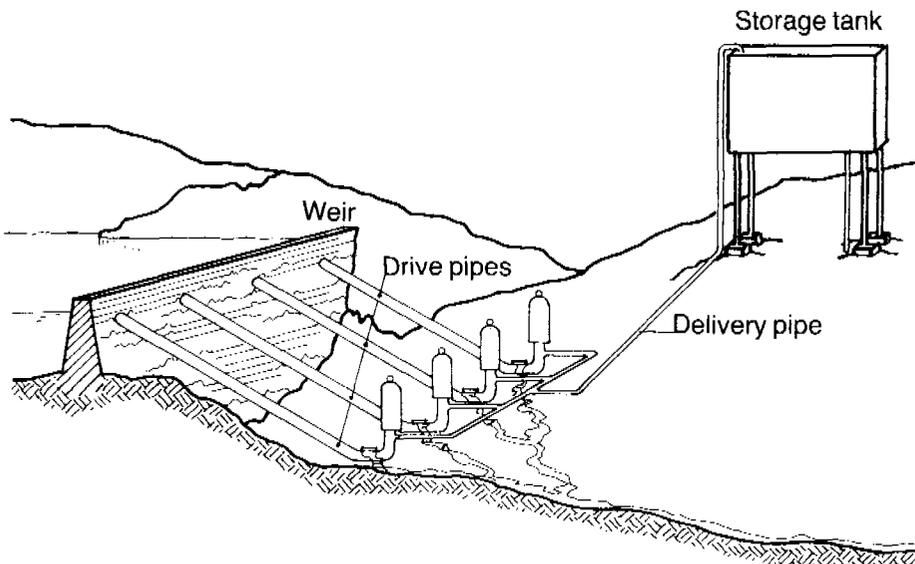


Figure 7.7: Hydraulic ram pumps operating in parallel

7.2 TURBINE PUMPS

In the People's Republic of China, turbine pumps are widely used. Although a relatively recent development from the early 1960s, as many as 90 000 turbine pumps have been installed, mostly for irrigation purposes.

Water turbines operate at relatively high rotational speed, converting the hydropower to mechanical shaft power to drive the pump. The turbine shaft is coupled directly to the pump. Essentially, a turbine pump consists of a water turbine with a centrifugal pump mounted immediately above the turbine on the same shaft (Figure 7.8). The turbine operates under water and is driven by the

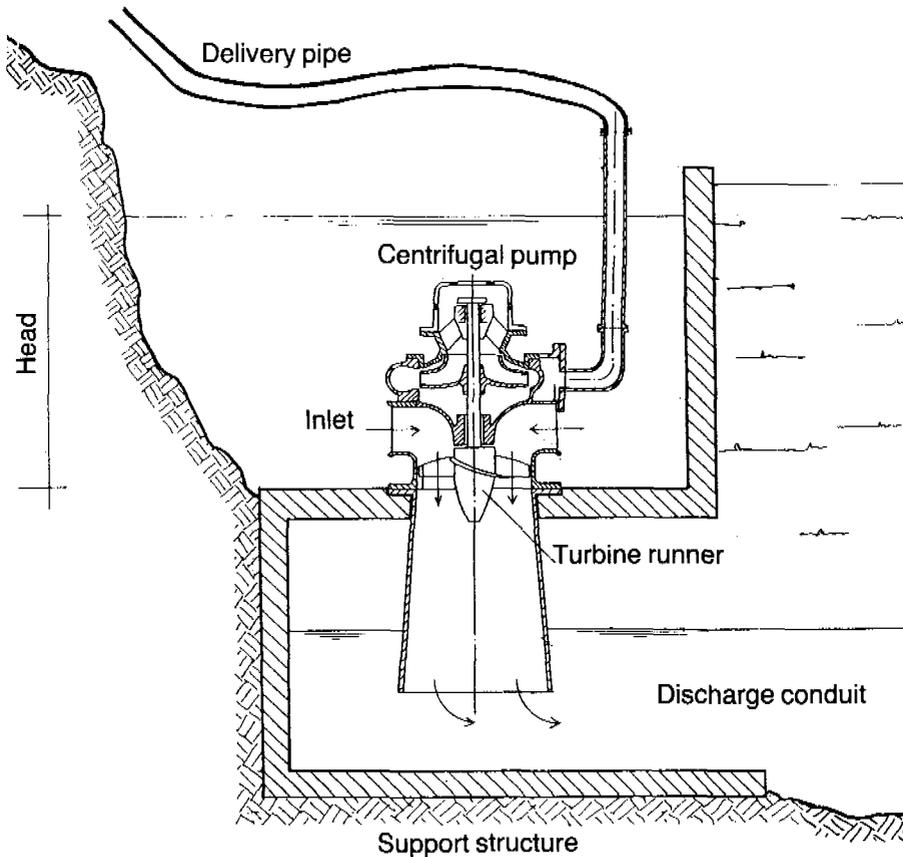


Figure 7.8: Main features of turbine pump developed in China (Collett, 1982)

water running through it. Usually, it has an axial-flow propellor with fixed blades rotating in a casing with fixed or adjustable guide vanes. The support structure on which it is installed is usually in a separate channel, with a sluice gate used to control the water flow. A wide range of turbine pumps is available for varying conditions and requirements. Rivers, streams or channels with water flows of 15 l/s minimum, and where a head of at least 0.5 m can be obtained, provide suitable conditions for turbine pumps.

Cost analyses based on the limited data available from China, show that turbine pumps are significantly cheaper per kWh of hydraulic energy output than electric motor pumps or diesel pumps. Turbine pumps, therefore, may be expected to be economically attractive in most situations where conditions are suitable for their use.

Turbines with fixed blades are only efficient for a narrow range of flow rates. In locations where the supply flow varies considerably, it is advantageous to install several small turbine pumps rather than a single large unit, because each individual unit can then be operated at the flow rate for which it has been designed. It is good practice to provide at least two units, one of twice the design flow rating of the other. In this arrangement, the larger unit can be operated in flows about two-thirds of the maximum flow, and the smaller unit when the flow is one-third of the maximum. Efficient operation will then be possible at one-third of the maximum flow with the smallest unit, at two-thirds of maximum flow with the larger unit, and at maximum flow with the two units operating together.

7.3 RIVER-CURRENT PUMPS

There are a number of river-current or in-stream pump models that use the kinetic energy of river current, without the need for civil works, such as dams or penstocks, to drive the pump. They extract energy from the current in a large river, instead of using the head of a stream.

The ITDG pump has a vertical shaft rotor which is suspended in the river water from a floating pontoon (Figure 7.9). The power from the rotor is transmitted by a belt to a small centrifugal pump which delivers water through a floating pipeline to a tank on the river bank. Tests conducted on the River Juba in southern Sudan have shown that a prototype pump with a rotor of about 3 m diameter operating in a river current of 1.0 m/s, could deliver about 100 l/min against a head of 5 m. Design calculations indicate that the water output would be about 300 l/min in a river current of 1.5 m/s. Cost analyses indicate that the device is generally competitive in cost with diesel pumps, especially where fuel is scarce and expensive.

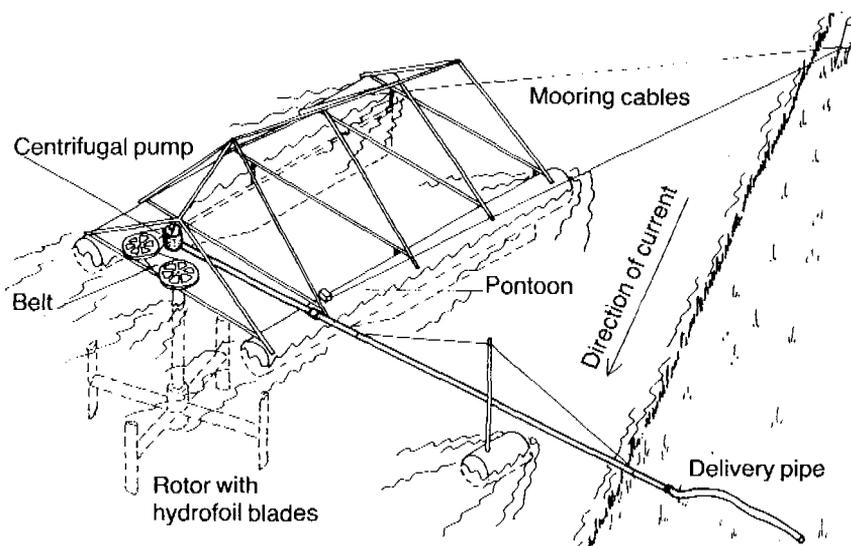


Figure 7.9: ITDG river-current pump (Collett, 1981)

A similar pump, known as the Rio-Bomba, has been developed in Colombia to supply water to riverside communities. A water output of 50 l/min has been obtained in river currents of 1.0 m/s and against a head of 8 m.

The Plata pump has been designed to pump water from streams or rivers using the energy available from a small fall. A working flow of 30 l/s with a fall of 0.4 m is sufficient to operate the pump. The available flow at potential sites has to be measured to establish whether stream flow is sufficient, taking into account seasonal variations. The maximum head for the Plata pump is about 0.9 m. According to test results, at a flow of 85 l/s and 0.6 m fall, sufficient power is produced to deliver 45 l/min against a head of 3 m, or 10 l/min to a height of 40 m. The drive unit is a special low-head water turbine, in which propeller runners are mounted in tandem. The turbine generates maximum power when half full, and will cease to operate when water fills it completely. The shaft is connected by a reciprocating crank to two small single-acting plunger pumps. There are a number of settings available on the crank disc to adjust pump operation to the available head and the discharge capacity required at a given site. A small dam of planks, sand bags, or similar materials may need to be constructed to create the required head. To avoid damage from floating debris, the turbine intake is fitted with a delta-shaped grid which may have to be cleared daily.

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8. Biomass energy

Combustible gases or fluids can be produced from biomass, such as human and animal waste, crop residues, sugar-cane, cassava, eucalyptus, palm-oil, and aquatic weeds and plants. These gases or fluids can be used as fuel for engines driving a water pump. The two main groups of biomass conversion technologies to produce combustible gases or fluids are biochemical conversion and thermochemical conversion. Biochemical conversion, or digestion, of organic biomass is a natural process involving several concurrent bacterial and enzymatic processes. When occurring in an oxygen-free environment, the digestion is anaerobic and a combustible gas known as biogas is produced. Energy-rich fluids, such as alcohol, ethanol and methanol, are produced by another biochemical conversion process of biomass, namely, fermentation. Thermochemical conversion of biomass occurs when it is heated under partial or complete exclusion of air. The main processes taking place are pyrolysis, in which biomass material is transformed by heating, and gasification, in which gas is produced by incomplete combustion of heated biomass. The combustible gas produced, which consists of a mixture of carbon monoxide, hydrogen and methane, is known as producer gas.

8.1 BIOGAS PRODUCTION PROCESS

The most common method of biogas production is anaerobic digestion in a closed tank, called a "digester". The biomass is mixed in the digester with water to form a slurry, in which anaerobic digestion takes place in two steps. In the first step, called liquefaction, organic matter is broken down by enzymatic hydrolysis and fermented to form mainly acids and alcohols. Subsequently, in the gasification phase, methane bacteria break the acids and alcohols down to methane and carbon dioxide, and small amounts of other gases, such as carbon monoxide, nitrogen and hydrogen sulphide. Biogas contains about 60% methane and 40% carbon dioxide; the small amount of hydrogen sulphide gives the gas a slight odour of rotting eggs. The calorific value of biogas is 23-26 MJ of heat energy per m³ gas.

The bacterial and enzymatic processes of anaerobic digestion are sensitive to variations in temperature, water content, and general composition of the slurry in the digester. Biogas is only produced if air is completely excluded from the digester so that an anaerobic condition can develop. Therefore, the digester tank must be airtight.

Water content of slurry

If the water content of the slurry is too low, the bacteria and other micro-organisms cannot function effectively and the quantity of biogas produced will be small. If the slurry is too dilute, relatively little organic material can be digested and biogas production is limited.

If human excreta and urine, manure, and wastes from poultry are mainly used as digester feed, then the biomass water ratio should be between 1:1 and 1:2. Thus, for every 100 kg of faeces and urine, 100-200 litres of water is required. If the raw material is mainly crop stalk, more water is needed in a ratio of 1:3 or 1:4. Good mixing of the liquid in the digester tank is essential to promote effective digestion, especially if raw, stinky biomass is used.

Temperature and retention period

The temperature of the slurry in the digester is a very important factor for the efficiency of the digestion process. Most anaerobic bacteria function best in the temperature range of 30 to 35°C, and this is the optimal temperature for biogas production. The temperature in the digester tank should always be above 20°C, because at a lower temperature, little biogas is produced and below 10°C, digestion stops completely.

Retention periods of 40-60 days for the slurry in the digester tank are usual in most tropical countries. If ambient temperatures are high, for example, on average between 30 and 35°C, a shorter retention period of 30-40 days may be sufficient. In cooler climates, longer retention periods of 80-90 days are common (Figure 8.1).

Acidity/alkalinity of mixture

Methane bacteria are very sensitive to variations in the acidity/alkalinity (pH) of the slurry in the digester. For optimal functioning, the pH value of the slurry should be kept within the range of 6.8 to 7.5, that is, neutral to slightly alkaline. The pH value can be determined reasonably accurately from a litmus-paper test in a water sample. During the digestion process, organic acids are produced, and if not controlled, the mixture in the tank may gradually become acid, thus seriously disturbing the bacterial and enzymatic processes. Alkaline material, such as lime or ashes, should be added regularly to the mixture to keep the pH value within the desired range.

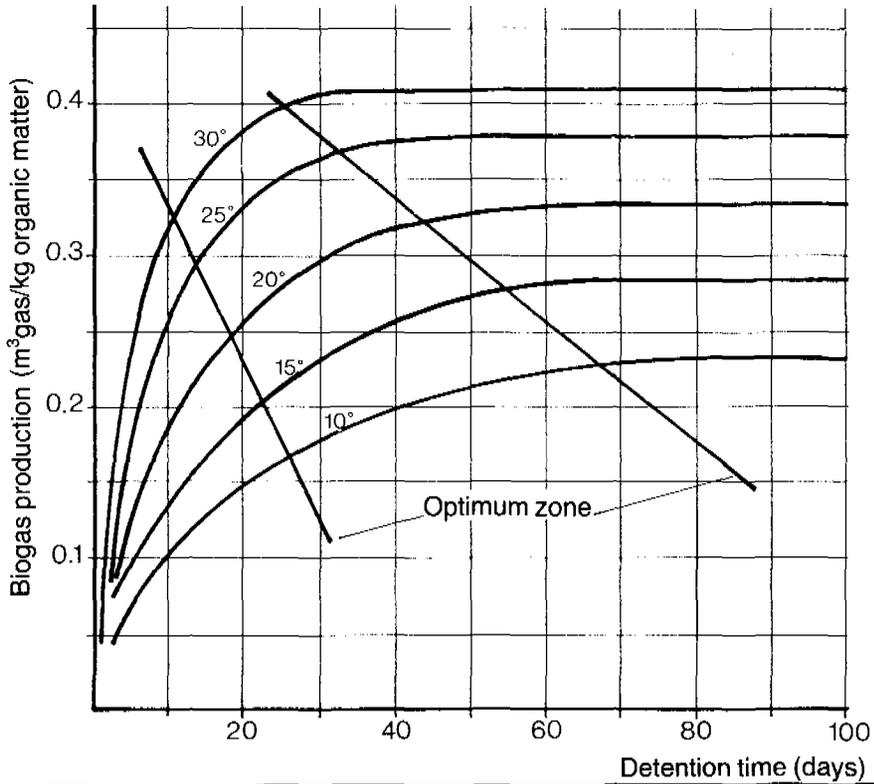


Figure 8.1: Biogas production as a function of retention period and temperature (BORDA, 1982)

Nutrients

Nitrogen is essential for bacterial growth and activity. Raw materials having a low carbon/nitrogen ratio are readily digested, but crop stalks, such as wheat or rice straw (see Table 8.1), require an additional supply of nitrogen for efficient digestion. The high cellulose content of grass and crop stalks makes them difficult to digest. Human faeces and urine, and also animal wastes, are rich in nitrogen and nutrients suitable for growth and multiplication of anaerobic bacteria. For optimal biogas production, the various types of biomass material must be fed in carefully balanced and mixed proportions. It is recommended that the carbon/nitrogen ratio of the combined input materials is kept below 30:1. A summary of the optimal ranges for biogas production parameters is given in Table 8.2.

Table 8.1: Carbon/nitrogen ratios of various biomass materials (Gary, 1979)

Raw materials	Carbon/nitrogen ratio
Wheat straw	87 : 1
Rice straw	67 : 1
Fresh cattle dung	25 : 1
Fresh human faeces	3 : 1

Table 8.2: Parameters of biogas production and general range of optimal values

Parameter	Optimal range
Temperature (°C)	30 – 35
pH	6.8 – 7.5
Carbon/nitrogen ratio	20 – 30
Retention time (days)	40 – 60
Water/solids ratio	6 – 10

8.2 BIOGAS PRODUCTION PLANT

A very simple biogas production plant, comprising one or more digesters and a gas holder, can be made from oil drums (Figure 8.2). The biomass is fed in batches into the digester drums, filling one after the other.

Several types of small-size biogas production plants are used in China, and since the early 1970s, several millions have been built, mostly in Szechuan Province. The majority are family units of 6-10 m³ volume, producing 1-2 m³ biogas daily from human and animal waste, with some vegetable material as additional feed. There are also tens of thousands of medium-size (about 50 m³ volume) and large (more than 100 m³ volume) plants, with gas production rates of 10-20% of digester volume per day.

A circular digester of brick or cemented masonry with a fixed dome is common in China (Figure 8.3). There are no metal parts except for a small length of steel pipe to deliver the gas. This design requires a relatively high level of technical skill to construct. In practice, many digesters of this type appear to be not completely airtight and gas leakage is a common problem.

In India, about 80 000 small biogas plants of 8-10 m³ volume have been installed, most producing biogas from cow dung. The plant has been named the KVIC digester, after the Khadi and Village Industries Commission promoting it. The digester tank is a concrete, cylindrical pit sunk partly into the ground, and

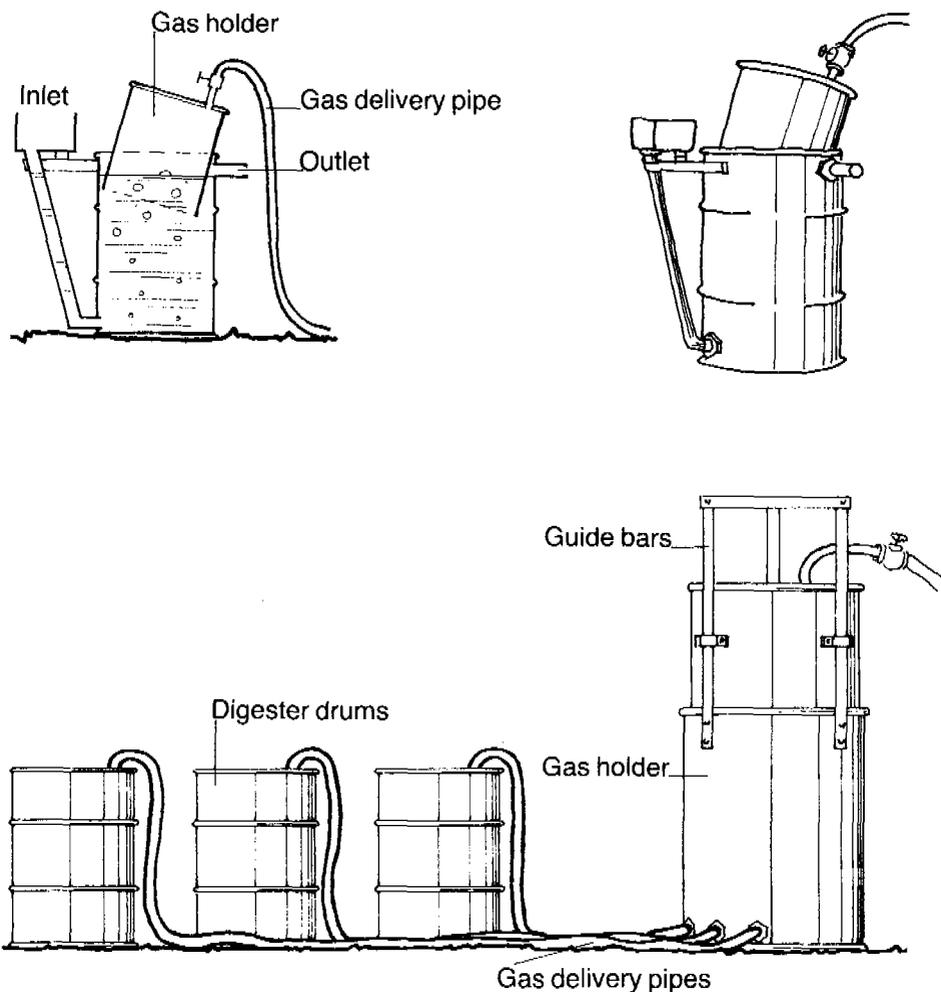


Figure 8.2: Basic biogas production plant using digester drums

2.5-4 times as high as wide (Figure 8.4). The gas production rates achieved with this digester design are 20-30% of digester volume per day. An inverted steel dome is placed over the slurry in the digester to collect the biogas produced. As the gas accumulates, the steel gas holder rises. The recommended gas holder capacity is 50-60% of the daily gas production.

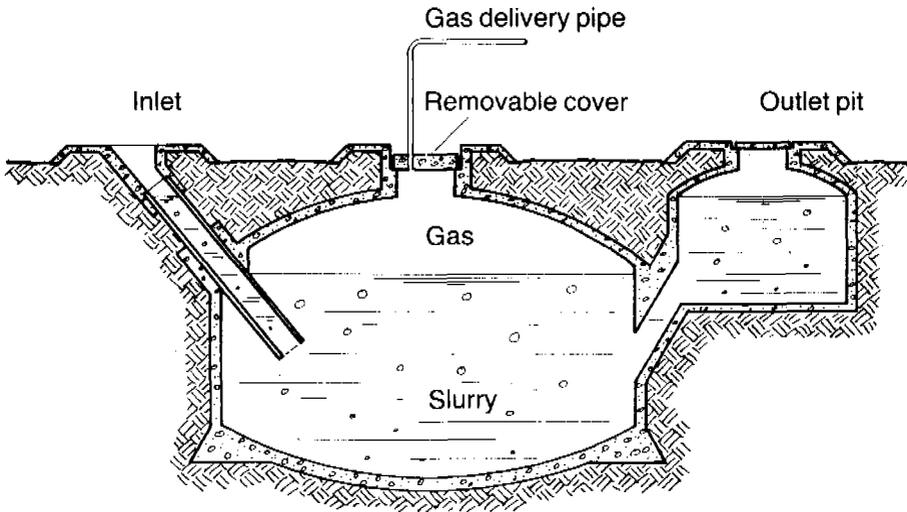


Figure 8.3: Circular fixed-dome digester used in China (McGarry, 1978)

A similar type of digester has been developed in India, and is known as the Janata digester. A fixed, dome-shaped cover built over the digester serves as the gas holder (Figure 8.5). The simple design, which can be constructed from local materials without the need for a steel dome, makes this an attractive alternative.

In Pakistan, a biogas production plant has been developed which has an external water seal around the gas holder wall to eliminate foul odours, and to reduce the corrosive action of the hydrogen sulphide in the biogas (Figure 8.6). This design reduces gas leakage and maintenance costs, but is relatively expensive to construct.

A simple biogas production plant, using a flexible bag for both the digester tank and gas holder, has been developed in Botswana (Figure 8.7). These units, which vary in size from 10-400 m³ volume, are easy to transport, simple to install, and inexpensive to construct. In the Philippines, a biogas production plant is constructed with a digester tank comprising two compartments (Figure 8.8). Most of the sludge settles in the first compartment, thus preventing blockage of the pipe connection to the second compartment. A floating gas holder is used.

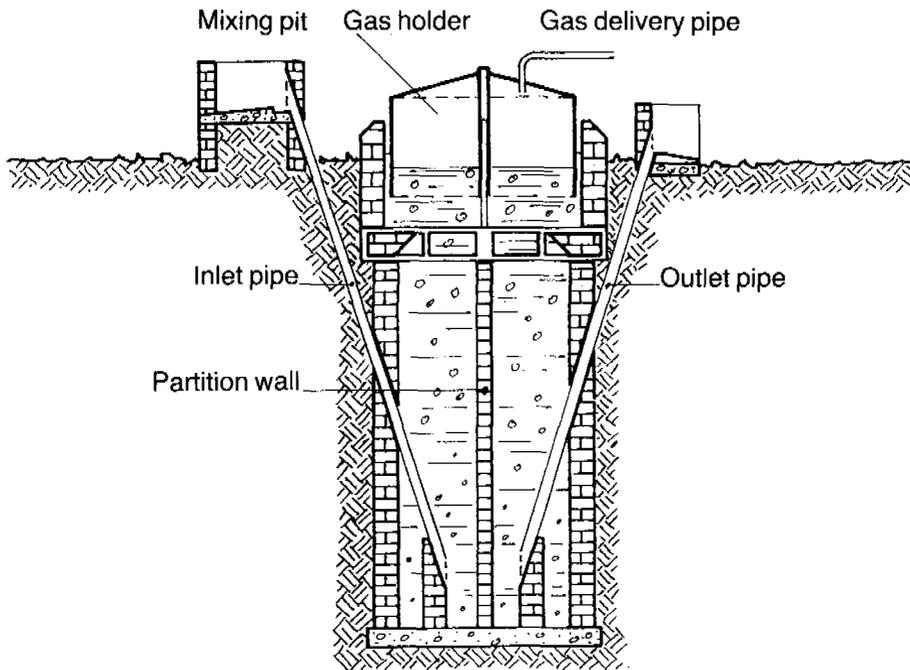


Figure 8.4: KVIC digester with floating gas holder (Tam, 1983)

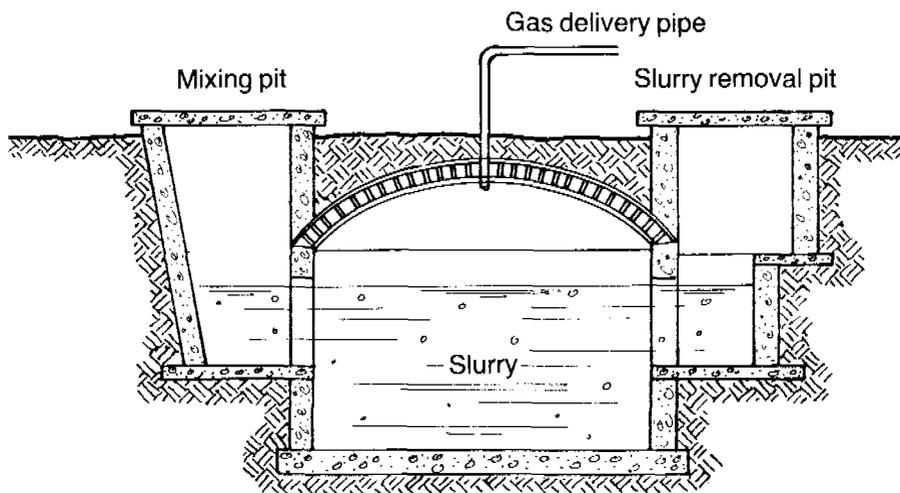


Figure 8.5: Janata digester with fixed dome (Barnett, 1978)

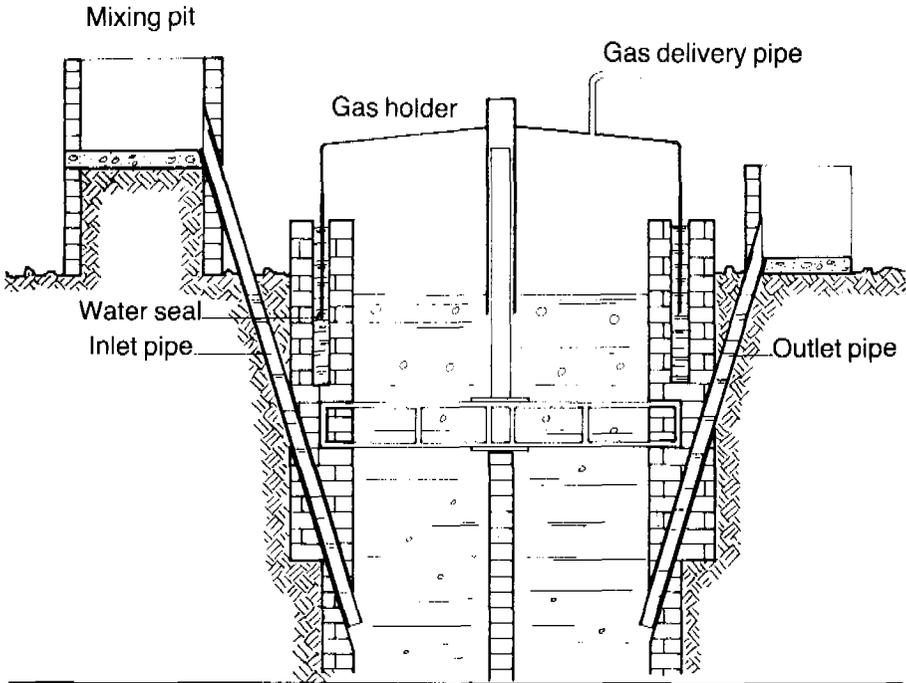


Figure 8.6: Digester with water-sealed floating gas holder (Pyle, 1982)

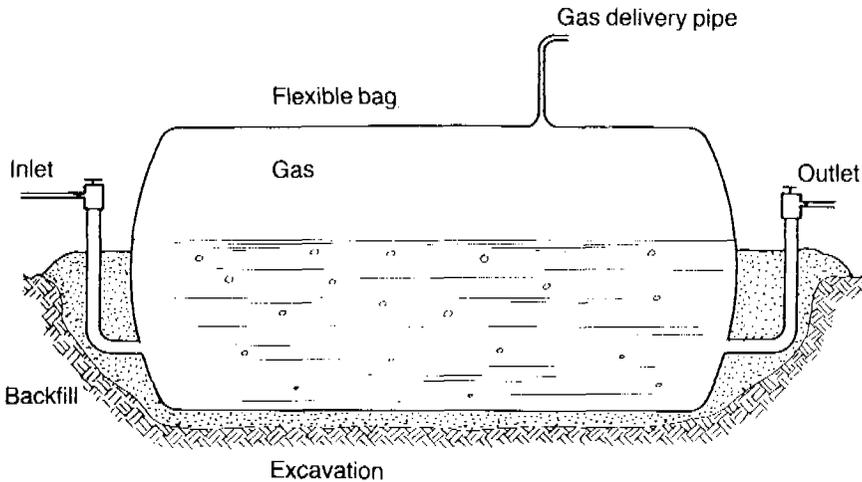


Figure 8.7: Flexible bag digester (Pyle, 1983)

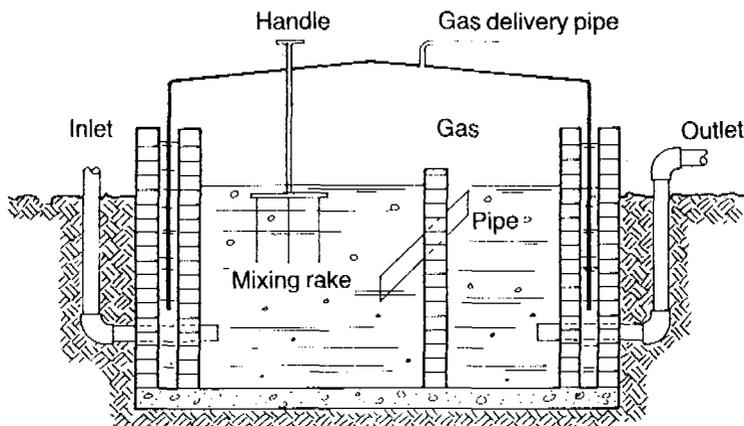


Figure 8.8: Two-compartment digester with floating gas holder, the Philippines (Arceo, 1983)

Biogas production rates

The rate of biogas production depends on the biomass material and type of plant used. A rough indication of production rates for various types of animal waste is given in Table 8.3. Generally, the gas production rate may be roughly estimated to be 10-30% of digester volume per day, depending on feed material, type of digester plant, ambient temperature, and other operating conditions.

Production of sufficient biogas to supply fuel for water pumping may be difficult in the cooler season. If the biogas digester were designed to produce sufficient gas to replace the entire diesel fuel requirement even in the cool season, the digester would have to be very large and thus construction costs would be extremely high. It will be more economical to design the biogas

Table 8.3: Biogas production rates for various types of feed materials (Mazumdar, 1982)

Animal waste	Amount available	Gas production rate (kg/d) (m ³ /d)
1 buffalo	10	150.50 – 0.75
1 zebu cow	8	100.25 – 0.40
1 calf		0.15 – 0.25
1 pig		250.05 – 0.10
10 chickens		0.02 – 0.04
1 sheep/goat		0.02 – 0.04
1 latrine user		10.02 – 0.03

production plant to provide most of the fuel requirement, say 80%, in the warmer months of the year, but less, say 40%, in the cooler months. Although more diesel fuel will be required, the saving on the construction cost of the gas production plant will result in lower overall costs.

8.3 ENGINES USING BIOGAS AS FUEL

Spark-ignited engines can run on biogas alone. Diesel engines require some modifications to enable them to run mainly on biogas supplemented by diesel fuel. This is "dual-fuel" operation, with up to 60% of the diesel requirement replaced by biogas. Experience shows that it is not practical to replace more of the diesel requirement, because of operating constraints with diesel engines. The temperature in the engine's combustion chamber is highest (about 700° C) at the end of the compression stroke, but this is lower than the temperature at which a biogas/air mixture ignites spontaneously. Thus, injection of a small supplement of diesel fuel is always required to ensure ready ignition of the biogas/air mixture.

Most diesel engines can be modified for dual-fuel operation. In many cases, the simplest arrangement is to connect the biogas supply pipe directly to the air intake pipe of the engine, behind the filter (Figure 8.9). To ensure satisfactory

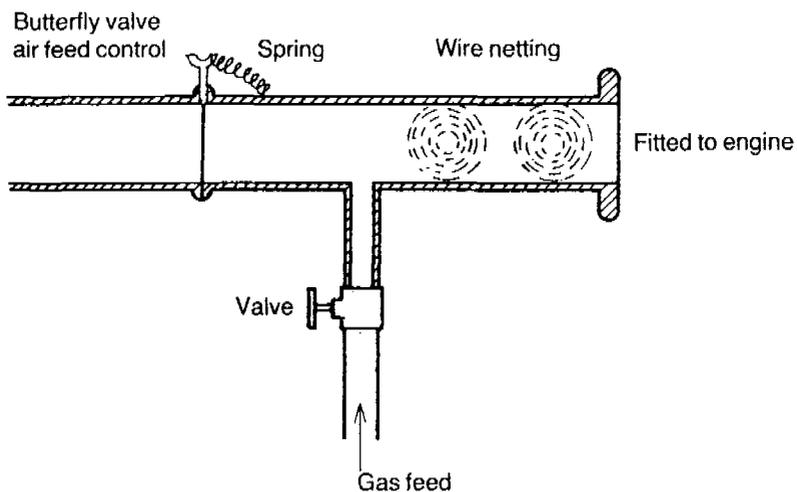


Figure 8.9: Diesel engine modification for dual-fuel operation (Kasturirangan, 1976)

dual-fuel operation, the hydrogen sulphide component of the biogas must be removed by purification. The peak power output of a modified diesel engine running on biogas is 25-35% less than if diesel fuel is used exclusively.

In principle, petrol engines can also run on biogas with a little petrol for starting up. A standard carburettor may be used for feeding the biogas in, but specially designed gas carburettors will generally give better results (Figure 8.10).

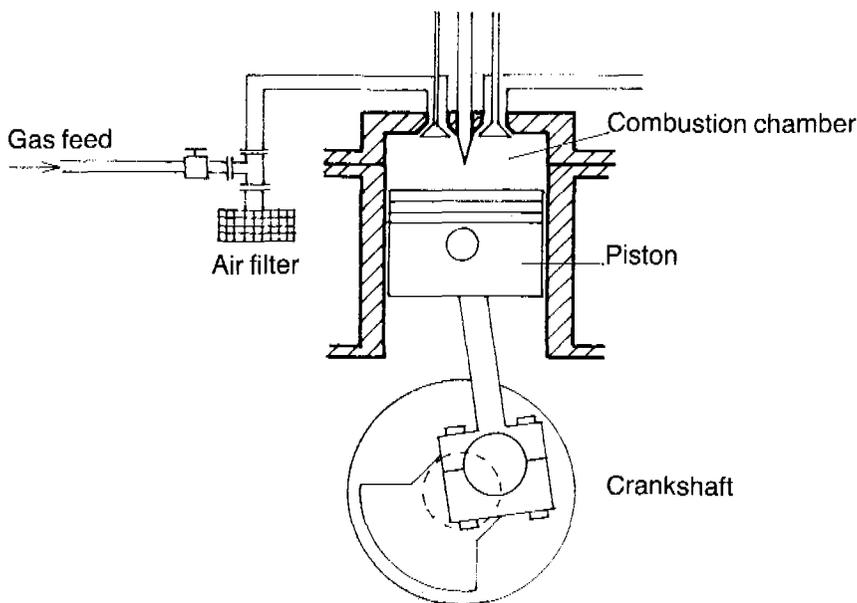


Figure 8.10: Carburettor designed for petrol engine running on biogas (Kasturirangan, 1976)

8.4 GASIFICATION

In the gasification process, dry biomass is heated and gasified to produce combustible gas known as producer gas. Suitable biomass materials for gasification are wood, charcoal, coal, and a variety of other dry organic materials, such as woodchips, sawdust, coconut shells, maize cobs, palmnut kernels, and fruit pits. Gasification is quite different from biogas production, because the process takes place in a dry environment.

Generally, the gasifier is an upright container into which the dry biomass material is fed from the top (Figure 8.11). A restricted supply of air is admitted at the bottom of the unit, just sufficient for part of the feed material to burn slowly as in a stove or furnace. It is essential that the supply of air is restricted, so that the entire fuel load does not combust. Only a small part of the material should burn to produce the heat required for gasification of the remainder.

A mixture of hot gases is produced, of which the main combustible components are hydrogen and carbon monoxide (together about 30-35% of the total gas volume), the remainder being mainly nitrogen. The calorific value of producer gas is relatively low, about 3-5 MJ per m³ gas.

There are several types of gasifiers, such as the fixed bed, fluid bed and molten bath gasifiers, each producing gases of different composition. Fixed-bed gasifiers are the most widely used and work best if the moisture content of the

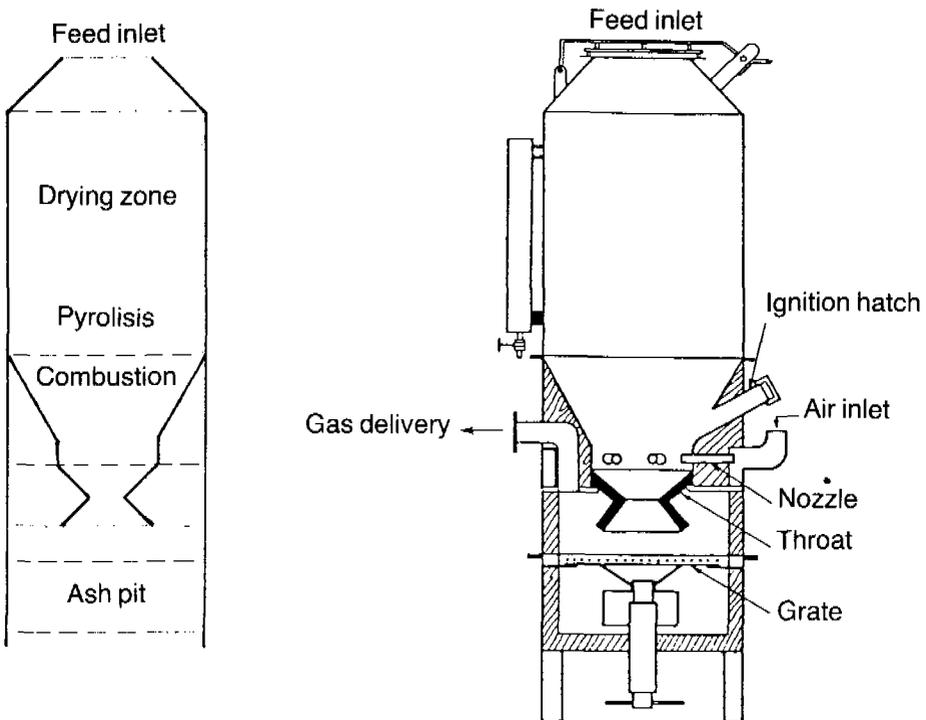


Figure 8.11: Schematic diagram of gasifier (Jain, 1984)

feed material is less than 25%. However, counter-current gasifiers may effectively use biomass feed with a moisture content of up to 40-50%.

Depending on the gasifier design, type of feed material, and operating conditions, the gas produced may contain substantial quantities of tar and soot and may be toxic because of the high carbon monoxide content. Therefore, the gas may need to be purified before use.

Feed material for gasifiers should not be too large in size because the efficiency of the gasification process depends on the contact surface between air and feed material. The best results are obtained with feed materials which are highly porous, reasonably moist, and of low ash content. Because of the many variables involved, operation of gasifiers is not easy to control and requires considerable skill. The efficiency of gasification is generally higher for large plants than for small plants.

8.5 ENGINES USING PRODUCER GAS AS FUEL

The power output of a gasifier is usually given as the peak shaft power of the engine using the producer gas. Gasifiers are available with peak shaft power ratings of 7.5 kW and more. Spark-ignited engines can run on producer gas alone, whereas for diesel engines, the gas needs to be mixed with a supplement of diesel fuel to ensure ready ignition and combustion. Most petrol engines can run on producer gas, but efficiency is low. Modern high speed petrol engines are not particularly suited to operation on producer gas, because they have small inlet valves which are easily blocked by the impurities in the gas. The mixture of producer gas and air also has a much lower combustion rate than has petrol/air vapour, and the power output of a petrol engine running on producer gas is only 50-60% of the petrol rated output.

8.6 ETHANOL PRODUCTION

Ethanol is produced by anaerobic conversion of sugars by micro-organisms, such as yeasts, bacteria or fungi. Sugars are present in biomass in the form of carbohydrates, starch, and also in cellulose material. Sugar crop residues, such as sugar-cane, cassava, sugar beet and sweet sorghum, are more suitable for ethanol production than are grain wastes. An indication of the ethanol production from various types of carbohydrate sources is given in Table 8.4.

Table 8.4: Ethanol production from various types of carbohydrate sources (Alam, 1982)

Carbohydrate source	Ethanol production (litre/tonne)
Sugar-cane	67
Cassava	180
Sweet sorghum	85

Data represent averages obtained in Brazil with conventional production processes.

8.7 ENGINES USING ETHANOL AS FUEL

Ethanol can be blended with petrol and used in spark-ignited engines which need no modifications, provided the ethanol content is less than 20%. If fuel of a higher ethanol content is to be used, then modifications must be made to the carburettor, ignition system or cylinder head. Special engines have been developed which can run on ethanol exclusively.

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APPENDIX A

GLOSSARY OF TERMS

Alternating current	Electrical current of which the direction is reversed at frequent intervals, 120 times per second (60 cycles per second), as used in electric grid power supply.
Anemometer	A device for measuring wind speed.
Aquifer	Water-bearing geological formation.
Basement (geological)	Subsurface interface beneath which only dense rock is found.
Calorie	Unit of measurement of heat energy; quantity of heat energy required to raise the temperature of one gram of water by one degree Celcius.
Capital recovery factor	The proportion of a capital investment to be recovered each year to amortize fully the original amount in the specified number of years at the selected discount rate.
Capital costs	All costs associated with the construction or installation of a system.
Centrifugal pump	A pump using the principle of centrifugal force to lift water; the centrifugal force is imparted on the water by an impeller rotating within a casing; an impeller and its casing are called a "stage"; centrifugal pumps having more than one impeller are called multi-stage centrifugal pumps.
Community involvement	The active involvement of the community in the planning, operation and control of amenities and facilities.

Cut-in wind speed	The wind speed at which a windmill starts producing useful output; not identical to the start-up wind speed which is required for a wind pump to start operation.
Cut-off wind speed	The wind speed at which a wind pump is designed to stop operation, to prevent it from being damaged by strong winds.
Deep-well pump	Pump capable of lifting water from a deep well or borehole; the term applies to both powered pumps and hand pumps.
Design month	For the purposes of sizing a solar pump, wind pump, hydro-powered pump, it is convenient to choose a "critical month" (least solar irradiation, least wind, least water flow rate) for which the pump must provide the water requirement; this month is termed the design month.
Diffuse radiation	Solar radiation scattered by the atmosphere.
Direct current	Electric current of which the direction is constantly the same.
Direct radiation	Solar radiation transmitted directly through the atmosphere.
Discount rate	The rate at which the value of future money is discounted to calculate present value; usually expressed in an annual percentage.
Distribution system	The pipes, valves, pumps, and other (for water) equipment used to bring water from the source, treatment plant, or bulk supply, to the users.
Drinking water	Potable water; water safe for human consumption.

Draw down	The distance the water level in a well drops during pumping.
Efficiency	<ul style="list-style-type: none"> – The daily energy efficiency (of the subsystem) is the ratio of hydraulic energy output to electric energy output of the energy supply system, over a day. – The power efficiency (of the subsystem) is the ratio of hydraulic power output to electric power input at any time.
Equivalent annual costs	The costs of a pumping system expressed as the equivalent annual payment to be made over its lifetime.
Excreta	Solid and liquid waste products, human and animal (faeces and urine).
Extra terrestrial	The solar radiation received at the periphery of the earth's atmosphere.
Ferrocement	Sand/cement mixture reinforced by thin wire mesh or similar reinforcement; used as building material for water storage tanks, housing, boats, etc.
Flow rate	The volume of liquid pumped per unit of time; usually expressed in cubic metres per second.
Global irradiance	The sum of diffuse and direct solar irradiance incident on a horizontal surface at ground level.
Groundwater	Without further specification: water occupying all voids within a geological formation. In practice: water which infiltrates into, travels through and is stored in sub-surface formations, in appreciable quantities.
Groundwater level	The level below which all voids of the rock or soil are full of water; same as groundwater table.

Hydraulic energy	The energy effectively used to lift water.
Hydrogeology	The branch of science which deals with the occurrence, distribution and movement of water below the surface of the earth.
Impedance matching	The process of matching the output of the power supply source to the power requirement of the motor-and-pump sub-system so that there is an optimal transfer of power between the two.
Inverter	An electronic device for converting direct electric current to alternative current.
Joule	Measure of work; one Joule is approximately the amount of work done when 0.1 kilogram mass is lifted vertically over one metre against gravity (at sea level) (abbreviation, J).
Kinetic energy	The energy which a moving mass possesses by virtue of its motion.
Kilowatt hour	Amount of energy; one kilowatt-hour is consumed when a power source of one kilowatt capacity is used for a period of one hour (abbreviation, kWh).
Level of service	Degree of accessibility and convenience of the water supply, or of the waste and waste water disposal services.
Maintenance	Activities related to the running and upkeep of equipment, necessary for efficient functioning.
Manpower development	Systematically planned action towards attainment of a balance between available manpower and manpower requirements, both present and future, and in quantity and also as quality.
Maximum power	Electronic impedance matching device to point trackerhold the output of a photovoltaic array at its maximum value.

Open circuit voltage	The voltage of a photovoltaic cell, module or array, measured at the terminals when there is no electrical load.
Opportunity cost	The best alternative use of a cost; the true value of money paid for a good or service.
Packing factor	The ratio of cell area to gross area for a photovoltaic array.
Peak watt	Unit of measurement for power output of a photovoltaic module or array under reference conditions (abbreviation, Wp).
pH	The parameter denoting acidity or alkalinity of water; pH values range from 0 to 14; a pH of 7 indicates neutrality, pH values below 7 indicates increasing acidity, and pH values above 7 indicate increasing alkalinity.
Photovoltaic array	An assembly of photovoltaic modules set in a framework together with the necessary wiring, capable of producing electric power output.
Positive-displacement	Type of pump in which a certain quantity of pumpwater is entrapped at the beginning of each pumping cycle; capable of delivering this quantity of water at a higher elevation or against pressure; for example, a reciprocating plunger pump.
Power	Capacity of supplying energy; measured in watt.
Power coefficient	Ratio representing that proportion of the total power available in the wind which is extracted from it by a wind rotor; the theoretical maximum value is 16/27 (abbreviation, Cp).
Present value	The value of a future cost or benefit expressed in present day money.
Prime mover	Power source (for a pumping system).

Pumping head	The total difference in head between the pumping level of the water source and the level at which the water is delivered in free discharge; also called total head.
Pump stroke	The distance the plunger in the cylinder of a pump travels between its highest and lowest point.
Recurrent costs	All costs associated with operating and maintaining a (water supply or pumping) system.
Revolving fund	Fund established by the initial deposit of a fixed amount, and receiving periodic returns on this investment; loans made from this fund are earmarked for a specified purpose (such as water supply improvements); repayments on loans to the fund are used again for the specified purpose.
Rotor (of a wind pump)	The main component of a wind pump which intercepts the wind and converts the kinetic energy present in the wind, into mechanical energy as shaft power.
Solar cell	Photovoltaic device (semi-conductor) which can convert solar radiation directly into electricity.
Solar irradiance	The radiant power received per unit area from the sun.
Solar irradiation	The energy received per unit area from the sun in a specified time period, generally taken to be a day with the solar irradiation expressed in kWh or MJ per m ² per day.
Standard design	Set of technical drawings, specifications, bills of quantities, and description of construction method, which can be applied on a large scale and under a wide range of conditions.

Static head	The vertical height through which water is lifted by a pumping system.
Submersible pump	A pump/motor set consisting of a centrifugal pump and a directly coupled electric motor; suitable for submerged operation under water.
Sub-system	The motor-and pump component of a solar pumping system; converts the electric output of the power supply system into useful hydraulic output.
Swept rotor area	The area swept by the blades of a wind rotor.
Torque	The force that acts to produce rotation.
Turbine pump	Type of pump which lifts water by mechanical action, similar to an aircraft propellor.
Watt	Unit of measurement of rate of work generally, and electric power specifically. 1 kilowatt = 1,000 watt 1 megawatt = 1 million watt
Yield	Flow rate of water from a well or borehole.

APPENDIX B

CALCULATION OF UNIT COSTS

The procedure for the calculation of unit cost for each type of pumping system is as follows:

1. Calculate the hydraulic energy output (kWh/d) on the basis of delivery head (m) and water output (m^3/d). (Section 4.3)
2. Calculate the required size of pumping system and its capital cost (\$). (Sections 3.5 and 3.6)
3. Select the adequate size of storage tank (m^3), and calculate the capital cost (\$). (Section 3.7)
4. Estimate lifetime of pumping system (years). (Sections 3.5 and 3.6)
5. Calculate the annual equivalent capital cost (\$/year) for pumping system and storage tank, using appropriate discount rate.
6. Estimate annual recurrent costs (\$/year). (Section 3.4)
7. Add the amounts in steps 5 and 6 to determine the total annual costs (\$/year).
8. Divide by 365 to find total costs per day (\$/day).
9. Divide by daily water output (m^3/d) to find cost per m^3 of water pumped (\$/ m^3).
10. Divide by daily hydraulic energy output (kWh/d) to find cost per kWh hydraulic energy output (\$/kWh).

Hydraulic Ram Pump

Drive head and supply flow	adequate							
Delivery head (m)	15		15		50		50	
Water output (m ³ /d)	10		50		10		50	
Hydraulic energy output (kWh/d)	0.42		2.08		1.39		6.94	
	O	P	O	P	O	P	O	P
Capital cost of pumping system (x \$ 1,000)	5	7.5	15	37.5	10	30	50	150
Lifetime of pumping system (years)	20	15	30	20	30	20	30	20
Cost of storage tank (x \$ 1,000) (2 day's supply)	0.1	0.5	0.5	2.5	0.1	0.5	0.5	2.5
Annual equivalent capital costs (x \$ 1,000)								
– ram pump	0.53	0.98	1.39	4.31	1.06	3.93	5.30	19.65
– storage tank	0.02	0.05	0.08	0.27	0.02	0.05	0.08	0.27
Annual recurrent costs (x \$ 1,000)								
– ram pump	0.05	0.13	0.15	0.75	0.10	0.60	0.50	3.00
– storage tank	0.01	0.01	0.03	0.03	0.01	0.01	0.03	0.03
Total annual costs (x \$ 1,000)	0.61	1.17	1.65	5.36	1.19	4.59	5.91	22.95
Total costs per day (\$/day)	1.67	3.20	4.52	14.68	3.26	12.57	16.19	62.88
Cost per m ³ pumped (\$/m ³)	0.17	0.32	0.09	0.29	0.33	1.26	0.32	1.26
Cost per kWh _{hydr} (\$/kWh)	4.08	7.80	2.20	7.16	2.40	9.24	2.38	9.23
O = optimistic assumptions								
P = pessimistic assumptions								

Turbine Pump

Hydraulic head and flow	adequate							
Delivery head (m)	15		15		50		50	
Water output (m ³ /d)	10		50		10		50	
Hydraulic energy output (kWh/d)	0.42		2.08		1.39		6.94	
	O	P	O	P	O	P	O	P
Capital cost of pumping system (x \$ 1,000)	0.8	4.4	0.8	4.4	1.4	5.0	1.4	150
Lifetime of pumping system (years)	20	10	20	10	20	10	20	10
Cost of storage tank (1 day's supply) (x \$ 1,000)	0.10	0.50	0.50	2.50	0.10	0.50	0.50	2.50
Annual equivalent costs (x \$ 1,000)								
– turbine pump	0.09	0.72	0.09	0.72	0.16	0.81	0.16	0.81
– storage tank	0.02	0.05	0.08	0.27	0.02	0.05	0.08	0.27
Annual recurrent costs (2%) (x \$ 1,000)								
– turbine pump	0.02	0.13	0.02	0.13	0.03	0.15	0.03	0.15
– storage tank	0.01	0.01	0.03	0.05	0.01	0.01	0.03	0.05
Total annual costs (x \$ 1,000)	0.14	0.91	0.22	1.17	0.22	1.02	0.30	1.28
Total costs per day (\$/day)	0.38	2.49	0.60	3.21	0.60	2.80	0.82	3.51
Cost per m ³ pumped (\$/m ³)	0.04	0.25	0.01	0.06	0.06	0.28	0.02	0.07
Cost per kWh _{hydr} (\$/kWh)	0.93	6.07	0.29	1.57	0.44	2.06	0.12	0.52

O = optimistic assumptions

P = pessimistic assumptions

Wind Pump

Average wind speed in design month (m/s)	4							
Pumping head (m)	15	15	50	50				
Water output (m ³ /d)	10	50	10	50				
Hydraulic energy output (kWh/d)	0.42	2.08	1.39	6.94				
	O	P	O	P	O	P	O	P
Area of rotor (m ²) (A = P/0.1 V ³)	2.66	13.3	8.83	44.3				
Wind pump cost (\$/m ²)	150	350	150	300	150	300	150	250
Capital cost of wind pump (x \$1,000)	0.40	0.95	2.0	4.0	1.3	2.6	6.6	11.1
Storage tank size (day's supply) (m ³ volume)	4	7	4	7	4	7	4	7
Storage tank cost (\$/m ³)	10	50	10	50	10	50	10	50
Capital cost of storage tank (x \$ 1,000)	0.40	3.50	2.0	17.5	0.4	3.5	2.0	17.5
Lifetime (years)								
– wind pump	20	10	20	10	20	10	20	10
– storage tank	30	10	30	10	30	10	30	10
Annual equivalent capital costs (x \$ 1,000)								
– wind pump	0.06	0.14	0.31	0.62	0.20	0.42	1.02	1.72
– storage tank	0.06	0.16	0.31	2.63	0.06	0.52	0.33	2.63
Annual recurrent costs (\$ 1,000)								
– wind pump	0.02	0.05	0.09	0.20	0.07	0.14	0.31	0.61
– storage tank	0.02	0.05	0.11	0.88	0.02	0.16	0.10	0.92
Total annual costs (x \$ 1,000)	0.16	0.40	0.82	4.33	0.35	1.24	1.76	5.88
Useful water output per year (m ³ /y)	3650	3650	18250	18250	3650	3650	18250	18250
Cost per m ³ pumped (\$/m ³)	0.04	0.11	0.04	0.24	0.10	3.28	0.09	3.18
Cost per kWh _{hydr} (\$/kWh)	1.04	2.61	1.05	5.66	0.69	2.37	0.67	2.29

O = optimistic assumptions
P = pessimistic assumptions

Solar pump

Solar irradiation in critical month (kWh/d)	4							
Pumping head (m)	15	15	50	50				
Water output (m ³ /d)	10	50	10	50				
Hydraulic energy output (kWh/d)	0.41	2.05	1.36	6.81				
	O	P	O	P	O	P	O	P
Sub-system efficiency (%)	40	35	45	40	40	35	45	40
Electric energy requirement (kWh/d)	1.05	1.20	4.62	5.20	3.48	3.97	15.42	17.35
Peak watt rating (kWp)	0.22	0.35	1.00	1.54	0.74	1.17	3.29	5.10
Unit installation cost (\$/Wp)	15	25	14	22	15	25	13	20
Capital cost of pumping system (\$ 1,000)	3.30	8.75	14.00	33.90	11.10	29.30	42.80	102
Storage tank size (day's supply) (m ³ volume)	3 30	5 50	3 150	5 250	3 30	5 50	3 150	5 250
Capital cost of storage tank (\$/m ³)	10	50	10	50	10	50	10	50
Capital cost of storage tank (\$ 1,000)	0.3	2.5	1.5	12.5	0.3	2.5	1.5	12.50
Lifetime (years)								
– solar pump system	20	10	20	10	20	10	20	10
– storage tank	30	10	30	10	30	10	30	10
Annual equivalent capital costs (\$ 1,000)								
– solar pump system	0.39	1.43	1.63	5.51	1.30	4.76	5.00	16.62
– storage tank	0.05	0.27	0.24	1.33	0.05	0.27	0.24	1.33
Annual recurrent costs (\$ 1,000)								
– solar pump system	0.20	0.50	0.35	0.85	0.25	0.70	0.40	1.00
– storage tank	0.03	0.03	0.15	0.13	0.03	0.03	0.15	0.13
Total annual costs (\$ 1,000)	0.67	2.23	2.37	7.82	1.63	5.76	5.79	19.08
Cost per m ³ pumped (\$/m ³)	0.18	0.61	0.13	0.43	0.45	1.58	0.32	1.05
Cost per kWh _{hydr} (\$/kWh)	4.49	14.90	3.20	10.44	3.28	11.60	2.33	7.68

O = optimistic assumptions

P = pessimistic assumptions

Diesel pump

Pumping head (m)	15	15	50	50				
Water output (m ³ /d)	10	50	10	50				
Hydraulic energy output (kWh/d)	0.42	2.08	1.39	6.94				
	O	P	O	P	O	P	O	P
Diesel fuel price (\$/litre)	0.40	0.80	0.40	0.80	0.40	0.80	0.40	0.80
Efficiency of								
– pump unit (%)	60	40	60	40	60	40	60	40
– engine (%)	15	15	15	15	15	15	15	15
Overall efficiency of diesel pump (%)	9	6	9	6	9	6	9	6
Lifetime (years)								
– engine and pump	10	5	10	5	10	5	10	5
– tank	30	10	30	10	30	10	30	10
Size of engine (kW)								
– rated power	3	3	3	3	3	3	3	3
– nominal power	2	2	2	2	2	2	2	2
Hydraulic power of engine (kW)	1.2	0.8	1.2	0.8	1.2	0.8	1.2	0.8
Water output rate (l/s)	8	5.3	8	5.3	2.4	1.6	2.4	1.6
Hours operation per day (h/d)	0.34	0.52	1.74	2.62	1.15	1.74	5.78	8.68
Fuel consumption (l/yr)	169	253	847	1270	563	844	2823	4234
Capital cost of engine & pump (\$ 1,000)	4.5	7.5	4.5	7.5	4.5	7.5	4.5	7.5
Capital cost of tank (\$)	50	500	250	2500	50	500	250	2500
Fuel costs (x \$ 1,000)	0.08	0.20	0.34	1.02	0.23	0.68	1.13	3.39
Annual equivalent capital costs (\$ 1,000)								
– engine/pump	1.19	1.98	1.19	1.98	1.19	1.98	1.19	1.98
– tank	–	0.08	0.04	0.27	–	0.08	0.04	0.27
Annual recurrent costs (\$ 1,000)	0.27	0.75	0.27	0.75	0.27	0.75	0.27	0.75
Operator's salary (\$ 1,000)	0.25	0.50	0.50	0.75	0.75	1.50	0.75	1.50
Total annual costs (\$ 1,000)	1.79	3.51	2.34	4.79	2.44	4.99	3.38	7.89
Volume of water pumped per year (1000 m ³ /yr)	3.65	3.65	18.25	18.25	3.65	3.65	18.25	18.25
Hydraulic energy output (1000 kWh/yr)	0.15	0.15	0.75	0.75	0.50	0.50	2.49	2.49
Unit costs								
\$/m ³ pumped	0.49	0.96	0.13	0.26	0.67	1.37	0.19	0.43
\$/kWh _{hydr}	11.93	23.4	3.12	6.39	4.88	9.98	1.36	3.17

O = optimistic assumptions

P = pessimistic assumptions

APPENDIX C

MANUFACTURERS AND SUPPLIERS

C.1 MANUFACTURERS AND SUPPLIERS OF SOLAR WATER PUMPING SYSTEMS

This list does not imply recommendation or endorsement of the products of any of the suppliers. It is not intended to be a complete list of solar pump suppliers.

Manufacturer/Supplier	Address
AEG/Telefunken	Industriestrasse 29 D-2008 Wedel (Holstein) Federal Republic of Germany
Alsette SpA	Cadriano de Granarolo E. 40057 Bologna Italy
Ansaldo SpA	Via Nicola Lorenzi 8 16152 Genova Cornigliano Italy
Arco Solar Inc.	P.O. Box 4400 Woodland Hills, California 91365 USA
BP Solar Systems Ltd.	Aylesbury Vale Industrial Park Farmborough Close Stocklake Aylesbury, Bucks. HP20 1DQ UK
Central Electronics Ltd.	4 Industrial Area Sahibabad, U.P. India 201 010
Chronar Trisolar	10 De Angelo Drive Bedford, Massachusetts 01730 USA
Dinh Company	Box 999 Alachua, Florida 32615 USA

Duba S/A	Nieuwstraat 31 B-9200 Wetteren Belgium
Ebara Corporation	Asahi Building 6-7 Ginza, 6-Chome Chuo-Ku, Tokyo 104 Japan
GPL Industries	Box 306 (Grundfos) La Canada, California 91011 USA
Grundfos	Poul Jensens Vej Bjerringbro 8850 Denmark
Heliodinamica	Caixa Postal 8085 01051 Sao Paulo, S.P. Brazil
IDE Industries	Zone Industrielle B-5430 Rochefort Belgium
Komatsu Electronic	2612 Shinomiya Metals Company Hiratsuka Kanagawa 254 Japan
KSB A/GP.O.	Box 360 6650 Homburg Federal Republic of Germany
Kyocera Corporation	5-22 Kitainoue-Cho Higashino Yamashina-Ku Kyoto 605 Japan
Wm. Lamb Company Inc.	P.O. Box 4185 North Hollywood, California 91607 USA
Lowara SpA	36075, Montecchio Maggiore Vicenza Italy

A.Y. McDonald Mfg.Co.	P.O. Box 508 Dubuque, Iowa 52001 USA
Mono Pumps (UK) Ltd.	Cromwell Trading Estate Cromwell Road Bredburry Stockport SK6 2RF UK
Mono Pumps (Australia) Ltd.	338 Lower Dandenong Road Mordialloc, Victoria 3195 Australia
Photowatt International	131, route de l'Empereur 92500 Rueil Malmaison France
Pragma SpA	Via Po 25/4 00198 Roma Italy
RJM Solar Technology	Casè Postale 10 1294 Genthod Switzerland
R & S Renewable	P.O. Box 45 Energy Systems BV 5600 AA Eindhoven The Netherlands
Sharp Corporation	22 Nagailke Abenu-Ku Osaka 545 Japan
Solapak Ltd.	Factory 3, Cocklane High Wycombe Bucks. HP13 7DE UK
Solar Electric	77, Industrial Estate International Inc.Luga Malta
Solar Electric Specialties	P.O. Box 537 Company Willits, California 95490 USA

Solar Energie-Technik	1, Industriestrasse D-4503 Altlussheid Federal Republic of Germany
Solarex I.td.	1335 Piccard Drive Rockville, Maryland 20850 USA
Solarex (Australia) Ltd.	Box 204 Chester Hill New South Wales 2162 Australia
Solar Voltaics	Hunoldstrasse 3 A-6020 Innsbruck Austria
<i>Southern Cross International</i>	Box 754 Toowoomba Queensland 4350 Australia
Sun Amp System Inc.	7702, East Gray Road Scottsdale Arizona 85260 USA
Sunpump Company	P.O. Box 3336 South El Monte, California 91733 USA
TPK Solar Systems	149 Bentley Ave. B-4A Nepean, Ontario Canada

C.2 MANUFACTURERS AND SUPPLIERS OF WIND PUMPS

An extensive list of manufacturers/suppliers of wind pumps and wind-electro-generators, with details of the equipment offered, is available in the "Catalogue of Wind Machines", prepared by Consultancy Services Wind Energy Developing Countries (CWD) and the Twente Working Group on Development Techniques (WOT). CWD Publication CWD 83-1, March 1983. Copies of the "Catalogue of Wind Machines" are obtainable from:

Consultancy Services Wind Energy
Developing Countries
P.O Box 85
3800 AB Amersfoort
The Netherlands

Another useful list of manufacturers/suppliers of wind pumps, with details of the equipment offered, is included in the publication "Le Point sur Les Eoliennes de Pompage", prepared by the Groupe de Recherche et d'Echanges Technologiques (GRET). GRET Dossier "Le Point Sur", No.1, January 1984. Copies of the publication "Le Point Sur Les Eoliennes de Pompage" are obtainable from:

Group de Recherche et d'Echanges
Technologiques
30, rue de Charonne
75011 Paris
France

C.3 MANUFACTURERS AND SUPPLIERS OF HYDRO-POWERED PUMPS

A. Hydraulic ram pumps

Manufacturer	Name of hydraulic ram
Ab Bruzaholms Bruk	BZH Hydrauliska 570 34 Bruzaholm Sweden
Berry Hill Ltd.	Davey Hydram 75, Burwell Road St. Thomas, Ontario N5P 3R5 Canada
Briau S.A.	Briau Hydram B.P. 43 370009 Tours France

CeCoCo	CeCoCo Hydro-Lift Pump P.O. Box 8 Ibaraka City, Osaka 567 Japan
Centro Las Gaviotas	Alta Cabeza "Gaviotas" Paseo Bolivar no. 20-90 Bogota Colombia
C.W. Pipe Inc.	Fleming Pump P.O. Box 678 Amherst, Virginia 24521 USA
Godbole & Sons	Auto-lift Pump New Ramdaspath Kachipura Nagpur-1 India
Green & Carter Ltd.	Vulcan Hydram Grange Farm, Northington Airesford, Hants. SO 24 9 TG UK
Industrias Mecanicas Rochfer Ltda.	Bomba Hydraulicas Rochfer Avenida Jose de Silva 3765 Jardin Moria Rosa Caixa Postal 194 Sao Paulo, CEP 14400 Brazil
Jandu Plumbers Ltd.	Jandu's Hydram P.O. Box 409 Uhuru Road Arusha Tanzania
John Blake Ltd.	Blake Hydram P.O. Box 43 Accrington, Lancashire BB5 5LP UK
John Danks & Son. Pty Ltd.	Billabong Doody Street, Alexandria Sydney, New South Wales Australia

Pfister & Langhanns

SANO Ram Pump
Sandstrasse 2-8
Postfach 3555
8500 Nürnberg 1
Federal Republic of Germany

Pilter

Pompe Pilter
22, Rue FlorianPompe Alto
75020 Paris
France

Premier Irrigation Equipment Ltd.

Premier Hydram
17/1C Alipore Road
Calcutta 700.027
India

Rife Hydraulic Engine Manufacturing Co.

Rife Ram Pump
316 W. Poplar Street
P.O. Box 790
Norristown, PA 19401
USA

Schlumpf AG

Schlumpf Pump
CH-6312 Steinhausen
Kanton Zug
Switzerland

Singh Metal Casting Works

Chandra Hydram
110-D Nirala Nagar
Lucknow
India

WAMA Maschinenbau

Wama Pump
Bergstrasse 8
8018 Grafing bei München
Federal Republic of Germany

B. Turbine pumps

There are a considerable number of manufacturers of turbine pumps in the People's Republic of China. Some are prepared to provide quotations for export:

Fujian Provincial Agricultural Machinery
Import & Export Corporation
24 Dongda Road
Fuzhou, Fujian Province
People's Republic of China

C. River-current pumps

Ndume Agricultural
Turbo pump
Machinery Manufacturers Ltd.
P.O. Box 62
Gilgil
Kenya

APPENDIX D

SOURCES OF INFORMATION ON RENEWABLE ENERGY SOURCES AND THE APPLICATION FOR SMALL-SCALE WATER SUPPLY SYSTEMS

D.1 National Organizations

Algeria	Organisme National de la Recherche Scientifique Station de l'Energie Solaire Route de l'Observatoire Bouzareah Alger
Argentina	Centro de Estudios Fotointeticos y Bioquimicos Fundacion Miquel Lillo Universidad Nacional de Rosario Suipacha 531 2000 Rosario Grupo de Energie Solar Universidad Nacional 4400 Salta, Buenos Aires
Australia	Appropriate Technology Development Group 20 Holdsworth Street Woolahara, NSW 2025 Australian Wind Energy Association P.O. Box 1965 Canberra City, ACT 2601 Commonwealth Scientific and Industrial Research Organization P.O. Box 225 Dickenson, ACT 2602
Belgium	Appropriate Technology for Developing Countries Blyde Inkomststraat 9 B-3000 Leuven Collectif d'Echanges pour la Technologie Appropriée 18 rue de la Sablonniere B-1000 Brussels

Bolivia	Instituto de Energia Academy of Sciences Casilla 5279 La Paz
Botswana	Botswana Technology Centre Private Bag 0092 Gaborone Rural Industries Innovation Centre P.O. Box 138 Kanye
Brazil	Laboratory of Solar Energy University Campus Paraiba Federal University Joao Pessoa 58000 Paraiba Technology Center of Minas Gerais Avenida Jose Candido da Silveira 2000 P.O. Box 2306 Belo Horizonte, Manas Gerais
Burkina Faso	Centre Interfricain d'Etudes Hydrauliques B.P. 369 Ouagadougou
Burundi	Groupe de Recherches d'Utilisation des Energies Alternatives Université de Burundi Faculté des Sciences B.P. 2700 Bujombara
Cameroon	Unité de Recherches Energetique de l'Onarest B.P. 4110 Yaoundé
Canada	Brace Research Institute McDonalds College of McGill University P.O. Box 900 Ste. Anna de Bellevue, Quebec H9X 1C0 International Development Research Centre P.O. Box 8500 Ottawa K1G 3H9

Chile	Solar Energy Program Institute of Technological Research P.O. Box 667 Santiago
China	Beijing Institute of New Technology Applications (People's Republic)Shi Zhi Men Beijing Guangzhou Institute of Energy Conversion Technology Chinese Academy of Science 81 Martyrs' Road C.P.O. Box 1254 Guangzhou Zhejiang Research Institute for Biogas and Solar Energy Hangchow, Zhejiang
Colombia	Institute for the Development of Renewable Natural Resources Carresa 14, No. 25 A-66 Bogota, D.E. Las Gaviotas Centre Apartado Acreo 18261 Bogota, D.E.
Costa Rica	Renewable Energy Resources Programme Centro Agronomico Tropical de Investigacion Apartado 74 Turrialba Instituto Tecnologico de Costa Rica Centro de Informacion Technologica Apartado 159 Cartago
Ecuador	Instituto Nacional de Energia Stam Prisca 233 Quito
Egypt	Solar Energy Laboratory National Research Centre El Tahrir St. Dokki, Cairo

	<p>University of Alexandria Faculty of Engineering Solar Application Laboratory El-Hadara, Alexandria</p>
Ethiopia	<p>Ethiopian National Energy Commission P.O. Box 486 Addis Ababa</p> <p>National Water Resources Commission P.O. Box 1008 Addis Ababa</p>
Fiji Islands	<p>Institute of Natural Resources University of the South Pacific P.O. Box 1168 Suva</p>
France	<p>Agence Française pour la Maitrise de l'Energie Immeuble "Le Bearn" 27 rue Louis Vicat 75015 Paris</p> <p>Groupement pour l'Exploitation Rationnelle de l'Energie Solaire Université de Provence Centre de Saint Jérôme 13397 Marseille</p> <p>Groupe de Recherches et d'Echanges Technologiques 30, rue de Charonne 75011 Paris</p> <p>Institut Technologique Dello Le Moulin Rouge 60410 Verberie</p>
Gabon	<p>Ministère de l'Energie et des Ressources Hydrauliques B.P. 874 Libreville</p>
Germany	<p>German Solar Energy Industrial Association (Federal Republic) Kruppstrasse 5 D-4300 Essen</p>

Bremen Overseas Research and Development Association
Bahnhofplatz 13
2800 Bremen

German Appropriate Technology Exchange
Postfach 5180
D-6236 Eschborn

Ghana Council for Scientific and Industrial Research
P.O. Box 74
Kade

Technology Consultancy Centre
University of Science and Technology
Kumasi

Greece National Council for Energy Research
P.O. Box 5568
Athens

Guatemala Central American Research Institute for
Industry
P.O. Box 1552
Guatemala City

Honduras Rural Technology Programme
Apartado Postal 703
Tegucigalpa, D.C.

India Birla Institute of Technology and Science
Pilami, Gobar Research Station
Ajitmal, Etawah, U.P.

Central Power Research Institute
P.O. Box 1242
Bangalore, Karnataka 560012

Centre for Rural Development and Appropriate Technology
Haus Khnas
New Delhi 110016

Khadi and Village Industries Commission
Gobar Research and Development Centre
Kora Gramadyog, Kendra
Bombay 400 092

Indian Institute of Technology
Powai, Bombay 400 076

National Aeronautical Laboratory
Wind Power Division
P.O. Box 1779
Bangalore 560 017

Tata Energy Research Institute
Bombay House
24 Homi Mody Street
Bombay 400 023

Indonesia

Dian Desa
Jl. Kali Urang Km 7
P.O. Box 19
Bulaksumur

Institute of Technology Bandung
Development Technology Centre
Jl. Ganesha No. 10
P.O. Box 276
Bandung

Solar Energy Research Centre
Gajah Mada University
Sekip Unit III
Yogyakarta

Israel

Applied Research Institute
Ben Gurion University
P.O. Box 11025
Beersheva 814120

Scientific Research Foundation
P.O. Box 8745
Jerusalem 991036

Italy

Fiat-Energy Sector
Renewable Energy Systems
Via Cuneo 20
10152 Turino

International School on Solar Energy and other Renewable
Energy Resources
P.O. Box 65
61029 Urbino

Japan

Government Industrial Research Institute
Solar Research Laboratory
1, Hirate-Machi, Kita-Ku
Nagoya 1462

Jordan	Royal Scientific Society P.O. Box 4014 Amman
Korea	Appropriate Technology Centre (Republic of)Umwol-ri, Hongdong-myum Hongseong-gun Chungnam 350-11 Rural Energy Resources Division Office of Rural Development Institute of Agricultural Sciences Suweon
Kuwait	Kuwait Institute for Scientific Research P.O. Box 24885 Safat, Kuwait City
Libya	Centre for Solar Energy Studies P.O. Box 8004 Tripoli
Madagascar	Polytechnic Institute University of Madagaskar B.P. 1500 Antananarivo
Mali	Centre de Recherches Solaires B.P. 134 Bamako
Mexico	Mexican Institute of Renewable Resources Avenida Dr. Vertiz 724 Mexico City
Nepal	Research Centre for Applied Science and Technology Tribhuvan University Kirtipur, Katmandu
New Zealand	Centre for Scientific and Industrial Research Charles Ferguson Building Bowen Street Wellington
Niger	ONERSOL l'Office de l'Energie Solaire B.P. 621 Niamey

Pakistan	<p>Appropriate Technology Development Organization 1-B Street 47th, F-7/1 Islamabad</p> <p>Pakistan Council for Scientific and Industrial Research Press Centre, 2nd Floor Shahra-e-Kamal Ataturk P.O. Box 672 Karachi 0109</p>
Papua New Guinea	<p>Papua New Guinea University of Technology P.O. Box 793 Lae</p> <p>South Pacific Appropriate Technology Foundation P.O. Box 6937 Boroko</p>
Philippines	<p>Centre for Non-Conventional Energy Development PNPC Complex Merritt Road, Fort Bonifacio Metro Manila</p> <p>National Institute of Science and Technology 625, Pedro Gill Street, Ermita Metro Manila</p>
Rwanda	<p>Université Nationale de Rwanda Centre d'Etudes et d'Applications de l'Energie B.P. 117 Butare</p>
Senegal	<p>Centre d'Etudes et de Réalisation pour les Energies Renouvelables B.P. 476</p>
Dakar	<p>Société Industrielle des Applications de l'Energie Solaire B.P. 1277 Dakar</p>
Sierra Leone	<p>Advisory Unit for Technology Research and Development Faculty of Engineering University of Sierra Leone Mount Aureol, Freetown</p>

Sri Lanka	Water Resources Board Wind Energy Unit 2A Gregory's Avenue Colombo 7
Sudan	National Council for Research Institute of Energy Research P.O. Box 2404 Khartoum
Suriname	University of Suriname Department of Engineering University Complex, Building II Leyweg Paramaribo
Sweden	Swedish National Board for Energy Source Development P.O. Box 1103 S-16312 Spanga Swedish Agency for Research Cooperation with Developing Countries (SAREC) Birger Jarlsgatan 61 S-10525 Stockholm
Switzerland	SKAT Swiss Centre for Appropriate Technology Varnbuelstrasse 14 CH-9000 St Gallen
Tanzania	Arusha Appropriate Technology Centre P.O. Box 764 Arusha
Thailand	Asian Institute of Technology Renewable Energy Resources Information Centre P.O. Box 2754 Bangkok Khon Kaen University Faculty of Engineering Solar Energy Group Khon Kaen King Mongkut's Institute of Technology Thonburi Campus Bangkok 14

	<p>National Energy Administration Energy Research Section Wind Energy Unit Pibultham Villa Kasatsuk Bridge Bangkok 5</p>
The Netherlands	<p>Centre for International Cooperation and Appropriate Technology Delft University of Technology P.O. Box 2350 Delft</p> <p>Consulting Services Wind Energy Developing Countries P.O. Box 85 3800 AB Amersfoort</p> <p>TOOL Foundation Mauritskade 61 1092 AD Amsterdam</p>
Togo	<p>Solar Energy Department School of Sciences University of Benin B.P. 1515 Lome</p>
Tunisia	<p>Association pour le Developpement et l'Animation Rurale 10 rue Eve Nohelle Tunis</p>
Turkey	<p>Turkish Solar Energy Institute P.O. Box 37 Bakanliklar, Ankara</p> <p>Power Machinery Department Faculty of Agriculture University of Anakara Cengiz Sotah No. 119/3 Yeninahalle, Ankara</p>
United Kingdom	<p>Intermediate Technology Development Group Myson House Railway Terrace Rugby CV21 3HT</p>

IT Power Ltd.
Mortimer Hill
Mortimer, Reading, Berks. RG7 3PG

National Centre for Appropriate Technology
Llyngwern Quarry
Machynlleth
Powys, Wales

University of Reading
Energy Group
Whiteknights
Reading, Berks. RG6 1A7

United States of
America

Wind Energy Association
America1609 Connecticut Avenue
Mount Rainier, Maryland 20822

IT Power Inc.
1015, 18th Street, N.W.
Suite 801
Washington, D.C. 20036

National Academy of Sciences
Board on Science and Technology for
International Development
2101 Constitution Avenue
Washington D.C. 20418

National Center for Appropriate Technology
P.O. Box 3838
Butte, Montana 59702

New Alchemy Institute
237 Hatchville Road
East Falmouth, Massachusetts 02536

Peace Corps
906 Connecticut Avenue, N.W.
Washington D.C. 20525

Sandia National Laboratories
Division 621
P.O. Box 5800
Albuquerque, New Mexico 87185

Volunteers in Technical Assistance
P.O. Box 12438
Arlington, Virginia 22209

Zambia Technology Development and Advisory Unit
University of Zambia
P.O. Box 32379
Lusaka
Zambia

D.2 INTERNATIONAL ORGANIZATIONS

FAO Food and Agricultural Organization of the
United Nations
Via delle Terme di Caracalla
00100 Rome
Italy

IRC International Reference Centre for
Community Water Supply and Sanitation
P.O. Box 93190
2509 AD The Hague
The Netherlands

UNESCO United Nations Education and Science Organization
UNESCO Network on Renewable Energy Sources
7 Place de Fontenoy
75007 Paris
France

UNICEF United Nations Children's Fund
Water and Environmental Sanitation
Advisory Team
866 U.N. Plaza
New York, N.Y. 10017
USA

UNIDO United Nations Industrial Development Organization
P.O. Box 2300
A-1180 Vienna
Austria

UNCNRET United Nations Centre for Natural
Resources, Energy and Transport
1 U.N. Plaza
New York, N.Y. 10017
USA

- UN/ESCAP United Nations Economic and Social
Commission for Asia and the Pacific
Sala Santitham
Rajdamnern Avenue
Bangkok 2
Thailand
- UN/ECAF United Nations Economic and Social
Commission for Africa
Africa Hall
P.O. Box 3005
Ethiopia
- UN/ECLAC United Nations Economic and Social
Commission for Latin America and the
Caribbean
Edificio Naciones Unidas
Avenida Dag Hammarskjold
Casilla 179
Santiago
Chile

IRC Publications

The Technical Paper Series published by IRC provides expertise on selected topics on community water supply and sanitation in developing countries. Wherever possible in these publications, an integrated approach incorporating technical, economic, social and organizational aspects is developed to address pressing problems in this area.

These publications are produced jointly by consultant specialists and IRC staff. They are widely used in many countries by staff at all levels, from engineers and decision-makers at the national level to public health officials and technicians at the community level.

IRC also publishes the Bulletin Series comprising reports of international meetings organized by the Centre and also jointly with participating institutions in developing countries. The Occasional Paper Series, which is in photocopy format, presents ongoing work at IRC and related organizations. Many of these publications are available in French and can be obtained from IRC. Several of these are now available in Spanish and can be obtained from: CEPIS, Casilla 4337, Lima 100, Perú.

IRC titles of related interest:

SMALL COMMUNITY WATER SUPPLIES IN DEVELOPING COUNTRIES

Compiled by E.H. Hofkes

(TP 18 E)

442 pages

enlarged edition 1983

HANDPUMPS FOR USE IN DRINKING WATER SUPPLIES IN DEVELOPING COUNTRIES

(TP 10 E)

266 pages

1st edition 1977