# Introduction to Wave Power

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## ABSTRACT

Wave power, resulting from the transfer of energy from wind into water, represents a large potential source of energy for the UK, Europe and some other parts of the World, see Figure 1 .

The wave power around the UK and Eire has an estimated annual average of 120GW [1]. When factors such as the need to avoid heavy shipping areas, the need to leave space between devices and the inability of devices to capture all of the incident energy are taken into consideration the technical resource may be of the order of 25GW. The technically achievable total world potential might be around 2000GW.

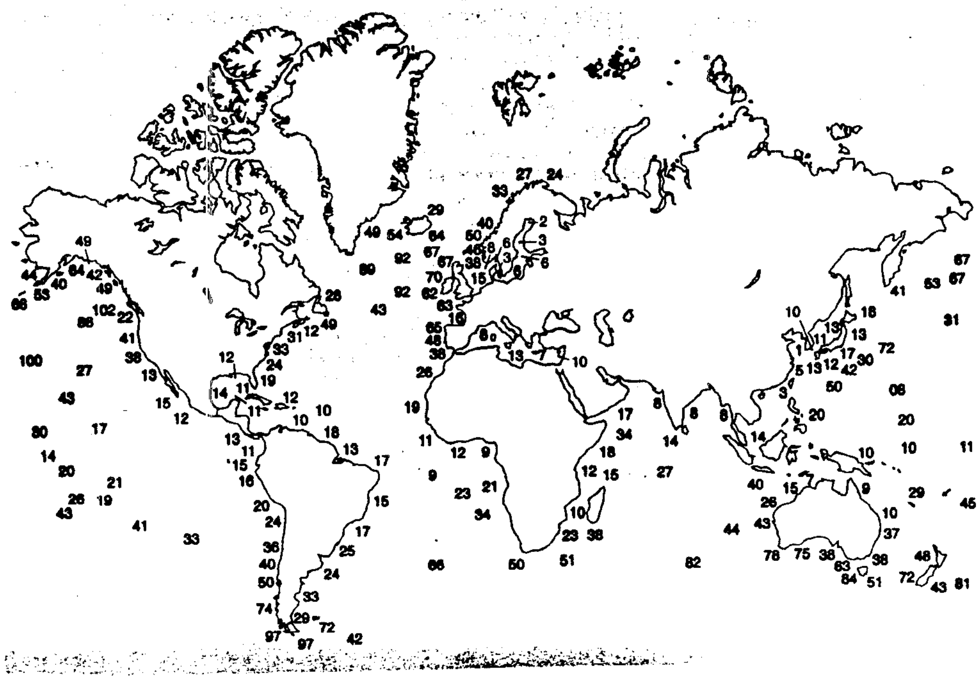


***Figure 1.*** *Annual average wave power in kW/m (adapted from [5])*

Exploiting a significant proportion of this large potential sources of energy would demand the deployment of arrays of large numbers of offshore wave energy converters. These would have to be floating in deep water to capture the maximum available energy. Devices fixed to the seabed or to the shore will generally be in shallow water where the wave power resource is lower, although the technical constraints are less severe.

Two decades of research have produced many ideas and technical developments for possible designs. A number of prototypes have been installed in a variety of countries, however, the majority of these prototypes have been shore mounted, where the structural costs and maintenance are lower than for those floating structures intended for deep water operation.

An almost trivial fraction of the wave power resource has been tapped to date. Technical developments and political and financial incentives arising from fossil fuel depletion and associated pollution damage will increase the interest in wave power over the next two decades.

In this paper the properties of waves and the range of means of extracting energy from them will be outlined. Later presentations will amplify some of the issues.

## WAVE CLIMATES

Sea waves are characterised by their waveheight ($H$), period ($T$) and crest length. A particular wave climate will consist of many monochromatic waves like that shown in figure 2, each with its own $H$,$T$ and hence wavelength, velocity and power per metre of crestlength ($\lambda$, $V$ and $P$).

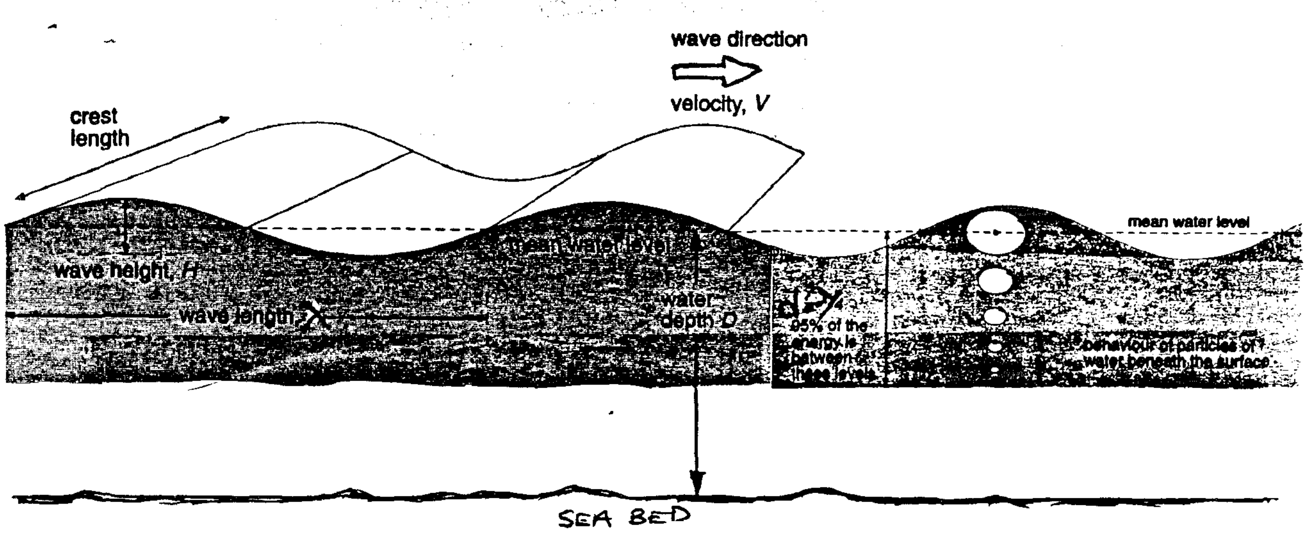



*Figure 2. Characteristics of monochromatic waves.*

in deep water $V = \dfrac{gT}{2\pi}$ m/s $\quad \lambda = \dfrac{gT^2}{2\pi}$ m $\quad P = H^2T$ kW/m

e.g. *H=2.5m T=8s* then $\lambda$=99.9m *V=12.5m/s P=50.0kW*

*H=2.5m T=10s* then $\lambda$=156.0m *V=15.6m/s P=62.5kW*

Note here that these waves are dispersive, that is to say that their velocity is dependent on period, whereas in shallow water the velocity is only a function of depth, $D$ ($V = \sqrt{gD}$) . In deep water, usually taken to be at least half of the wavelength, the longer period waves will arrive at a given location before their shorter and less energetic counterparts. In shallow water the dependence on depth leads to refraction of waves which accounts for the tendency of waves to approach beaches with crests almost parallel to the sea shore. This phenomena can be used to identify the most energetic locations for shore or floor mounted devices by ray tracing. As waves travel into shallower water they become less powerful as illustrated in figure 3.

In the complex pattern of real waves $H$ and $T$ are replaced by significant waveheight ( $H_s \approx 4H_{rms}$ ) and energy period ( $T_e$ ). See figure 4. The power density is then $P \approx 0.5 H_s^2 T_e$ kW per metre of crestlength. e.g. $H_s = 3.7m$ $T_e = 9.5s$ $P = 65.0 kW/m$.

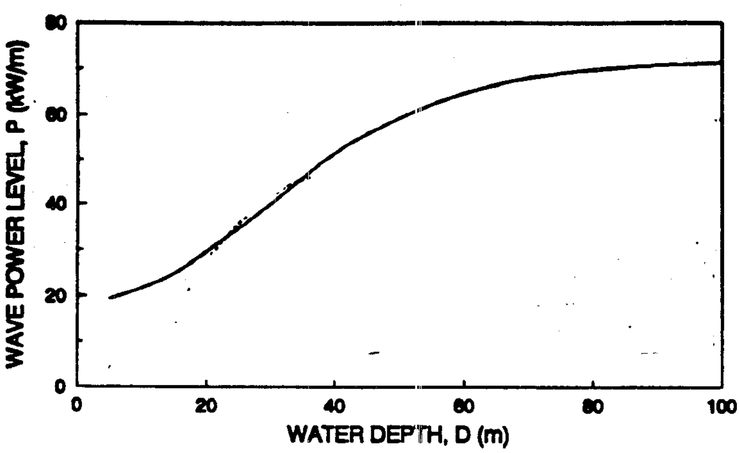



***Figure 3.***
*Wave Power/Depth for South Uist*

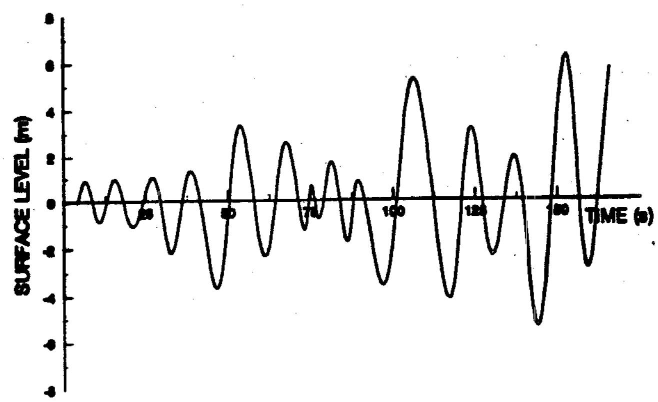



***Figure 4.***
*Characteristics of Real Waves*

Wave power devices are designed to capture energy from a spectrum of wave climates such as that illustrated in the form of a scatter diagram in figure 5 to represent the annual wave climate at a particular location.

Another important feature of waves in water is the exponential attenuation of energy flux with depth as shown in figure 2. The fraction of energy, $F$, between the surface and depth , $d$, is given by $F = 1 - \exp\left(-4\pi \frac{d}{\lambda}\right)$.

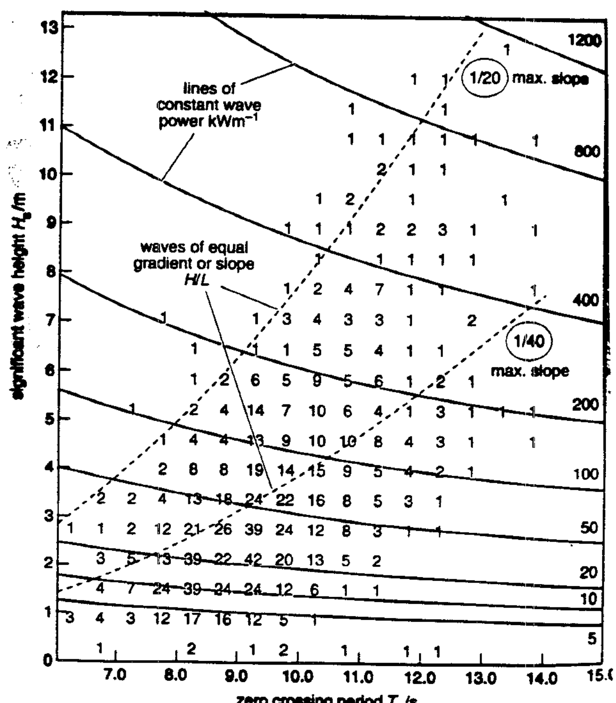



***Figure.5.***
*A North Atlantic Scatter Diagram*

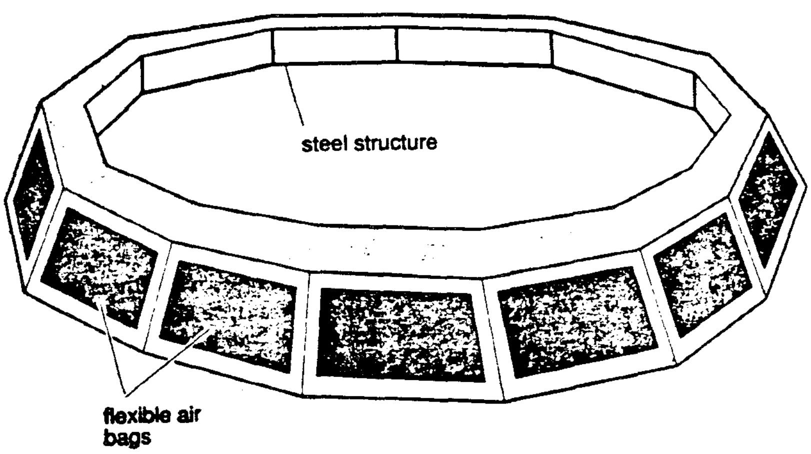
## HOW IT STARTED

In the wake of the oil crises of the early 1970s the UK government invested some R&D funds to several teams investigating wave power devices. In addition to the privileged wave climates enjoyed by the UK and Eire a stimulating factor to this funding was the elegant concept of the Salter Duck. The rotation of the Duck about its axis mimics the orbital beahviousr of particles of water in that physical excursions are greatest at the surface and decrease with depth just as shown in figure 2. This gives near perfect impedance matching to waves of a particular period (or wavelength) and so there is good transfer of energy from water into the Duck. Power take off is from the applied torque. A major consideration for all design teams is then to obtain the best performance from a range of wave heights and periods, and to design structures to survive the worst storms.

## FRAMES OF REFERENCE

Narrow tank experiments conducted at Edinburgh confirmed the promised performance. Translating this concept to open water raises the difficult problem of establishing a stable frame of reference to replace the fixed sides of the tank. An extreme but unworkable civil engineering solution would be to build massive supports up from the sea bed. An alternative approach is to arrange for a number of ducks (say 10 to 20) to share a common spine so that the entire structure spans several wave crests in normal seas and therefore remains reasonably stable.

The Duck has been developed over the years and with technical improvements to the power take off train may represent the best long term choice of floating wave energy device.




This crest spanning approach is shared by the Circular Clam, which is essentially a collection of 12 air chambers around the circumference of a toroid (see figure 6). The air chambers are separated from the sea by flexible rubber membranes which pump air throughout the device in response to incident wave activity. Energy is extracted from the air flow by a series of Wells self rectifying turbines.

***Figure 6.*** *The Circular Clam*

The Duck and Clam are floating devices designed to utilize the deep water off shore potential. Costings of £0.16/kWh and £0.08/kWh reported by Thorpe [1] may be reduced by further development, although UK government funding was halted some years ago. Arrays of many floating devices in water 50m or so deep will be a few km off shore and will constitute wave farms, capable of delivering MW or GW back to the main land via subsea cables. As they will be moored to the sea bed they will be able to swing to face the principal wave direction in order to maximise the total energy capture in a particular sea state. Both device teams have made considerable progress in design and technology, further developments of the Clam and Duck are necessary before the wave farm concept can be realised. Proposals to the UK government for further R&D and possible prototypes have been refused because the declared policy is only "keeping a watching brief" on overseas activities.

## OTHER FRAMES OF REFERENCE

There have been other attempts to provide a frame of reference by using bodily inertia in for example the Lancaster PS Frog which contains a 1250 ton reaction mass which slides back and forth along guide rails as the device moves.(See [2] for example)

Some device concepts involve anchoring part of the device to the sea bed such as the Bristol cylinder, the tethered buoys of Denmark and Sweden, and the latched Norwegian buoy.

The Hose pump wave energy converter (figure 7) has been developed over 15 years by Technocean in Sweden is intended to pump sea water from an array of hose pumps fixed to the sea bed.[3]. A Pelton wheel extracts energy from the water as it is released from an upper reservoir back to sea. A hose-pump lightbuoy is undergoing pre-production tests, and evaluation of wave power plants in Ireland,Spain, Sweden and the USA have been carried out. The Swedish Government has halted research funding because it does not envisage wave energy as a major contributor to Sweden's energy system despite the low cost/kWh predicted for such schemes. The potential along the Swedish coast is about 5-10TWh/year (0.57-1.1 GW average, 3-7% of demand) but the potential along the Norwegian coast is put at around 3.0-3.5GW which could contribute 12-15% of Sweden's electricity demand via the Nordic grid.

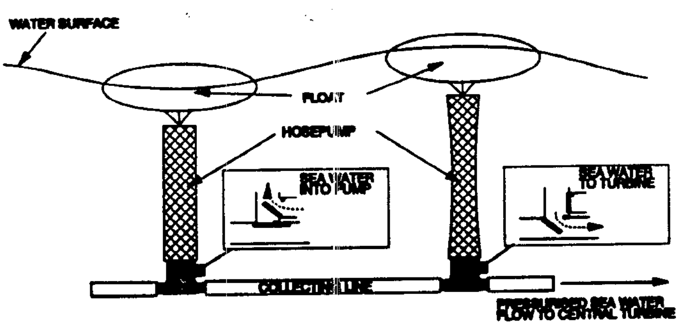



*Figure 7. The Hosepump Device*

A five phase project to build a semi-commercial hybrid wave/hydro power plant at Amorgos in Greece is in preparation and the subject of bids for funding to the EU. The first phases would have a mean rating of 6MW from an average wave climate of 8-9kW/m, with the ultimate goal of 50-100MW plant.

The IPS converter was developed in the early 1980s and tested at 1:10 scale in a lake and at full scale prototype at sea. It consists of a tall buoy with a tube open at both ends attached underneath. A piston inside the tube is linked to the buoy and power is extracted by the interaction of the buoy and the water in the tube, figure 8. Swedish groups are also involved in a project with Ocean Technologies in USA to test an IPS converter with piezo electric generator in the Gulf of Mexico later this year [4]. A new configuration, the sloped IPS, embodies a number of attractive features, and offers firm power for slender electricity networks of small islands [12].

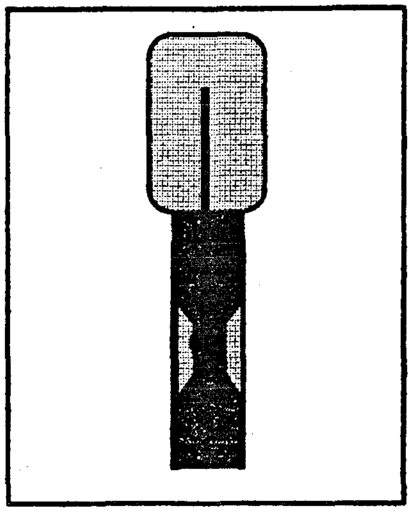


***Figure 8.*** *The IPS Wave Device*

Oscillating water columns are the subject of presentations later today and so only the Japanese and Indian work is mentioned here. Kaimei was a floating vessel equipped with chambers to act as OWC which was deployed in the 1970s. Principally because of the heave and surge of the vessel the response of the individual chambers was poor.

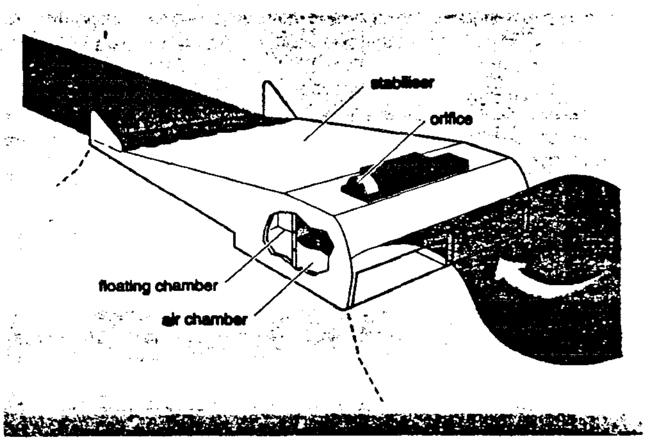



***Figure 9.*** *The Mighty Whale Concept*

Subsequent activity in this area has centered on the Bent Backward Duct Buoy (BBDB) and the Whale. Figure 9 shows the Whale concept of a floating, multichambered OWC. A proposed prototype with a length of 50m, width of 30m would displace 4400tons and be equipped with 3 sets of tandem type Wells turbines. Performance characteristics and cost estimates suggest that electricity could be produced at about £0.18/kWh [6]. The Tohoku Electric Co and Mitsui Engineering and Shipbuilding Co in Japan have recently started testing a 130kW capacity device built into a harbour breakwater which is called a "wave energy centralizing system". Newly developed water rectifying valves are used to deliver air to a single axial flow turbine [7].

The OWC at Vizhinjam near Trivandrum was originally rated at 150kW. This is currently being fitted with a 55kW turbine. A proposed 1.1MW prototype in Thangassery harbour on the SW coast of India which would consist of 24 55kW units is shown in figure 10 [4]. In both countries the low wave power resource (at a mean of say 15kW/m) makes the economics very difficult to justify. In Japan secondary uses for wave energy converters help to improve matters whereas in India the low cost of civil construction will ameliorate the problem.

Oscillating water columns operate to a large extent on resonance. Another Japanese device which resonates is the Pendular, shown in figure 11 [5]. The hinged plate is arranged to be 1/4 of a wavelength from the rear wall of the chamber and so acts at an antinode. A proposed 20m wide structure on the Kantou coast would be designed for a mean wave power of 11.5kW/m and, with an overall efficiency of 0.5 would produce a rated output of 115kW. Estimates of cost of electricity are given as £0.22/kWh [11].

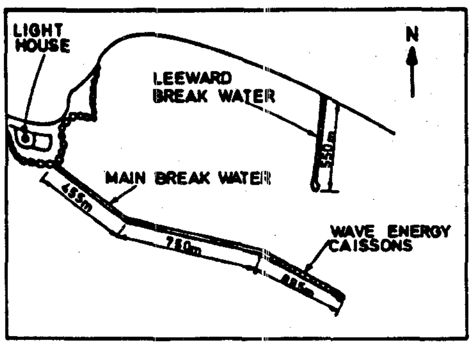



*Figure 10. Thangassery Harbour*

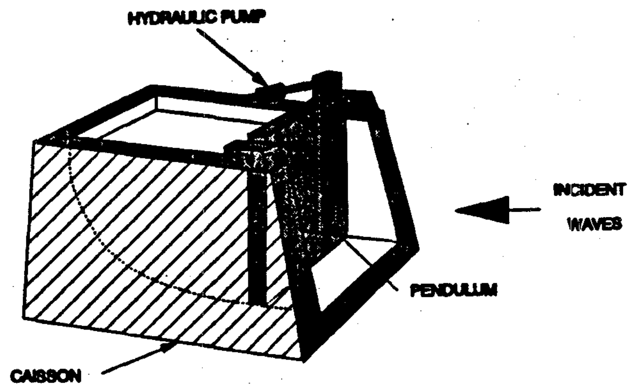



*Figure 11. The Pendular Device*

Another fixed device is Tapchan, which contains some inherent energy storage. As waves approach the mouth of the channel they become compressed in width and so build up in height. This process continues along the length of the channel until the waves spill into the upper reservoir or lagoon. The water is then several meters above sea level and is allowed to return to the sea via a conventional Kaplan water turbine. The 350kW prototype Tapchan in Norway operated successfully for a number of years before the wave power station on Toftestallen, built by Norwave AS and Kvaerner AS, became insolvent a few years ago.

Indonor AS is to build a Tapchan on the Indonesian island of Java, which should be started in winter 1988. This will consist of a 7m wide, 7m deep channel which narrows down to 25cm over its 60m length. The bay has its own natural basin with an area of 7500m2 capable of holding water 4m above sea level. The total cost is expected to be about £6M and the predicted cost of electricity exported from the plant is £0.05/kWh [9]. Tapchan represents an ideal wave energy converter where a suitable site can be found, as for example on Java, with a natural basin and a low tidal range.

## SUMMARY

Wave power technologies offer clean and secure energy. In some countries the annual energy provided could be quite significant. Fixed devices such as OWCs, IPS, hose-pumps and Tapchan are already being tested at prototype scales. These will have valuable roles to play, and may have niche markets such as remote communities. Major contributions to the electrical grids could be made by the floating devices because they could be deployed in large numbers and operate in more powerful wave climates. Political commitment is needed to undertake the longer term R&D programmes necessary to bring these offshore concepts to successful, economic reality.

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