

# Wave Power as a Source of Energy along the Indian Coast

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## Introduction:

The awareness of the exhaustible nature of conventional energy sources and increasing demand for energy prompted man to look for alternate renewable energy sources. The oceans which cover about 71 per cent of the earth's surface have been found as a storehouse of renewable energy sources. Some of the promising sources of energy in the sea are, tides, waves, thermal gradient, salinity gradient, wind, currents and biomass. Except the tides and tidal currents, which originate from gravitational processes, all other sources are indirect forms of solar energy. In general, ocean energies have low kinetic energy densities. Although considerable work has been carried out in various countries over the last two decades towards extraction of energy from these resources, commercial scale exploitation of these resources has not been realised yet, except for the tides.

Tidal power has been developed well in France, China, USSR and Canada. In France, a 240 MW plant has been in operation in the Rance estuary since 1968. There are eight major tidal power plants with a total installed capacity of 9,370 kW in China. The estimate of tidal power potential in India is about 10,000 MW. Good potential exists in the Gulf of Kutch and Cambay on the west coast and Hooghly estuary on the east coast (1). A 600 MW Tidal Power Plant is being planned to be set up in the Gulf of Kutch by the Central Electricity Authority in association with the Gujarat Electricity Board. The site investigations (2) have been completed and the project is under consideration for techno-economic clearance and investment decision. This project, the biggest in the world, is to be executed by the National Hydroelectric Power Corporation. The cost of the project is estimated to be Rs.2,000 crores (3).

Considerable work has been carried out in several countries on development of Ocean Thermal Energy Conversion (OTEC) (4) and prototype technology has been developed in U.S.A, Japan and China. In India, some feasibility studies have been carried out along with the evaluation of the power potential. Maximum potential is around Andaman-Nicobar Islands and good potential is available around Lakshadweep and

in some parts along the east coast of India (5-8). The Tamil Nadu Electricity Board has been proposing to set up OTEC plants off Tamil Nadu coast for quite some time. Now a fresh proposal is being considered to set up a plant near Kulasekhrapatnam in collaboration with Sea Solar Power Corporation, U.S.A. The Department of Non-conventional Energy Sources (Government of India) which has earlier sponsored some feasibility studies on OTEC is studying the proposal (9).

Although sea-based wind power has not received much attention globally, power plants have been developed by Sweden and Denmark. The world's first wind power plant in the offshore was recently commissioned in Blekinge in south-east Sweden, yielding 500,000 kW annually (10). Denmark also plans to have an offshore wind farm which is being built off Vindeby on Lolland island in the Baltic Sea. It is expected to generate 12 million kWh electricity annually when it comes into operation in June 1991 (11). In India, no attempt is known to have been made on utilisation of offshore winds.

Development of salinity gradient energy is still in infancy the world over, though various concepts are available (12). Energy density of this source is perhaps the highest among ocean energy sources. Israel has made some headway and put up a plant in the Dead Sea. China has developed a prototype unit (13). Some R & D efforts are in progress in USA, Sweden and Japan. In India, the estimation of salinity power indicates that the potential is more on the east coast, as major rivers discharge into the Bay of Bengal (14).

Wave energy is one of the promising forms of ocean energy. Wave power research has a long history which dates back to 1799 (15). The countries which seriously pursue the developments of wave power devices are Japan, U.K., U.S.A, Norway, Sweden, France, China and India. In this paper an attempt is made to present the state-of-the-art of the development of wave power in the global and Indian contexts.

## Wave Energy Potential:

Ocean waves have always inspired the human mind.

The sizes of waves in the ocean range from a ripple to a planetary tide and the generation of these waves have different origins. Here, what we are interested are the waves generated by winds which are called wind waves. About 1.5 per cent of the incoming solar energy, the primary source, is converted into wind energy and part of this energy is transferred to the wind waves providing a convenient and natural concentration of energy in the surface of the oceans. The waves as they propagate, carry this energy to the shorelines, undergo changes in direction, undergo attenuation/concentration due to changes in bathymetry and bottom topography, and finally dissipate the energy on the coasts as they break. Waves in the generating area are called 'sea' and when they run out of the generating area as regular waves, are called swells. When one comes down to the practical realm of extraction of wave energy, one will confront with waves of different lengths and heights travelling at different velocities, interacting with one another in a complex manner and what one observes is a 'random sea'.

Extraction of wave energy from the sea is not an easy task, though it may be more efficient than extracting the wind energy at sea. The waves store the energy transferred from winds as mechanical energy, and the inertia of the waves provides this short time storage and partly smoothens the high variability of the wind in time and space. However, the wave climate varies from place to place and from time to time and so is the wave energy. Typical wave records along the Indian coasts for each month is given in Figure 1. The wave energy is proportional to the square of the wave height. The wave power ( $P$ ) is proportional to the square of the wave height multiplied by the period and can be computed approximately as  $P=0.55 H_s T_z$  kW/m length of wave crest where  $H_s$  is the significant wave height in metres and  $T_z$  is the zero crossing period in seconds.

Wave power potentials on a global scale were estimated by various researchers (16-20). The estimated wave power is of the order of  $10^{13}$  kW and is renewable at the rate of  $10^9$  to  $10^{10}$  kW. Panicker (18-19) estimated the wave energy dissipation rate along the coastlines of the world as about  $2.6 \times 10^9$  kW which is comparable with those of Issacs and Seymour ( $2.5 \times 10^9$  kW) (17) and Kinsman ( $2.2 \times 10^9$  kW) (16). Wave power is more in the mid latitudes than in the trade wind belt. Some of the European countries and Japan are well placed in the high energy zone. These estimates are mainly based on visually observed wave data, as recorded wave data over the world oceans is meagre.

A few estimates on wave power potentials along the Indian coasts are available (21-26) and most of them are based on visual observations. These estimates

though differ in magnitudes, show similar seasonal patterns. The estimate of Kesava Das *et al* (26) shows that the wave power along the Indian coasts varies seasonally and geographically from 1.2 to 39.6 kW/m with an average of 9.4 kW/m. The annual mean potential varies from place to place between 8 and 11 kW/m. The maximum wave power potential occurs along the Konkan coast in July. The southwest monsoon period (May - September), in general, offers a greater potential all along the coast with a mean of about 15 kW/m.

During the northeast monsoon, wave power is generally low and is particularly so along the west coast as compared to that along the east coast where cyclones occur during this period. The directional distribution of wave power shows that along the east coast about 65 per cent of the total wave power is contributed by waves from south and southwest and along the west coast about 85 per cent by waves from south to southwest and northwest (25). The monthly wave power potential for six areas marked in Figure 2 is given in Table 1. However, it is important to use measured wave data for making realistic estimates. A comparison of wave power potential estimated from visual data and measured data for a year indicates that the estimates based on visual data are of greater magnitude (25).

### Global Development of Wave Power Technology:

The first recorded patent for a wave energy extraction device was taken in 1799 by a French named Girard. In 1892, Stahi (27) described nineteen wave power

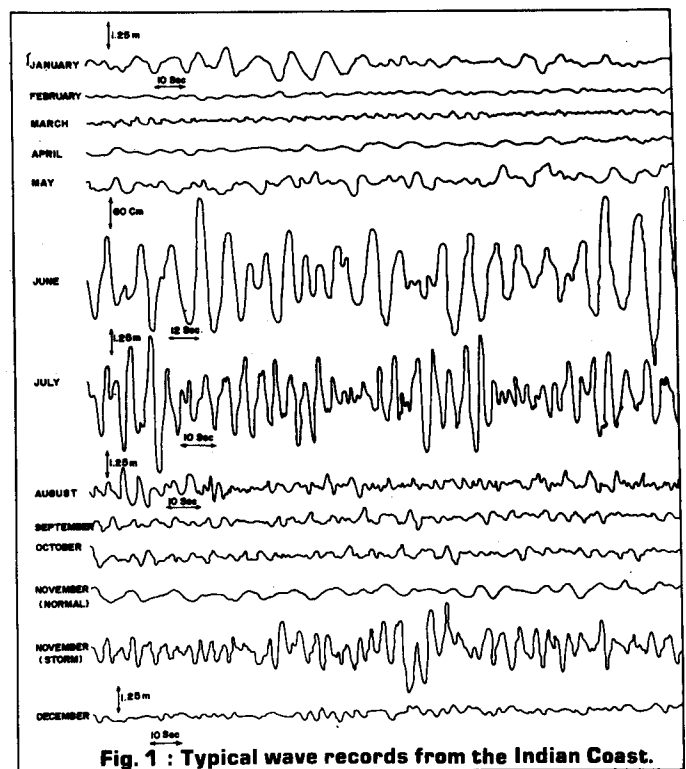


Fig. 1 : Typical wave records from the Indian Coast.

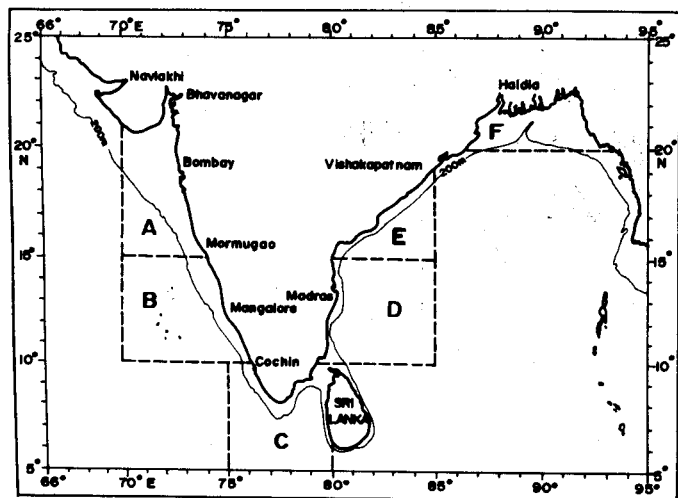


Fig. 2 : Map showing different zones for which wave power potential was estimated.

devices. Panicker (28) has reviewed the wave power technology and classified the devices into 4 groups: propulsion schemes, buoy power supply devices, off-shore power stations. There are few other reviews also on wave power devices (29-33). Dhaille (1956) devised a technique of the converging wave channels (34). He found that a conventional low head power station run on wave power supplied through a converging wave channel was very attractive and technically feasible. He also reported that 600 brief descriptions of wave-power devices were found in France. Valembois, in 1956, proposed tapping of wave energy by means of resonators. A resonator is an open vertical pipe immersed in water whose natural frequency when equalled to the frequency of waves, raises the water level in the tube. In 1962, a device utilising subsurface pressure variations in a wave field, a device was tested successfully in Buzzards Bay off Massachusetts, USA (35). In UK alone, about 100 patents on wave energy devices were registered till 1974 (47). David Ross (33) described a scheme suggested by Walton Bott to generate electricity from a coastal lagoon formed by a coral reef. His plan was to install low-head generators at the island of Mauritius where nature itself provided the water head, through a nearshore coral reef. However, none of these devices were put to use either because

they were not economical, or because of practical problems. Since the oil crisis in 1973, wave energy research was given a new thrust and a wide variety of new devices have been invented with the view to tap wave energy on a large scale. Some of the promising concepts and designs developed or being developed in different countries are summarised below.

**Japan:**

Japan is pursuing wave energy programmes very vigorously. Although Japan initiated its wave energy programme much later than U.K. it could make better progress in setting up plants for sea trial. Yoshio Masuda of Japan Marine Science and Technology Center (JAMSTEC) has developed a device for extracting wave energy (36 - 37) known as Masuda buoy which is an inverted canister with its open end beneath the sea surface with two holes at the top. It is held floating upright in the water. When the water level rises during the passage of a crest, the pressure inside the canister increases and air is blown out of the can. The pressure inside is reduced using the passage of the trough and air from outside is sucked in. In both the cases, the air flow drives a turbine which in turn, drives a generator producing power. Presently, there are more than 1500 such buoys operating in the seas around Japan (38). This basic concept has been adopted for further development which is now known as Oscillating Water Column (OWC) and appears to be the most promising concept (Figure 3).

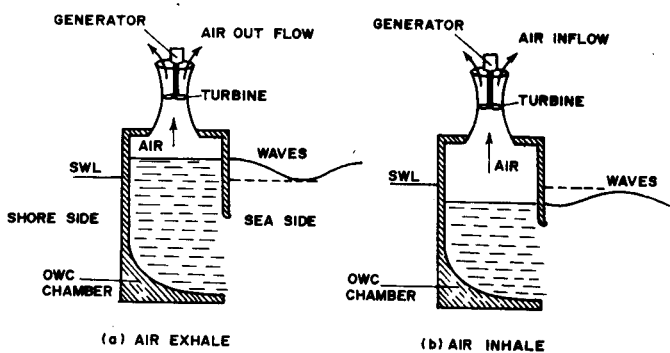


Fig. 3 : Principle of Oscillating Water Column.

Table 1  
Wave Power (kW/m) along the Indian Coast for areas shown in Figure 1

Area	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
A	3.02	3.73	3.91	4.47	6.98	26.77	39.57	24.84	10.03	2.69	3.58	4.74
B	5.13	5.05	2.24	1.56	6.31	17.21	27.04	17.14	8.15	4.55	3.52	5.40
C	9.26	4.45	4.05	5.50	11.44	18.85	17.69	15.34	10.11	7.21	6.67	7.52
D	5.78	5.13	3.30	3.58	10.60	16.67	14.79	12.57	8.49	7.94	10.98	14.05
E	4.03	1.69	2.35	3.69	11.14	17.24	17.45	16.16	9.18	6.90	9.71	5.62
F	1.24	1.39	3.28	12.34	14.30	11.90	13.24	16.67	16.07	6.28	2.80	1.85

In 1976, the JAMSTEC has constructed a full scale prototype of a 2 MW wave power generator called 'Kaimei' and the first field tests were conducted in 1978 off Yura, Yamagata. The experiment on electric output from the system for commercial use was done in 1980. Canada, Ireland, United Kingdom and U.S.A. participated in this programme under the auspices of the international Energy Agency. The phase II of Kaimei began in September 1985 and was completed in March 1986. 'Kaimei' is a shiptype floating structure with 80 m width, and 5 m height with a dead weight of 500 tonnes. The basic principle of the system is the same as that of the Masuda Buoy and it is an attenuator device. It has 4 buoyancy rooms and 22 air pump rooms (Figure 4). When the waves pass through the air pump rooms, the air is pushed and sucked into the top of each room and the air flows are guided through air turbine nozzles to produce a high speed turbine rotation for an electric generator. The sea trials were encouraging though a few problems were encountered (39-41). It generates 150 kW power and transmits to the shore.

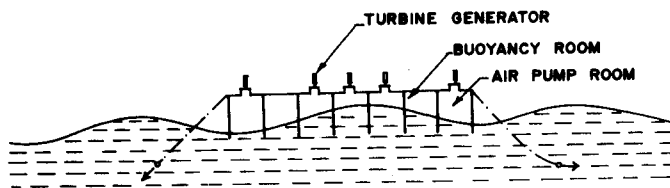
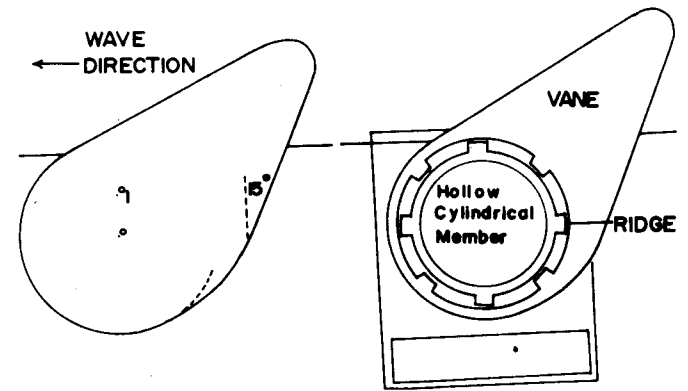


Fig 4 : Principle of KAIMEI.

A pneumatic type wave power converter fitted on vertical breakwaters was developed at the Port and Harbour Research Institute (42). A new type of wave power buoy based on the concept of Backward Bent Duct Buoy (BBDB) has been proposed as the most economical pneumatic wave energy conversion system for island communities (43). A shore fixed wave power generation plant fixed to a coastal cliff was commissioned in 1983 at Tateiwa, Yamagata (44). This device was about 8 m wide and has 50 sq.m water line area and average generated power was 11.3 kW. A ten cylinder type wave energy conversion system was built for further experimentation on the coast of Kujukuri (38). JAMSTEC is now engaged in developing a terminator device which greatly increases wave energy absorption (Photograph 2). This will create a calm water area behind its system, thereby improving the marine environment for ocean structures such as artificial island. JAMSTEC. is also developing a wave control technology by installing underwater structures through which wave energy can be concentrated and absorbed to economically create wide, calm ocean areas, along with construction technology for marine control structures (Photograph 3) using electricity generated from this wave power and the resulting electrodeposit (JAMSTEC Brochure).



(a) SALTER'S VANE

(b) VERTICAL SECTION OF VANE

Fig 5 : Salter's Ducks.

The Institute of Ocean Environmental Technology has developed and installed a full scale experimental plant called Kaiyo, off Saba Cape in 1984. Kaiyo is a type of floating terminator which employs hydraulic oil motors and electric generators. Wave energy is converted to pressured-oil energy through the relative motion between floating bodies and the stationary construction, which are connected by links (45). A pendulum-type wave energy converter was designed by Muroram Institute of Technology. The system consists of a caisson which has an open chamber facing the offshore. When the incident waves come to the chamber, they become standing wave by reflection. The pendulum drives a generator through a simple hydraulic transmission. The maintenance of the system is easy, as all the mechanical parts are out of water except the pendulum's tail (46).

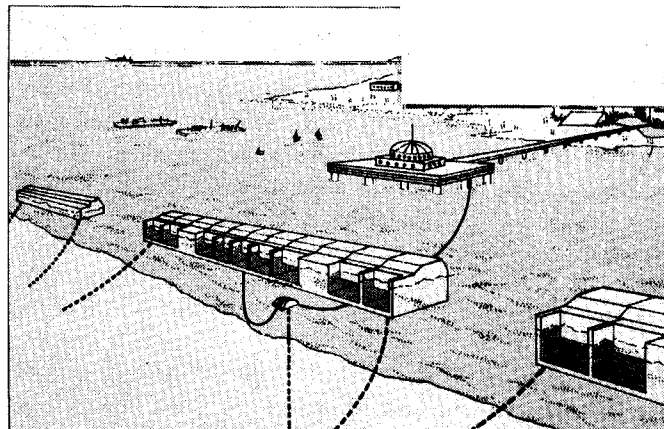
#### United Kingdom:

In U.K. several wave power devices have been patented (28-31). But none of these devices are put into use so far. Some of the devices are described here. Stephan Salter of Edinburgh University has demonstrated experimentally the possibility of extracting more than 80 per cent of the energy of waves (47-49). He designed a duck shaped vane now known as Salter's Duck which has a circular rear section and a front section with non-uniform radius (Figure 5). A series of ducks (Vanes) are held together on a spine — a hollow cylindrical member with paraxial ridges on its surface. As the waves pass, the ducks bob up and down all along the spine. The relative motion between the ducks and the spine activates the hydraulic rotary pumps placed inside the spine. The pumps push out a fluid either water or oil, inside an enclosed system. The fluid in turn drives a generator to produce power. A scale model consisting of 20 ducks was tested in Loch Ness (50).

Sir Christopher Cockerell has designed a Contouring Raft for the extraction of wave energy. It consists of

three articulated pontoons which are hinged together, floating on the sea surface in a line, oriented in such a manner that the advancing waves travel down the series. The hinges swing backwards and forwards by the relative motion of the pontoons and drive the pistons which pump out hydraulic fluid and drive a motor. The motor in turn drives a generator. A scale model was tested in the sea off Solent, U.K. (51-52). Robert Russell of Hydraulic Research Station (H.R.S.) at Wallingford (U.K.) has designed a device to tap energy from the water level differences between the crest and the trough. The idea is similar to that of Walton Bott's Mauritius project described earlier (33). The device known as H.R.S. Rectifier is planned to be mounted on the sea bed. It has two reservoirs, one over the other, which have non-return valves facing the waves. The valves (gates) open and close as the water pressure changes with the crest and the trough of the waves. The water trapped in the upper reservoir passes through the only exit (turbine) which leads into the lower reservoir. The water flow drives the turbine which is connected to a generator producing power. The Cockerell Raft and the H.R.S. Rectifier are not pursued further on grounds of cost and technical difficulties (32).

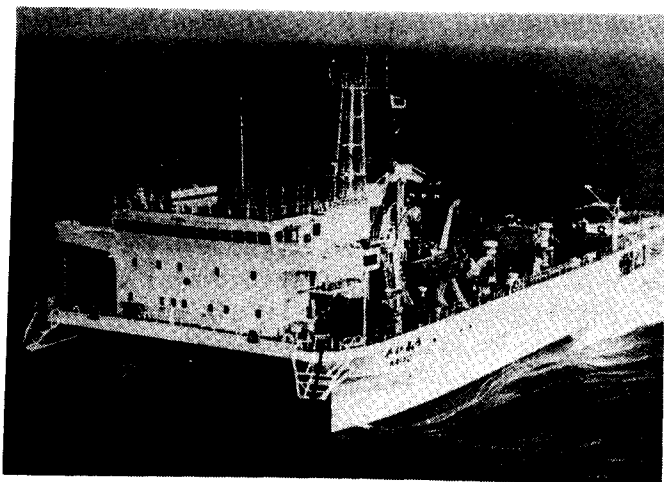
The National Engineering Laboratory at East Kilbride (U.K.) has adopted the principles of the Masuda buoy (Japan) and modified the system which is now termed 'Oscillating Water Column' (OWC). This device called NEL OWC contains chambers which are coupled to the sea through a side opening which faces the incoming wave, instead of through the bottom opening in the case of the Masuda's design. There is one air turbine of the Francis type for each chamber (53-54). This is a terminator type contrary to the JAMSTEC's Kaimei, which is an attenuator type. The OWC is planned to be designed either as a floating structure in deep sea or as a mounted structure on sea bed in shallow water. The shallow water OWC is a breakwater in the true



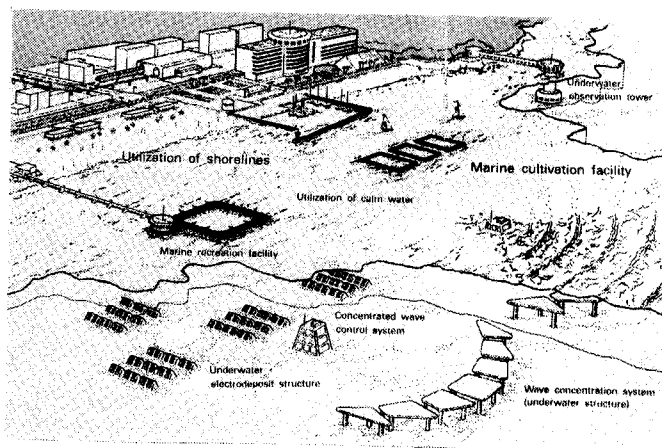
Conceptual drawing of the new wave utilization system (JAMSTEC, Japan).

sense with most of the wave energy being absorbed rather than reflected. A scale model of OWC has already been tested. A Scottish-led consortium has planned a 5 MW plant to be in operation off the isle of Lewis in the Hebrides, to produce 6.4 million kWh annually (55). It is doubtful whether this has materialised or not.

The Lancaster University (U.K.) developed a system called Lancaster Flexible Bag consisting of a long concrete beam which is kept afloat by flexible rubber air bags attached along its upper side and floating normal to the main wave direction. The air bags communicate via non-return valves with two longitudinal air ducts along the beam. As the wave crest approaches a bag, the air is squeezed out of it and it flows into the "high pressure" duct and when the water level falls, the bag fills again from the "low pressure" duct. The air passes through air turbines and returns from the 'high' to 'low' pressure side. This device is an attenuator type. High cost of the beam structure and poor productivity in terms of air-cells make it least cost effective system (56-57).



KAIMEI. (JAMSTEC, Japan)



Conceptual drawing of wave control system (JAMSTEC, Japan).

A system known as Bristol Cylinder, developed jointly by the Bristol University and M/s. Robert McAlpine Limited (U.K.) is a submerged oscillating cylinder which utilises the mooring lines for power take-off and has the capability to be fully submerged in storm conditions. The theoretical aspects are given by Evans (58). Problems in designing a high pressure, closed circuit pump system have made this relatively uneconomic. A review of the steps taken to optimise the hydrodynamic performance is given by Shaw (59).

Vicker's Limited (U.K.) has developed a system which is a submerged version of a row of OWCs with its surface within an enclosed duct to be located on the sea bed (60). Two device configurations (terminator and attenuator) were developed (61). The power take-off is through manifolds feeding axial flow turbines and similar to the Lancaster Flexible Bag. Wave forces on the structure are reduced because of submergence but wave energy capture is also reduced. The Queen's University, Belfast (U.K.) has developed a version of the simple oscillating buoy with a unidirectional turbine (62). This device, known as Belfast OWC, originally a floating system, has now evolved into a sea-bed fixed device. Novel features of the device include the multi-resonant concept which considerably widens the frequency band width response (32 & 63).

The Sea Energy Associates Ltd., and the Lanchester Polytechnic (U.K.) have developed a system called Sea Clam which utilises the displacement of air to extract energy from waves where a hinged vane attached to a rectangular 'spine' operates an air turbine through a rubber bag. These bags are partially submerged and breathe air into the hollow spine in response to wave actions. Air is thus pumped in a closed circuit through self rectifying air turbines. The randomness of the sea waves allow phased operation of 'Clam' elements (64-65). A scale model was tested. It appears that this system could be very cost effective and was deemed as

the leading one among the devices developed in U.K. although the viability of the bags remains as a question. The Sea Clam was redesigned on a smaller scale for use in island areas (66). A new configuration of the Sea Clam called the Circular Sea Clam was also developed and tested (67).

According to Maeda *et al* (68), OWC, Salter Duck and Clam are the most promising devices. It was found that the wave energy absorption efficiency is increased by the use of a harbour and that the devices become multi-resonance type in an experiment on a fixed air chamber in OWC (69). Over 10 million pounds was spent on wave energy research since 1976, but no major plants could be set up and the wave energy programme in U.K. has been facing some rough weather since 1983 (70). Now it appears that Queen's University, Belfast will install the first British wave power station in a gully on the Island of Islay in the Inner Hebrides, which will provide electricity to first light 360 living rooms (71).

#### U.S.A:

Although U.S.A. does not appear to have programmes to utilise wave energy, a few devices have been designed to convert wave power. John D. Issacs of Scripps Institution of Oceanography (USA) developed a wave pump (72-73) consisting of a vertical pipe containing a one way check valve and a buoyant float at the surface. The principle involves inertial periodic coupling and decoupling between the pipe and the buoy. When the float and pipe descend into a wave trough, the water flows up the pipe past the check valve. When it ascends a crest, the entrapped water is prevented from flowing down, by the check valve. Subsequent cycles elevate the water into an accumulator tank. This water will flow through a pelton wheel or a turbine to produce power. A device with 2.4 m diameter was tested in the sea of Hawaii and produced about 200 W (74).

Lockheed Missile and Space Co. designed a system called Dam-atoll which utilises the principle of wave refraction to focus and concentrate the incoming wave energy. It is a dome-shaped submerged structure with a cylindrical well at the centre (Figure 6). A set of radial grid vanes at the opening of the cylinder will capture the bores formed by refraction of the waves and flow to the well creating an enormous fluid flywheel. The vortex action inside the well activates a turbine, placed at the bottom, which in turn drives a generator above the surface of water. The fluid flywheel smooths out the variation in the incident wave energy and thus provides continuous power output. A scale model was tested. Apart from the generation of electricity, the device, can be used to protect beaches from erosion, to create artificial open sea harbours and to clean up oil spills etc. (30,70 & 75). Other systems developed in

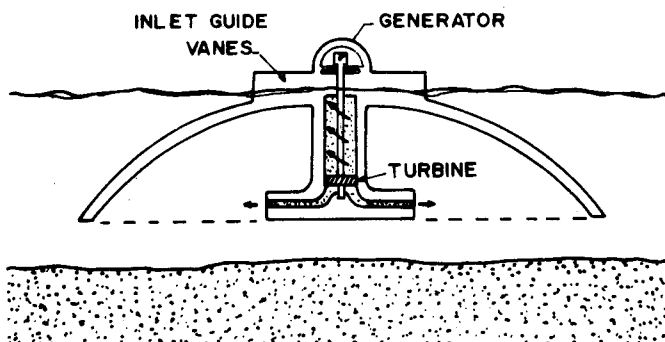


Fig 6 : Dam-Atoll (A cross section).

USA are: a free-floating model of the Tandem-Flap wave power system (76), a hydraulic float pump reservoir system to utilise heaving motion of waves to pump water to an elevated reservoir and generate power through a hydro-electric plant by Tetra Tech. Inc., (77), an OWC on a fixed offshore platform (78), and a contouring raft system (79).

#### Norway:

Kavaerner Brug A/S in association with Norwegian Hydrodynamic Laboratories, have developed an OWC which has a harbour chamber at its mouth (80). The guide walls in front also known as harbours produce additional resonance. Interaction between the OWC and natural modes of harbour oscillation increases power output by upto 200 percent (81). This device is known as Multiresonant OWC (MOWC). Two different type of wave energy prototype plants were commissioned in 1985. The first one was a 500 kW plant based on MOWC. It was installed on a rock cliff projecting into the sea. The advantage of shore based plants are low construction cost and ease of construction. However, this plant was knocked down by storm in 1988. The second prototype is based on the principle of wave focusing to concentrate energy. Focusing of waves can be achieved through a 'water lens'. This concept has been developed by the the Central Institute of Industrial Research. A 'water lens' also can be created by constructing a structure consisting of a number of plates placed horizontally at different depths below the water surface. Because of difference in water depths, the incident wave transforms into a spherical wave, as the speed differs at different depths (82-83). Now it is known as Tapered Channel Wave Power Plant (TAP-CHAN). This system has four sub-systems. Firstly, a collector which is designed to concentrate the water energy and optimise collection efficiency for a range of frequencies and directions. Secondly, the energy converter in which the energy of the collected waves is transformed into potential energy in an onshore water reservoir i.e., the waves enter the wide end of the channel and as they propagate down the narrowing channel, the wave height is amplified until the wave crests spill over the walls. Thirdly, a reservoir which provides a stable water supply for the turbines. Finally, a hydroelectric power plant, where well established techniques are used for the generation of electricity. The water turbine driving the electric generator is of a low head type, such as a Kaplan or a tubular turbine (84).

A resonant buoy system tuned to incident wave conditions was also developed (85). A revolutionary concept of phase control has been introduced and it was found that controlling the heaving motion of the buoy results in an increased output. Successful tests were con-

ducted on this concept. Malmo (1986) studied the wave power absorption by a finite row of OWC's in a reflecting wall with linear theory (86).

#### Sweden:

The Swedish Group for Wave Energy Research (SG-WER) developed a heave buoy point absorber system. It consists of a buoy and a rod with horizontal plate. The waves cause the buoy to heave in relation to the central rod which acts as the rotor of the generator. The relative motion between the buoy and the rod is the motive force to run a generator or a piston. A series of such buoys can be interconnected in a power plant. This system was sea tested. Swedyards Corporation and Techno Ocean have developed a special hydraulic pump which is also called a petro-pump. It consists of a rubber tube where cord layers cross each other under certain angle. When the tube is elongated its volume decreases, thus causing a pump-action. The pump can simultaneously act as a mooring line to a fixed point at the bottom. In a power plant, several pumps can be connected to a main tube which ends at a water turbine which in turn runs a generator (87). A process of extracting valuable minerals from the sea by means of ocean waves is being introduced in Sweden. The method is based on an invention by Goran Lagstrom for producing electricity by means of waves led into a basin on pontoons anchored at sea and provided with gradient planes along the sides. The Gottenburg based company Power AB plans to build production units at sea. They say that in regions where big waves occur, electric energy alone can be produced at a very low price (88).

#### China:

In China, wave energy research began in 1968 with the application of variable-angle aerofoils to absorb wave energy. In 1985, Guangzhou Energy Research Institute successfully developed a wave power device, which is a symmetrical wing - section air turbine wave power unit for navigation lighthouses. Since then, more than thirty units have been developed and put into operation in China's coastal regions (13). Work was initially concentrated on sea trials at low power levels for navigational buoys. These used both the self-rectifying symmetric wells turbine and impulse turbines with valve rectification. Government support is now aimed at larger bottom-standing OWC for island communities at the mouth of the Pearl River in the South China Sea (89).

#### France:

As mentioned earlier, the first known patent on a wave energy device was taken by a Frenchman named Girard. A number of successful projects were operated in France during early part of this century. In 1920,

Bouchaux-Praceique constructed an OWC type device by tunneling through the cliff near his home and generated 1 kW power (90). In 1962, M. Coyne made an attempt to harness wave energy from a shore-based plant by applying the principle of conventional low head hydropower generation. Incidentally, the French engineers were the pioneers in Ocean Thermal Energy Conversion also. Some work on the Converging Wave Channel and point absorbing system have been studied (32). The main application under consideration is the production of electricity at remote sites and islands.

#### Other Countries:

In Germany, Kayser (91) developed a wave energy conversion device involving mechanical systems for conversion of wave motion into high pressure fluid and electric power and constructed a prototype power device for buoys of 1 m diameter with an output of 500 W. In USSR, a device for artificial upwelling using wave power was successfully tested in the Black Sea and showed high efficiency. This can be used for habitat improvement in large reservoirs, in the seas and for climate control in nearshore areas (92). In Portugal, a small programme at the University of Lisbon on OWC device using a Wells air turbine is in progress. In Canada, though low priority is given for wave energy, two devices have been developed similar to Cockerell's raft and Sea Clam.

#### Development of Wave Power in India:

Ocean wave research in India is only about two decades old. Most of the available information on waves along the Indian coasts are based on the visual observations carried out by ships of opportunity and reported in the Daily Weather Reports of India Meteorological Department. Based on these observations, three atlases have been published so far (93-95). The National Institute of



Norwegian wave power plant

Oceanography (NIO), Goa has initiated recording of waves in the 1970's by OSPOS wave recorder, later by the ship borne wave rider buoys and directional wave measurement buoys at a few locations along the Indian coasts. An account of ocean wave research in India is given by Baba (96).

The total wave power potential along the entire coast length of 5,700 km at a given time is estimated to be about  $5.36 \times 10^7$  kW. Even after allowing for 75 percent loss of energy due to inefficiency in conversion and transmission, the net average power for the Indian coast is about 13.4 GW and if it is possible to deploy power devices at least for 1 percent of the coast length (57 km), the available power is about 134 MW (26). According to Baba (24) the wave power potential for Lakshadweep, Andaman and Nicobar group of Island is 10 kW/m (annual) with about 20 kW/m during southwest monsoon season. Lakshadweep area has more potential during the SW monsoon (June-September). With the deep sea conditions existing very close to all the islands, maximum power generation appears possible. However, wave energy potential along the Indian coasts is much less than that off the coasts of the mid latitude countries such as U.K. Japan, etc. and it is highly variable seasonally and geographically. In general, the wave power potential is greater during SW monsoon season. Therefore, a wave energy system on commercial scale to generate electricity alone may not be economically and technically viable, except during the SW monsoon. Nonetheless, wave energy can be utilised for several purposes together an integrated system.

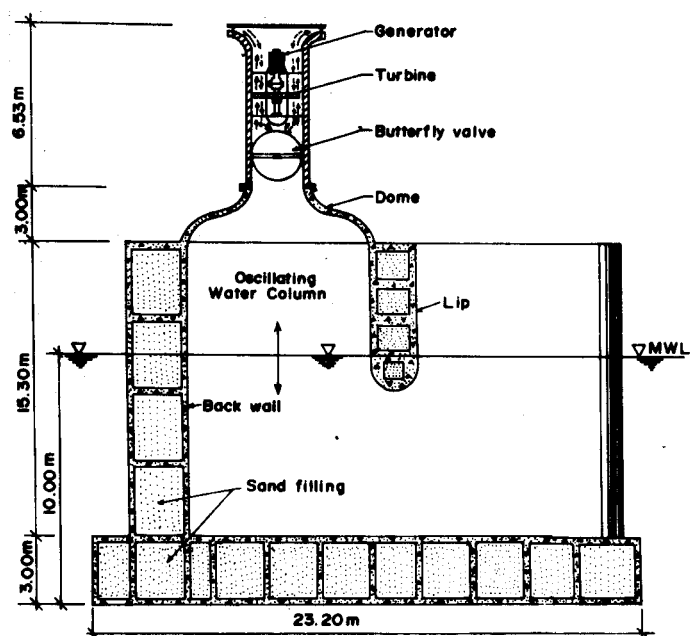


Fig 7 : Wave Power Device (Section) of IIT, Madras.



Wave power, in India, so far has been utilised to light a navigational buoy in Madras harbour. This device of wave activated electrical generator was developed by the engineers in the Madras Port Trust and has been in use for quite some time. This device, consisting of a compact watertight unit can be mounted conveniently on top of buoy installation. The design which is strikingly simple, has ensured maintenance free performance for continuous periods upto 18 months. The development is patented and commercially exploited through the National Research and Development Corporation of India (97).

A wave energy oscillator was designed at NIO with a view to regulate the wave energy in the neighbourhood of the wave breaking zone where the waves tend to be asymmetrical and horizontal motions of particles are considerable. This was designed to use in the surf zone for absorbing wave energy and thus helps in shore protection. This consists of a prime mover assembly which moves up and down on an inclined ramp associated with the oscillatory nature of the wave thus absorbing a part of the wave energy. A few models, which were tested showed good promise (98). However, this programme was not pursued further.

The NIO organised a national workshop on energy from the sea during December, 1980, the first of its kind in India and also brought out status reports on ocean thermal energy, tidal power, wave power, salinity power and biomass conversion for the first time in the country. The workshop and the status reports generated enthusiasm among policy makers and viable ocean energy projects have been initiated.

In 1982, the Indian Institute of Technology (IIT), Madras started a project on wave power sponsored by the Department of Ocean Development (DOD), Government of India. This programme is to develop a multipurpose wave regulator system with the following objectives: (1) To absorb the energy of the waves by providing a long wave barrier and to convert the energy into electricity; (2) the long barrier results in a calm pool of water between the barrier and shore and, this pool could be used as a natural harbour, space for aquaculture and space for coastal transport with lighter crafts; (3) this wave absorber system also pro-

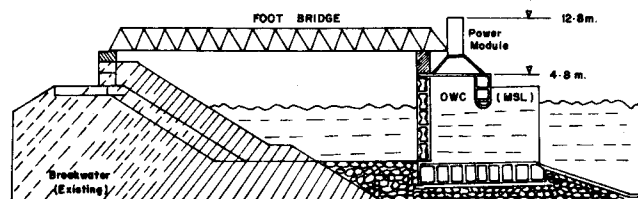
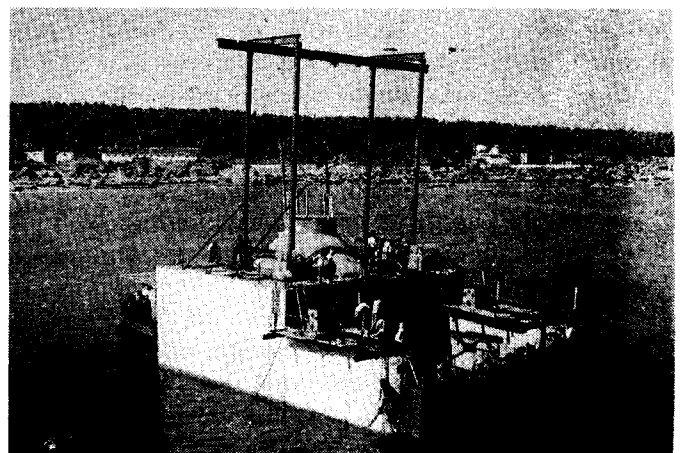


Fig 8 : Cross-section of wave energy plant designed by IIT, Madras.

vides shore protection against erosion by the waves (99-101). This multifunctional wave regulator system, because of its multipurpose nature, is to be placed not far from the shore. After conducting model experiments on different types of devices, a terminator type bottom standing oscillating water column (OWC) device was found suitable for the multipurpose wave energy system required for the Indian coast.

For the sea trial, the site off Vizhinjam Fisheries harbour near Trivandrum, Kerala has been selected based on scientific investigations of wave climate (102), power potential and other site specific advantages. The site specific model studies have been conducted and a suitable design of the device has been developed and fabricated. This device will be installed in 10 m water depth, 45 m in front of a breakwater off the Vizhinjam fishing harbour (Photo 5). The device (Figure 7) is a concrete chamber (caisson) of 13 x 19 x 17 m high with a dry weight of 2,500 tonnes on which sits the power module consisting of an air turbine 2 m in diameter, matching induction generator of 150 kW capacity with controls and a butterfly valve to shut the system in emergency. An OWC induced by the wave action through an entrance at the bottom of the chamber pressurises or expands the air inside the chamber. The air movement drives the turbine, which in turn drives the generator to produce electricity. The turbine is coupled to the induction generator so that power can be pumped directly to the grid without the need for any rectification and inversion. This generator can also be started as a motor and then changed over to generator operation. A 45 m long bridge spanning the breakwater to the device acts as an all weather approach to the system (Figure 8).

The first sea trial was attempted in 1989. Due to the failure in the towing and seating operation of the caisson, the installation was not completed and it ap-



Caisson ready for towout at Vizhinjam harbour

pears that a system with some modifications that include increasing the base of the caisson to 23 m x 17 m and the height to 15.3 m will be installed during January/February 1991 off Vizhinjam. On successful completion of sea trial, it is expected that the device will generate 75 kW power during April-November, 25 kW during December-March and 120 kW with a peak of 150 kW during the SW monsoon (June-September). The output from this prototype is proposed to be interfaced to the power grid by the Kerala State Electricity Board.

The developmental effort is totally indigenous. The project group at IIT, Madras, is responsible for the overall design, coordination, execution, performance monitoring and evaluation of the project. The Harbour Engineering Department, Trivandrum, is providing the local infrastructure for construction of the caisson. The design of the generator is by IIT, Delhi and Kirloskar Electric Co., Bangalore. The detailed engineering of the mechanical assembly is by Sarnath Consultants, Madras. Construction, launching and final positioning of the caisson with the bridge is by L & T - ECC Construction Group, Madras. Manufacturing and integration of power modules is by KCP. Ltd, Madras; Generator and controls by Kirloskar Electric Co., Bangalore. The butterfly valve is by Audco (India) Ltd., Madras and the data acquisition system by Texel Systems, Madras. The evaluation of the input wave potential for the site is by the Centre for Earth Science Studies, Cochin. The DOD has funded the project to the tune of 12 million rupees (DOD Annual Reports). The success of this programme will probably pave the way for further development of wave power in India.

### Energy Conversion Considerations:

Wave energy extraction has different steps such as conversion, generation, transformation and transmission. After extraction, it is transferred into mechanical, hydraulic or pneumatic energy, then it is to be transmitted as electric, hydraulic or chemical energy through various transmission systems like cables, pipes or transportation by ships. Finally, the energy should reach the users through a power grid or by other means. Wave power plants can be either shore based or offshore based, floating or non-floating. A wave power device has three major components which are interface elements, deployment system and power take-off system.

The interface elements can be grouped into active and passive devices. Active devices move in response to wave action and do useful mechanical work against a stable reference frame. Examples are Bristol Cylinder, Cockerell Raft, Salter's Duck, etc. In passive devices, the whole structure remains stationary to form the

reference frame and relative movement of the water surface is used to do work (32). These devices can either be floating or fixed to the seabed. Examples are NEL OWC, Overtopping Channel System, Kaimei, SEA clam etc.

The three modes of deployment are terminator, attenuator and point absorber systems. Terminator systems are those which are deployed perpendicular to the direction of predominant wave energy-flux. These devices must be asymmetric to absorb as much incoming wave energy. Attenuator system lie parallel to the predominant wave direction and absorb wave energy progressively as the wave crests move down along their length (103 & 104). Wave force on attenuator type is lower as was demonstrated by Kaimei experiment. Point absorbers are individual devices which are small in relation to the length of the waves. They will have to be deployed in large arrays and interactive effects allow them to absorb energy from an area many times the device size. This type of system offers low overall costs in terms of device volume per given equivalent area of energy absorption (32). The NTH Buoy, the Swedyard Petro-pump, buoys used in Japan and China are examples. The studies indicate clearly, that in terms of structural effectiveness, terminators offer the best solution as long as the device motions are limited in some manner (104). This is the system adopted in Indian devices.

The power take-off systems are direct mechanical systems, low pressure hydraulics, high pressure hydraulics and pneumatic systems. The two main stages of power take-off in any realistic wave energy device are the primary conversion of wave energy into useful mechanical energy into some useful form (32). Other possible conversion systems suggested are linear generator device, Piezoelectric methods, use of gas concentration cells, etc. (105 - 107).

A major problem in wave energy conversion is that of energy transfer from the device to the shore. This can be done through direct transfer via cables or stored in the form of electrochemical energy or by creating and transporting energy intensive products like, hydrogen, uranium, etc. similar to the suggestion in connection with OTEC (108) or use it for desalination (109). Winer (110) and Konopka *et al* (111) suggest alternate modes of storage and transport of energy from the site to the shore.

It is seen from **Table 1** that the wave power potential varies considerably from month to month and place, to place due to the varying wave climate. Therefore, it is not a firm source. Because of the high irregularity and variability of the waves, it is unlikely that the overall

efficiency of wave power devices will exceed 60 percent. The density of power in waves is quite low as compared to several other sources, but is more than winds, sunshine and ocean currents. If the wave power is to be competitive, it is necessary to amplify the power density per unit length before conversion. There are several means of increasing energy density by processes such as resonance, refraction, reflection, accumulation with time and convergence in wave channels, etc, and some of the devices described earlier are based on these principles. However, it is very much necessary to estimate the wave power more realistically and for reduced grid size using recorded data before going in for large scale exploitation. Unfortunately, recorded wave data for all the regions along the Indian coast and for all months are not available at present.

It is worthwhile to mention that waves in deep water receiving wave energy from all directions possess energy of an order of magnitude greater than that of waves in shallow water because of the dispersive and shoaling processes near the coast such as refraction, diffraction, etc. Therefore, from the resource point of view, it may be better to have wave energy conversion in deep waters rather than coastal waters. However, in deep water only moored floating system can be used and this will have less energy absorption efficiency. Therefore, the deep water device should be made more efficient to capture the same percentage of the total energy that can be recovered in a coastal energy conversion plant. Moreover, the system should be designed to extract energy from a wide range of wave conditions and to withstand the hostile marine environment. Since the economics of wave energy conversion depends much on the efficiency of the system, the cost and risk of its construction, deployment and maintenance, and power storage and transmission capability, the deep water devices may not become attractive at all places. On the other hand, in shallow water, any system designed should accommodate water level changes due to tides, storm surges, etc. Other aspects to be considered for deployment are bottom topography, frequency of storm, seabed conditions, etc. The tidal variations along the Indian coast is given in Table 2. The effect of storms and storm surges will be more on the east coast of India especially on the northern part. From the maintenance point of view, the choice and availability of materials, and biofouling and corrosion of materials, assume significance. The assessment of behaviour of any system in a full range of wave and environment conditions is required to evaluate design parameters. It appears that floating systems are inferior to fixed ones.

#### Environmental Impact:

The environmental impact of the wave energy conver-

sion is low, though it may not be a completely benign activity in the coastal seas. The devices as such are non-polluting. The impact on marine ecosystem will be minimal but site specific problems may arise (112-113).

The environmental aspects to be mainly considered are the effects on coastal, littoral and shoreline processes, sea life, navigation and perhaps aesthetics. Deep water devices may pose least environmental problems although it may affect the sea life in surface layers. Shallow water devices in large numbers are likely to alter the nearshore circulation, the sediment transport, the littoral processes, the beach stability, and the shore line morphology which are normally controlled by waves. The changes in the water circulation can affect migratory marine biota. The devices in coastal waters also may affect the navigation and fishing activities which can perhaps be overcome by providing navigational aids on devices and navigational channels between the devices.

The environmental effects may be beneficial in some cases. For example, the leeward side of the power plant will be relatively calm and provide a harbour for small boats, and the power devices themselves can act as an artificial reef attracting fish and thus enhancing fisheries. But care must be taken to avoid breeding and nursery grounds of fishes and other species. Another advantage is that where coastal erosion problem exists, the wave power devices can perform dual roles of producing power and protecting the coast by taming the waves which cause erosion. In India, this may be considered as an option especially during southwest monsoon when the wave energy potential is more and for the same reason, eroding potential, are greater at different places along the coast.

**Table 2**  
**Tidal Ranges at some locations along the Indian Coast**

Area	Spring Range (M)
Navlakhi - Gulf of Kutch	7.0
Bhavnagar - Gulf of Cambay	11.0
Bombay	5.0
Mormugao	2.5
Mangalore	1.5
Cochin	1.0
Madras	1.5
Visakhapatnam	1.5
Haldia	5.0

#### Economic Considerations:

Realistic economic assessment of wave energy projects is difficult as there are no commercial units available

and sea trials are minimal, though some estimates are available based on extrapolation from laboratory scale experiments or prototypes. Economically, as of now, the wave power plants cannot compete with conventional power production. There is no simple relationship between the size of wave energy devices and energy cost. Most of the devices are small and have low capital cost; but the nature of their operation means that they suffer reliability penalties. Economic cost assessment must include all factors to achieve realistic results. The economic viability of any scheme ultimately depends on the cost of the delivered power. Cost estimates of power per unit at 1981 prices for some systems developed in UK are given in Table 3. However, the ongoing developmental efforts indicate that the cost of wave power could be reduced as the technology improves.

**Table 3**  
**Cost Estimate (1981) of Power from Various Devices**

Device	P/kWh
Lancaster Flexible Bag	3.5 - 4.7
Salter Duck	4.5 - 5.6
Bristol Cylinder	5 - 10
Vicker's OWC	6
Lanchester Clam	6
Belfast Buoy	8
Cockerell Raft	9
NEL OWC	10 - 11

Source: Shaw (1982). Ref. 59. P - Pence (U.K.)

One useful way of assessing the economics of non-conventional energy systems is to take the value of energy produced and calculate the allowable capital investment based on this annual payment. This involves information on the power delivered by the device and set target value for that power. The operation and maintenance costs are then deducted to give the net annual value of the power output (32). While assessing the cost factor, one should consider the advantages of the wave energy that it is non-exhaustible, renewable and least polluting and its fuel cost is zero. The techniques for evaluating energy cost of systems incorporating zero fuel cost and environmental impact is inadequate. As suggested by some economists, the traditional concept of added value should be replaced by Utilisation value. Perhaps, because of poor cost effectiveness the commercial establishments have not come forward to invest capital in the high risk wave energy programmes. Most of the funding for wave energy development in the world including India has come from governmental agencies.

Wave energy may be viable in areas where the conven-

tional energy cost is very high like offshore islands and remote areas along the coast and in small scale systems like navigational buoys, pumping systems, etc. The socio-economic impact on the areas where wave power plants are setup will be more on the positive side as it can generate employment, attract industries and therefore, leading to development of that region.

### Conclusion:

In spite of the development of a large number of wave energy conversion devices, commercial use of wave energy has not taken place and only a few of them have the potential for being developed commercially. The main reason is that the present level technology does not make the wave energy option economically competitive. However, some progress is discernible in the implementation of the most promising concept of the Oscillating Water Column (OWC) device in Japan, Norway, UK and India.

In India, a wave power device based on OWC will be put into operation soon near Trivandrum, Kerala. From the point of view of resource potential, the wave energy extraction may not be feasible on a large scale in India, except during the S W monsoon period. However, it is certain that in small scale, wave energy can be utilised for navigational buoys, lighthouses, oceanographic buoy systems, sea water pumping, for salt pans, etc. It can be thought of utilising wave energy for pumped storage schemes along the coasts and for shore based stations in the Lakshadweep and Andaman group of islands is a possibility. These can be combined with applications for desalination, creating calm sea, and pumping sea water for aquaculture, etc. Nutrient rich deep water can be pumped from the deep ocean and used for aquaculture, similar to OTEC system. One of the successful systems has been used in Monaco for over forty years. Electricity generation from wave energy can be integrated with beach erosion control at some locations where beach erosion is a problem especially in places like Kerala coast. Extraction of wave energy as a secondary function of breakwaters is also worthy of investigation in the Indian situation as this gives an economic advantage.

The most favourable features of wave power are : its total quantity is very large; it is renewable; it is non-exhaustible; it is available near to the shore; its fuel cost is zero and it is non-polluting. But the initial investment and maintenance cost will be quite high which warrants continuous operation of the wave power plants to recover the investment. Moreover, power source is largely fluctuating with time. Hence, it is not a firm source. But this could perhaps, be absorbed by the available grid system. The density of power in waves is quite low compared to several other

sources but is more than winds, and sunshine. If power generation from waves is to be competitive it is necessary to amplify power density per unit length before conversion. This is especially true in the case of Indian seas where the wave heights are less than 1.5 m for major part of the time.

The pattern of the electricity demand in India is such that no single source can meet the whole demand, but a variety of power sources have to be utilised in the optimised total energy system. In such a situation, wave energy can be one of the candidates. Nevertheless, it is prudent to strengthen the technology of wave energy utilisation in view of the energy crunch. Moreover, the socio-techno-economic and political strength of a country depends largely on energy availability and therefore, development of energy sources in any form should not be disregarded merely on the basis of cost factor, which can be optimised with continued technology improvement. Further, it should be borne in mind that energy has always been in short supply and will continue to be so.

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