Part Three

DOCUMENTATION ON WIND ENERGY

I. WORKING PAPERS PRESENTED BY THE SECRETARIAT

DEVELOPMENT OF WIND ENERGY UTILIZATION IN ASIA AND THE PACIFIC
(NR/ERD/EWGSW/3)*

INTRODUCTION

About 10,000,000 MW is continuously available in the earth's winds, and attempts have been made from time to time to use some of this power.   It is mentioned in reference W 1 that the Babylonian ruler Hammurabi planned to use wind pumps for large-scale irrigation in the seventeenth century B. C.   The raising of water by contrivances worked by wind power is mentioned in a Hindu classic (reference W 2) dated 400 B. C.   By the fourth century A. D., windmills were widely used in Persia, and applications spread widely through the Moslem civilization and into China. From 1,100 A. D. onwards, wind energy utilization developed in Europe and, by the nineteenth century, was a significant source of industrial power, especially in the Netherlands.

Approximately 80 per cent of the population of the developing countries of the ESCAP region is engaged in agricultural production in rural areas, and uses mainly non-commercial sources of energy, such as human and animal muscle power, firewood and charcoal, cow dung and agricultural waste, and, to a limited extent, wind energy and solar energy (see reference W 3).

In any evaluation of energy utilization patterns in rural areas, it is noted that wind and solar energy have

---

*Prepared by Mr. M. M. Sherman, consultant on wind energy, at the request of the ESCAP secretariat.   The views expressed in this paper are the author's own and do not necessarily reflect those of the secretariat or the United Nations.
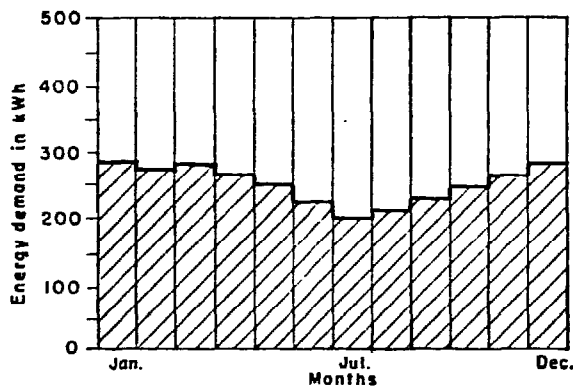
several important characteristics that make them well adapted to rural utilization: they are renewable sources; they are widely distributed and do not require a distribution network; they are under the direct control of the user; and their development and use can be based largely on local resources.

I. POTENTIAL INCREASE IN ENERGY UTILIZATION

A. LOCAL ENERGY NEEDS

Assuming that an increase in energy utilization is desirable in a particular rural area where transmitted electricity or energy based on oil products is not freely available, the first requirement is to quantify the present supplies and uses of energy and then to determine the additional uses and the minimum increase in energy required.   Demand data should preferably be arranged in a form similar to the hypothetical examples of figure 1 and figure 2.

When the amount of increased energy supplies required has been determined, all available energy sources should be evaluated for their ability to satisfy the demand, proceeding in turn from increased efficiency in the use of currently-used sources to increased usage of locally available energy supplies, including biological fuels, solar energy and wind energy, before considering the use of transmitted electricity or oil products.
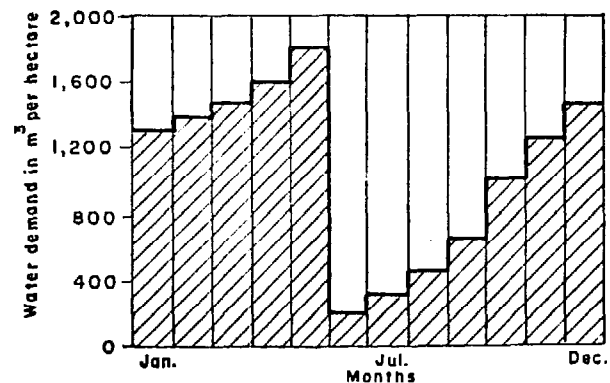

Figure 1.   Monthly energy demand for electric lighting (50 families)

Figure 2. Monthly demand for irrigation pumping

B. *CALCULATION OF WIND ENERGY*

The wind velocity is continually varying in both magnitude and direction, but is broadly predictable over significant periods of time, and the power in the windstream is proportional to the cube of the velocity. The equation for total available wind power is $P = K A v^3$ where A is the cross-sectional area of the windstream and v is the velocity. The value of the constant K is 0.0000137 where the units used are kW, m^2 and km/h. (See reference W 4).

Theoretically, 0.5926 per unit of the available wind power could be extracted by a wind rotor, but allowance must also be made for the practical efficiency of the rotor, transmission and power utilization device, which is normally in the range of 0.3 to 0.7 per unit. Expressing the over-all efficiency as E, the practical equation becomes:

$$P = 0.0000137 \ A \ v^3 \ x \ 0.5926 \ E$$

C. *RELEVANT WIND MEASUREMENT INSTRUMENTS*

Much valuable work has been done by the World Meteorological Organization on standardization of wind data collection for meteorological and navigational purposes. Preliminary efforts have been made at wind energy assessment (reference W 5), and it is hoped that further work will be carried out on standardization of instruments and methods of analysis of data for wind energy.

The most complete information on wind velocity behaviour is gained from anemometers giving continuous records of speed and direction. The Dines pressure tube anemograph is widely used as the standard wind-measuring device in many permanently established meteorological stations, but determination of average hourly wind velocities from the charts of this type of anemograph is difficult and time-consuming.

The electric cup-contact recording anemometer is extensively used for accurate determination of average hourly wind velocities. This device incorporates rotating cups which drive a device which makes a contact in an electric circuit once for some selected value of wind run, preferably 1 km. The circuit causes a pen to mark a continuous chart recorder, thus making it possible to determine the hourly run of the wind by counting the marks on each hourly segment of the chart. However, instruments of this kind are expensive to purchase and install and need skilled daily maintenance.

In a variant, a narrow paper tape is moved forward a short distance for each contact produced by the anemometer. A time switch is used to operate a pen or marker so that a mark is made on the tape at hourly intervals, and the distance between successive marks represents the run of the wind. This type of instrument is designed particularly for economy and for simplicity in operation and chart interpretation.

An inexpensive method of wind recording used at some stations is a Robinson cup or propeller type of anemometer which is connected to a cyclometer type of digital indicator. The difference between any two readings indicates the run of the wind during the time interval, and hourly averages can be readily obtained.

Anemometers which give "instantaneous" wind speeds are used at many minor observation stations, including airports. These are indicating instruments, not recorders, and their readings are noted at certain specified times in the day, usually once per hour. The wind speed values thus measured are useful as a general guide, but do not give a good basis for an accurate statement of hourly average wind velocities.

There is a great need for a standardized, simple and inexpensive wind recording device specifically designed for the purpose of wind energy estimation. It has been reported (reference W 6) that a battery-powered energy sampling unit has recently been developed which counts the numbers of hours of duration of each wind velocity and also records solar energy intensity. This device is intended for use in remote locations and is expected to be commercially available in 1976.

D. *COLLECTION OF WIND VELOCITY DATA*

It is highly desirable to determine accurately the total hourly duration of each wind velocity during each month of the year at the proposed windmill sites for a period of at least three years, in order to quantify the wind energy potential and to provide a basis for windmill selection and design. However, recording at the exact location and height of each proposed windmill is usually practicable only for the siting of large electric generating windmills.

When undertaking a comprehensive wind survey covering a large area with a similar weather pattern throughout, a reasonable procedure is to locate one continuous recording anemometer at a fully exposed primary site in conjunction with simple run of the wind unattended digital recording anemometers at several secondary locations where windmills are needed. Comparison of the average weekly or monthly wind velocity at the primary site and each secondary location will yield correlation factors which can be applied to the secondary site data to estimate the detailed wind characteristics. If data are available from a station which has a similar wind regime to a proposed site, a similar correlation procedure can be applied by making accurate hourly average measurements with a portable instrument at the proposed site for a fixed period and

comparing the results with the recording station hourly average measurements for the same period. Such a method has limitations, as the correlation factor may vary widely with different wind directions according to terrain differences between the primary site and the secondary recording station.

If adequate data are not available, an approximate assessment of wind patterns may be made by taking short-period observations of wind velocity with a portable instrument, in conjunction with individual discussions with several local inhabitants. Such discussions should seek to determine the relative windiness on a month-to-month basis (especially the months, with most and least wind), the periods and times of day when the wind is most and least and the direction and relative velocities of these winds, the maximum velocity during the year and the maximum length of time with no wind. This method is easy to undertake and may be the most appropriate for immediate widespread implementation of low-cost hand-crafted windmills.

E. *ANALYSIS OF WIND VELOCITY DATA*

Using the average monthly or annual wind velocity for determining the energy potential of a site may not give an accurate result, because some of the velocities included in the average may be above the rated wind velocity of a windmill and because $(A + B + C)^3$ does not equal $(A^3) + (B^3) + (C^3)$.

A duration curve should be prepared as a graph of (v^3), which is proportional to power, against time as shown in figure 3. It is also useful for determination of the optimum rated wind velocity of a windmill to plot a graph of wind velocity against time, as shown in figure 4.

For a particular wind pump at a particular location, the following basic data are required in order to predict the monthly and annual water output:

(a) Hourly average wind velocity records processed to become monthly and annual power duration curves of the type shown in figure 3;

(b) Water pumping rates of the wind pump under consideration within the range of minimum and maximum operating wind velocities when working against any fixed gross head, corrected for the actual gross head. These output rates may be depicted as in figure 5.

Multiplication of the number of hours duration per month at each wind velocity by the relevant hourly output rate will give a series of quantities which, when summed, will yield the total monthly output. The result of calculations for each month of the year may then be shown as in figure 6. A comparison between figure 6 and figure 2 will indicate the seasonal correlations between water pumping demand and wind pumping capacity. It should be noted however that it may also be necessary to consider minimum outputs for shorter periods in order to assess storage requirements.

For estimates of wind-electric generator output, it is usual to assume that the total windmill efficiency is constant for all wind speeds. For a given tentative design, the wind velocity for starting, rated wind velocity and maximum allowable wind velocity are assumed, and figure 7 can be constructed from figure 3. Referring to figure 7, the shaded area (bcfgh) represents the actual output of energy, which will be some proportion of the rectangle (adeo) which represents the output if the windmill were running at full rated power throughout the period, the proportion being the load factor. Using data on a month-by-month basis, figure 8 may be constructed, indicating monthly production of wind energy.

II. STATUS OF WINDMILLS FOR WATER PUMPING[1]

Priority consideration should be given to utilization of windmills for water pumping to supply the increasingly critical needs of domestic consumption, animal husbandry, agriculture and aquaculture.

Water pumping windmill systems can be broadly classified into three major categories: manually produced, mechanical drive; industrially produced, mechanical drive; and electric pumps powered by wind-generated electricity.

A. *MANUALLY PRODUCED, MECHANICAL DRIVE TYPES*

Several different types of simple hand-crafted water pumping windmills have been developed and are now in seasonal use in various parts of the world. However, construction of each of these non-commercial types has tended to be localized because of communication barriers. These wind pumps have several common characteristics: they are constructed of locally available materials (often wood) and are produced with local skills, using simple hand tools; they may operate at low wind velocity; they require daily attendance when in operation; they require frequent but low-cost maintenance; and they are generally used for irrigation or drainage requiring relatively low lift.

---

[1] Illustrations of the basic types of windmills may be found in the second secretariat paper in this section.
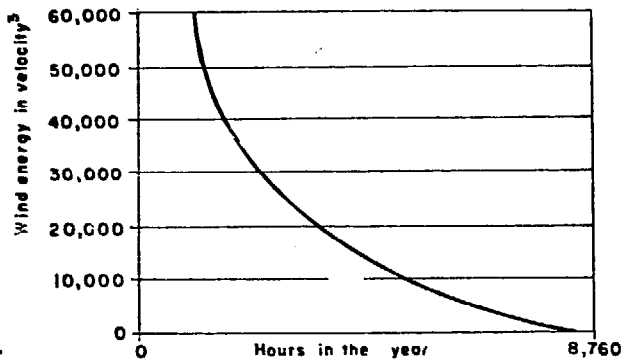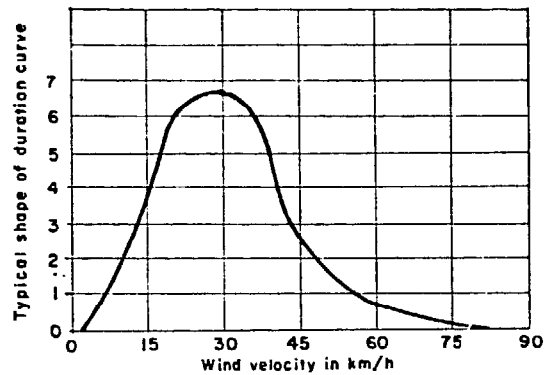
Figure 3. Power duration curve

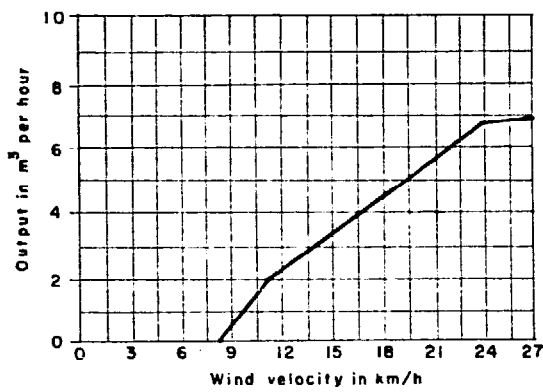Figure 4. Velocity distribution (annual or monthly)
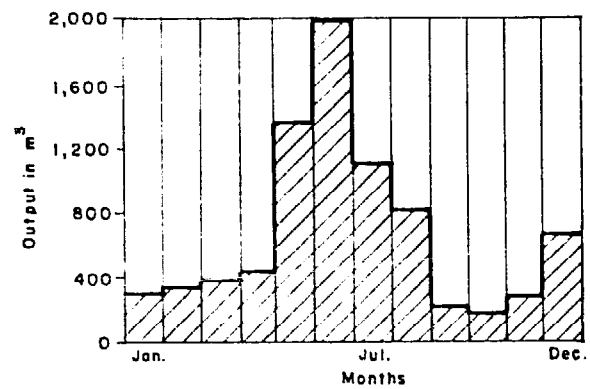
Figure 5. Wind pump performance

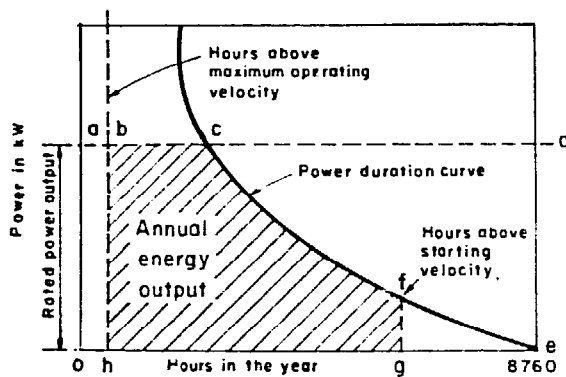Figure 6. Monthly output of water per wind pump
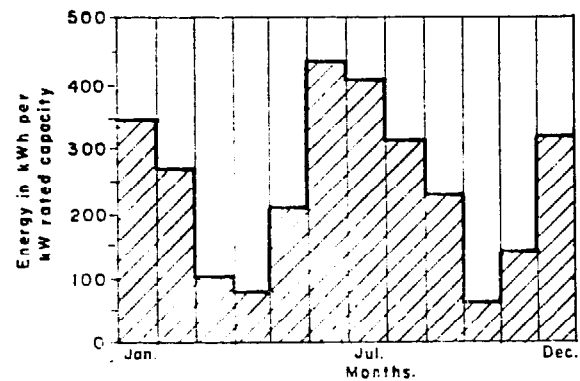
Figure 7. Estimate of energy output

Figure 8. Monthly distribution of energy in the wind

1. The wind pumps of Lassithiou, Crete (Greece)

(a) Usage

In the Mediterranean region, large stone tower mono-directional windmills with triangular cloth sails were historically used for grinding corn and pressing olive oil. Shortly before 1913 this traditional design was adapted in Crete to smaller lightweight structures for pumping water for seasonal irrigation of intensively cultivated plots of vegetables and grains. At least 6,000 of these devices are now in use in the broad fertile plain of Lassithiou which is isolated in the mountains, and some hundreds are also in use in other parts of Crete (see references W 7 and W 8).

(b) Components

Viewed from a distance, all Cretan wind pumps look alike, but large variations in construction become apparent upon close examination. The components described here are generally accepted by the local farmers as being the most successful. The Lassithiou windmill design consists of 11 basic elements; sails, spars, hub, crankshaft, main bearings, tail, carriage, turntable, tower, storage tank and base-well.

Sails — A triangular cloth sail measuring 2.6 m x 1.2 m x 2.4 m is attached to each of the radial spars. The loose corner of each sail is secured by a rope to the tip of the adjacent spar, thus forming a strong uniform surface for catching the wind. The sails can be wrapped around the spars to control the amount of sail area exposed to the wind.

Spars—Commonly, eight wooden spars, each 2.7 m long, radiate out from the hub to form a total windmill diameter of 5.4 m. Stones are attached to the tips of some spars for balancing if required. An axial spar of angle iron extends 2 m out in front of the hub along the main axis of the crankshaft. Steel wires radiating back and out from the end of the axial spar to the tips of the radial spars provide bracing against strong winds, and steel wires between the tips of all the radial spars provide additional bracing. A 60-cm diameter flat steel ring around the hub is bolted to each spar to keep them secured tightly within the hub.

Hub — The front end of the crankshaft is inserted through a 30-cm diameter, 15-cm thick wooden hub with eight 5-cm square holes chiselled in the perimeter to receive the squared ends of the spars. The hub is fixed to the end of the shaft by a bolt passing through both. An improved hub made of two 30-cm diameter, 0.5-cm thick steel discs separated 5-cm apart by 16 small rectangles of 10-cm x 0.5-cm steel plate welded to form eight square holes has recently been adopted.

Crankshaft — The crankshaft is made of a 5-cm diameter, 160-cm long mild steel rod incorporating a U-shaped crank. The U-shape, which was formerly fashioned by bending, but more recently by welding, has an inside width of 7 cm and a height of 7.5 cm, giving a stroke of 15 cm. A 2-cm diameter steel connecting rod attached with two bolts to a wooden crank bearing transfers the rotary motion of the crankshaft into vertically reciprocating motion of the pump piston.

Main bearings — Two 34-cm wide, 15-cm high, 8-cm thick blocks of hardwood, each with a 5-cm diameter hole in the centre of the large surface, are bolted to the front and rear of the carriage to support the crankshaft.

Tail — A triangular tail of corrugated sheet steel 1.5 m x 1.5 m x 1 m is supported by two 2-m long pieces of angle iron from the rear of the carriage. (Some units have a manually-operated tail pole with no vane).

Carriage — The carriage is a rectangular angle iron frame 35-cm wide and 140-cm long, connected by four bolts to two 35-cm long pieces of angle iron riveted to a 45-cm diameter flat steel ring which rotates on the bottom inside surface of the turntable ring. This arrangement keeps the carriage firmly attached to the top of the tower, while, at the same time, allowing it and the attached shaft, sails, etc. to rotate when the wind direction changes.

Turntable — The turntable, riveted to the top of the four tower legs, is made of a 160-cm long piece of 5-cm mild steel angle iron bent into a 50-cm diameter ring to form a flat horizontal greased bearing surface for the carriage.

Tower — Normally the four-legged 5-m high tower is made from 5-cm mild steel angle iron, with flat steel riveted cross bracing, and is bolted and wired to the 1.5-m square base. (In some of the coastal villages several wind pumps are mounted on stone towers offset from the well.) Projecting stones or stepping holes in the tower give access to the sails and top mechanism.

Storage tank — A 13-cm diameter, 15-cm stroke piston pump, made from a discarded cannon shell and fitted with a leather foot valve and a leather-sealed piston, is mounted on the base in the centre of the tower.

Base-well — A 15-cm thick concrete slab covering a 2-m diameter, 7-m deep well forms the base of the windmill.

(c) *Construction materials and skills*

All the wooden bearings and spars are of local origin. The metal shaft and lengths of angle iron are fabricated using ordinary blacksmith's tools and skills. Recently, some electric welding has been utilized for construction of improved crankshafts and hubs.

(d) *Operation and maintenance*

To decrease sail area during periods of high wind, the operator wraps each cloth sail one or more times around its spar. During periods of very high winds, and when the operator is not in attendance, the sails are fully wrapped around the spars. The windmill can be stopped during operation by pulling the tail cord so that the surface of the sails is parallel to the wind. The sails are fully removed from the spars and stored during seasons when the wind pump is not required for irrigation. All bearings are greased twice a month. Sails and pump valves are normally replaced every two years. Spars and main bearings are replaced every five years.

(e) *Performance*

The Cretan windmills start pumping at a wind velocity of 8 km/h and reach optimum performance of 25 rev/min at 13 km/h. The wind pump will increase speed up to about 40 rev/min in higher winds before it controls itself through excessive tip drag and sail fluttering, although the sails are usually reefed at speeds above 25 rev/min. Lifting water as much as 5 m, this type of windmill pumps 3,000 litres per hour, 10-12 hours per day, 4-5 months per year, and has an expected lifetime of about 20 years.

(f) *Economics*

Each wind pumping system costs about $US 480 (windmill $US 320, storage tank $US 120, pump $US 40). The cost of water pumped is approximately one US cent per m³. The widespread success of the Cretan windmill design can be attributed to several factors, namely: the use of lightweight and inexpensive cloth as efficient aerofoils, the use of simple wooden bearings, availability of skilled local carpenters and blacksmiths for construction, large rotor diameter in relation to tower height, favourable local winds, high water-table, intensive agricultural production of cash crops and high cost of petroleum fuels and electricity.

In the 20-year period up to 1973, many of the original 10,000-12,000 windmills on Crete were retired owing to increased availability and low cost of oil products and electricity. Recently, however, many of the "retired" windmills have been put back in service.

2. Adaptations of the Greek windmill configuration

(a) *United States of America*

A 7.6-m diameter sail windmill with six triangular sails of the classical Greek configuration has been designed by Windworks (reference W 9) and tested by the Brace Research Institute, Canada (see reference W 10). This adaptation incorporates durable sails of dacron polyester fibre, mounted on wooden spars. The rotor is mounted on a used automobile differential gear drive which transfers rotary motion with a speed increase ratio of 4:1. A vertical drive shaft delivers this rotary motion to the ground where it can be used for a variety of mechanical tasks, including water pumping. A unique steel octahedron truss tower design, with very high strength to weight ratio, is used. The complete unit costs about $US 600 for materials plus 400 hours of skilled labour, and may be constructed by the owner.

(b) *India*

A 10-m diameter sail windmill with eight triangular cloth sails of the Greek configuration was constructed and tested by the Madurai Windmill Committee for irrigation pumping in low winds in southern India. This design utilizes a maximum of local materials and skills in an effort to keep the price within reach of common farmers. The eight sails, of khaki canvas, are fitted to bamboo spars which are clamped to a central hub adapted from an oxcart wheel. A steel crankshaft mounted in ball bearings transfers reciprocating motion, via a wooden connecting rod and a variable-stroke lever arm, to a 10-cm bore piston pump with a stroke of 30 cm. 6,000 litres of water per hour can be lifted 10 m at a rated wind velocity of 16 km/h. The welded steel turntable carriage, supporting the crankshaft and bamboo-mat tail, rests upon a turntable base made from a steel truck tyre rim which is bolted to the top of a tower made from six 8-m long teak poles. The total construction cost of this windmill was $US 400. Construction plans are available from the TOOL Foundation (reference W 11).

Further design optimization and testing is currently in progress at the Agricultural Engineering Division of the Indian Agricultural Research Institute.

A 6-m diameter, six-sail adaptation of this wind pump has been constructed for second crop rice irrigation, and is currently undergoing trials with a 20-cm diameter piston pump at the Sarvodaya Educational Development Institute, Sri Lanka (see reference W 12).

(c) *Ethiopia*

The American Christian Mission at Omo, near Lake Rudolph, Ethiopia, has established a project called Food from Wind and is selling 6-blade Greek-type sail rotor wind pumps at a subsidized price to

local farmers for lifting river water for irrigation. In August 1975, 19 of these windmills were being operated by the local villagers and five more were being operated by the mission. This project, sponsored by the British charity organization OXFAM, intends to build a total of 100 wind pumps for use in the area. This adaptation may be utilized in areas where there is a shortage of wooden construction materials, and metal working facilities are available. A detailed report and drawings of the design are available from the Inter-mediate Technology Development Group, United Kingdom (see reference W 13).

3. Wind pumps of China

(a) Luffing-sail type

Simple hand-crafted windmills have been used in China for many centuries (see references W 14, W 15 and W 16). Reportedly the first of these were the hand-crafted luffing-sail vertical-axis wind pumps which are still extensively used along the eastern coast north of the Yangtze River, particularly near Tientsin, for lifting salt water into evaporating ponds. A minutely detailed study of these pumps has recently been made (reference W 17). The windmill has a central vertical wooden drive shaft from which radiate two sets of eight equally-spaced wooden poles, to give a total diameter of about 9 m. Eight vertical masts suspended between the tips of the 16 poles support eight 3 m x 1.8 m sails similar in construction and rigging to those on Chinese junks. When being pushed down-wind, each sail presents its full surface to the wind, being held in position by a rope. When returning against the wind, the sail turns automatically on the mast so that it presents only its edge, and no surface, to the wind. At the base of the vertical shaft, a 3-m diameter drive wheel with 88 wooden teeth engages a 15-tooth pinion gear mounted on one end of a horizontal shaft. At the other end of the horizontal shaft is a wheel with nine arms which drives the wooden chain of a square-pallet ladder pump. The whole unit is simple and inexpensive.

Further developments, including a more compact and economical arrangement, were shown at the Agricultural Machinery Exhibition at Peking in 1958.

Prototype construction of adaptations of this design has recently been undertaken in Thailand by the Division of Agricultural Engineering, Department of Agriculture.

(b) Adaptation of Greek design

In northeastern China, Greek-type windmills of wooden construction, with 12 cloth sails, are connected to paternoster pumps to lift irrigation water (reference W 18). These windmills use an eight-blade automatic fan tail for directional control, and each windmill is fitted with a simple wooden anemometer.

(c) Oblique-axis type

In some of the eastern provinces, especially between Shanghai and Hangchow, oblique-axis wind pumps similar to the Tjasker type (Netherlands) have been used for water lifting (reference W 19). These devices are fitted with six mat and batten type sails at the top end of the shaft, pointed into the wind. A steel wheel with 19 or 20 steel teeth, fitted to the bottom of the shaft, engages a similar toothed wheel fixed to the top of a vertical drive shaft supported by a short wooden four-legged tower. The vertical drive shaft is connected to a square-pallet ladder pump. The rotor can be pivoted around the vertical drive shaft to point into the wind by changing the position of the two wooden poles which form an A-frame supporting the top end of the shaft.

4. Hand-crafted wind pumps of Thailand

Several types of low-cost wind pumps are used in Thailand for pumping water for rice irrigation and salt production. These devices are explained in the paper presented by the National Energy Administration of Thailand. (See also reference W 20).

5. Wind pumps of the Netherlands

(a) Hollow post type

The wipmolen or hollow post type of wind pump (reference W 21) was developed in the fifteenth century and used extensively for drainage. It consists of four cloth-covered wooden lattice frames up to 10 m long, fixed to a wooden main shaft. The main shaft carries a large drive wheel with wooden teeth, driving a wooden toothed wheel fixed at the top of a vertical driveshaft, which extends down through a large hollow wooden post to the bottom, where its weight rests on a thrust bearing. At the lower end of the vertical shaft, a small wooden gear wheel meshes with the teeth of a large gear wheel which is fixed to the pump shaft on which the pump is mounted.

In the second half of the sixteenth century, the relatively simple hollow post units evolved into very large smock and cap tower units used extensively for land reclamation projects. Although proportionately larger than the hollow post units, the internal machinery is similar. Each of these units could pump as much as 57 m³ of water per minute to a height of 1.5 m. The Archimedean screw, consisting of a wooden spiral enclosed in a wooden casing, was adapted to drainage wind pumps in 1634. Using such a device, it was possible to increase the lift to 5 m.

(b) Meadow type

The meadow type with a 4-m diameter, four-blade rotor, is an adaptation of the hollow post type, and is still widely used in the northern area. This unit has a

wooden body resting on a concrete foundation. Steel ball bearings are used on the shafts of the traditional power transfer system of wooden gearing. At the rear of the movable cap is a large tail vane which incorporates a spring-operated control mechanism for turning the rotor out of the wind during periods of very high wind. The base of the structure encloses a large-diameter, slow-speed, centrifugal pump.

(c) Tjasker type

The Tjasker type is the simplest and smallest of the Netherlands water pumping windmills. It consists essentially of a long wooden shaft mounted at an angle of 30° to the horizontal, the upper end of the shaft carrying four cloth sails on a wooden framework, 6 m in diameter, and the lower end terminating in a closed Archimedean screw. The shaft is supported by a wooden A-frame and the assembly can be moved in a circle around a central pivot pole to point the sails into the wind.

6. Tanzanian design

A low-cost locally-constructed windmill suited for deep borehole water pumping has been developed by a team in co-operation with the Ministry of Lands, Settlement, and Water Development, Tanzania (reference W 22). Twelve of these windmills are being constructed for use in Tanzanian villages, and one unit will be displayed in June 1976 at the UNICEF Appropriate Technology Centre, Nairobi.

The 5-m diameter rotor consists of six 0.9 m x 0.7 m corrugated, galvanized metal sheets mounted with a root pitch angle of 45° and a tip pitch angle of 30° on six steel spars. Each blade is cambered along its chord to a 2.7-m radius, and blade pitch control is incorporated into the hub mechanism. The tail vane is of sheet steel. The tower is constructed from three 6-m long galvanized steel pipes. Power transfer by an adjustable eccentric wheel permits adjustment of the reciprocating stroke for different pumping conditions.

7. French design

A low-cost multi-blade windmill intended for local construction has been developed by a group of French engineers and tested over a period of 30 months. Prototypes have been on trial at Ougadougou, Upper Volta, and at Agades, Niger, since the end of 1973. A pilot series of 20 windmills was manufactured in 1974 and 1975 and sent for trial and demonstration to Chad, Cape Verde Islands, Niger, Haiti, Laos, Democratic Yemen, Mali and Senegal.

The 3-m diameter rotor has 16 canvas vanes mounted on wooden spars with a variable pitch and self-feathering control mechanism, and a canvas and

bamboo tail vane. A steel crankshaft mounted in metal/teflon bearings converts the rotary motion to vertically reciprocating motion, which is transferred by a wooden connecting rod to an adjustable balance arm. At the starting wind velocity of 7 km/h, with the rotor turning at 10 rev/min, the unit will lift water 6 m at the rate of 120 litres per hour. The maximum rotational speed in higher winds is 60 rev/min. The simple wooden guyed pole structure is 4 m high. The cost of this windmill is somewhat greater than $US 400. Details of construction and assembly are available (see reference W 23).

8. Savonius rotor

The Savonius rotor has been widely publicized as being appropriate for use in developing countries (reference W 24). This vertical-axis rotor incorporates two semi-cylindrical surfaces, mounted on a vertical shaft so that the view from above presents the shape of the letter S. Typical models of this design are made from two halves of an oil drum split longitudinally. The potential advantages of this system are that it will accept the wind from any direction, and the rotor is simple and inexpensive to build. Many organizations and individuals throughout the world have experimented with this design and found it to be generally unsatisfactory for practical application (reference W 25). The disadvantages are small collection area, large weight/surface area ratio, low aerodynamic efficiency, vibration problems and difficulty in making a connexion to a pump. Potential is seen for this design only in applications requiring very little power, such as the stirring of algae cultures and the starting of Darrieus rotors.

B. INDUSTRIALLY PRODUCED MECHANICAL WIND PUMPS

1. Multi-vane wind pumps

(a) Usage

The most commonly used and widely distributed type of wind pump is the slow-running multi-vane metal fan driving a piston pump. Originally developed in France, the multi-vane windmill first attained widespread use in the United States of America in the late 1800s for domestic and livestock water supply. Use and manufacture have gradually spread to many parts of the world, especially the United Kingdom, Australia, South Africa and South America. Local adaptations of this design have been developed in the Philippines, India, Syria, Indonesia and Thailand, but have not been widely used in those countries because of the high cost of all-metal construction and economic and technical limitations on the capability of the owners to undertake proper maintenance. Many multi-vane wind pumps made in the United States of America and Australia have been exported to developing countries throughout the world, often on a

subsidized basis, but these units often cease functioning within 10 years because of the lack of skilled maintenance.

(b) Components

Although there may be variations between different manufacturers, the basic components are as follows:

Rotor — The windwheel or fan consists of 8 to 24 galvanized sheet steel vanes which are cambered to provide optimum aerodynamic efficiency. The vanes are carefully balanced, and fastened to two concentric steel rings which are supported by five or six tensioned steel spokes connected to a cast steel hub. This assembly is mounted on a shaft which runs in automatically-oiled ball or babbitt bearings, or wooden bearings. The diameter of the rotors available ranges from 1.8 m to 9 m.

Gearbox — The shaft is mounted in a cast iron head unit incorporating a reciprocating crank system. In smaller models, a speed reduction gearing of ratio 2:1 to 4:1 permits the rotor to turn with a relatively low torque load and deliver a longer stroke to the pump connecting rod than if it were connected directly to a crankshaft.

Turntable — The gearbox is mounted on a turntable, through which passes the reciprocating steel connecting rod and the tail pullout chain.

Tower — A three-legged or four-legged angle iron lattice tower is used, varying in height from 5.5 to 18 m. The large quantity of steel used for the towers is a major expense. The tower is mounted directly above, or adjacent to, the water supply, on a concrete foundation.

Control devices — The rotor is pointed into the wind by a galvanized sheet steel tail vane. The rotor may be turned parallel to the wind, when necessary during exceptionally strong winds (above 60 km/h), by means of a cable winch or lever fitted at the base of the tower and connected to the tail pullout chain. In some models, a brake on the rotor operates simultaneously with the tail pullout mechanism.

The main shaft is often offset slightly from the centre of rotation of the turntable, so that in higher winds the rotor is automatically turned partially out of the wind by the unbalanced distribution of wind pressure at the centre of rotation.

Pump — Pumps are commonly of the single-acting reciprocating piston type. The piston cylinder is usually of brass or PVC plastic 5-15 cm inside diameter. The piston incorporates a single or double leather seal and a one-way valve. A steel ball or leather flap valve is fitted at the base of the cylinder and a third one-way valve may be fitted at the bottom of the inlet pipe.

Storage tank — Water is usually stored in an elevated steel tank for domestic water supply and in a ground-level tank or pond for stock watering.

(c) Construction materials and skills

Multi-vane windmills are shipped from the manufacturer complete and ready for assembly, with ordinary mechanic's wrenches and screwdrivers, by semi-skilled workers. Considerable skill and dexterity are required to lift up the tower, the gearbox assembly and the rotor, which are each quite heavy.

(d) Operation and maintenance

Once assembled, the only normal maintenance required is annual replacement of the oil in the gearbox. After several years, the replacement of damaged rotor blades, worn bearings and worn pump valves and seals may be required. These tasks may present some difficulty in rural areas, especially when the new part must be obtained from the manufacturer.

(e) Performance

The standard types start working with a wind velocity of 6-8 km/h and have a constant operational speed and output for wind velocity of 28 km/h and above. (It should be noted that the rotational speed decreases as the rotor diameter increases, so that selection of a rotor larger than that required to supply the necessary torque to the pump to start operating may have a negative effect on pumping rate).

Table 1 gives an example of the performance of a typical multi-vane wind pump (Comet) operating at a mean hourly wind velocity of 12.4 km/h.

Table 1. PERFORMANCE OF COMET WIND PUMP

| Pump diameter (cm) | Rotor diameter | | | | | | | |
| | 2.44 m | | 4.88 m | | 7.32 m | | 9.14 m | |
	Lift (m)	Output (m³ per day)	Lift (m)	Output (m³ per day)	Lift (m)	Output (m³ per day)	Lift (m)	Output (m³ per day)
5.08	38	5.8	167	9.6	—	—	—	—
7.62	19	13.1	83	21.8	237	23.4	—	—
10.16	11	23.2	49	38.2	136	41.4	236	37.6
15.24	5	47.7	21	86.4	58	93.4	109	84.3
20.32	—	—	11	154	34	163	61	149
30.48	—	—	—	—	15	366	28	336
45.72	—	—	—	—	7	832	12	746

2. Lubing wind pump

The Lubing company in the Federal Republic of Germany manufactures a highly reliable precision-made wind pump, which has three aerodynamically-shaped high speed rotor blades mounted down-wind in a coning angle. Speed control is achieved through radial feathering of the rotor blades by centrifugal weights mounted on each blade shaft. The single guyed steel pole tower is hinged at the base so that the complete unit may be easily lowered to the ground by means of a winch at the base of one of the three guy cables, which is a useful feature in typhoon areas. This wind pump will operate unattended for long periods of time but it is very expensive.

3. Sparco wind pump

The Sparco wind pump, manufactured in Denmark, is intended for cattle watering. It is mounted on a single guyed steel pole tower, and has curved plate steel alloy blades individually mounted on steel shafts, and self-regulating, with a tail for directional orientation. All moving parts are mounted in sealed ball bearings.

4. Bosman wind pump

The Bosman wind pump is manufactured in the Netherlands for small-scale drainage pumping on farms and grazing land. It consists of four flat steel plates, twisted to achieve a low pitch angle at the tip and high pitch angle at the root, and fixed to four steel arms to give an effective diameter of 3 m. The rotary motion of the horizontal main shaft is transferred through 90° by a sealed oil-bath gear system to a vertical shaft, which runs down the centre of the 4-m high steel lattice tower to a submerged centrifugal low-lift pump. A unique control system incorporates two tails mounted 90° apart and capable of simultaneous radial twist, so that only one tail is vertical at any time, the operation being controlled by the water level.

Detailed studies are being made at Eindhoven University, Netherlands, on the potential for further development of plate blades such as those used on the Sparco and Bosman wind pumps.

C. ELECTRIC PUMPS POWERED BY WIND-GENERATED ELECTRICITY

High-speed wind-electric generators can be used to pump water by transmitting power to electric motors connected to centrifugal immersion pumps (reference W 26). This method has several advantages: (a) the pump and wind motor need not be mounted at the same location, e.g. the generator may be located on a windy hill and the pump on a river flat; (b) one

generator may be used to operate several pumps; (c) several generators may supply a single pumping station, e.g. in Germany a 64 kW pumping station is supplied by eight Allgaier wind power plants; (d) the manufacture of wind-electric generators may be carried on independently of the manufacture of the pumps or the intended application; (e) the efficiency of high-speed wind rotors and high-speed centrifugal pumps is greater than the efficiency of slow-speed wind rotors and piston pumps; (f) energy may be used from time to time for other purposes.

Despite these advantages, the method has not been widely used, because of the high capital cost of large wind-electric generators.

III. STATUS OF WIND-DRIVEN ELECTRIC GENERATORS

The first wide-scale use of wind-generated electricity occurred in the 1930s, following the development of medium-speed generators for automobiles, and using the increased knowledge available of aerofoils and aircraft propellers.

Wind-electric generators can be broadly classified as suitable for small-scale generation for localized use, or large-scale generation for supply to a distribution grid.

A. SMALL-SCALE GENERATION

During the late 1930s more than 300 companies around the world were producing various types of small wind-electric generators with rated output as high as 3 kW. Following the rapid development of fossil-fueled central electric-generating stations and the development of distribution systems, wind-electric generators tended to become uneconomical. At present there is a much smaller number of manufacturers, but many new developments are taking place (see reference W 27).

1. Elecktro wind generators

The Elecktro company in Switzerland, established in 1938, manufactures a large range of DC wind-electric generators with specifications as summarized in table 2.

Most models are available with special dust-proof bearings, and insect-proof wiring for use in tropical areas. A DC/AC inverter is also available.

These highly reliable windmills are used around the world in all extremes of climate to supply power for communications relay stations and navigation aids.

Table 2. ELECKTRO WIND-ELECTRIC GENERATORS

Model	Rated output (watts)	Rated wind velocity (km/h)	Rated voltage (v)
W 50	50	—	DC 6/12/24
W 250 . . .	250	—	DC 12/24
WV 05 . . .	600	—	DC 12/24/36
WV 156 . . .	1,200	37	DC 12/24/36/48/65/110
WV 256 . . .	2,200	35	DC 24/36/48/65/110
WV 356 . . .	4,000	38	DC 48/65/110
WVG 506 . .	6,000	42	DC 65/110
WV 15 W . .	1,200	37	AC 110, 1-phase
WV 250 . . .	2,000	35	AC 110, 3-phase
WV 35 D . .	3,500	38	AC 110/220, 3-phase
WVG 50 D . .	5,000	42	AC 110/220, 3-phase

2. Aerowatt wind generator

The Aerowatt company in France manufactures several models of exceptional wind-electric generators especially adapted for long periods of unattended reliable operation in severe environments. Specifications are summarized in table 3.

Table 3. AEROWATT WIND-ELECTRIC GENERATORS

Model	Starting wind speed (km/h)	Rated wind speed (km/h)	Rated output (watts)	Rated voltage (V)
24 FP 7 . . .	14	25	28	24
150 FRP 7 . .	11	25	130	24
300 FP 7 . . .	11	25	350	110
1100 FP 7 . .	11	25	1,125	110, 220, 380
4100 FP 7 . .	14	27	4,100	110, 220, 380

These units are frequently used to supply power for critical remote installations, such as communications relay stations and navigation aids.

3. Dunlite wind generator

The Dunlite company in Australia manufactures two models of high quality reasonably-priced wind-electric generators. These have been used in remote places in Australia and the ESCAP region for the past 30 years for domestic power supply as well as power supply to communications relays and navigational aids. Specifications are summarized in table 4.

Table 4. DUNLITE WIND-ELECTRIC GENERATORS

Model	Starting speed (km/h)	Rated speed (km/h)	Rated output (watts)	Rated voltage (V DC)
L	—	—	14	32, 36
M	16	40	2,000	24, 32, 48, 115

4. Winco battery charger

The Winco-Dynatechnology company in the United States of America manufactures a wind-electric battery charger model No. 1222 H. This device has a starting speed of 11 km/h and a rated speed of 37 km/h and delivers 14 amperes at 15 volts DC.

5. Lubing battery charger

The Lubing company in the Federal Republic of Germany manufactures a wind-electric battery charger, based on 25 years of experience in the design and construction of wind-electric generating units.

The rotor consists of a propeller with three aerodynamically profiled blades made of epoxy resin reinforced with glass fibre, and a centrifugal governor is provided to limit rotor speed to approximately 600 rev/min. Three additional smaller blades provide a starting facility at a wind velocity of 12-14 km/h. Transmission of power from the shaft to the special brushless AC generator is by means of a two-stage oil-bath gearbox.

The resulting AC output is transformed to 24 V, rectified and stored in batteries. Electronic controls regulate the charging of the batteries automatically and, when the battery voltage reaches 28.5 V, the charging current is automatically switched off. The designed output for various wind velocities is:

Wind velocity (km/h)	—	14	22	29	36	43
Output (watts)	—	24	136	325	400	400

6. Bucknell wind generator

The Bucknell company in the United States of America manufactures a 12 V 200 watt wind-electric generator.

7. Enag wind generator

The Enag company in France manufactures three models of wind-electric generators:

Eolienne, 400 watts, 24/30 V

Super Eolienne, 1,200 watts, 24/30 V

Super Eolienne, 2,500 watts, 110 V

8. USSR wind generators

The USSR Institute for Farm Electrification is responsible for several wind-electric generators rated from 0.5 to 25 kW.

9. NOAH wind generators

NOAH company in the Federal Republic of Germany has recently tested several pre-production prototype wind-electric generators with maximum outputs up to 90 kW with variable voltage and variable frequency AC, suitable for electrical heating and cooling, water pumping and hydrogen production.

10. DAF wind generators

The DAF company in Canada is currently undertaking the manufacture of two models of vertical-axis Darrieus rotor wind-electric generators. Selected characteristics are given in table 5.

This type of unit has been especially designed for developing countries and a preliminary economic analysis (reference W 28) indicates that this design has an economic advantage over some other machines.

11. Sencenbough wind generator

The Sencenbough company in the United States of America provides a complete kit for construction of Model 750-14 wind-electric generator. This 790 watt, 14.4 V DC device has a starting velocity of 12 km/h rated wind velocity of 29-32 km/h and maximum operating velocity of 48 km/h, and is equipped with a 3.7-m diameter propeller.

Table 5. CHARACTERISTICS OF DAF WIND GENERATORS

Average wind velocity per month (km/h) .	14.4	17.6	20.8	24.0	28.8
Average monthly kWh output at 110 V (4.6-m diameter)	110	210	360	560	1,000
Average monthly kWh output at 24 V (4.6-m diameter)	110	190	290	420	680
Average monthly kWh output at 24 V (6-m diameter)	210	400	680	1,070	1,900

12. Windworks battery charger

The Windworks company in the United States of America has prepared a plan for a 12 volt DC wind-electric generator (reference W 9). The estimated power output is as follows:

Average wind velocity per month (km/h)	16	19	22	26
Average monthly output (kWh)	86	150	236	350

Considerable time, skill, specialized power equipment and some special materials are required for construction of this unit.

13. Brace wind generator

The Brace Research Institute in Canada has designed and tested a 9 kW 110-230 V AC wind-electric generator for use in developing countries (reference W 10). This design, intended for local assembly, utilizes automobile and truck components and a 9.8-m fibreglass rotor manufactured in Canada. The estimated electrical output is as follows:

Average wind velocity per month (km/h)	16	19	22	26
Average monthly output (kWh)	740	1,278	2,030	3,030

14. Kedco battery charger

The Kedco company in the United States of America has begun production of a simple, reliable

wind-electric generator. Model 1200 produces 1,200 watts, 85 amps at 14.4 V DC at a rated wind velocity of 34 km/h, the starting wind velocity being 11 km/h.

15. Models no longer manufactured

Many of the wind-electric generators previously manufactured in the United States of America were of simple reliable construction, and several of these units are still providing reliable service. A detailed study of the components of these units is recommended prior to finalization of any design of wind-electric generators for manufacture and use in the region.

B. *LARGE-SCALE GENERATION FOR SUPPLY TO DISTRIBUTION GRIDS*

From 1930 to the late 1950s, many large prototype wind-electric generators, the largest of which was rated at 1,250 kW, were constructed and tested in a number of countries, including Denmark, the United Kingdom, France, Germany, the USSR and the United States of America. Although technically successful, they were not generally adopted because they were not cost-competitive with large-scale fossil-fueled generation. New activities in this field have occurred recently (reference W 29).

1. ERDA projects

In 1973, considering recent technological developments in related fields, the United States National Aeronautical and Space Administration (NASA) and the National Science Foundation undertook a major wind energy development programme which was followed up by the Energy Research and Development Administration (ERDA) in 1975.

The first ERDA prototype wind-electric generator commenced operation in November 1975. The general specifications of this Model 0, 100 kW experimental unit were:

Cut-in wind speed (first load applied) 13 km/h

Rated wind speed (100 kW at busbar) 28 km/h

Maximum operating wind speed 95 km/h

In 1976, ERDA is planning construction of two prototypes each rated 200 kW, and commencement of a significant programme for development of small wind-electric generators.

2. Danish wind-electric generators

In 1941-1943, the Smidth company in Denmark manufactured twelve 60 kW and six 70 kW DC wind-electric generators which supplied a local electricity grid for about 10 years. In 1957, the same company installed a 200 kW AC wind-electric generator, which supplied electricity to the national distribution grid for 10 years.

In 1974-1975, the Danish Academy of Technical Science re-examined the possibilities of large-scale wind-electric generation and concluded that wind energy could supply 10 per cent of the country's electricity. Large Darrieus rotors supported on icosahedron frames were proposed as an appropriate design.

3. French wind-electric generator

In 1957 an 800 kW 3,000 V wind-electric generator was constructed and operated for 5,000 hours, including 600 hours connected to the distribution grid. In the early 1960s, the NEYRPIC organization constructed a 1,000 kW, 3,000 V asynchronous AC wind-electric generator which supplied a maximum output of 220,000 kWh in November 1963. A reduction in petroleum prices discouraged plans for widespread use of these machines.

4. Canadian wind-electric generator

The Canadian National Research Council is proceeding with a plan for erection of a 200 kW Darrieus rotor wind-electric generator which is expected to supply 500,000 kWh per year to a local distribution grid.

5. New Zealand study

The New Zealand Aerospace company is studying a 10 kW version of the Darrieus rotor design as a model for a larger unit intended to be connected to the national grid.

IV. WINDMILLS FOR OTHER USES

In many countries, windmills have been traditionally used for grinding grains, oilseed pressing, sugarcane crushing, wood cutting and other semi-industrial tasks. Construction and performance details of some of these machines are available in the literature and present some potential for adaptation for use in the region.

A. *MULTIPLE USAGE*

Considerable potential appears to exist for adaptation of wind rotors already used in the region for water pumping, such as the Greek sail configuration and the Thai high-speed type, to tasks able to use variable intermittent mechanical power, including grain threshing, winnowing and grinding, concrete mixing, load lifting and compost grinding.

It would be desirable to consider development of wind utilization systems that can be used for several purposes, thus allowing the windmill to be used whenever wind is available, and this would depend largely on the proper selection or development of the utilization devices. Some activity in this field has been initiated by the Social Work and Research Centre at Tilonia in India, and some commercial applications are being developed by the Bharat Heavy Electricals company in India.

B. *CHINESE WIND-POWERED PLOUGH*

The use of a wind-powered cable plough in China has been reported in reference W 30. This device incorporates a wind-powered winch consisting of an upper and a lower capstan and a coupler capable of changing direction. A bi-directional plough is connected to a continuous cable which passes through a pulley at the end of the field. The system is operated by two persons, one person operating the windwheel and winch and the other person operating the plough, and can plough 0.25 to 0.8 hectares of land per day, depending on wind velocity.

V. SELECTION AND MATCHING OF TRADITIONAL COMPONENTS FOR DESIGN OF NEW HYBRID WINDMILLS

Components may be broadly classified as follows:

The rotor consists of a surface area for receiving the pressure of the wind and a support structure which converts the horizontal pressure of the wind to rotary motion.

The hub connects the rotor to the main shaft.

The main shaft and bearings support the weight of the rotor and carry the rotary motion to a power transfer mechanism.

The power transfer mechanism carries the rotary motion of the shaft to the power utilization device.

The power utilization device converts the mechanical power delivered to it into some form of useful work.

The tower supports the rotor above the ground at a height where it can receive a useful amount of wind and in most cases rotate freely.

The orientation system consists of a turntable, shaft carriage and sometimes a tail. It is required on horizontal axis devices to maintain the plane of rotation of the rotor perpendicular to the direction of wind flow.

The control system is required to match the performance of the windmill to the available wind and the energy demand, and to prevent structural damage in high winds.

The primary factors determining the design of each component are: function, physical stress related to wind speed and load demand, materials available and the skills and tools required to work with these materials. The matching of individual components into a system should aim to have all components able to withstand similar maximum stress loads and to require a minimum number of different materials, skills and tools for assembly of the system.

A large number of successful components is described in detail in the literature. The construction and performance characteristics of an appropriate selection of these, and others not reported, could be carefully documented for each major use (mechanical, electrical) for two power ranges (less than 5 kW, greater than 5 kW). Such documents would be most useful for the development of hybrid wind-energy systems for specific applications.

VI. CURRENT INTERNATIONAL ACTIVITIES

Several international organizations are involved in the development and promotion of small-scale wind utilization devices.

A. *UNITED NATIONS*

The Centre for Natural Resources, Energy and Transport of the Department of Economic and Social Affairs in New York has an expert adviser on non-conventional resources on its staff. In 1974, an economic evaluation of wind-power systems was made.

The Economic and Social Commission for Asia and the Pacific will conduct a roving seminar on rural energy development in 1977.

The Economic Commission for Africa is sponsoring the Second African Meeting on Energy in 1976. This meeting will include discussions on the future role of wind energy utilization in Africa.

The Economic Commission for Latin America is undertaking a study, and experts are being hired to undertake the implementation of wind-electric generators in rural areas of Paraguay.

The Food and Agriculture Organization of the United Nations is currently updating reference W 4.

The United Nations Environment Programme is undertaking the establishment of a few demonstration centres which will integrate solar, wind and bio-mass energy sources into self-sufficient energy systems for communities in some of the typical rural areas of Asia, Latin America and Africa. Sri Lanka has been chosen as the site of the Asian centre.

Although the United Nations Industrial Development Organization is concerned primarily with industrial development, it has several programmes related to energy, and is supplying expert advice to the Government of the Sudan on the utilization of wind energy. A small production unit for the manufacture of water pumping windmills is being set up in Kenya.

The United Nations Children's Fund is establishing a village technology demonstration unit in Nairobi that is expected to be completed by the end of May 1976, and is sponsoring a seminar, commencing 10 June 1976, that will include demonstrations of local renewable energy resources, including two types of windmills, and simple technology for the rural family.

The United Nations Educational, Scientific and Cultural Organization has been supporting activities related to non-conventional energy resources including wind energy and has established a committee to coordinate this activity.

B. UNITED STATES OF AMERICA

The New Alchemy Institute-East is developing a 6 kW wind-electric generator to be demonstrated as part of the United Nations Human Settlement Programme in Canada. They have also been involved in the development of low-cost wind pumps in India.

Volunteers for International Technical Assistance publishes details on the construction of several varieties of windmill appropriate for construction and use in developing countries and has several voluntary wind-energy experts who respond to enquiries regarding wind energy utilization.

The Energy Research and Development Administration is actively collaborating with several countries in the development of large-scale wind-electric generating devices.

The Technical Assistance Information Clearing House has recently devoted some effort to international co-ordination of work on small-scale wind energy utilization.

The Wind Energy Society of America is concerned with dissemination of wind energy information within the academic and research community. The Society has several international members.

C. NETHERLANDS

The Netherlands development foundation TOOL publishes an international newsletter with the aim of increasing communication between technical workers. TOOL is providing direct technical collaboration on wind energy development projects in India, Indonesia and Sri Lanka and has published technical information on windmill construction for use by rural development workers.

D. CANADA

The Brace Research Institute has been actively involved in the development of windmill designs and their implementation in developing countries for several years, and has issued several relevant technical publications.

E. UNITED KINGDOM

The Intermediate Technology Development Group has provided direct technical assistance on wind pumps in Africa and has prepared a technical report on this work. It is currently building a prototype wind pump with a 6-m diameter rotor with three metal aerofoil blades, a fail-safe governing device and an improved pump, primarily for irrigation.

The Oxford Committee for Famine Relief (OXFAM) has been active in promoting and financing the development of windmills in India and Africa.

F. FEDERAL REPUBLIC OF GERMANY

The Foundation for International Development organized a conference in September 1975.

A Wind Energy Research Institute has recently been established at the University of Stuttgart. This institute will consider problems of wind energy utilization and will hold regular classes in wind energy techniques.

G. MALAYSIA

The Malaysian Agricultural Research and Development Institute has recently developed a 6-m diameter, tail-less (down-wind) Greek type sail rotor and peristaltic pump suitable for rural construction, and use for irrigation and drainage of rice fields.

H. SWITZERLAND

The World Council of Churches publishes original information on windmill construction for use by development workers.

THE DESIGN AND CONSTRUCTION OF LOW-COST WIND-POWERED WATER PUMPING SYSTEMS (NR/ERD/EWGSW/6)*

INTRODUCTION

Recently there has been an increasing demand for information on designs of water pumping windmill systems suitable for construction with low-cost locally-available materials and skills, and it appears that the general unavailability of properly-documented technical information on indigenous wind pumps is a major factor limiting more widespread implementation of wind pumps in rural areas.

Because of the complex interrelationships of the variables of wind characteristics, water supply, materials and skills at each different locality, adaptation of low-cost wind pumps to new areas without modification or redesign has had limited success in the past. However, such interrelationships may be identified and rationalized, and the design process presented as a sequential flow of information analysis, rational decisions, and calculations, as in the flow chart figure 1.

I. PRELIMINARY INVESTIGATIONS

A. SURVEY OF LOCAL WIND CHARACTERISTICS

A reliable determination of local wind characteristics is required, especially for the period when water pumping is most needed. Summarized average hourly wind velocities (figure 2) are required for preparation of velocity and power frequency curves (figure 3) and power duration curves (figure 4). The maximum wind velocity, and directional distribution of winds (figure 5) should also be determined.

B. SURVEY OF LOCAL WATER PUMPING NEEDS

A survey of local water pumping needs should be carried out to determine the total pumping head and the daily water demand on a monthly basis for each likely agricultural and domestic requirement.

C. CLASSIFICATION OF WIND ROTORS

Several different types of wind rotors are well-known, but their construction and performance characteristics have not been comprehensively classified in a format suitable for design purposes. Complete information for comparative analysis of rotors should include: starting velocity, rated velocity, maximum operating velocity, tip speed ratio, rated efficiency,

range of diameters, construction materials, rotor solidity (total swept area divided by total frontal area of blades), control mechanisms, velocity/power graph, and, where relevant, root chord, tip chord, root angle, tip angle and aerofoil section. Compilation of these parameters for existing wind rotors would greatly assist the design and development of new hybrid wind-pumping systems.

1. Horizontal-axis rotors

(a) The classic Greek type sail rotor (figure 6) is widely used in Greece (references W 7, W 8, W 31), and adaptations are widely used in Thailand (figure 7 and reference W 20) and China (reference W 18). It is suitable for wind pumps because of its high starting torque, low starting speed, low weight and cost, and its ability to be easily adjusted on the occurrence of higher wind velocities. It consists of 6 to 12 triangular cloth sails, each attached to a wooden spar along its longest edge and held tight by a rope leading from the free corner to the adjacent spar tip or circumferential wire between spar tips. Radial wires, leading from the tip of each spar to the tip of a central axial spar, brace the spars against wind pressure. Maximum rotor solidity is about 45-50 per cent. Sail area can be reduced by wrapping each sail one or more times around its spar. This type of rotor appears to be the most appropriate design for use in areas with limited resources of materials and skill. It has been further developed by several organizations for use in India (figure 8 and references W 11, W 32), Malaysia (figure 9), Sri Lanka (reference W 12), Ethiopia (reference W 13) and other developing countries (figure 10 and references W 9 and W 10).

(b) The steel multi-vane fan rotor (figure 11) consists of 8 to 24 curved sheet metal blades mounted on two concentric steel rings supported by 5 or 6 tensioned steel spokes. Rotor solidity is 90-100 per cent. Local adaptations of this design have been developed by the National Aeronautical Laboratory in India, the General Administration for the Development of the Euphrates Basin in Syria, a private company in Thailand, the Bandung Institute of Technology in Indonesia (reference W 33) and USAID (reference W 34). A cloth multi-vane rotor has also been developed (reference W 23).

Multi-vane rotors are characterized by a very low starting wind velocity of 6-8 km/h, and high starting torque, and are normally used in conjunction with a piston pump. They are most appropriate for industrial manufacture and use in areas where the necessity for long-time durability and reliable unattended operation can justify the large capital expenditure required.

Figure 1. Sequential flow chart for design of water pumping windmill systems

v' (knots)	0	1	2	3	4	5	6	7	8	9
v (km/h)	0	1.85	3.70	5.55	7.41	9.26	11.11	12.96	14.81	16.67
t(hours duration)	291	32	619	331	857	387	604	219	517	92
$v^3 \times t$	0	202	31,354	56,585	348,687	307,287	828,281	476,714	1,679,402	426,180

v' (knots)	10	11	12	13	14	15	16	17	18	
v (km/h)	18.52	20.37	22.22	24.07	25.93	27.78	29.63	31.48	33.33	
t(hours duration)	293	23	104	25	14	5	1	0	2	
$v^3 \times t$	1,861,187	194,401	1,140,943	348,631	244,081	107,193	26,013	0	74,052	

Figure 2. Summary of ½ hourly wind velocity readings at Don Muang airport, Bangkok, for March, April and May 1975

Figure 3. Velocity and power frequency curves

Figure 4. Shape of power duration curve

Figure 5.   Wind rose, Bangkok, March, April, May

Figure 6.   Greek sail rotor water pump

Figure 7.   Thai sail rotor water pump

Figure 8. Madurai prototype sail rotor water pump

(c) A very simple and durable rotor consists of four rectangular cambered steel plate blades twisted to give low pitch angle at the tip and high pitch angle at the root (figure 12). Rotor solidity is about 35 per cent. It is commonly used in the Netherlands and Denmark for small-scale drainage and cattle watering, and has also been used on low-cost wind pumps at some salt works in France (figure 13). Optimization investigations are being carried out at the Technical University, Eindhoven, the Netherlands. A 6-blade cambered metal plate rotor has been developed in Tanzania (reference W 22). This type of rotor seems to have considerable potential for use in low-cost water pumping systems because of simplicity of contruction, durability and good aerodynamic efficiency.

(d) The Princeton sail wing rotor (figure 14) was developed in 1960 at Princeton University, United States of America. It consists of two blades, each having a double thickness of sailcloth supported by a rigid straight leading edge, rigid tip and root chord sections and a trailing edge cable stretched between the tip and root sections. The ratio of root chord to tip chord is about 3:1. The sail is cut with a catenary arc trailing edge, which allows equal chord tensions to be developed along the length of the sail as a function of the tension at the trailing edge cable. The aerodynamic performance of this rotor is similar to that of conventional rigid rotors, but the weight, cost and complexity of construction are all substantially reduced. Detailed plans of the original Princeton design and an

adaptation for water pumping are available (see references W 35 and W 36).

(e) High-speed propeller-type rotors are not usually considered for water pumping, but they are successfully used for this purpose in Thailand (figure 15) and they may be adapted to high-speed centrifugal pumps. A rotor of this type for use with a wind pump is proposed in reference W 37. These rotors are characterized by high starting velocity, high rotational speed and low starting torque. Most high-speed rotors are carved from wood, although some are made from aluminium by casting or rib construction (reference W 38) or fibreglass (references W 39 and W 40). High-speed rotors for pumping applications would normally be used in conjunction with pumps requiring low starting and constant operating torques, such as square-pallet chain pumps, centrifugal pumps, chain pumps and archimedean screws.

(f) The classic Netherlands type of rotor, consisting of four spars supporting a wooden lattice covered with cloth sails, is best adapted to very large machines where high power output at low rotational speed and high torque are required. Recent use of this type of rotor for water pumping is rare, and its use in new hybrid designs will be limited primarily by the large amount of skilled carpentering required to construct the lattice structure.

(g) Several other horizontal-axis rotors have been used that incorporate four to eight fixed rectangular blades of wood or fibre mat construction; their cost, efficiency and durability are each quite low. Generally speaking, a rotor blade can be made from any flat thin material, including metal, cloth, wood, plastic, bamboo and fibre mats, with appropriate supports.

2. Vertical-axis rotors

Many different varieties of vertical-axis wind machines rotating in a horizontal plane have been reported (reference W 41). The primary advantage of these rotors is that they can accept wind from any direction and thus do not require any orientation mechanism, but their construction is usually very bulky and requires a large quantity of material in relation to the effective collection area. These rotors have maintenance difficulties as a result of the large weight resting on one thrust bearing at the base of the main shaft. Aerodynamic efficiency is low because the rotor turns as a result of direct wind pressure which is a function of the square of the wind velocity, unlike horizontal-axis rotors which extract wind energy as a function of the cube of wind velocity. Also, only about half of the rotor blades are doing work while the other half are returning up-wind. However, two classic vertical-axis rotors which may have some practical importance for modern applications, because of their light construction,
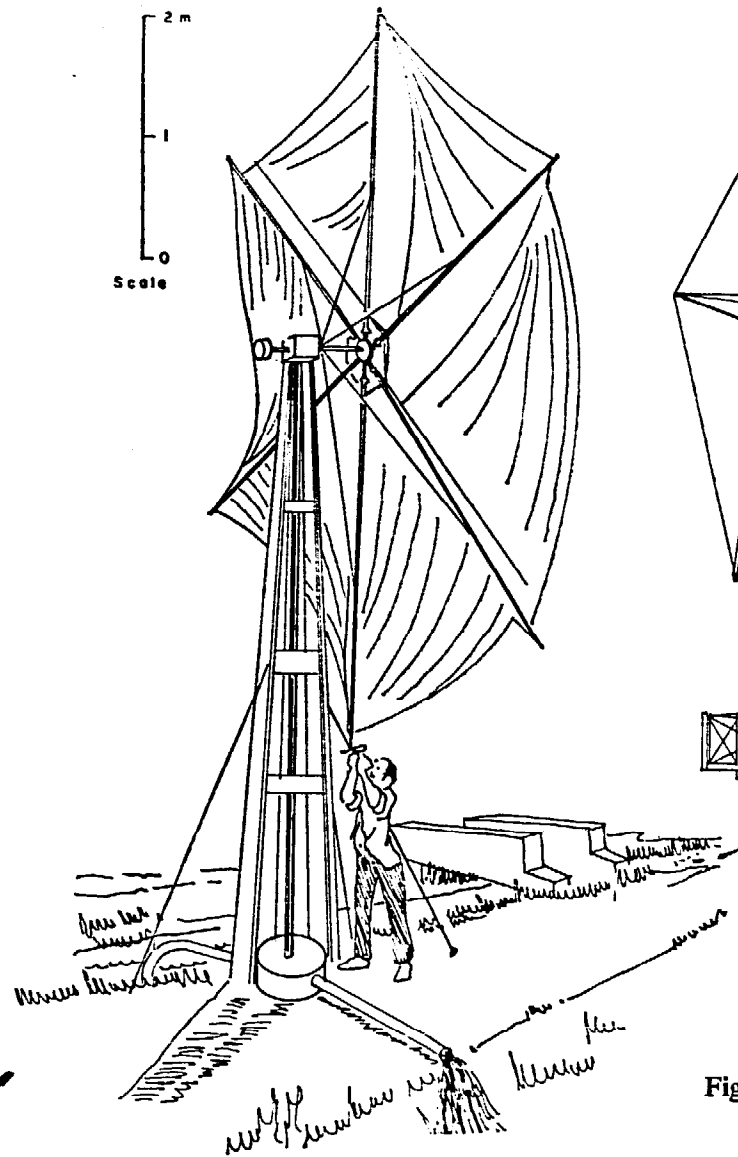
Figure 9. Malaysian Agricultural Research and Development Institute down-wind sail rotor water pump
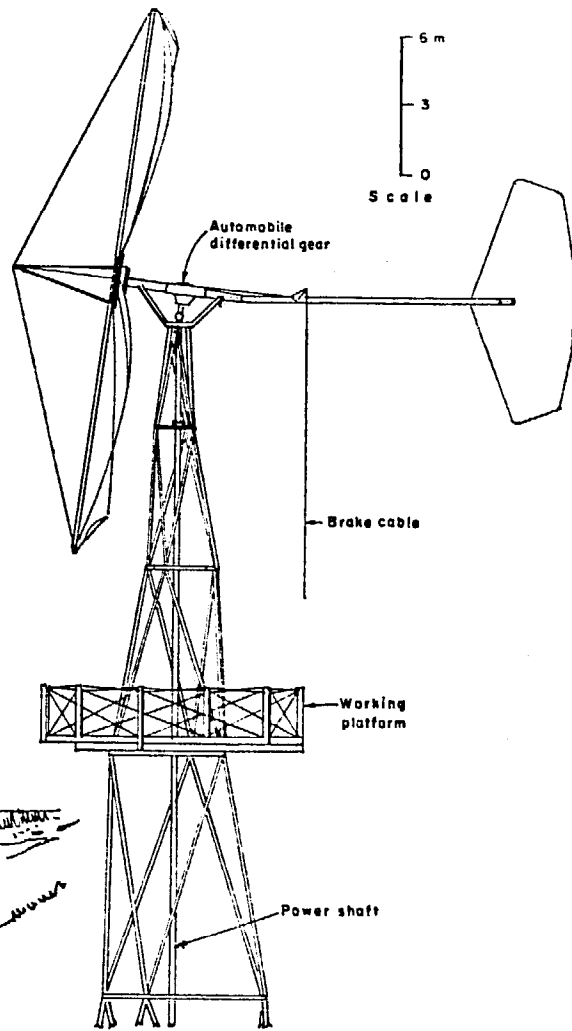

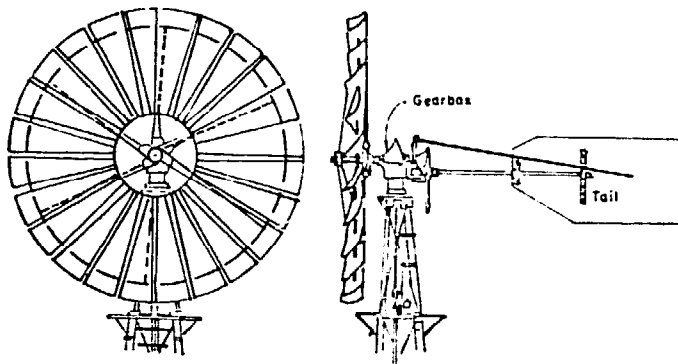Figure 10. Brace Institute-Windworks sail rotor with octahedron module tower
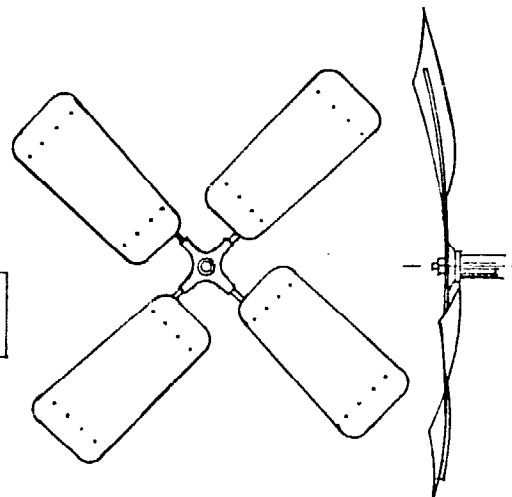

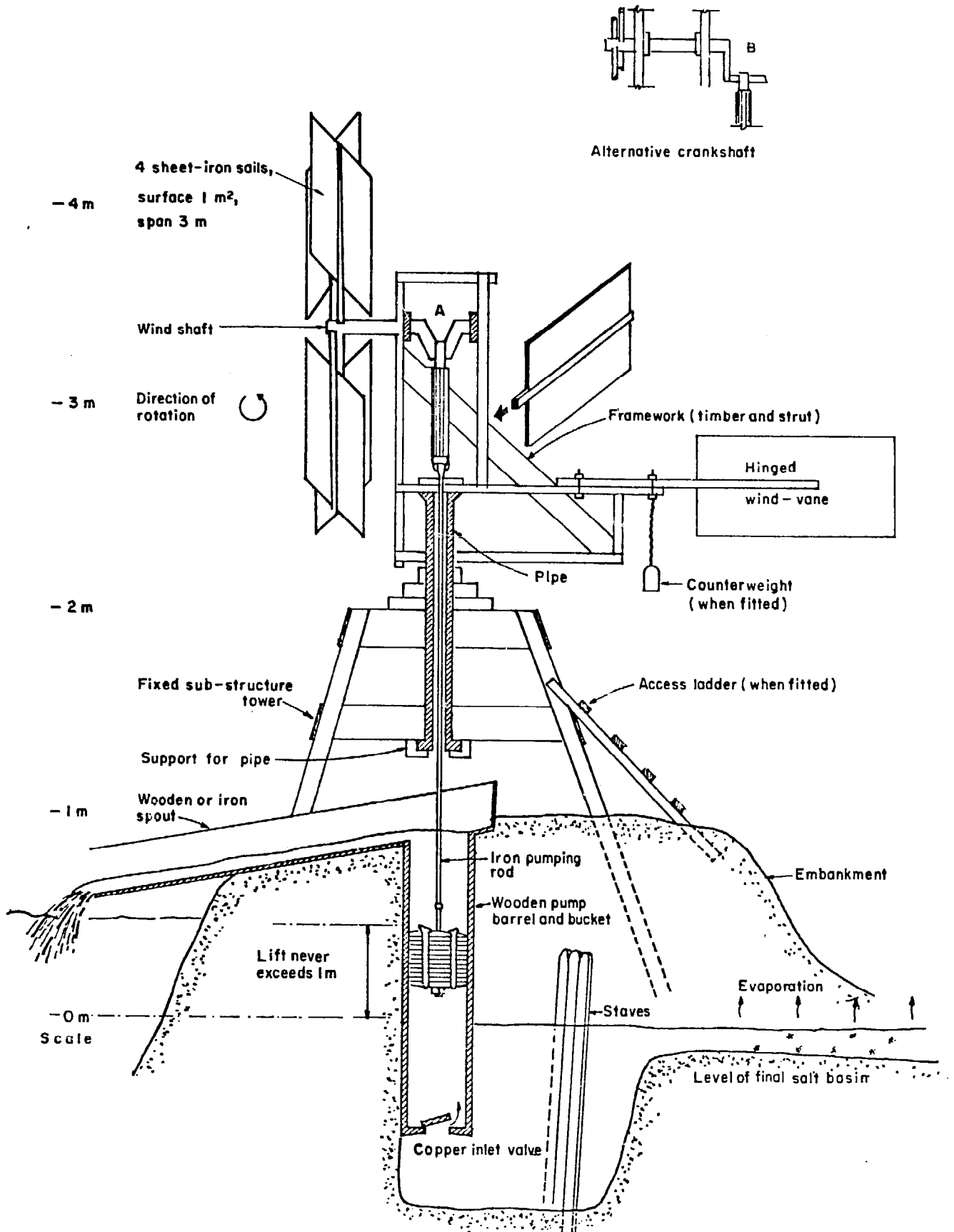Figure 11. Multi-vane metal rotor

Figure 12. 4-blade metal rotor

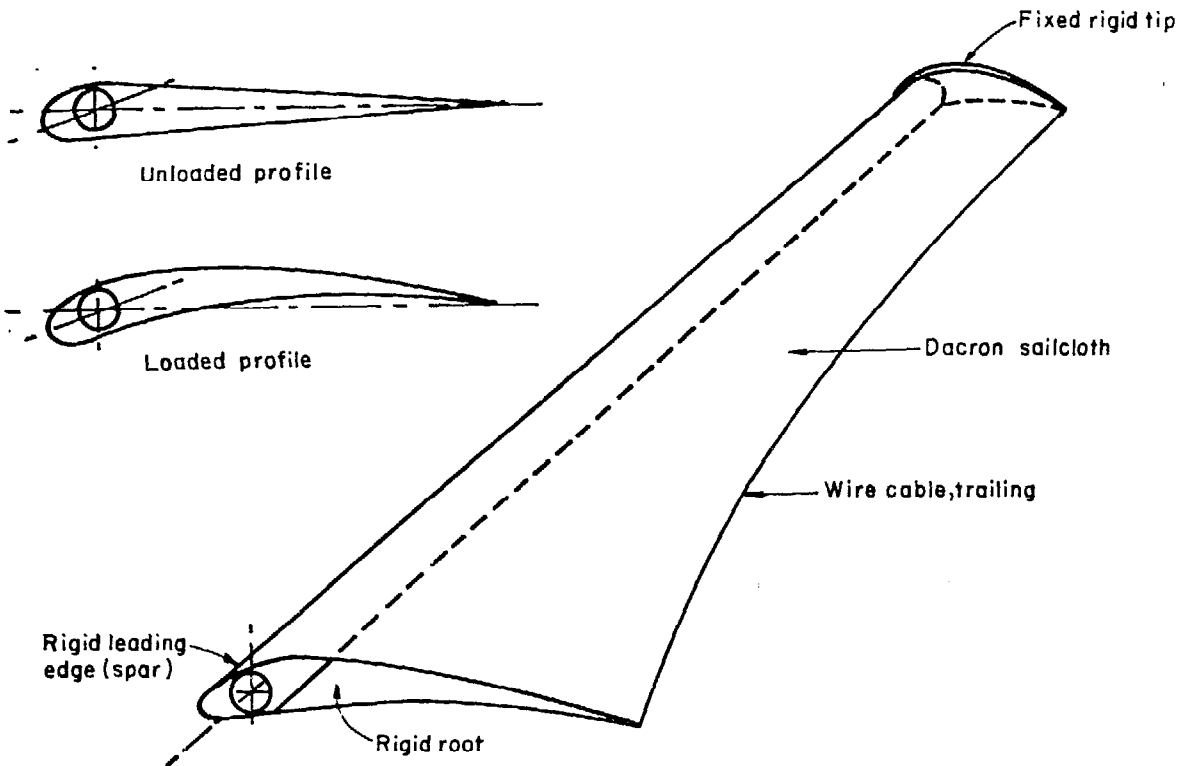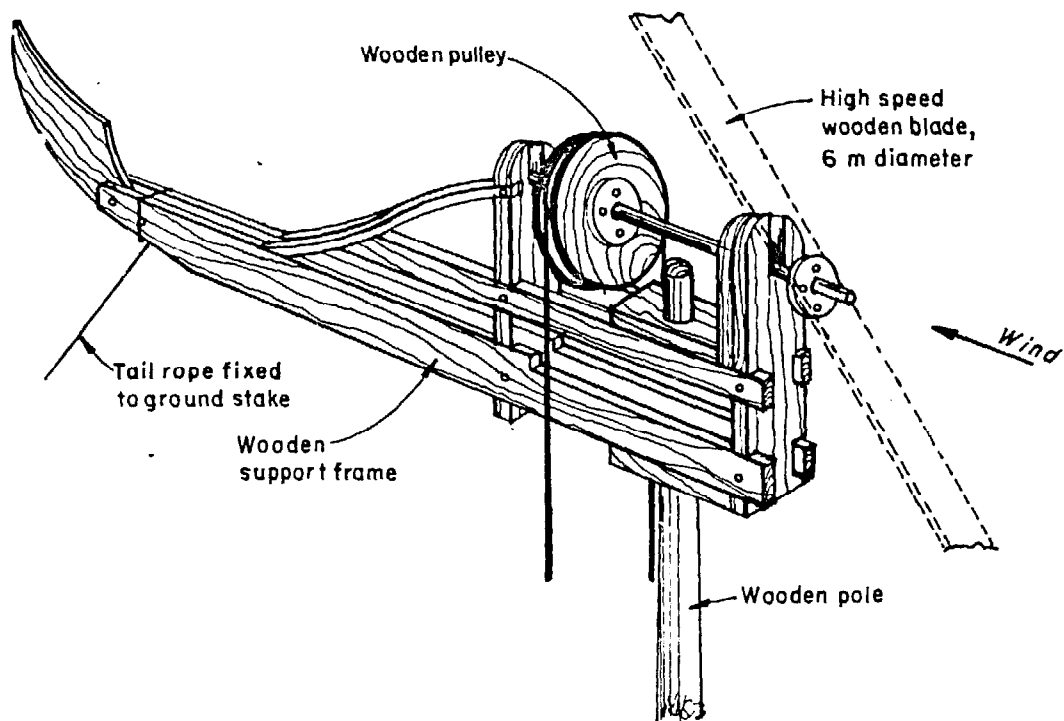Figure 13.   4-blade metal rotor water pump at Ile de Noirmoutier, France

Unloaded profile

Loaded profile

Fixed rigid tip

Dacron sailcloth

Wire cable, trailing

Rigid leading edge (spar)

Rigid root

Figure 14. Princeton sail wing rotor blade

Wooden pulley

High speed wooden blade, 6 m diameter

Wind

Tail rope fixed to ground stake

Wooden support frame

Wooden pole

Figure 15. Thai high-speed rotor water pump — wooden mounting assembly

are the Chinese type (figure 16) and the Turks and Caicos Islands type (figure 17). These rotors may be particularly adaptable to Persian wheel and bucket types of water lifts in addition to continued traditional use with square-wooden-pallet chain pumps.

(a) The rotors used in the Turks and Caicos Islands, British West Indies, for pumping salt water to evaporating ponds consist of six triangular cloth jib sails supported along their long edge by a vertical pole, and held by a rope tied from the loose corner to the adjacent vertical pole. Each vertical pole is supported by two horizontal wooden poles which radiate out from the central vertical main shaft. A similar jib-sail rotor utilizing eight sails has been proposed for use in Thailand (figure 18).   :

(b) The Savonius rotor (figure 19) has been well documented (reference W 25). Its use for practical water pumping and electricity generation has met with limited success only.

(c) The Darrieus rotor (figure 20) consists of two or three constant-chord aerofoil blades bent into a catenary curve and fixed at each end to a vertical axis which is supported by guy wires at the top and connected to a power utilization device at the base (reference W 42). The advantages of this rotor are that, unlike other vertical-axis rotors, a minimal support structure is required, the proportion of materials to total swept area is very low (solidity about 5 per cent), and efficiency is high. The main disadvantage is that it is not self-starting, and construction of the blades from fibreglass reinforced plastics or extruded aluminium is quite expensive. Although it has only recently been developed for electricity generation (reference W 43), it may have some potential for water pumping. Experimental work with a Darrieus rotor powered water pump has recently been undertaken at the National Aeronautical Laboratory in India.

(d) The gyro vertical-axis rotor (figure 21 and reference W 44) is similar to the Darrieus rotor in that it has a high efficiency of about 60 per cent, a very low solidity factor and minimal support structure requirements. This rotor consists of two or three straight symmetrical aerofoil blades supported vertically from horizontal support arms fixed to a vertical central power shaft. Orientation of the blades is reversed twice during each rotation so that maximum lift is achieved. High-speed small-diameter designs have considerable vibration. Further development of this rotor is currently in progress at the Cranfield College of Technology, United Kingdom.

3. Three novel concepts

Three novel concepts for utilizing wind power for water pumping have recently been proposed. Although these ideas have not yet been given full-scale demonstra-

tion, their simplicity of operation and low-cost construction makes them worthy of further consideration.

(a) The flapping-vane wind pump (figure 22 and reference W 45) has beeen designed for use with deep well piston-type water pumps, although it may be adapted to diaphragm pumps,or to a crankshaft flywheel to produce rotary motion. This device consists of a long lever arm with a cloth vane mounted on a horizontal axis at the outer end and a vertical reciprocating power rod at the fulcrum end. The vane can swing freely about its axis within the range of an upper and lower angular stop. Action of the wind on the vane alternatively depresses and lifts the lever arm with resultant power applied to the reciprocating rod. The lever fulcrum is mounted on a pedestal which can rotate on top of the tower in order to allow the vane to automatically orient itself to the direction of the wind. This device is expected to pump 100 m^3 per day from a depth of 40 m with a wind velocity of 16 km/h when the vane area is 29 m^2 and the lever arm is 20 m long. With increasing wind velocity, the amplitude of the up and down motion of the lever arm decreases and the frequency increases, so that the system is self-regulating.

(b) A tree pump has been proposed that converts the horizontal motion of a tree trunk swaying in the wind to reciprocating vertical motion of a piston pump, via cables and pulleys. In this device, the only cost is for the power transfer mechanism and pump. This method is limited to sites with tall unsheltered trees.

(c) A parachute pump (figure 23) has been proposed as a low-cost method of supplying power to traditional animal-powered bucket pumps. This system comprises a large parachute whose circumference ropes are tied to the lift rope. The force of the wind on the parachute pulls the bucket to the top of the well, at which point a rope attached to the centre of the parachute becomes tightened and collapses the parachute so that it may be returned to the starting point by the operator, and the bucket can return down to the base of the well. The parachute is then again allowed to fill with wind to begin another lifting cycle. With this system the only expense is the wind collection device (parachute). The pump and transfer mechanism exist and there is no need for a support structure.

D. CLASSIFICATION OF WATER PUMPS

A comprehensive international classification of all types of small pumps used for water pumping is urgently needed. Such a classification could include the following information regarding each type of pump; typical schematic diagram, normal range of suction and discharge heads, normal range of output, construction materials and skills required, usual mode of power supply, efficiency, range of operating speed and torque.
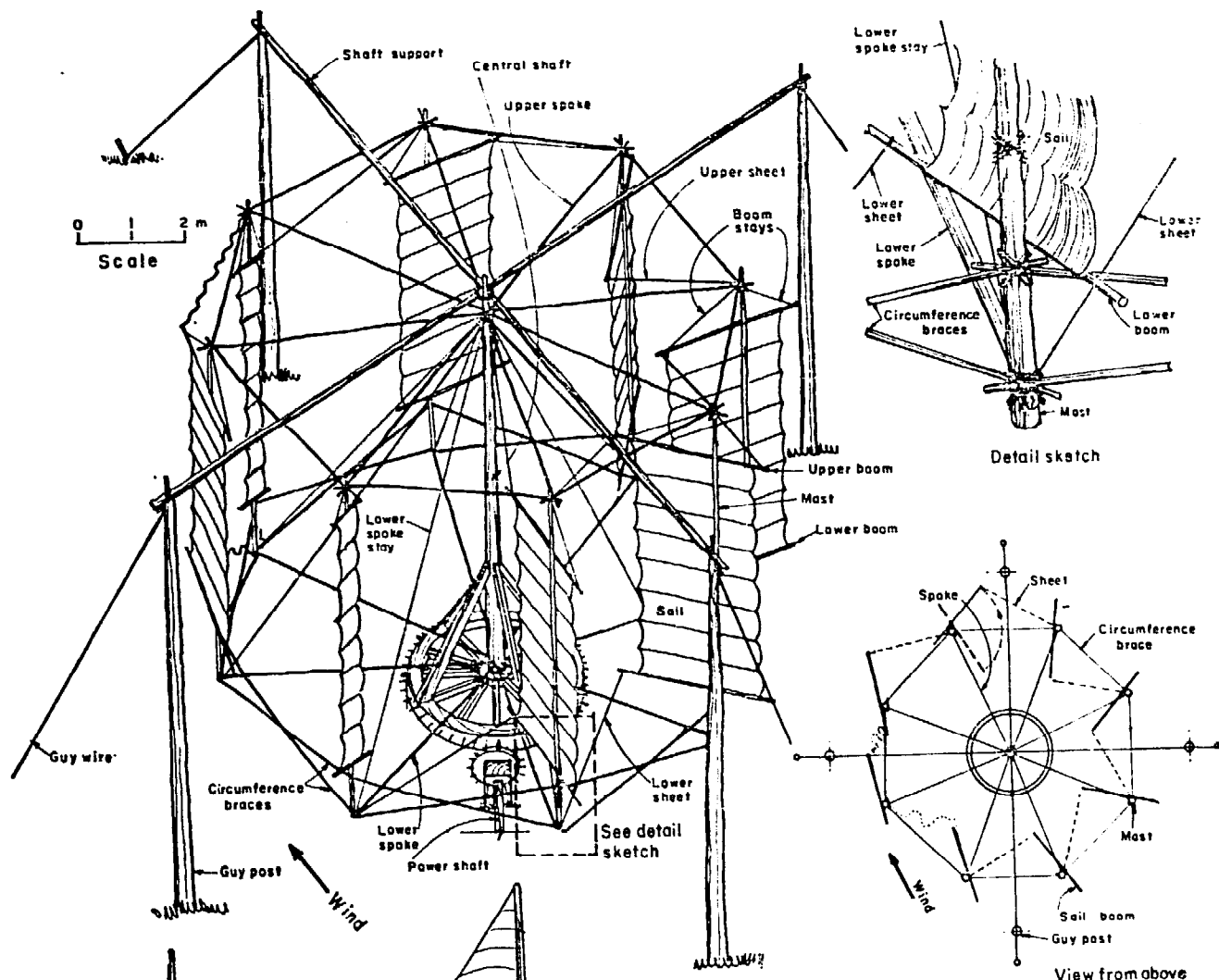
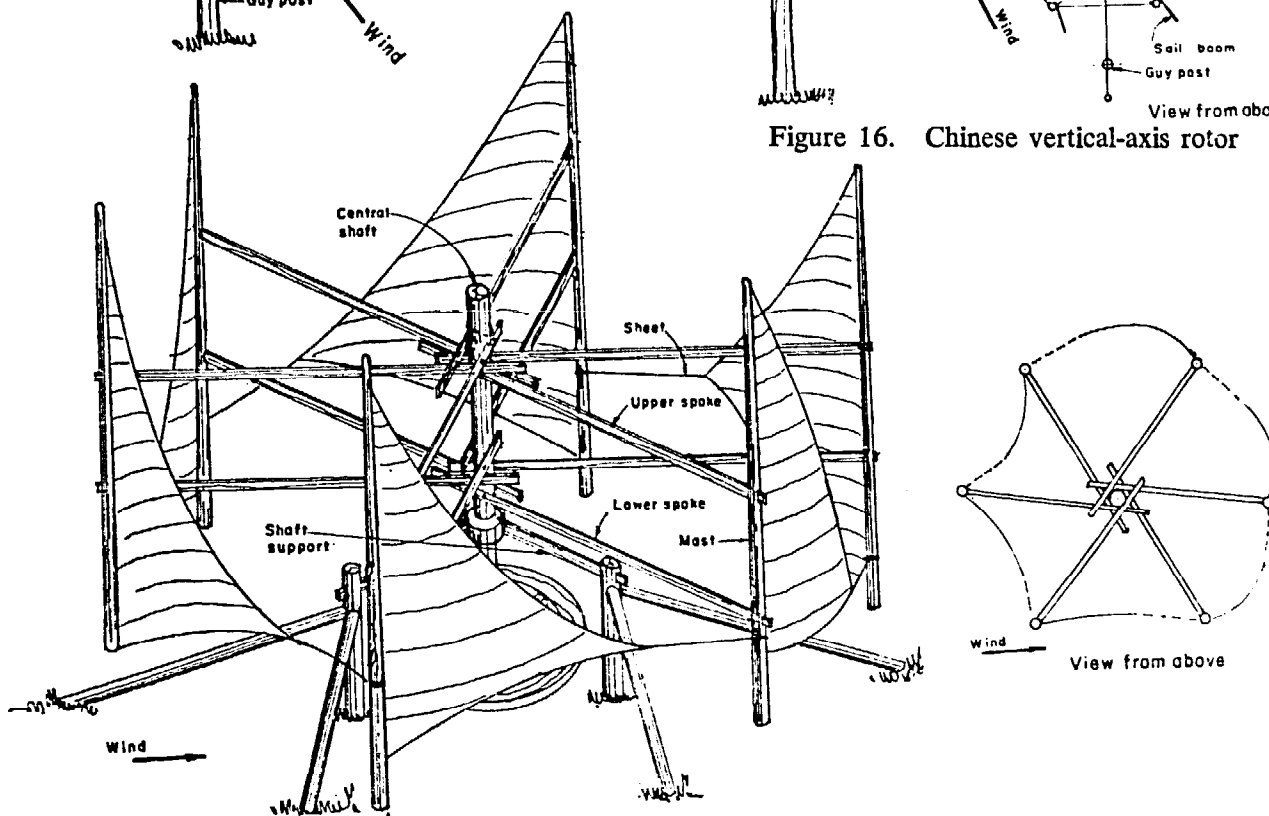Figure 16. Chinese vertical-axis rotor

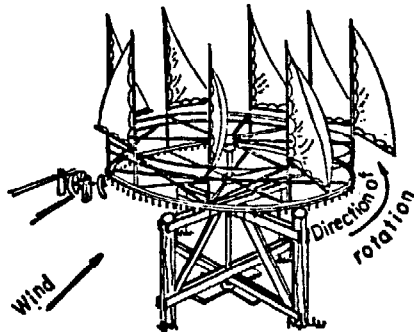Figure 17. Turks and Caicos islands vertical-axis rotor

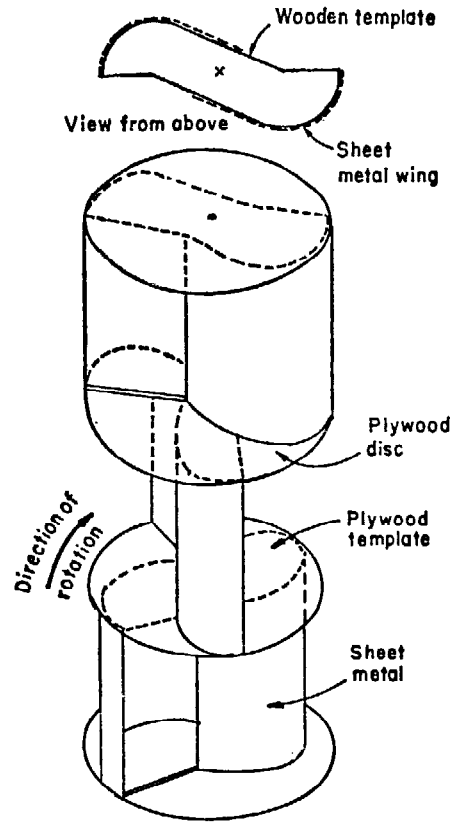Figure 18.   Thai jib-sail rotor

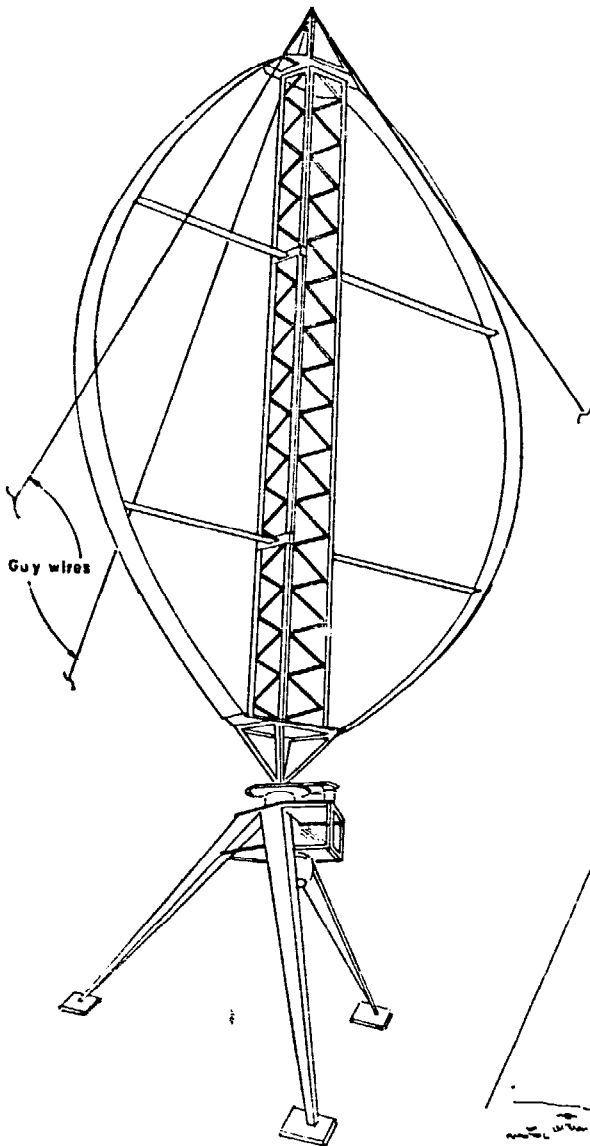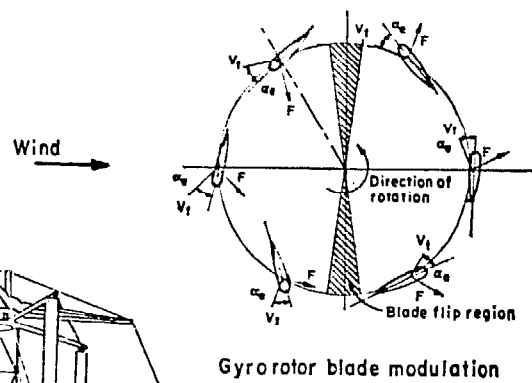

Figure 19.   Three-tiered Savonius rotor

Figure 20.   Darrieus rotor

Gyro rotor blade modulation

Figure 21.   Gyro rotor

1. Canvas sail
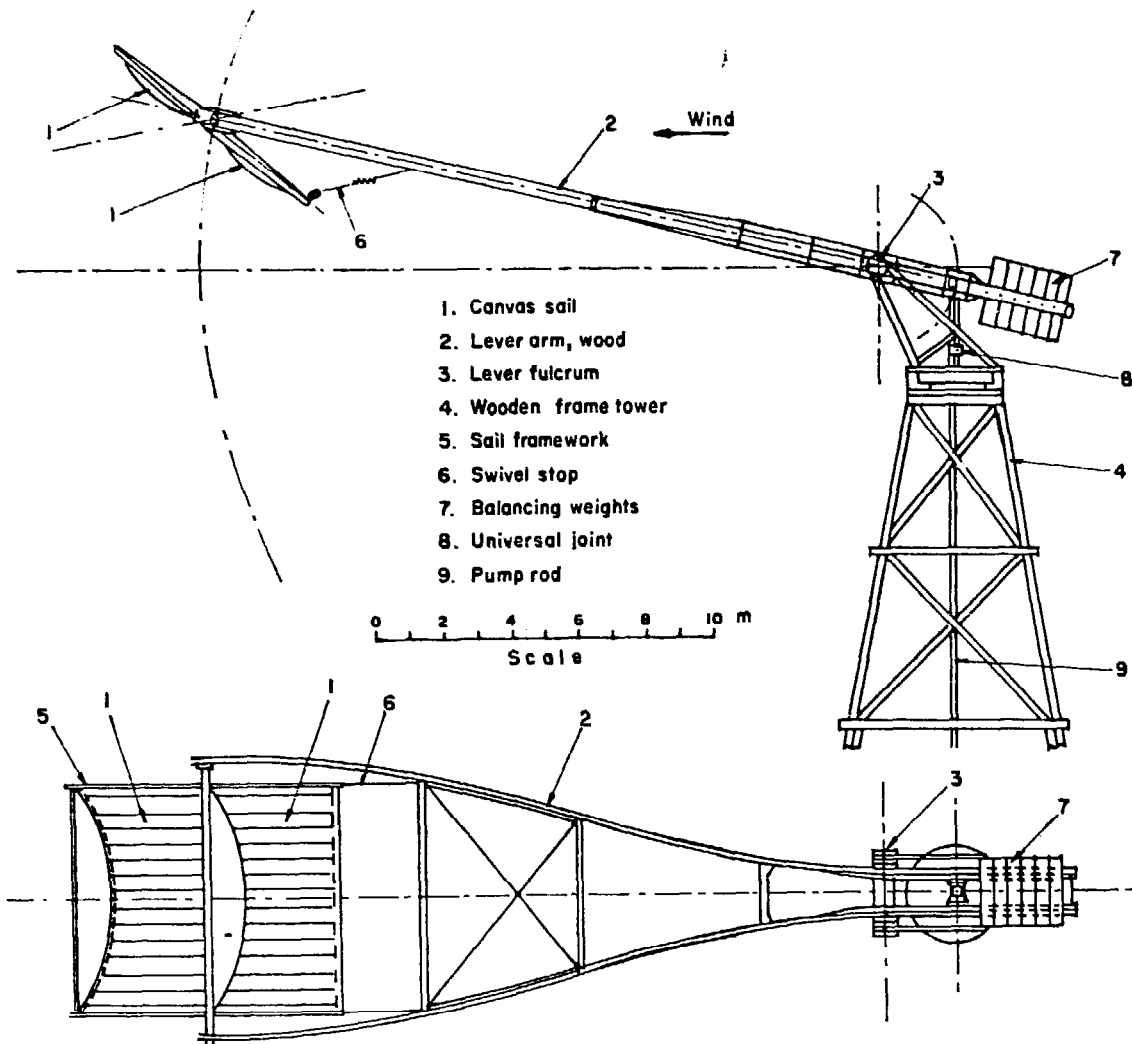2. Lever arm, wood
3. Lever fulcrum
4. Wooden frame tower
5. Sail framework
6. Swivel stop
7. Balancing weights
8. Universal joint
9. Pump rod

Scale

Figure 22.   Flapping-vane rotor water pump

Figure 23.   Parachute-type water pump

1. Reciprocating pumps

Most reciprocating pumps have the disadvantage that the torque load is not constant, thus requiring a higher wind velocity for starting, and variable stresses on the system when in operation.

(a) The single-acting cylindrical piston pump is most frequently used in wind-powered · pumping systems. It consists of a cylinder with an inlet pipe and valve at the base, a leather-sealed piston with a one-way valve and a water outlet at the top, water passing through the pump only on the lifting stroke of the piston. This type of pump is used to pump water from any depth, with an operating speed of up to 40 strokes per minute.

(b) A square wooden single-acting piston pump is commonly used by fishermen in eastern Canada (figure 24) and has recently been adapted to wind power (reference W 46). A square wooden pump powered by the wind has been proposed for use in Thailand (reference W 47). The height of lift is limited by the amount of water pressure that can be sustained by the wooden joints, although the simple construction is well adapted to basic carpentering skills.

(c) The double-acting piston pump (figure 25) is similar to the single-acting pump, except that there is no valve or passage of water through the piston, the water by-passing the piston cylinder through pipes and valves under pressure during both the upstroke and the downstroke. The advantage of this pump over the single-acting pump is that the load on the power source is more constant, but it is not usually used in wind pumping systems because any compression load during the downstroke could buckle the long piston rod leading from the top of the tower: this problem could be avoided if a very short piston rod were connected to an immediately adjacent rotary power transfer mechanism powered by a long belt leading directly from the rotor shaft.

(d) The diaphragm pump (figure 26) consists of a cylinder closed at the lower end, with a circular diaphragm of rubber or some other flexible material fixed at the top end. A reciprocating connecting rod is fixed to the centre of the diaphragm and, upon vertical movement, causes volumetric displacement in the cylinder. An arrangement of valves allows water movement in only one direction through the cylinder. The difficulty with this type of pump is the high rate of wear on the diaphragm at its connexions with the cylinder and connecting rod. A diaphragm pump has been developed for use with a Savonius rotor (reference W 24).

(e) The inertia pump (figure 27 and reference W 48) is a very simple and efficient device that depends upon the vertical inertia of a body of water in a reciprocating pipe to expel water at the end of the upstroke of the pipe. A one-way flap valve in the pipe is closed during the upstroke, and inertia is imparted to a fresh volume of water by the lifting force on the pipe. This pump must operate at a constant frequency which is dependent upon the mass of water in the pipe and the pipe itself. This recently popularized pump has probably not yet been used with wind power.

2. Rotary-motion pumps

Continuous rotary-motion pumps are well adapted to operation by wind power because they require a constant torque load and generally operate at a variable low speed.

(a) The square-wooden-pallet chain pump (figure 28 and reference W 49) is commonly used in China and southeast Asia for lifts up to 3 m and consists of rectangular wooden pallets or paddles mounted on a continuous wooden chain that runs up an inclined square-section open wooden trough. The paddles and chain pass around a large wooden driving gear wheel at the top and around a small passive gear wheel at the base of the trough which is submerged in water. This type of pump is commonly used with Chinese vertical-axis wind pumping systems and with Thai high-speed wooden rotors and Thai sail rotors.

(b) The round-steel-washer chain pump (figure 29 and references W 12, W 15) is used in conjunction with human and animal power, and consists of a continuous steel chain upon which are mounted steel discs with rubber or leather washers. The chain passes around an upper gear wheel, down the well, under the water source, around and then up into the bottom of a pipe with inner diameter the same as the washers. Water is lifted up within the pipe and expelled at the top. A square wooden adaptation of this pump is shown in figure 30.

(c) Large-diameter slow-speed centrifugal pumps (figure 31) have good potential for low-lift pumping. The meadow type wind pumps of the Netherlands are fitted with centrifugal pumps 1 m in diameter and 0.2 m high, with four wooden blades, and have an efficiency of 30 per cent and an output of up to 100 m³ per hour in a strong wind. Further design development and quantification of design variables of these pumps could be undertaken.

Another type of centrifugal pump is the centrifugal reaction pump (figure 32) which consists of a vertical pipe with a T-joint at the top, from which extend two pipes whose length is dependent upon the rate of rotation of the assembly in operation. An orifice at the end of each pipe arm points 90° away from the arm. When the assembly is filled with water and
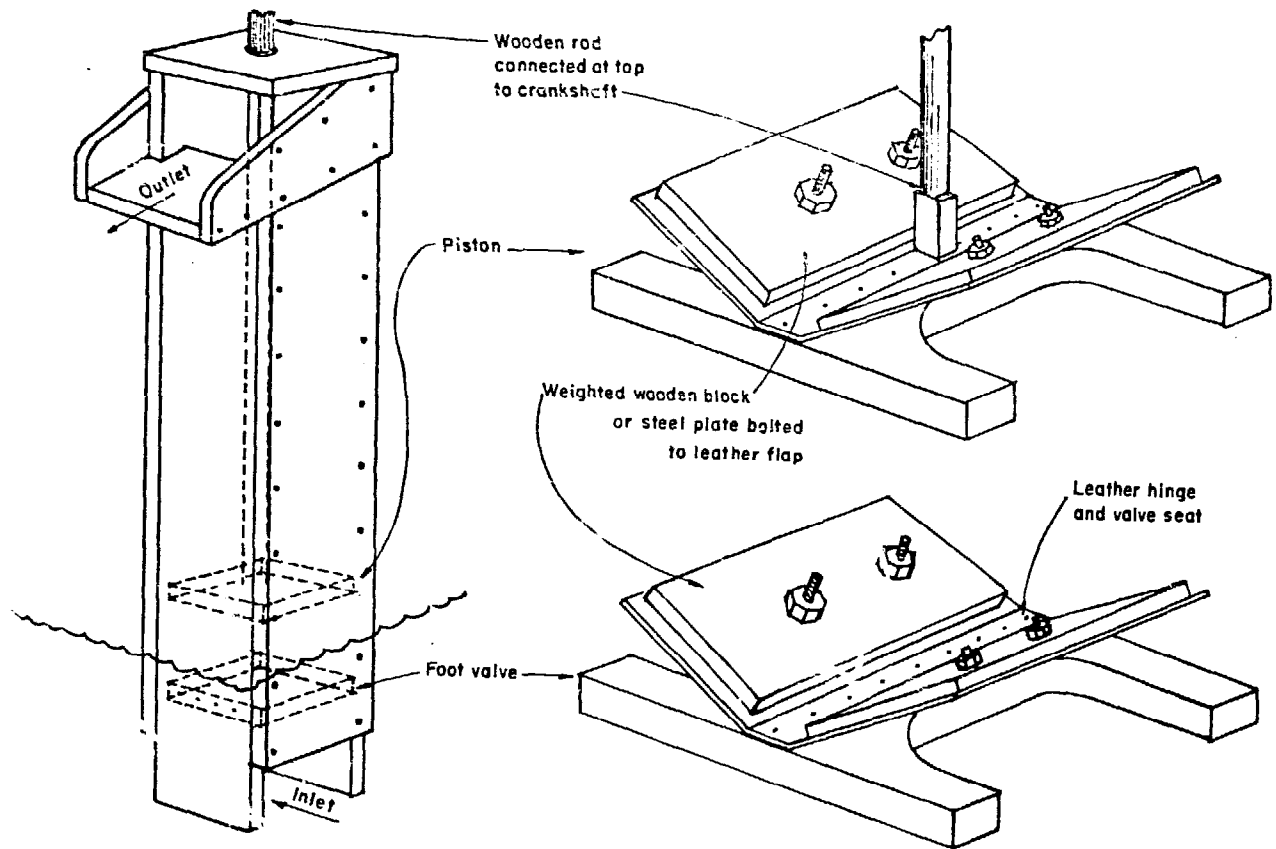
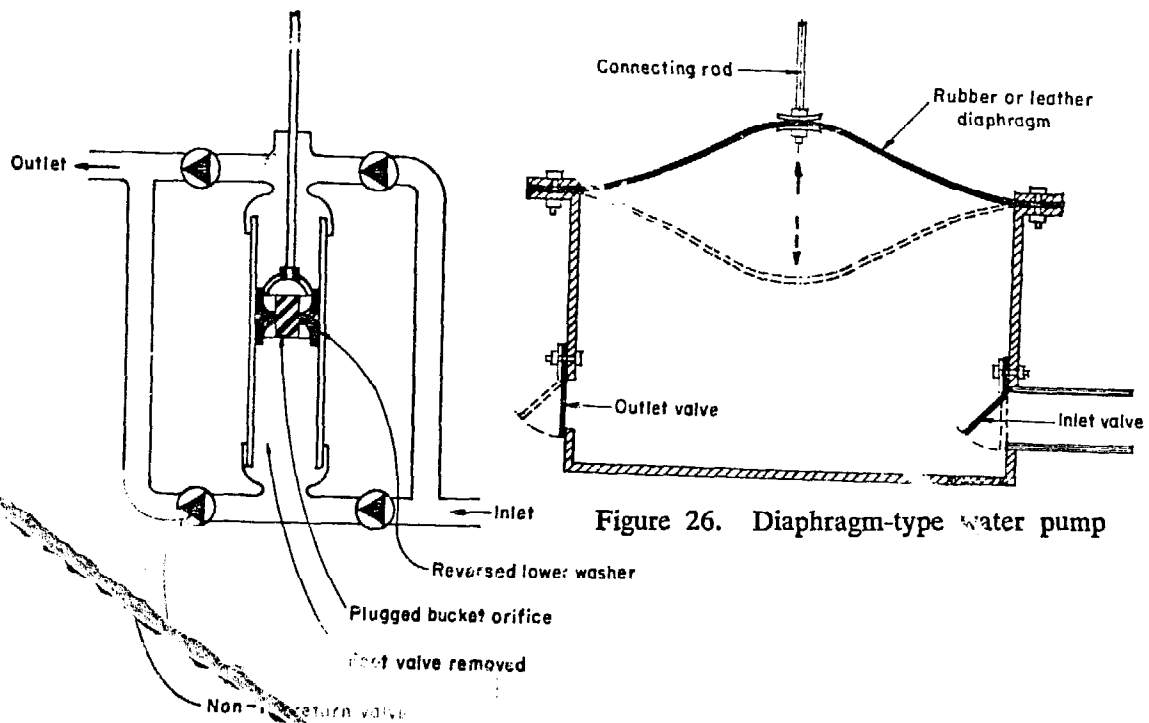Figure 24.   Square wooden piston-type water pump

Figure 26.   Diaphragm-type water pump

Figure 25.
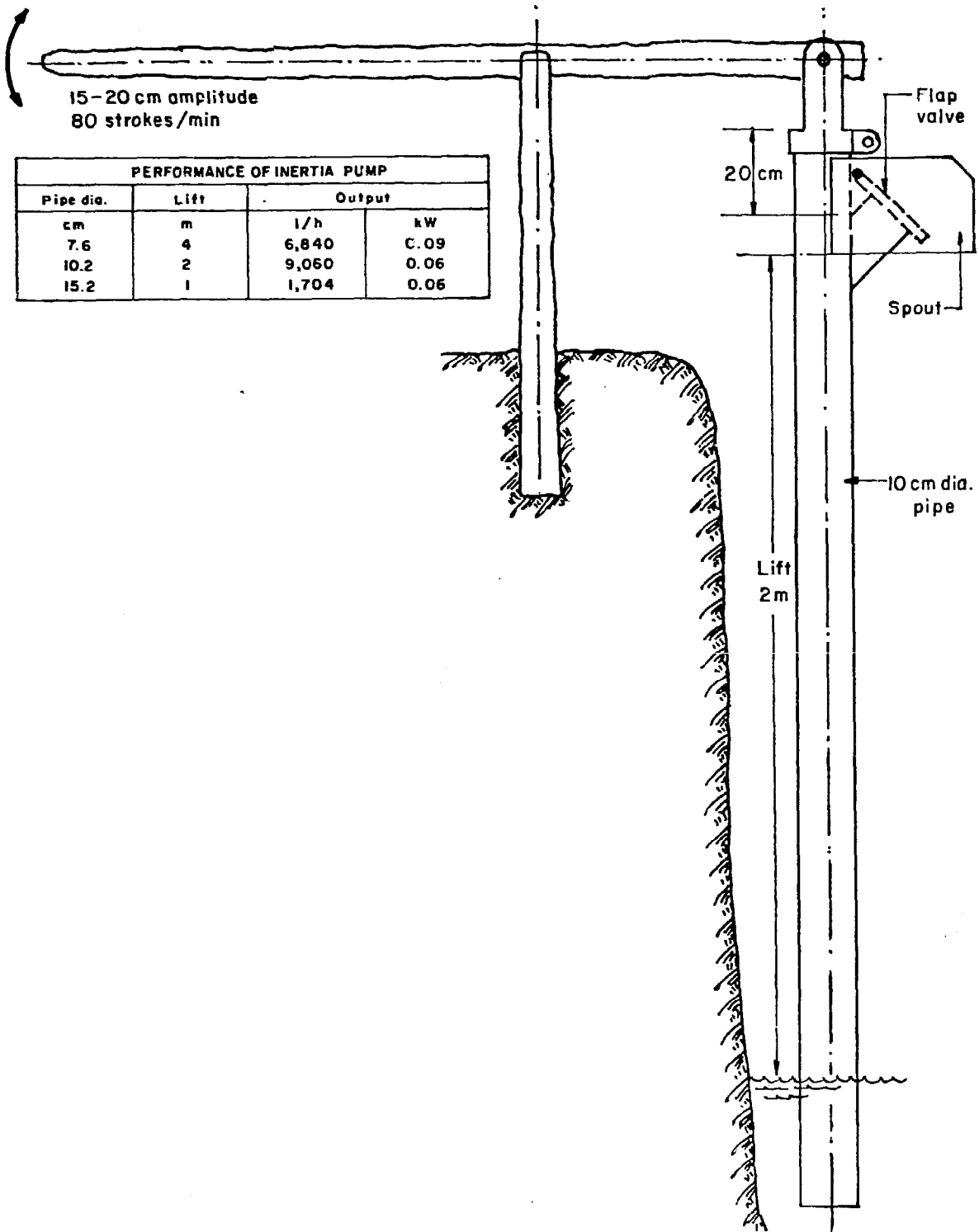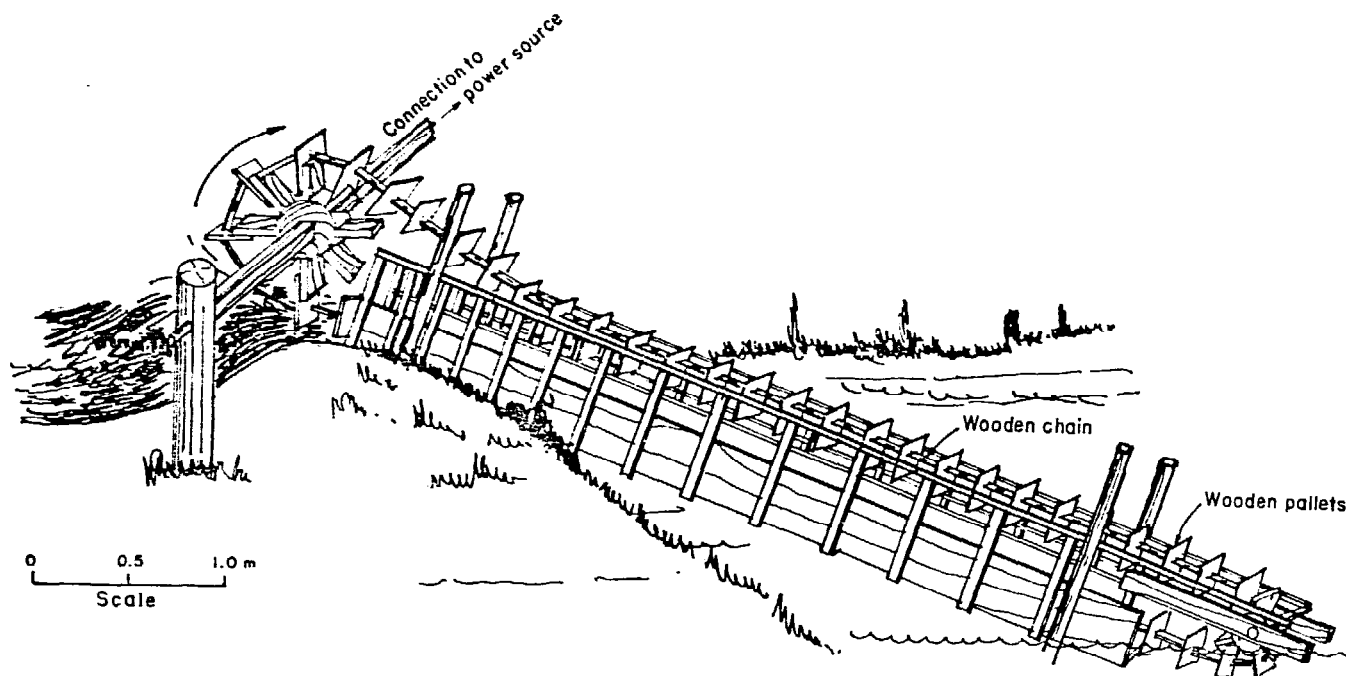Double-acting piston-type water pump

15-20 cm amplitude
80 strokes/min

PERFORMANCE OF INERTIA PUMP			
Pipe dia.	Lift	Output	
cm	m	l/h	kW
7.6	4	6,840	C.09
10.2	2	9,060	0.06
15.2	1	1,704	0.06

Flap valve

20 cm

Spout

10 cm dia. pipe

Lift 2 m

Figure 27.   Inertia-type water pump

Figure 28. Wooden-pallet-type water pump

rotated in the direction opposite to the orifices, the water is forced out through the orifices by centrifugal force and replenished by water coming up through a valve in the bottom of the vertical pipe. This pump is well adapted to variable low speeds, and construction is simple. One of these pumps, connected to a 3-m diameter high-speed wind rotor, pumped 30 m³ per hour at a head of 4.5 m in a 29-km/h wind (reference W 50).

(d) Axial-flow pumps have good potential for low-lift pumping because of their relatively simple construction and high efficiency. No use of these pumps with wind rotors is recorded, but it has been suggested that axial-flow pumps would be appropriate for high-volume pumping of sewage wastes in oxidation ponds (reference W 51). Theoretical studies of wind-powered axial-flow pumps are being carried out at the National Aeronautical Laboratory in India.

(e) Archimedean screws are very simple, and have efficiencies up to 80 per cent. They have been used in the Netherlands for large-scale drainage requiring a lift of up to 5 m. Three basic versions are known (reference W 48):

(i) The type with a rotating cylinder made of strips of wood and having a spiral partition inside (figure 33), as in the Tjasker type of wind pump in the Netherlands, requires a footstep bearing below the water level, and demands a fairly sophisticated level of construction skill. It can be made large in diameter and so suitable for slow-speed operation. Such a

screw, 2.7 m long, 0.56 m diameter and lifting through 1.3 m at a speed of about 30 rev/min, gives an output of 32.4 m³ per hour.

(ii) The type in which the outer casing is stationary and the helical rotor is supported on bearings at either end, attached to the casing, are normally of smaller diameter and run at a high speed, e.g. 12-cm diameter up to 200 rev/min, 40-cm diameter up to 127 rev/min. An advantage of this type is that the casing and rotor form a self-contained assembly which does not require external bearings but only simple supports to maintain it at the correct angle and axial position. The screw is made by rolling a flat steel strip between rollers set at an inclination to each other to squeeze one edge of the strip and hence cause it to curl into a helix, which is then welded to an inner cylindrical pipe.

(iii) A third method of constructing an Archimedean screw is to coil a section of pipe into a cylindrical helix. A particular type has recently been evolved for field drainage in which the tubing is corrugated with a fine pitch to strengthen it and to allow coiling to a small radius. This could form the basis of a simple low-cost pump, since most of the construction could be done locally. For example, a stout bamboo could serve as the main axle, and the coils of pipe could be held in place by lashing with rope, wire or any suitable local fibre, using longitudinal strips of bamboo or other wood to form a supporting cage on the inside of the coils.
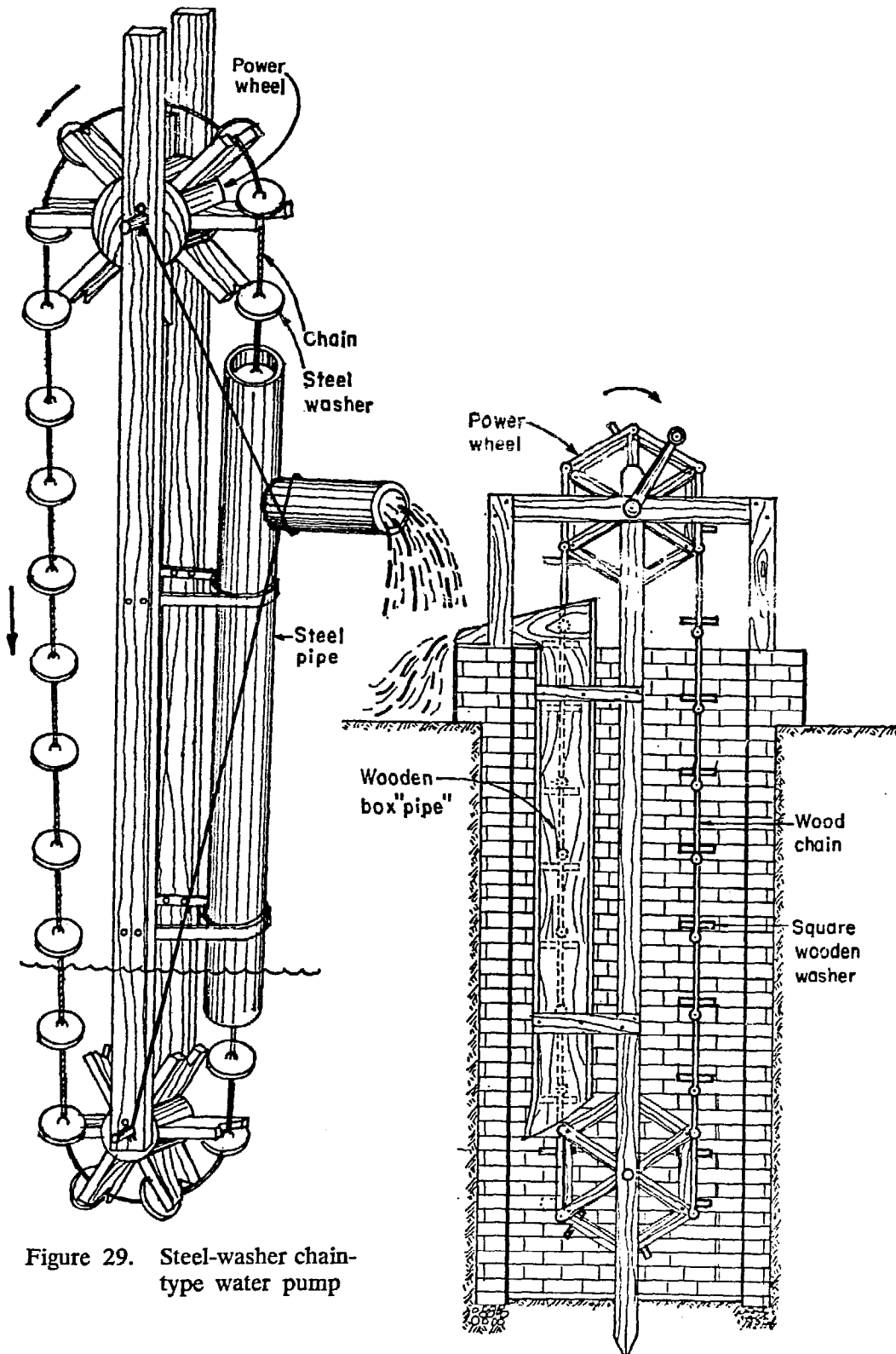
Figure 29.   Steel-washer chain-
type water pump

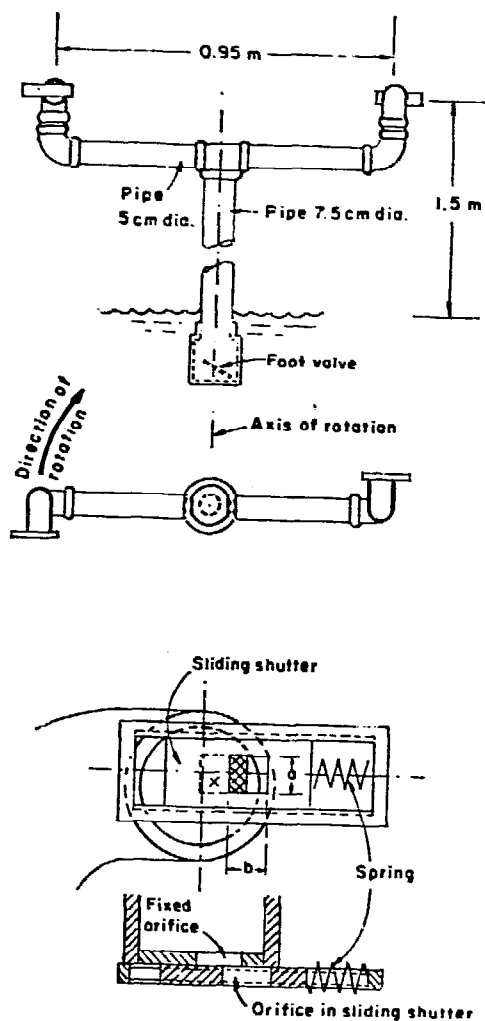Figure 30.   Square wooden enclosed
chain-type water pump
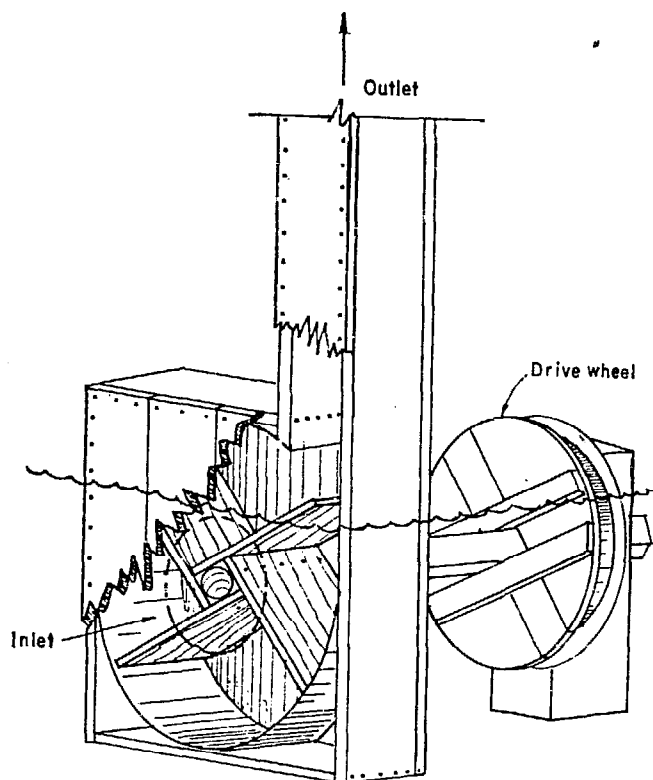
Figure 31.
Large-diameter slow-speed centrifugal-type water pump

Figure 32.
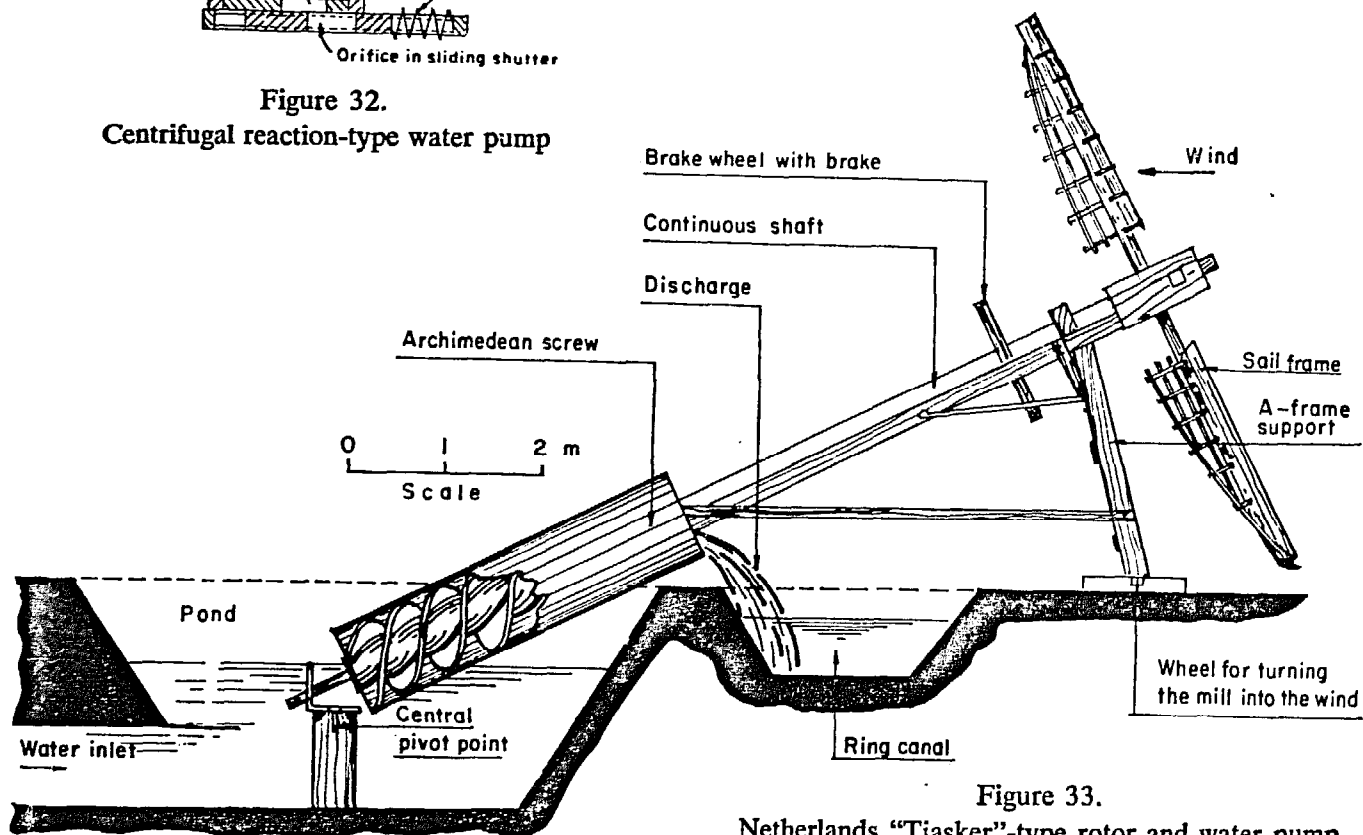Centrifugal reaction-type water pump

Figure 33.
Netherlands "Tjasker"-type rotor and water pump

(f)   The peristaltic pump (figure 34) consists of a flexible hose with a series of rollers rolled along the length of the hose in order to squeeze water through the hose.   This type of pump has reportedly been adapted to a Greek sail wind rotor at the Malaysian Agricultural Research and Development Institute.
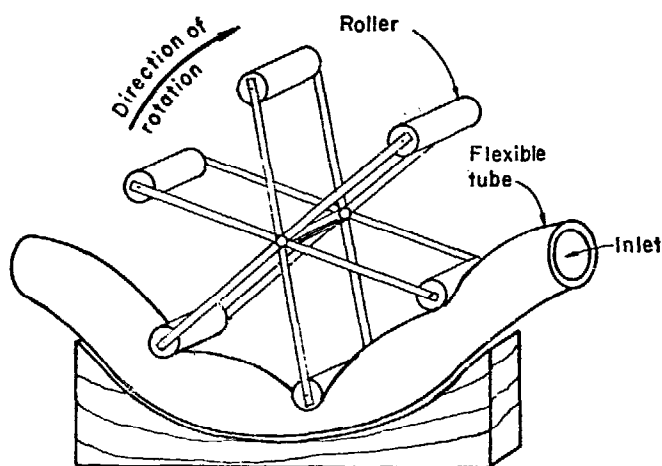

Figure 34.   Peristaltic-type water pump

(g)   A simple water pump operated by compressed air (figure 35 and reference W 46) is currently being tested.   The advantages of this pump are that it can be located some distance from the compressor, two or more pumps could be operated by one compressor, or one large pump could be operated by two or more smaller compressors.

(h)   A hydraulically operated water pump (figure 36) is currently under development by the Ministry of Lands, Settlement and Water Development in Tanzania. This pump was designed to solve the problems of using piston pumps in very deep and narrow borehole wells.

III.   DATA ANALYSIS AND CRITICAL DECISIONS

A.   DETERMINATION OF RATED WIND VELOCITY AND WATER DEMAND

For the months of greatest water pumping demand, graphs such as those in figures 3 and 4 should be prepared on a monthly basis.   If continuity of water supply is important, the rated wind velocity chosen would be somewhat lower than if maximum output were the only goal.   Daily water demand should be summarized on a monthly basis.

B.   SELECTION OF ROTOR

The selection of the type of rotor requires careful consideration of local skills and materials as well as operating and performance characteristics, bearing in

mind that the precise characteristics of the main types of low-cost locally-constructed rotors are not readily available.   A reasonable compromise must be made between high reliability, durability and maintenance-free operation on the one hand, and low construction cost on the other hand, taking into account that increased labour input will generally result in lower capital input.

Selection of a rotor is also dependent upon the type of pump to be used.   To maximize the efficiency of power transfer, the torque, speed and power characteristics of the rotor and pump should be as similar as possible.

C.   SELECTION OF PUMP

Selection of the type of pump depends on the total pumping head, the type of rotor and the local materials and skills available for construction.   The use of traditional local pumps, whenever possible, will reduce the problems of introducing a new technology.

D.   DETERMINATION OF DESIRED PUMP OUTPUT

The starting, rated and maximum operating wind velocities of the rotor must be known to determine the load factor (figure 4).   Division of the daily water demand by the load factor will yield the desired rated output of the pump.   If this rate is greater than the maximum output of the type of pump selected, the need for a pump with greater output or the use of more than one pump is indicated if the total demand is to be met.

E.   DETERMINATION OF THE RATED POWER REQUIREMENT OF THE PUMP

The rated power requirement of the pump may be obtained from the following relation:

$$\text{Power (kW)} = \frac{\text{Desired output in m}^3/\text{sec} \times \text{head in m} \times 9.8}{\text{Pump efficiency in per unit}}$$

F.   DETERMINATION OF THE NEED FOR AN ORIENTATION MECHANISM

The need for an orientation mechanism may be determined by analysing the frequency of each wind direction as in figure 5.   In many tropical, and especially coastal, areas, the wind blows mainly in either of two opposite directions.   In such cases, the use of a fixed-axis rotor can save considerable construction expense. If an orientation mechanism is required, the choice of manual or automatic orientation will depend on the number of changes in wind direction.
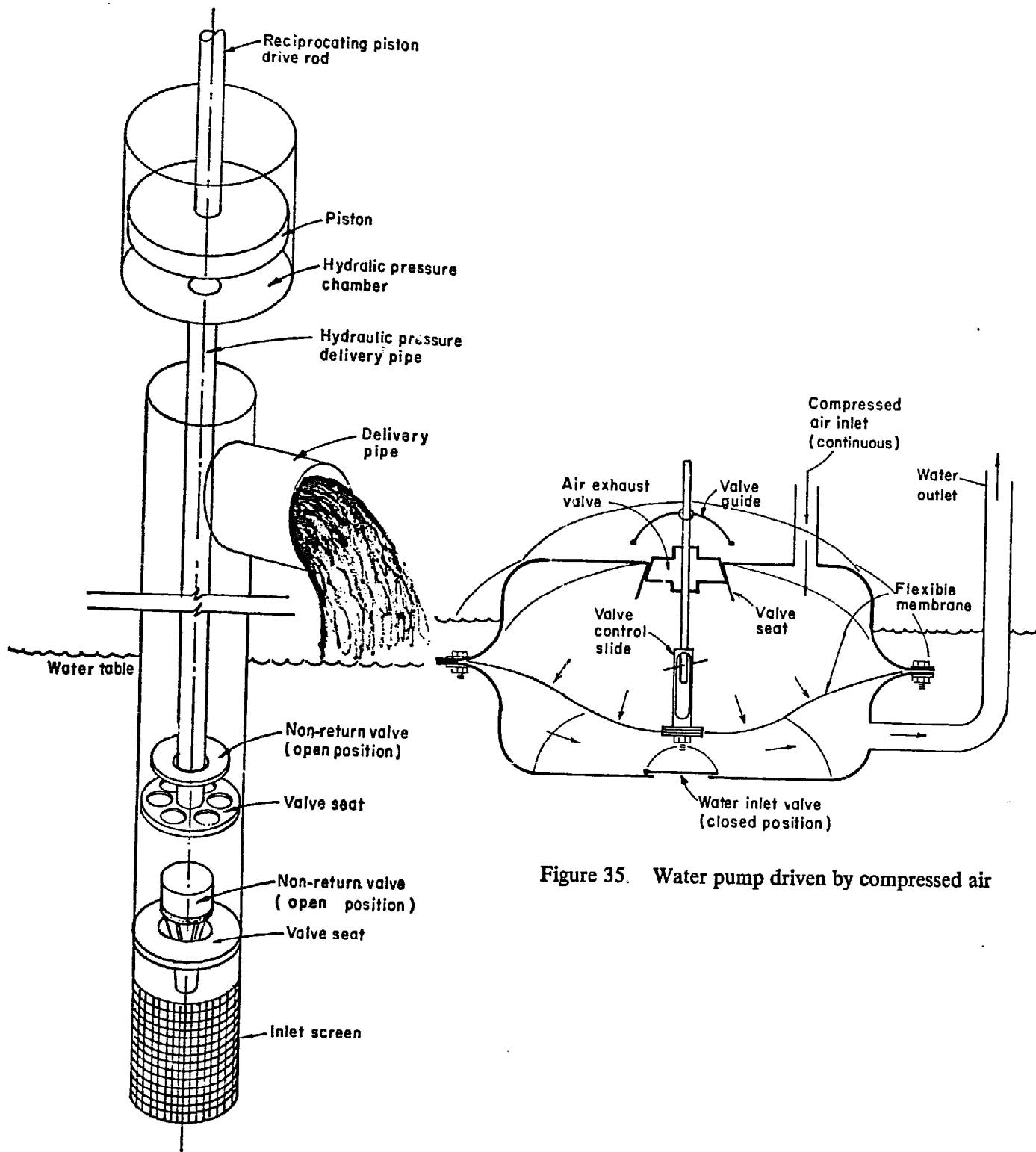
Reciprocating piston drive rod

Piston

Hydralic pressure chamber

Hydraulic pressure delivery pipe

Delivery pipe

Water table

Non-return valve (open position)

Valve seat

Non-return valve (open position)

Valve seat

Inlet screen

Figure 36. Hydraulic-drive water pump

Compressed air inlet (continuous)

Water outlet

Air exhaust valve

Valve guide

Valve control slide

Valve seat

Flexible membrane

Water inlet valve (closed position)

Figure 35. Water pump driven by compressed air

IV. COMPONENT DESIGN AND MATCHING

A. CONTROL MECHANISMS

Mechanisms to stop the rotor and to control rotor-blade pitch angle, blade area and pump stroke should be incorporated in the design in order to allow operation under a maximum range of wind velocities, without damage. The pitch angle of rigid blades may be controlled by centrifugal governors or blade coning. The pitch angle of non-rigid sails may be controlled by manual or spring adjustment of the trailing edge tension. The area of sails may be controlled by furling. Pump stroke may be adjusted by changing the fulcrum point of a lever.

B. ROTOR RADIUS

The required radius of the rotor in metres depends on the power output required in kW, the rated wind velocity in km/h, and the rotor and power transfer efficiency according to the relation:

$$\text{Power} = 0.0000255 \; R^2 \; v^3 \; (\text{eff}_r \times \text{eff}_t)$$

where: eff_r = efficiency of rotor in per unit

eff_t = efficiency of power transfer in per unit

The maximum size of the rotor may be limited by the maximum length of spar material available or by the type of tower materials.

C. PUMP SIZE

The size of the pump is a direct function of the desired rated output, speed of operation and efficiency. Materials or power available will usually determine the maximum pump size.

D. POWER TRANSFER MECHANISM

The function of the power transfer mechanism is to transfer the rotary motion of the rotor to the pump, and the design depends upon the type of pump used (reciprocating or rotary motion) and the type of rotor (horizontal- or vertical-axis).

For rotary pumps, differences in speed between rotor and pump up to a ratio of 4:1 can be compensated for by a single-step pulley or a gear transfer. Rotary motion of a horizontal shaft can be converted to vertical rotary motion by gears and transferred to ground level by a rotating power shaft, or horizontal rotary motion at ground level can be obtained by the use of large diameter upper and lower pulleys and a steel chain or cowhide belt.

Vertical reciprocating motion is usually obtained from a crankshaft, and passed down through the centre of the turntable to the pump by a steel or wooden connecting rod which incorporates a swivel to prevent the rod from being twisted when the carriage assembly and rotor shaft turn in response to change in wind direction. It is desirable to keep the stroke of a crankshaft as small as possible in order to minimize turntable diameter but, with commonly available piston pumps, it is desirable to make the stroke as long as possible. This apparent conflict can be resolved by using a lever arm as shown in figure 8.

E. ORIENTATION MECHANISM

The orientation mechanism can take the form of a classic tail vane for automatic orientation or, where changes in wind direction are not frequent, a manually operated tail rope as in Thai wooden-blade windmills (figure 15) or manually-shifted A-frame axis supports as in the Netherlands Tjasker type (figure 33) and Chinese diagonal-axis type (figure 37).

The function of the turntable is to allow the rotor, main shaft and carriage assembly to rotate only about a fixed point in a horizontal plane on top of the fixed tower and to prevent any vertical or horizontal movement. Vertical power transfer usually passes through the centre of the turntable, but a considerable saving in turntable construction cost may be achieved by having the power transfer outside the turntable.

Multi-blade wind pumps incorporate a ball-bearing turntable, but a simple greased circular steel ring has proved adequate for Greek type wind pumps. The Thai wooden-rotor wind pump (figure 15) uses a tapered wooden post inserted into a wooden hole in the carriage assembly, with the power going down outside the post.

F. HUB, MAIN SHAFT, BEARINGS

The selection of hub, main shaft and bearings is most important because rotor load stresses are concentrated on these components.

The function of the hub is to connect the root end of the rotor spars firmly to the main shaft. The hub must withstand the centrifugal force of the rotor, and bending loads of the rotor spar caused by wind pressure and rotor torque. These forces (indicated in figure 38) are quantified in the following formulae:

$$\text{Centrifugal force (kg)} = 0.00219 \; \frac{W \; t_i \; v^2}{R_1}$$

$$\text{Torque (m-kg)} = 367 \; \frac{RP}{tv}$$

$$\text{Wind pressure (kg)} = 0.00142 \; v^2 \; R^2$$

for a spinning rotor, and is increased by twice the solidity factor for a stationary rotor.
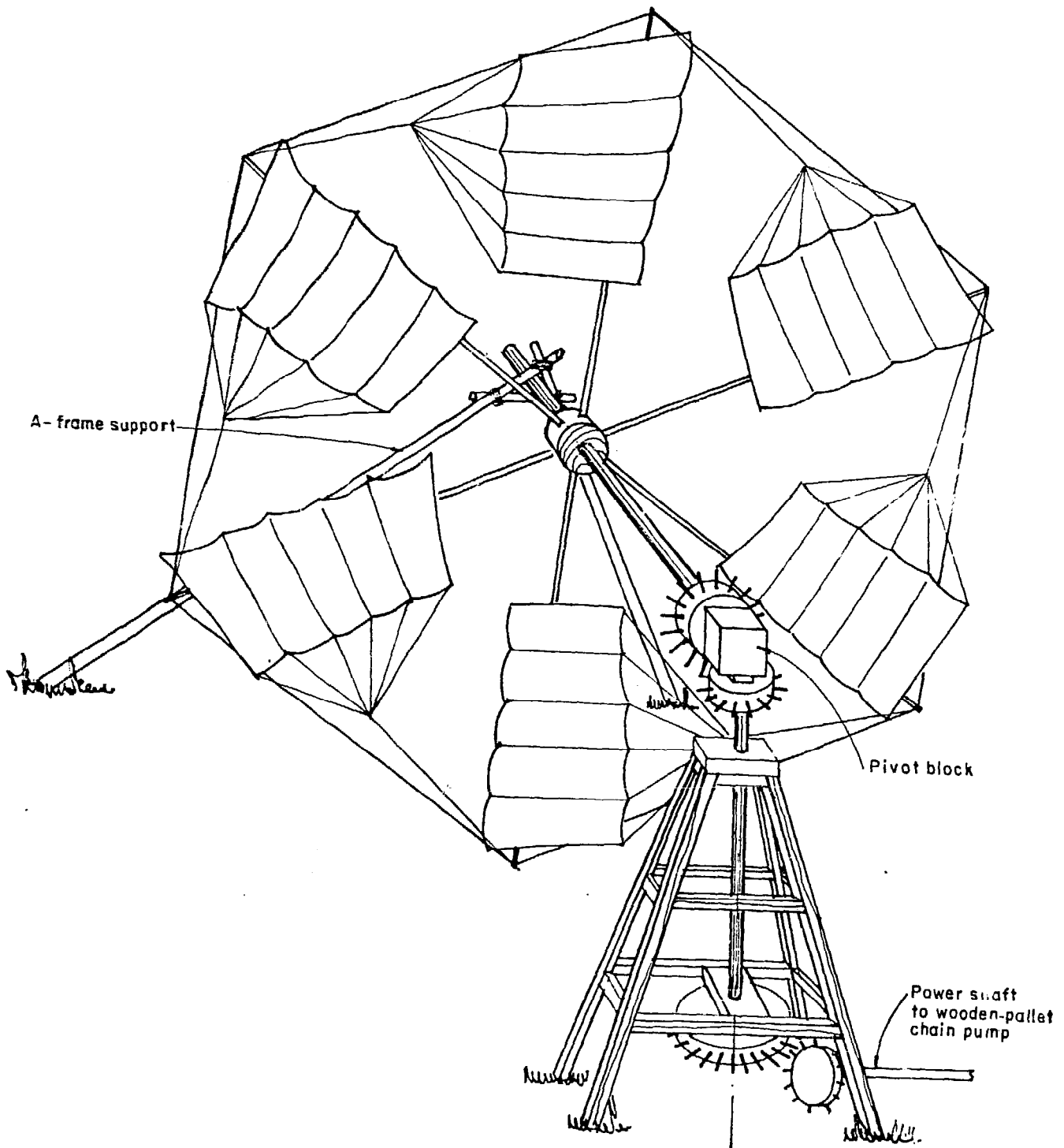
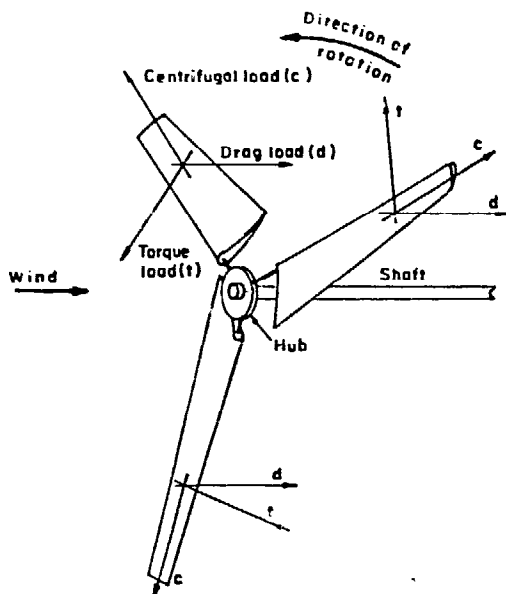Figure 37.   Chinese diagonal-axis rotor water pump

Figure 38.   Loads on rotor

where: P   = power in kW

R   = radius of rotor blade in m

R_1 = radius to centre of gravity of rotor blade in m

t   = tip speed ratio at tip

t_1 = tip speed ratio at centre of gravity of rotor blade

v   = wind velocity in km/h

W   = weight of the blade in kg

The main shaft must bear the weight of the rotor and withstand the torque and bending forces applied by the power transfer mechanism. The shaft may be made from wood, steel rod or steel pipe.

Simple wooden bearings or steel ball or thrust bearings may be used. If steel bearings are used, adequate protection must be provided against dust and rain. Wooden bearings should be capable of easy replacement. Provision must be made for lubrication.

G. *TOWER*

Determination of the type of tower is primarily a function of the materials and skills available. The Windworks octahedron module design (figure 10) has the highest strength-to-weight ratio of any non-guyed tower, but construction is complex and must be precise. Lattice steel towers (figure 6) are strong and well proven but quite expensive. Single wooden pole towers (figures 7 and 15) are the cheapest, but can only be used when it is not necessary to have the power transfer down the centre of the tower. Multiple wood pole towers (figure 8) are cheap, strong and easy to construct, and use is limited primarily by resistance to wood ants and termites. The use of guy

wires, when possible, will significantly increase over-all tower strength at little cost.

The minimum tower height should be at least equal to the rotor radius plus 1.8 m (for safety of personnel). Efforts to make the tower much higher than this should be avoided because the additional cost is likely to be greater than the increase in benefit, except in locations with nearby wind obstructions.

H. *CARRIAGE ASSEMBLY*

The carriage assembly provides a firm but movable foundation for the main shaft bearings upon the tower, and may be of wood or steel. It must be fastened to the turntable in such a way that it may turn in response to changing wind direction. The tail is fastened to the carriage assembly.

I. *STORAGE TANK*

The maximum capacity of the storage tank is determined by multiplying the longest period of wind less than starting velocity by the daily water demand. Overhead storage is not economical unless pressurized supply is required. A ground-level tank may be constructed of stone masonry about 1 m high. Possible additional uses of the storage tank for bathing and fish culture should be taken into consideration.

J. *WORKING DRAWINGS, MODEL*

After preliminary sketches of each component have been prepared, the final working drawings should be made, showing the details of and connexions between each component.

A 1/5 scale model should be made and tested in order to gain familiarity with the construction process and to carry out design optimization trials. Only after a model has been tested to full satisfaction should construction of a full-scale prototype proceed.

V. A HYBRID ASIAN WIND-POWERED WATER PUMP

In this section, an example is given of the design of a low-cost wind-powered water pump according to the sequential flow design process suggested in figure 1. An effort has been made to base the design on conditions common to many parts of Asia.

A. *PRELIMINARY INVESTIGATION*

1. Survey of local wind characteristics

The average wind velocity at Don Muang Airport, Bangkok, for 5 minutes of each half hour is recorded by the Meteorological Department of Thailand. As noted, the data for the months of March, April, May 1975 had been summarized and analysed as shown in figures 2, 3 and 4. Data from the airport were selected because of its exposed location in a rice-growing area

and its proximity to the Asian Institute of Technology and the proposed National Energy Administration windmill test location.

2. Survey of local water pumping needs

March, April and May were chosen as the period when irrigation pumping would be most beneficial because the first crop of rice is already harvested by February and, in the virtual absence of rain, the fields are normally not used until the onset of the monsoon in June.

3. Classification of wind rotors and pumps

As a complete classification of wind rotors and pumps is not available, reference will be made to previous sections of this report.

B. *DATA ANALYSIS AND CRITICAL DECISIONS*

1. Wind data analysis

(a) Consideration of the velocity and power frequency curves (figure 3) indicates an optimum starting velocity of 6 km/h and an optimum rated velocity of 20 km/h in order to obtain maximum output.

(b) The raw wind data indicate that the longest period of wind below optimum starting velocity of 6 km/h is 6 hours.

(c) Study of the wind power rose (figure 5) indicates that an orientation mechanism would be useful but not necessary; but, for the benefit of other areas with more variable wind direction, it is assumed that there is a need for an orientation mechanism.

(d) Analysis of the power duration curve (figure 4) yields a load factor of 0.30.

2. Selection of rotor

Based on the widespread success, low cost and light weight of the Greek sail rotor, this configuration was selected (figure 39). An alternative configuration that may be used in areas of higher wind speeds is based on the Princeton sail wing (figure 40).
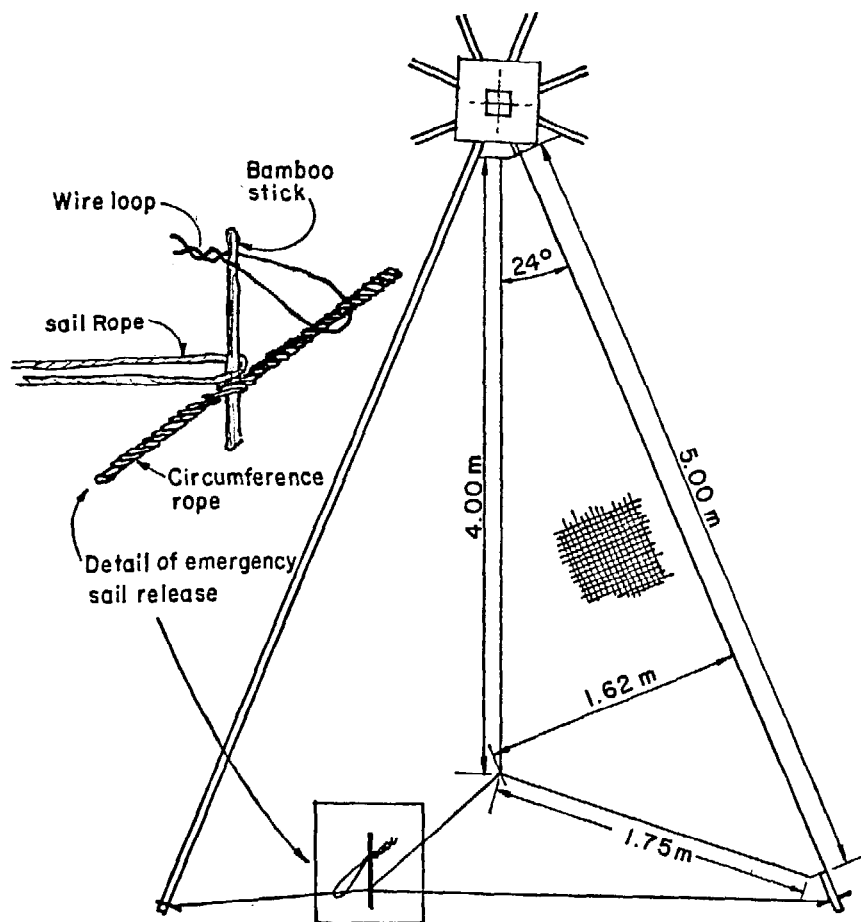

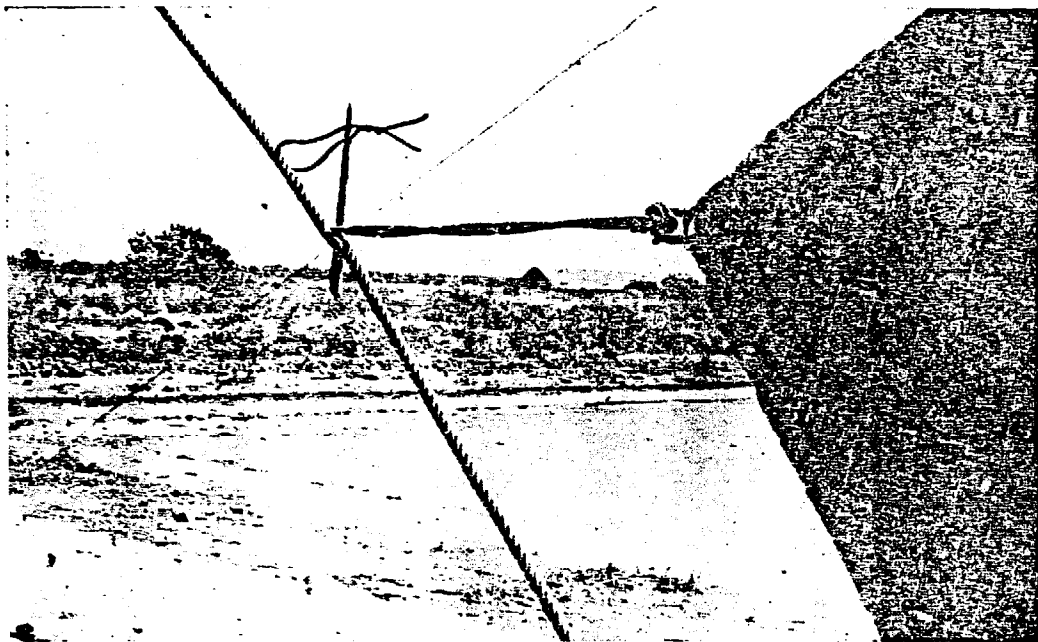Figure 39.   Greek cloth sail rotor configuration

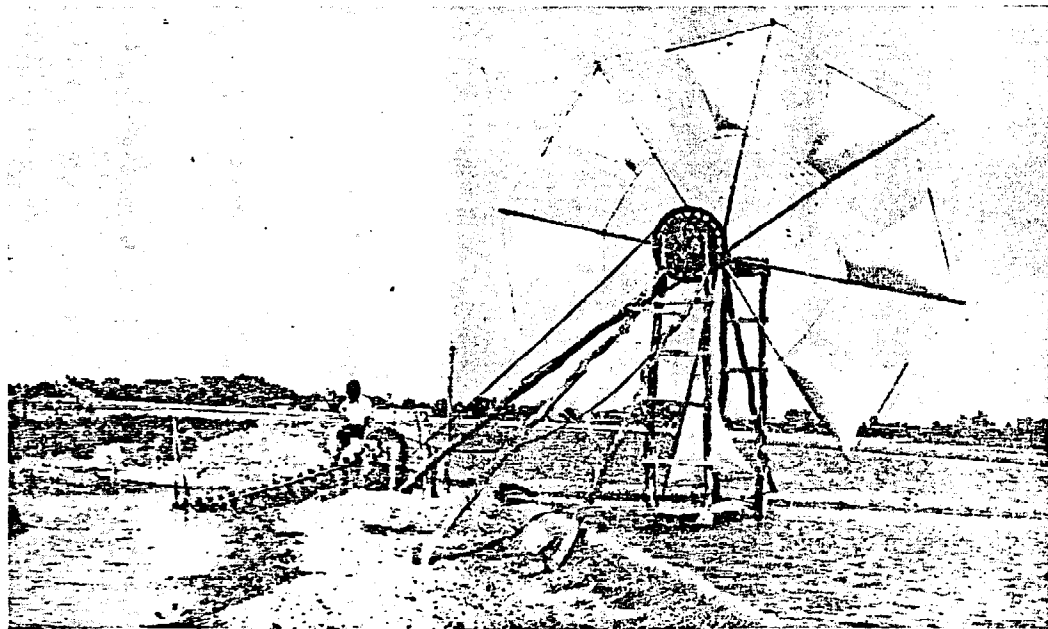Figure 3.   Quick-release sail-feathering device
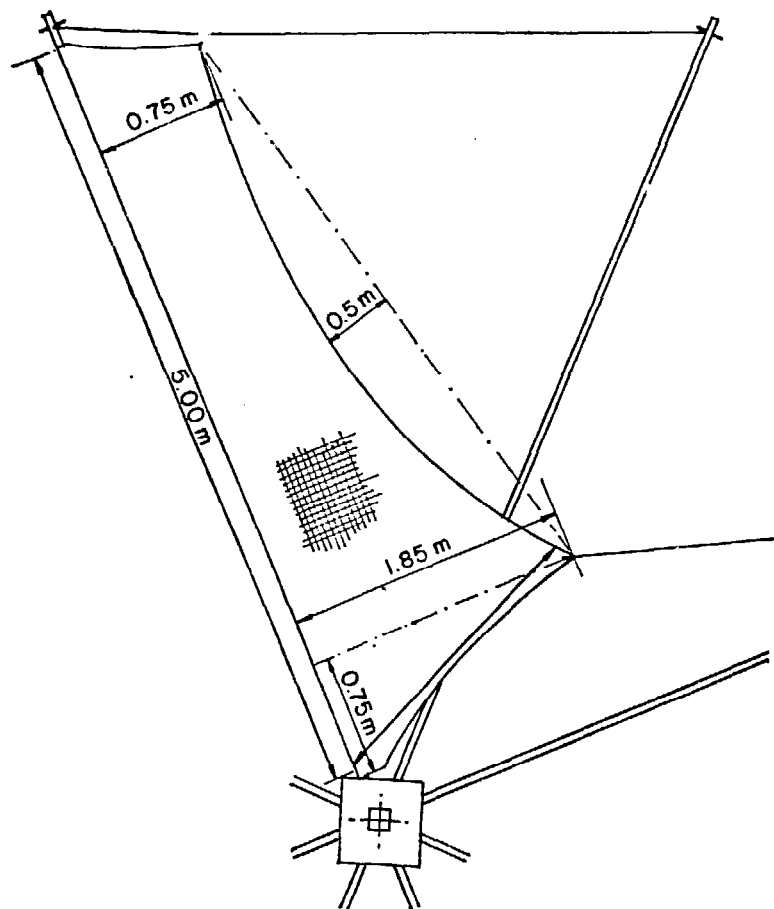

Figure 4.   Cloth sail windmill

Figure 40.
Hybrid Princeton — Greek sail rotor configuration

3. Selection of pump

For generalized design purposes, a total head of 10 m is assumed. Owing to its simplicity of construction and adaptability to variable low-speed rotary motion, the steel-washer chain pump was selected (figure 29). However, the square-pallet chain pump (figure 28) may be best for areas where this pump is traditionally used and only a low lift is required.

4. Determination of desired pumping rate

Assuming a daily requirement of 6.5-mm depth per day for rice cultivation and a desired irrigated area of 2 hectares, the daily water demand is 130 m³ per day. Multiplication by the reciprocal of the load factor indicates that the rated capacity of the pump should be 18 m³ per hour.

5. Determination of rated power requirement of the pump

Assuming 0.70 pump efficiency, the rated power requirement of the pump would be 0.703 kW (section III. E).

C. COMPONENT DESIGN AND MATCHING

1. Control mechanism

Assuming frequent presence of the operator, furling of the sails would be the primary control mechanism. An emergency sail-release mechanism similar to that used on Thai sail rotors would be incorporated (figure 39).

2. Size of rotor

Assuming 0.25 and 0.50 for the efficiencies of the rotor and power transfer respectively, the required rotor diameter from section IV. B would be 10.5 m.

This size is within the range of bamboo spars available in Thailand and most Asian places. Sail rotors have been operated successfully up to 10-m diameter so this size is acceptable.

3. Size of pump

Given the rated output of 18 m³ per hour and pump efficiency 0.70, the basis of calculation is 25.7 m³ per hour. Assuming a rated rotor speed of 12 rev/min

with a 2:1 speed increase and a 0.5-m diameter pump drive wheel, the size of the pipe within which water is lifted by the washers on the chain should be 12.0 cm. The size of the pipe may be decreased by increasing the speed of the chain, which may be effected by providing a higher drive speed ratio or by increasing the diameter of the pump drive wheel. The optimum speed of chain pumps is not known.

4. Orientation mechanism

Orientation of the main shaft by manual relocation of an A-frame support structure (figure 41) supporting one end of an extended shaft is suggested because of its simplicity and proven feasibility on the Netherlands Tjasker type (figure 33) and Chinese diagonal-axis type (figure 37). The opposite end of the shaft rotates about a fixed, guyed turntable post (figure 42).

5. Power transfer mechanism

Because horizontal rotary motion is required to operate the chain pump, only a simple direct pulley drive to ground level is required. Pulley wheels made of several laminations of wood boards are suggested (figure 42). Chains are widely used in Thailand as the transfer connexion and would be suitable.

6. Hub, main shaft and bearings

(a) A laminated wooden hub was selected (figure 43) because of its simplicity of construction and successful use on Thai sail rotors.

(b) An extended square wooden main shaft is successfully used on Thai sail rotors and has been selected for this hybrid design (figure 43). The shaft is rounded only at the point where it rests in the bearing (figures 41, 42).

(c) Simple wooden bearings have been well proven on Greek and Thai sail rotors and Australian Comet wind-powered pumps. An improved version of Greek wood bearings with increased bearing surface and provision for lubrication has been designed for both main bearings (figures 41, 42).

7. Tower

The tower in this case consists only of the two legs of the movable A-frame at one end of the shaft and the turntable post at the other end. The turntable post is guyed to the ground and the A-frame is guyed to the base of the turntable post so that it is stabilized but still free to move.

8. Carriage assembly

The large wooden bearing blocks also function as the carriage assembly.

9. Storage tank

Because the longest period of wind below starting velocity is only six hours, a storage tank is not considered necessary, although it would be useful for irrigation control.

10. Final drawings

An over-all sketch of this hybrid design (figure 44) is proposed as the basis for construction of models for testing only. For further development of this design, model test results should be evaluated and design modifications incorporated into final working drawings for prototype construction and testing.
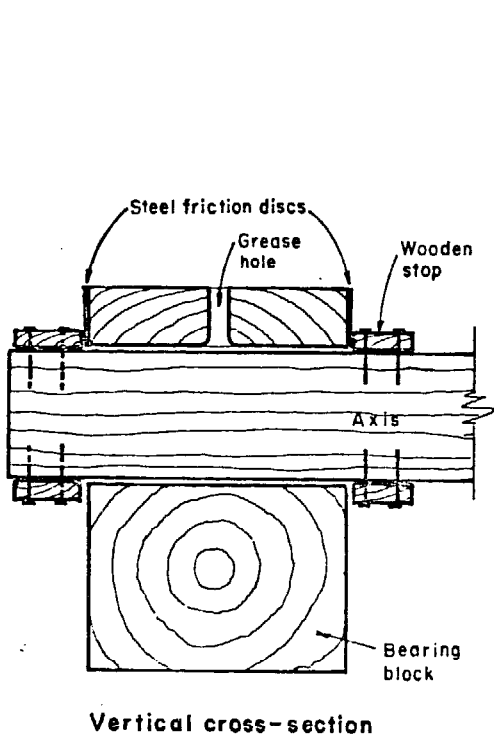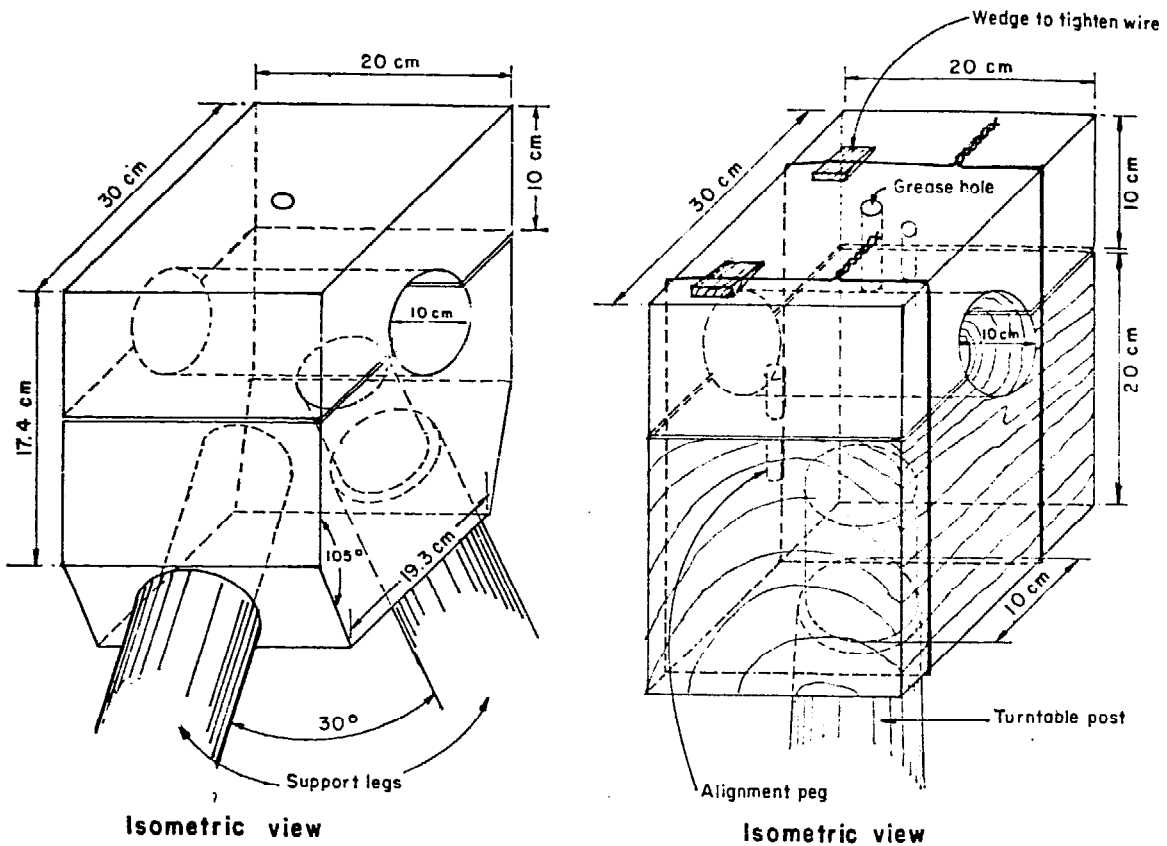
Isometric view

Isometric view

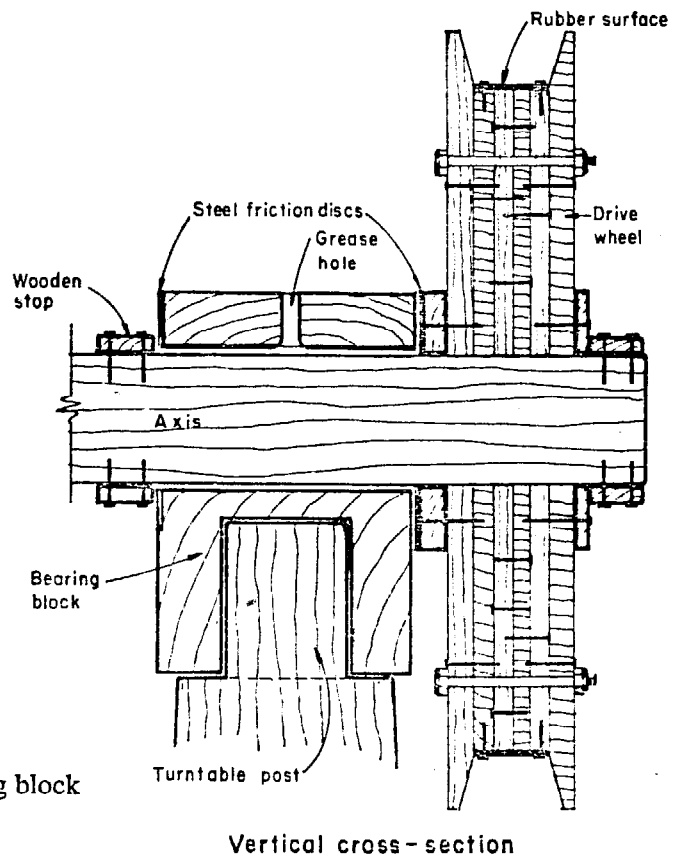Vertical cross-section

Figure 41.   Double leg support bearing block

Vertical cross-section

Figure 42.   Turntable post bearing block

Cover plate removed

34

0.50 m

A

B'

B

B

Bamboo spar

1 cm dia. bolt

Axis shaft

Wooden spacer

1 cm dia. bolt

A

A'

B'

B

Cross-section of hub through A–A'

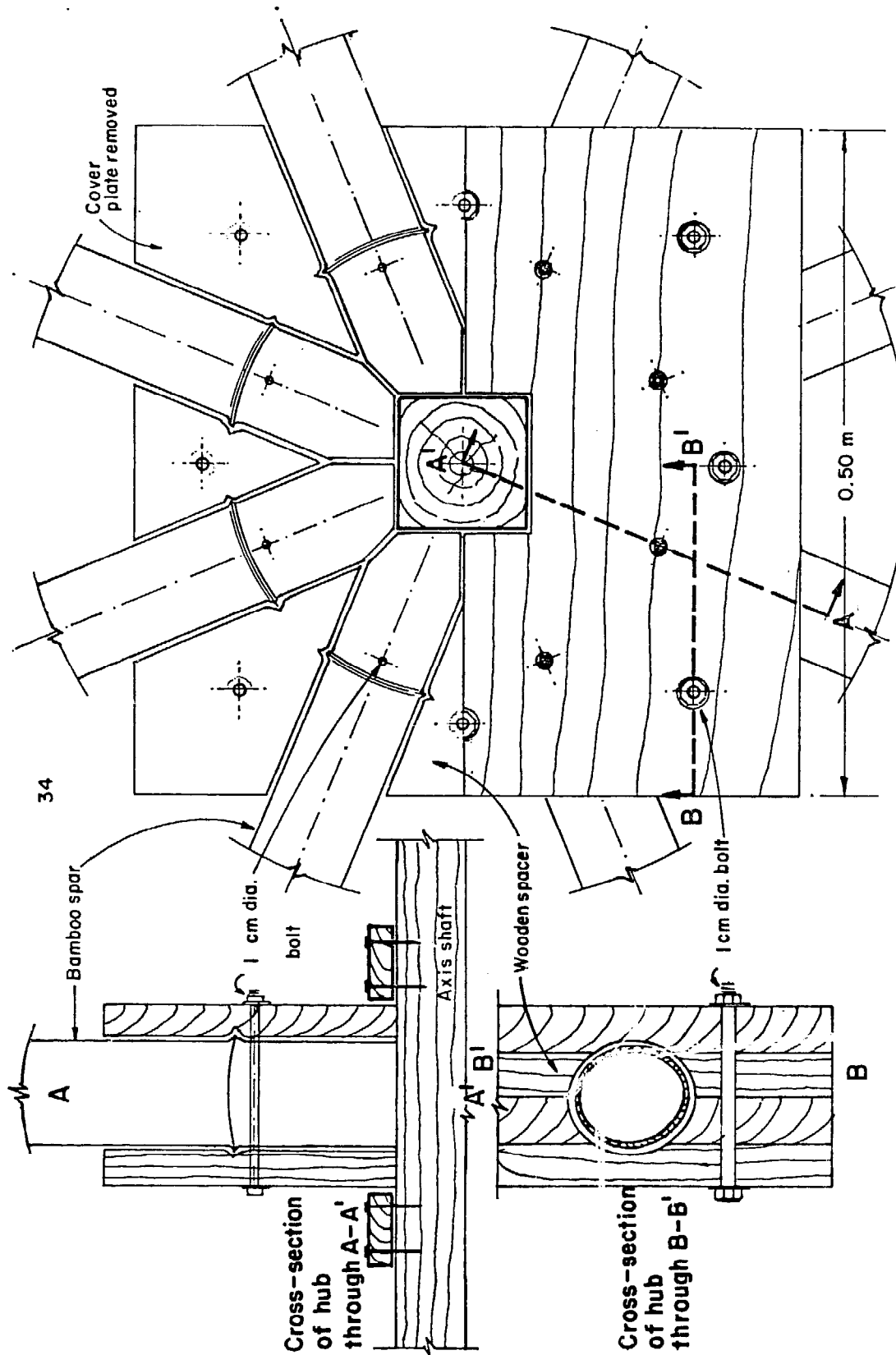**Cross-section of hub through B–B'**
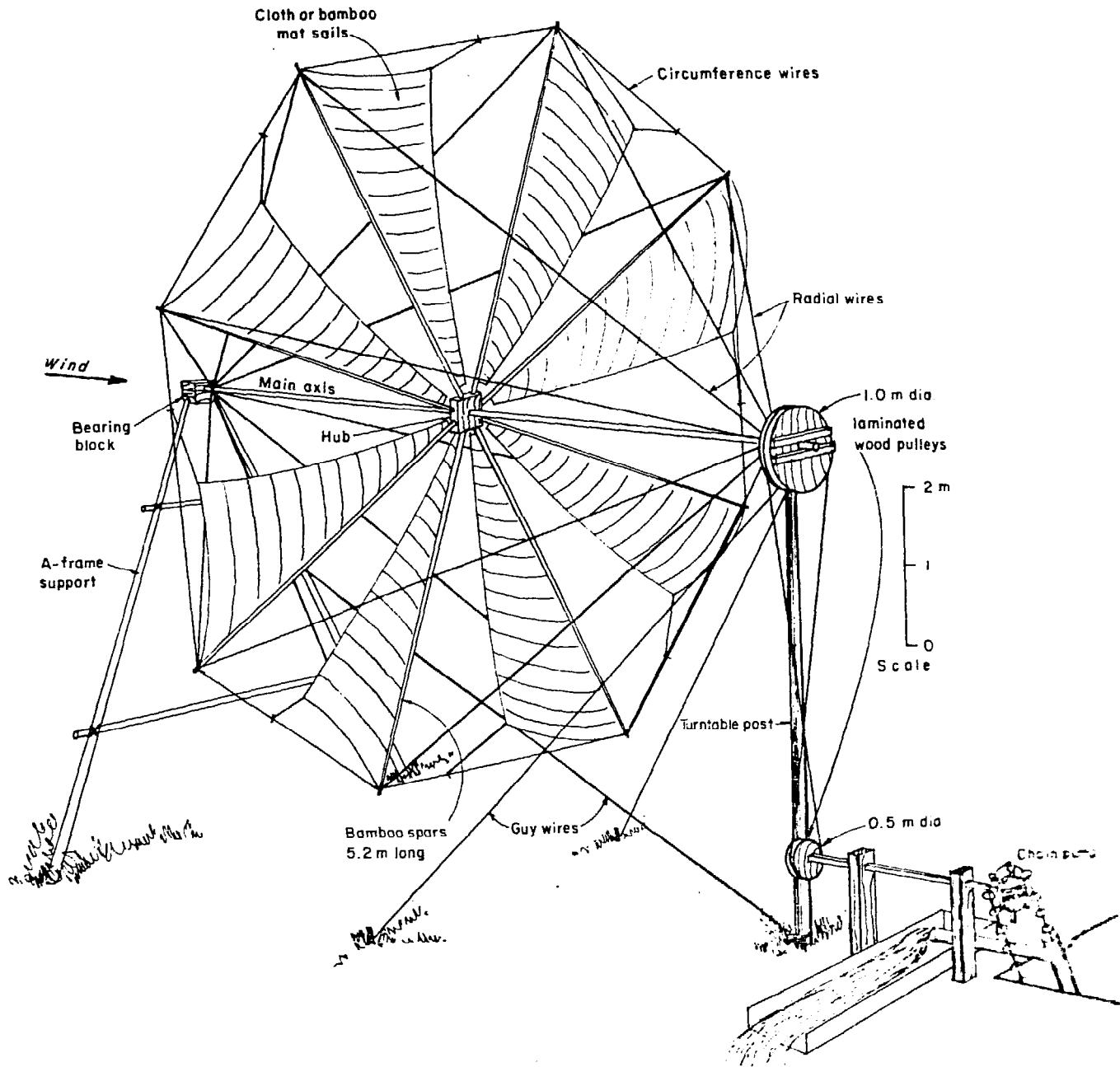
Figure 43.   Details of hub

Figure 44.   Hybrid Asian wind-powered water pumping system

III. CONSOLIDATED LIST OF REFERENCES ON WIND ENERGY

W 1. E. W. Golding, *The Generation of Electricity by Wind Power*, (London, E and F.N. Spon Ltd., 1955), pp. 22.

W 2. Arthasastra of Kautilya, quoted from *Studies in Ancient Hindu Polity* by Narenda Nath.

W 3. A. Makhijani and A. Poole, *Energy and Agriculture in the Third World*, (Cambridge, Massachusetts, USA, Ballinger, 1975).

W 4. E. W. Golding, "Windmills for water lifting and the generation of electricity on the farm", FAO Internal Working Bulletin No. 17.

W 5. "Energy from the wind — assessment of suitable winds and sites", WMO Technical Note No. 4, Geneva, 1954.

W 6. Communication from J. Park, (Helion), USA.

W 7. Calvert, 'Wind power in eastern Crete", *Transactions of the Newcomen* Society, UK, 1972, vol. XLIV, pp. 137-144.

W 8. M. M. Sherman, "6,000 handcrafted sail wing windmills of the Lassithiou, Greece, and their relevance to windmill development in rural India", *Proceedings, Wind and Solar Energy for Water Supply*, German Foundation for International Development, Berlin, 1975.

W 9. "Plans for 25 foot diameter sail windmill", Windworks, USA.

W 10. "Performance data for 25 foot diameter sail windmill", Brace Research Institute, Canada.

W 11. "Construction plans for 10 m diameter sail windmill", TOOL Foundation, Netherlands.

W 12. "Note on 6 m diameter sail windmill", Sarvodaya Educational Development Institute, Sri Lanka.

W 13. P. Fraenkel, "Food from windmills", Intermediate Technology Development Group, UK.

W 14. F. H. King, *Farmers of Forty Centuries*, (Wisconsin, USA, Madison, 1911).

W 15. J. Needam, *Science and Civilization in China*, (Cambridge University Press, UK, 1955), vol. 4:2, pp. 555-567.

W 16. *Nognye Jixie (Agricultural Machines)*, Northeastern Machinery Institute of China, Nos. 11 and 12, 1958.

W 17. Chen Li, "Why has the windmill not been more widely used in North China? A report on the construction of the windmill (of the Salterns) used on the coast of the Gulf of Chilli (near Tientsin)", *Kho Hsueh Thung Paro (Science Correspondent)*, 1951, vol. 2, No. 3, p. 266.

W 18. *Water Conservancy in New China*, Ministry of Water Conservancy, (Shanghai, People's Art Publishing House, 1956).

W 19. *Nogyne Jishu (Agricultural Techniques)* China, No. 9, 1958, pp. 15-16).

W 20. W. E. Heronemus, "A survey of the possible use of wind power in Thailand and the Philippines", USAID, Contract No. TA-C 1143, 1974.

W 21. F. Stokhuyzen, *The Dutch Windmill*, (New York, Universe Books, Inc., 1963), pp. 21-46.

W 22. R. Garcia, "Low-cost windmill", Volunteer Technical Assistance, USA.

W 23. Report by the commission on the Church's participation in development, World Council of Churches, Switzerland.

W 24. A. Bodek, "How to construct a cheap wind machine for pumping water", Brace Research Institute, Publication No. 5, Canada.

W 25. Koslowski, "Investigation of whether a Savonius rotor is a suitable prime mover", Intermediate Technology Development Group, UK.

W 26. U. Hutter, "Planning and balancing of energy of small output wind plant", *Proceedings of the Symposium on Wind and Solar Energy*, (UNESCO, October 1954), p. 85.

W 27. *Energy Primer*, (USA, Portola Institute, 1974), pp. 74-105.

W 28. P. Johnston, "Notes on rural electrification by windpower", report to the Ministry of Finance, Fiji Government, 1975.

W 29. *Proceeding of the Second Workshop on Wind Energy Conversion Systems*, Energy Research and Development Administration, USA.

W 30. *Nognye Jishu (Agricultural techniques)*, China, No. 19, p. 11.

W 31. M. M. Sherman, "The design and construction of an appropriate water pumping windmill for agriculture in India", *Transactions, Wind and Solar Energy for Water Supply*, German Foundation for International Development, Berlin, 1975.

W 32. D. K. Biswas, report to the Indian Agricultural Research Institute, India.

W 33. F. Harahap, "Design and construction of a windmill: an experience of the Mechanical Engineering Department of ITB", workshop paper, Bandung Institute of Technology, Indonesia, 1972.

W 34. "Wind pump for lifting water", Infrormation Kit Section II-Part B, vol. II, No. 5, USAID Technical Digest Service, Washington, USA, 1962.

W 35. Detailed plans of Princeton sail wing rotor windmill design, (New York, Flanagan Plans).

W 36. M. M. Sherman, "A water pumping windmill that works", *Journal II of the New Alchemists*, USA, 1973.

W 37. H. Stam, "Adaptation of windmill designs, with special regard to the needs of the less industrialized areas", *Proceedings of United Nations Conference on New Sources of Energy*, Rome, 1961, vol. 7, paper No. W/40, pp. 347-357.

W 38. J. Park, "Simplified wind power systems for experimenters" and "12/16 complete plans and instructions", Helion, USA.

W 39. H. Meyer, "12 footer plans", Windworks, USA.

W 40. R. E. Chilcott, "The design, development and testing of a low cost 10 hp windmill prime mover", Brace Research Institute, Publication No. 7, Canada, 1970.

W 41. R. Wailes, "Horizontal windmills", *Transactions of the Newcomen Society*, London, 1967/8, vol. XL, pp. 125-145.

W 42. P. South and R. S. Rangi, "An experimental investigation of a 12 ft. diameter high speed vertical axis wind turbine", National Research Council Report LTR-LA-166, Canada, 1975.

W 43. J. R. Godfrey, DAF Company report, Canada.

W 44. F. V. Brulle, H. C. Lavsen, "Gyron (cydogyro windmill) investigation for generation of electrical power", *Proceedings of the Second Workshop on Wind Energy Conversion Systems*, Mitre Corporation, Washington, USA, 1975, pp. 452-457.

W 45. P. Bade, "Flapping vane wind machine and rod-piston pump" and "Flapping vane wind machine", *Transactions, Wind and Solar Energy for Water Supply*, German Foundation for International Development, Berlin, 1975.

W 46. Communication from E. Barnhart, New Alchemy Institute-East, USA.

W 47. "Water lifting for agriculture using non-conventional power equipment", Ministry of Agriculture and Co-operative, Government of Thailand, 1974.

W 48. S. Wilson, "Note on low lift irrigation pumping", Department of Engineering Science, Oxford University, UK.

W 49. R. L. Pendleton, *Thailand, Aspects of Landscape and Life — An American Geographical Society Handbook*, (New York, Duell, Sloan and Pearce, 1963).

W 50. I. A. Rubinski and A. I. Rubinsky, "A low specific speed pump for small discharges", *Civil Engineering and Public Works Review*, vol. 50, No. 591, September 1955, pp. 987-990.

W 51. M. F. Merriam, *Wind Energy for Human Needs*, (UC 1 D—3724), (Berkely, California, USA, Lawrence Berkely Laboratory, 1974).

W 52. "Review of progress on utilization of wind power", National Aeronautical Laboratory, India, Report No. SR-WP-1-60, 1960.

W 53. S. P. Venkiteshwaran, "Operation of Allgaier type wind electric generator at Porbandar", National Aeronautical Laboratory, India, Report No. TN-WP-2-61, 1961.

W 54. R. Ramanathan and S. Viswanath, "Estimated annual energy output of two types of wind electric generators at selected stations in India", National Aeronautical Laboratory, India, Report No. TN-WP-4-62, 1962.

W 55. S. P. Venkiteshwaran, K. R. Silvaraman and C. G. Gupte, "A note on the feasibility of wind generation of electric power for communication links in India", National Aeronautical Laboratory, India, Report No. TN-WP-36-65, 1965.

W 56. S. K. Tewari and L. S. Srinath, "A systems approach towards utilization of wind energy (a preliminary study)", National Aeronautical Laboratory, India, 1975.

W 57. S. Janardhan, "Some preliminary considerations in the choice of rated speeds for wind machines", National Aeronautical Laboratory, India, Report No. TN-WP-20-63, 1963.

W 58. E. W. Golding, Electrical Research Association, UK, Report No. C/T 118, 1956.

W 59. P. Nilakantan, K. P. Ramakrishnan and S. P. Venkiteshwaran, "Windmill types considered for large scale use in India", National Aeronautical Laboratory, India, Report No. TN-WP-3-61, 1961.

W 60. K. R. Silvaraman and S. P. Venkiteshwaran, "Utilization of wind power for irrigation of crops in India with special reference to the distribution of wind and rainfall", National Aeronautical Laboratory, India, Report No. TN-WP-30-63, 1963.

W 61. S. P. Venkiteshwaran and K. R. Silvaraman, "Utilization of wind power in arid and semi-arid areas in India", National Aeronautical Laboratory, India, Report No. TN-WP-35-64, 1964.

W 62. S. K. Tewari, "How feasible is the substantial utilization of wind power in India?", National Aeronautical Laboratory, India, 1975.

W 63. S. K. Tewari, "It's time to talk about wind power", Science Today, November 1975.

W 64. P. N. Shankar, "The design, fabrication and preliminary testing of NAL'S 1 kW vertical axis wind turbine", National Aeronautical Laboratory, India, Report No. AE-TM-22-75, 1975.

W 65. P. N. Shankar, "On the aerodynamic performance of a class of vertical axis windmills", National Aeronautical Laboratory, India, Report No. AE-TM-13-75, 1975.

W 66. BHEL Research and Development News, Second Annual Day Issue, January, 1976.

W 67. J. O'M. Bockris, "The case for sea-borne wind-based power", Search, July 1975.

W 68. "The role of research and development in New Zealand's energy economy", Department of Scientific and Industrial Research, New Zealand, March 1974.

W 69. R. F. Benseman and F. W. Cook, "Solar radiation in New Zealand — the standard year and radiation on inclined slopes", New Zealand Journal of Science, No. 12, December 1969, pp. 696-708.

W 70. H. I. Odum, Environment, Power and Society, (New York, Wiley Interscience, 1971).

W 71. Proceedings of the Second New Zealand Energy Conference, University of Canterbury, New Zealand, May 1975.

W 72. G. C. Szego and C. C. Kemp, "Energy Forests and Fuel Plantations", Chemical Technology, May 1973, pp. 275-284.

W 73. E. Flatteau and J. Stansbury, "It takes energy to produce energy: the net's the thing", Washington Monthly, March 1974, pp. 20-26, and "Net Energy", April 1974, p. 6.

W 74. N. Geogescu--Roegen, "Energy and economic myths", Southern Economic Journal, vol. 41, January 1975, pp. 347-381.

W 75. J. G. R. Stevens, "Energy and agriculture", Span (Shell Oil Company), vol. 18, No. 1, 1975.

W 76. M. Slesser, "How many can we feed?", Ecologist, 3, 1973, pp. 216-220.

W 77. "Solar water heaters", Consumer, New Zealand, No. 114, January-February 1975, pp. 16-19.

W 78. D. A. Hills and G. L. Allen, "Solar water heating", Department of Scientific and Industrial Research, New Zealand (Christchurch), Technical Bulletin No. 1 (revised edition), June 1975.

W 79. "The status of solar energy utilization in Australia for industrial, commercial and domestic purposes", Commonwealth Scientific and Industrial Research Organization, Australia, Solar Studies Report No. 74/1, 1974.

W 80. Proceedings of the New Zealand Energy Conference, University of Auckland, New Zealand, May 1974.

W 81. J. van Meighem, Atmospheric Energetics, Oxford, 1973.

W 82. N. J. Cherry, "Preliminary analysis of meteorological data", Lincoln College, Canterbury, New Zealand, Report No. WER-1, 1975.

W 83. N. J. Cherry, D. J. Edwards and A. J. Roxburgh, "Low-cost instrumentation for a wind energy survey", paper to be presented at the 22nd International Instrumentation Symposium, San Diego, California, USA, May 1976.

W 84. J. R. Wood, "Wind energy utilization in New Zealand", University of Auckland, New Zealand, 1975.

W 85. D. Lindley, "New Zealand's place in the energy economics of the Pacific basin countries", Conference on Energy in the Pacific Basin, Pepperdine University, California, USA, December 1975.

W 86. C. O. Lee, "Study on windpower utilization as a source of energy", Ministry of Science and Technology, Republic of Korea, Report No. STF-74-2, 1974.

W 87. K. Z. Cho, "Performance analysis of a self-excited brushless generator", Korea Advanced Institute of Science, M. S. thesis, 1976.

W 88. H. V. O, "Frame analysis of structural design system", Korea Advanced Institute of Science, M. S. thesis, 1976.

W 89. T. S. Ahn, "Stress analysis of a windmill propeller", Korea Advanced Institute of Science, M. S. thesis, 1976.

W 90. A. Arismunandar, "The Indonesian energy demand in the year 2000: views and comments", Symposium on Energy and the Environment, Jakarta, Indonesia, February 1975.

W 91. D. J. Grace and others, Report of the Task Force on wind energy, Alternate Energy Sources for Hawaii, 1975, Hawaii Natural Energy Institute, February 1975.

W 92. D. E. Walshe, Wind Excited Oscillations of Structures, London, H. M. S. O., 1972.

W 93. Asyaman, Final project, Department of Engineering Physics, Bandung Institute of Technology, Indonesia, 1976.

W 94. R. Rosad, Final project, Department of Mechanical Engineering, Bandung Institute of Technology, Indonesia, 1976.

Other useful references

R. van Steyn, Wind Energy, A Bibliography with Abstracts and Keywords, Parts I and II, Department of Physics, Eindhoven University, Netherlands.

Wind Energy Utilization, a Bibliography with Abstracts, National Aeronautical and Space Administration, USA, 1974.

Wind Energy Bibliography (USA, Windworks).

Wind Power, (J. G. Symons, Mankato, Minnesota, USA).

Wind Powered Machines, (USA, National Technical Information Service).

T. Savino, Wind Energy Conversion Systems, Workshop Proceedings, Washington, D.C., June 1973, (USA, National Technical Information Service).

T. Savino, Status of Wind Energy Conversion, (USA, National Technical Information Service).

Soedergard, Analysis of Possible Use of Wind Power in Sweden, part I, Resources, Theory, Model 1 and 10 MW, (USA, National Technical Information Service).

Christaller, "Exploitation of wind energy", parts I and II, National Technical Information Service, USA.

U. Hutter, "The development of wind power installations for electrical power generation in Germany", National Technical Information Service, USA.

Bettlgnies, "Wind energy — its utilization in isolated areas of the Americas, ½ – 100 kW", Northern Engineering Centre, Ecole Polytechnique, Montreal, Canada.

M. F. Merriam, "Is there a place for the windmill in less developed countries", Working Paper Series No. 20, East West Centre, Honolulu, Hawaii, USA.

G. Smith, "List of manufacturers of water pumping and electric generating windmills", School of Architecture, Technical Research Division, Cambridge, UK.