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 m^3. 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