OCEAN ENERGY CONVERSION

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ABSTRACT

Oceans contain a huge energy resource with different origins. The most developed conversion systems refer to tidal energy, thermal energy (OTEC), marine currents and waves. The technologies to harness these resources are at different state of development. In this paper an overview of the resource, the technology, prototypes and existing plants, economics and environmental impacts for tidal, OTEC, marine currents and wave energy is presented.

1. INTRODUCTION

The oceans contain an enormous energy resource that can be exploited, contributing in a sustainable manner to meet the increasing global energy demand.

Several types of ocean energy sources with different origins exist. The most developed conversion systems concern: **tidal energy,** which results from the gravitational fields of the moon and the sun; **thermal energy** (Ocean Thermal Energy Conversion or **OTEC**), resulting directly from solar radiation; **marine currents,** caused by thermal and salinity differences in addition to tidal effects and **ocean waves**, generated by the action of the winds blowing over the ocean surface. Other technologies, namely **salinity gradient** devices, are at a much lower level of development and are not considered herein.

Tidal energy can be considered to have attained maturity since a 240 MW power plant is under successful operation for more than 30 years and other smaller plants have been built. However, the high cost of the construction has deterred further investments.

Although using standard components, the OTEC prototypes that have been tested since the 1930s have posed technical problems. This and economic factors did not encouraged relevant activity in this area since the middle 1980s.

The exploitation of marine currents can make use of underwater systems similar to the wind turbines, but development is still required. The first two prototypes for the exploitation of tidal currents are being presently constructed.

Due to the complex characteristics of ocean waves and its energy extraction hydrodynamics, the development of the technology to harness this resource requires research work to a larger extent than the others sources do.

In this paper an overview of the resource, the technology, the most relevant prototypes and existing plants, economics and environmental impacts for the four resource types are presented at the following sections.

2. TIDAL ENERGY

Tidal energy is the first ocean energy technology to have attained maturity probably due its similarity to conventional hydropower plants. The locations where tidal power could be developed economically are relatively few because a strong tidal energy concentration (leading to a tidal range of five metres or more) has been considered to be needed for the cost of electricity to be competitive. Additional requirements are a large reservoir, and a short and shallow dam closure.

2. 1 Resource

The tides are generated by the rotation of the earth within the gravitational fields of the moon and sun. The relative motions of these bodies cause the surface of the oceans to be raised and lowered periodically, according to a number of interacting cycles:

A *half-day cycle*, due to the rotation of the earth within the gravitational field of the moon, resulting in a period of 12 hours 25 minutes between successive high waters.

A *14-day cycle,* resulting from the superposition of the gravitational fields of the moon and sun. At new moon and full moon, the sun's gravitational field reinforces that of the moon, resulting in maximum tides or *spring tides*. At quarter phases of the moon, the sun's attraction partially cancels that of the moon, resulting in minimum or *neap tides.* The range of a spring tide is typically about twice that of a neap tide.

Other cycles, namely a half-year cycle, and a 19-year cycle, arise from other interactions between the gravitational fields.

In the absence of land, the theoretical mean tidal range in the ocean would be about 0.5m. The process by which this range is increased at some coastal locations and not at others is complex. It involves the steepening of the tidal wave as it enters shallow water, reflection by the coast line, and resonance which occurs in long estuaries when the length of the estuary is close to one quarter of the tidal wave length (a condition where the natural frequency of the basin oscillation equals the tidal frequency). The La Rance estuary in north-western France, the Severn estuary in the south-western UK, and the Bay of Fundy in eastern Canada where the tidal range can exceed 14 m, are famous examples. Extraction of energy from the tides is considered to be practical only where energy is concentrated in the form of large tides (mean tidal range larger than 5 m), and topography is favourable for tidal plant construction. Such sites are not abundant but a considerable number have been identified worldwide.

The amount of energy available from a tide varies approximately with the square of the tidal range. The power output from a tidal plant would therefore vary by a factor of four over a spring-neap cycle. Tidal energy is, however, highly predictable in both its timing and magnitude.

Most of the technically available resource in Europe lies in the UK (CEC, 1992a) where the total potentially installed capacity amounts to 25 GW, with annual energy production

50 TWh/y, and in France (23 GW, 44 TWh/y). Feasibility studies have been carried out in UK for several estuaries (namely the Severn and the Mersey). Of these, the Severn (on south-western England) represents a major resource (8000 MW) and has been object of extensive studies. In northern France, a large potential exists at the Cotentin Peninsula (Normandie). Several possible sites around the word (excluding Europe), namely in Argentina & Chile, Australia, Canada, South-eastern China, India, South Korea and former USSR with mean tidal range between 4.8 and 11.7 m have also been evaluated in the above study. Many of these sites are remote from centres of demand and therefore, although representing very substantial resources at reasonable unit cost, there has been no chance of their development.

2.2 Technology

A tidal power plant is similar in many respects to a conventional run-of-the-river hydro plant, one of the differences being lower heads, which implies large axial-flow turbines with low speed. The plant consists essentially of a barrage or dam constructed across an estuary with a series of gated sluices and a bank of low head axial flow turbines. Where it is necessary to maintain navigation to the upper part of the estuary, a shiplock may be required. Figure 1 shows the elements of a typical barrage design.

The construction method usually proposed for the dam involves the use of prefabricated caissons, made of concrete or steel, which would be manufactured at suitable construction yards and then be towed to the barrage site and sunk into position on prepared foundations. Separate modules would be used to house turbo generators or sluices, or simply be blank to make up the remainder of the dam. Another option is to construct the dam behind a temporary cofferdam, which is later removed. This was successfully carried out at the La Rance estuary, in France, in the 1960's. The caisson method is usually considered less risky and less expensive, especially for larger sites where economies of scale would reduce the costs of caisson yard construction.

Horizontal-axis water turbines of axial-flow (Kaplan or propeller) type are generally recognized as the most suitable type of machine for tidal applications. Turbines for tidal power are relatively slow-turning, usually in the range 50 to 100 rpm. The runner diameter of large units may reach 9 metres.

Most studies have selected bulb type units in which the directly driven multi-pole generator is located inside a steel bulb surrounded by water. This type of turbine is currently adopted in run-of-the-river conventional power plants of very low head, and was successfully used at the La Rance tidal plant (Fig. 2). Bulb type turbines are usually capable of double regulation, by means of adjustable runner blades and wicket gates (or

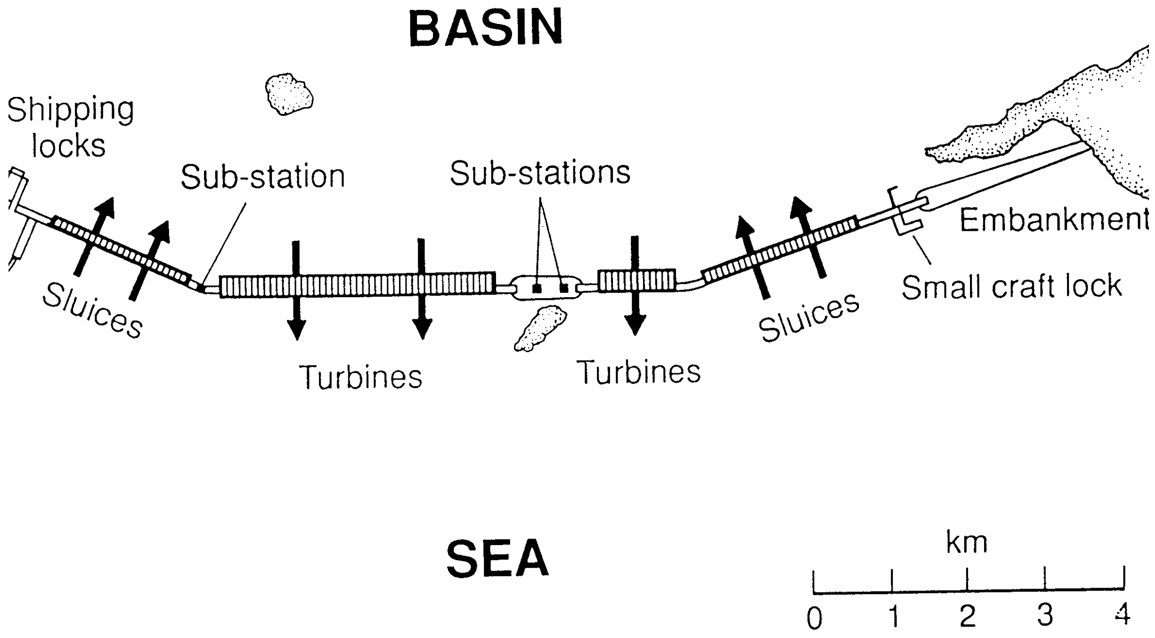


Fig. 1. Schematic representation of a typical large tidal plant (from Charlier and Justus, 1993).

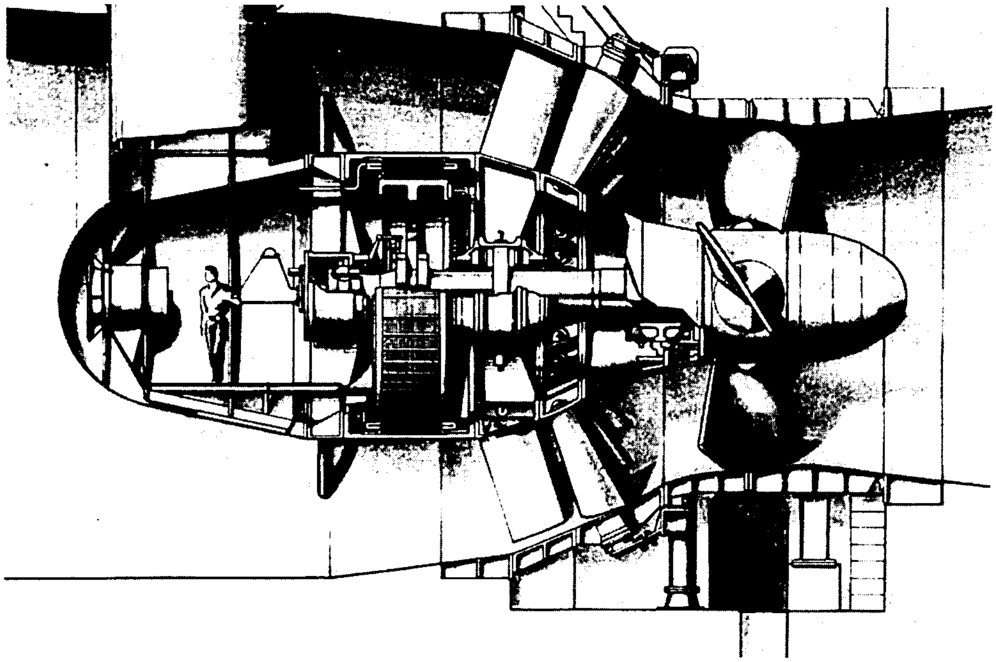


Fig. 2. Bulb turbine as used in La Rance power plant (from Charlier and Justus, 1993).

guide vanes). This may enable the machine to operate in both the generation mode and the (reversed) pumping mode.

The experimental tidal plant at Annapolis Royal (Nova Scotia, Canada) used a special type of turbo generator, called "Straflo", in which the generator rotor, located outside the water duct, is attached to the rim of the axial-flow turbine rotor. These units are less expensive than bulb units due to the reduced length and the absence of generator shaft. Favourable operating experience at Annapolis Royal may indicate that Straflo turbo generators could be economical options for future tidal plants in Canada. A disadvantage of Straflo turbines is the lack of double regulation (the runner blades cannot be adjusted).

Sluice gates must be designed to allow large flow rates (several times the turbine flow) in order to maximize the available head. The favourable type is the vertical lift gate with a motor operated hoist.

Modes of Operation

Ebb generation is the simplest mode of operation for a tidal plant and the one generally preferred. The production of electricity occurs during the part of the cycle when the water is flowing through the turbines from the basin to the sea. The operating cycle consists of four steps (see Fig.3):

(1) The water is allowed to pass through the sluice gates during the flood tide, to fill the basin.

(2) The gates are then closed until the receding tide creates a suitable head between the basin and the sea.

(3) The water is allowed to flow from the basin through the turbines on the ebb tide, until the head is reduced to the minimum operating point as a result of the rising tide and the decreasing water level in the basin.

(4) The gates are closed until the tide rises sufficiently to repeat the first step.

Flood generation involves reversing the cycle, with generation from sea to basin. This would reduce the basin water to a level lower than the average sea level, which could have serious consequences for navigation upstream of the dam, and adverse ecological and visual impact. In addition, due to the sloping nature of the basin shores, the decrease in basin area with elevation makes the basin to fill up faster during flood generation than is drains during ebb generation, and so flood generation would produce less energy than the corresponding ebb generation. These reasons explain why flood generation is usually excluded as a mode of operation.

Two-way generation on both ebb and flood (*double effect cycle*) is also feasible. This does not usually produce more energy and requires more complex machinery (namely reversible turbines). On the other hand, it does enable generation over a longer period of the day. This would have advantages if the plant output is to be integrated into a week grid. The La Rance tidal plant was originally designed for generation in both directions, but is presently being operated for ebb generation only.

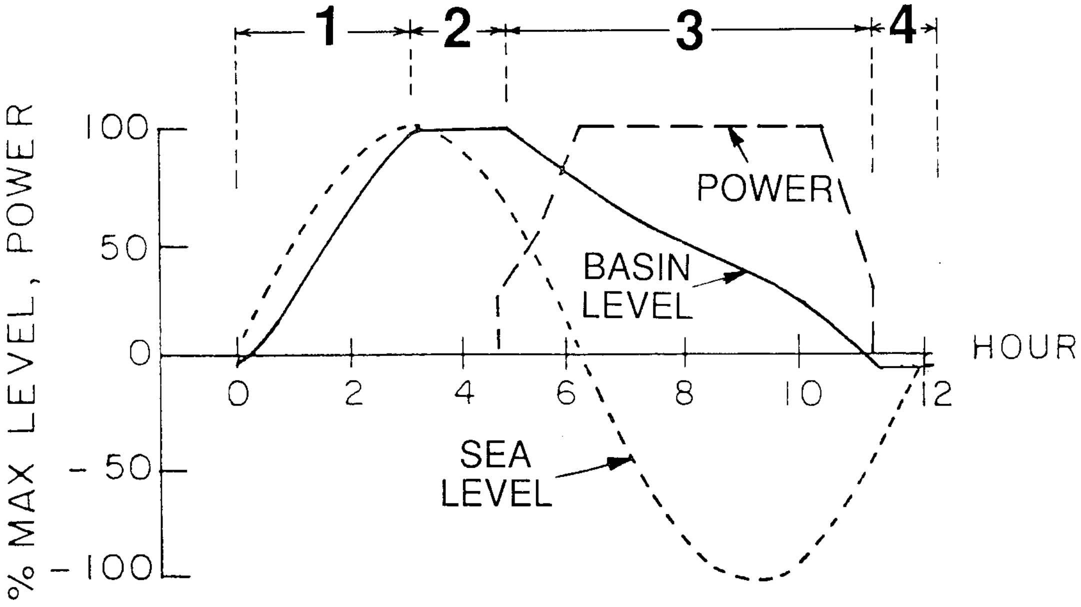


Fig. 3. Variation of sea level, basin level and power output for one-way ebb generation (from Carmichael et al, 1986).

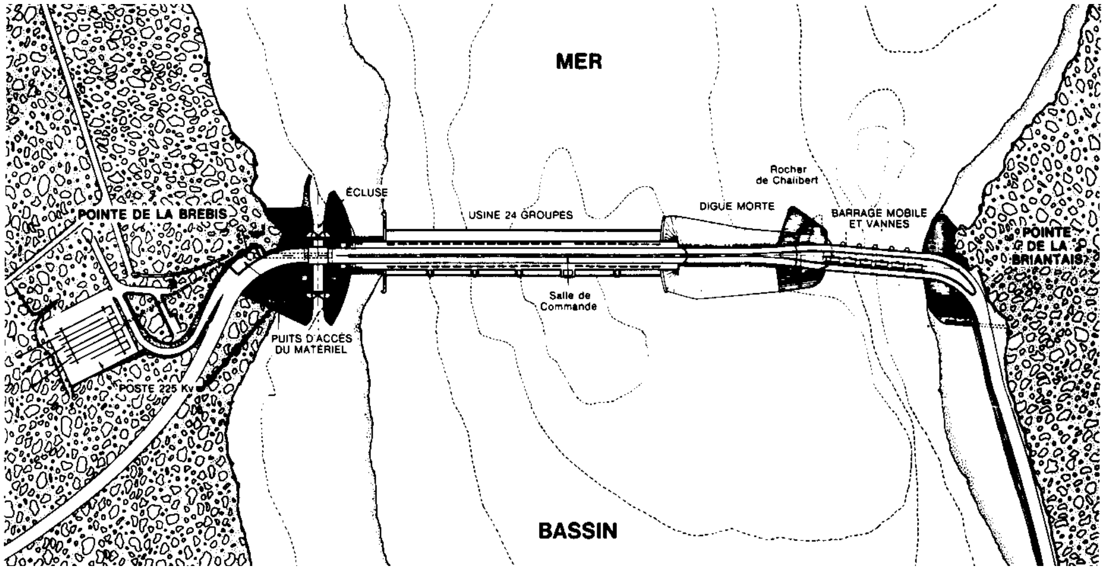


Fig. 4. Rance River plant layout (from Charlier and Justus, 1993).

Pumping is increasingly favoured because of its ability to increase energy output. In any of the modes of operation outlined above, it is in principle possible to pump the water against the water head between the basin and the sea, provided the turbine is suitably designed (this would require double regulation). For example, in ebb generation it would be possible in this way to raise the basin water level at the beginning of ebb generation and in this way increase the amount of generated energy. The energy required for pumping at a low water head is less than the energy generated by the same volume of water flowing back though the turbine at a greater head. This produces a net energy gain, typically in the range of 5 to 15%. Pumping has been used in the La Rance tidal plant.

Because the moon's position relative to the earth varies cyclically with a period of 24 h and 50 m, tidal phase shifts by almost an hour every day. Hence generation occurs at different times on different days and will not, in general, coincide with peak electricity demand. Tidal plants deliver one or two intermittent pulses of energy per tide, leading to rather low annual plant load factors in the range 22-35% and providing little significant firm capacity. Such an output can usually be absorbed into the electric distribution grid provided that the non-firm capacity is a small percentage (say less than 30%) of the total system capacity.

2.3 Existing Plants

Relatively few tidal plants have been constructed in the modern era. The first and largest one is the 240 MW plant built for commercial production across the La Rance estuary in north-western France between 1961 and 1967 (Fig. 4) and which has now completed more than 30 years of successful operation. A 750m dam (including sluices, powerhouse, ship lock and embankment) encloses a basin of 17km^2, and the turbo generator consists of 24 bulb-type Kaplan turbines rated 10 MW each.

In 1984, the Canadian began operating an 18 MW plant at Annapolis Royal on the Nova Scotia coast of the Bay of Fundy. The project utilised an existing flood control dam and was conceived to demonstrate a large diameter Straflo turbine and as a forerunner of much large projects in the upper Bay of Fundy, which have not been followed, however.

Other tidal plants include the 400 kW experimental unit at Kislaya Guna, built in 1968 in Russia on the Barents Sea, and the 3.4 MW Jianxia station built in China between 1980 and 1986. Further details are given in Table 1.

2.4 Economics and Environmental Impacts

Tidal power incurs relatively high capital costs, and construction times can be several years for larger projects. In addition, the operation is intermittent with a relatively low load factor (22-35%). Thus, although plant lifetime can be very long (120 years for the barrage structure and 40 years for the equipment), the high capital costs and long construction time have deterred the construction of large tidal schemes.

Like most renewable sources of energy, tidal energy is non-polluting and displaces fossil fuels. A tidal barrage can provide protection against coastal flooding within the basin during very high tides, by acting as a storm surge barrier. However, a tidal energy scheme can cause significant changes to the estuarine ecosystem. For each scheme, a site-specific environmental impact assessment would be needed. In the upper estuary away from the immediate effects of the barrage, salinity will reduce as a result of the reduction in the volume of seawater entering the estuary. The tidal range, currents and the intertidal area inside the basin are reduced by about half. These hydrodynamic changes can in turn influence both water quality and the movement and composition of bed sediments. Any reduction in water turbidity that may occur can result in increased primary biological productivity, with consequent effects throughout the food chain. Increases in low-water levels and a general reduction in currents and turbidity will make the enclosed basins more attractive for water-based recreation. Especially at large sites, the opportunity to build a road across the dam would be a major benefit.

Site	Mean tidal range (m)	Basin area (km^2)	Installed capacity (MW)	Approx. output (GWh/y)	In service (year)
La Rance (France)	8	17	240	540	1966
Kislaya Guba (Russia)	2.4	2	0.4	-	1968
Jingxia (P.R. China)	7.1	2	3.2	11	1980-86
Annapolis Royal (Canada)	.6	6	17.8	30	1984
Various (P.R. China)	-	-	1.8	-	-

Table 1. Existing tidal energy plants (from CEC, 1992a).

3. OCEAN THERMAL ENERGY CONVERSION (OTEC)

It is well known that power can be generated from two sources of heat at different temperatures. The idea of using the cold deep water of the ocean as the cold reservoir of a thermal engine whose hot reservoir is the warm surface water was proposed in France by D´Arsonval in 1881. Several prototypes were developed by French, American and Japanese teams and were tested in Cuba, Brazil, Hawaii, and Japan until the middle 1980s. Although OTEC operating principles are well documented and no scientific or technical breakthroughs of great magnitude are required, the schemes tested so far have posed complex engineering and cost problems, and no prototype of industrial size has been built yet.

3.1 Resource

It is known from thermodynamics that the maximum efficiency (i.e. the efficiency of the Carnot cycle) of an heat engine operating between the (absolute) temperature T_W of the warm water and the temperature T_C of the cold water is given by

$$\text{Thermal efficiency (Carnot cycle)} = 1 - \frac{T_c}{T_w}.$$

Assuming T_W = 298 K (25°C), T_C = 278 K (5°C), T_W - T_C = 20°C, we find for the Carnot efficiency the value 6.7%. In practice, the thermal efficiency of a practical engine drops to about 2-3% when power required for pumping the water (especially the bottom cold water) and losses are included in the evaluation. This means that in practice 1 to 4 m^3/s of warm water and the equivalent of cold water will be needed to produce 1 MW of net power. Although it is not too difficult to supply large flows of warm water from the surface of the ocean, the same is not true for the cold water which has to be pumped from deep regions through a long duct (700 to 800 metres for floating power plants and 1.5 km or more for a plant onshore).

The temperature gradients in the ocean provide a measure of the ocean thermal resource. In tropical seas, the surface water temperature usually lies between 24°C and 33°C, whereas the temperature at depths of 500 to 1000m remains between 3°C and 9°C.

Therefore, conservative estimates place potential OTEC areas between latitudes 10ºN and 10ºS. Suitable areas, however, may be found up to 20ºN and 20ºS latitude, and even beyond given favourable ocean currents and evolving technology.

3.2 Operating Cycle

The Rankine cycle is the only practical thermodynamic cycle that has been developed for the ocean thermal energy conversion (OTEC). This is the cycle representing the thermodynamic process taking place in a conventional thermal power plant in which a liquid is evaporated, expanded and then condensed. Two variants of the Rankine cycle have been developed for OTEC applications.

In the open cycle seawater is used as a “working fluid”, the warm surface water being flash-evaporated under a partial vacuum. The steam produced passes through and propels a turbine, and is later cooled in a condenser using cold seawater (4ºC - 7ºC) pumped from the deep ocean, generally found at several hundred metres depth. If a surface condenser is used, the output of the condenser is desalinated water.

In the closed cycle a secondary working fluid such as ammonia, propane or freon-type refrigerant is vaporised and re-condensed continuously in a closed loop to drive a turbine. Warm seawater is drawn from the sea surface and pumped through heat exchangers wherein the secondary fluid is vaporised; this fluid then expands and emerges as high-pressure vapour to drive the turbine.

In a so-called hybrid cycle combining open and closed cycles, steam is generated by flash evaporation of warm sea surface water and the steam acts as the heat source for a closed Rankine cycle.

3.3 Technology

The performance, component size and system optimisation for the closed Rankine cycle can be calculated using the same techniques and procedures as for a conventional thermal power plant. The two heat exchangers — evaporator and condenser — are two of the largest and most expensive components in the OTEC power plant. The optimisation of the cycle is therefore closely coupled to the optimisation of the heat exchangers.

The turbine is perhaps the most important component in the open cycle OTEC system. The low density of the steam at the cold water condenser conditions and the moderate level of steam expansion (more precisely the small available drop in enthalpy) through the turbine will result in very large turbines. For large power outputs this would require the development of special large turbines which would operate at low rotational speeds. As in the case of the closed cycle, the other large components are the evaporator and the condenser.

One of the priorities in OTEC development has been directed towards improving the heat exchanger technology, improve the heat transfer process, control the influence of bio fouling, and reduce the cost of the heat exchanger by an adequate choice of materials.

Floating platforms, fixed platforms and land-based facilities have been considered during the development of OTEC systems. The early designs assumed that large power plants would be supported from floating platforms. However it was realized that there would be formidable problems associated with the long cold water pipe, the deep moorings and the electrical cables.

More recent designs have assumed fixed platforms placed in relatively shallow water, using the technology of the offshore oil industry. The cold water pipe would follow the bottom contours, with special support structures at intervals along the length of the pipe. For example, in the project for a 40 MW plant at Kahe Point, Hawaii, the cold water pipe would be 3670 m long, and it was estimated that its cost would represent about one quarter to one third of the total cost of the project (Carmichael et al., 1986). For fixed platforms and land based power plants, it has also been suggested that a cold water tunnel could be superior to a pipe in some situations.

The large diameter pipes (up to 10 or 12 m) needed to go downwards to depths of 1000 m to tap the cold ocean waters will possibly limit OTEC plants to sizes of approximately 100 MWe (Trenka, 1993).

In addition to power and fresh water production OTEC plants can be useful for marine culture, namely fish farming because the pumped cold deep seawater is rich in nutrients.

3.4 Demonstration Power Plants

A first small power plant was constructed 1n 1930 in the shoreline of Cuba by the French scientist Claude who had undertaken d´Arsonval´s ideas, but the 22 kW output was insufficient to pump the bottom cold water. However, plans for the construction of a 7 MW OTEC plant off Ivory coast have been made but were abandoned. After that, only small demonstration OTEC plants were constructed, in the United States and in Japan.

A mini-OTEC plant was installed on a floating platform off the coast of Hawaii in 1979, with a gross power output of 50 kW. This was followed in 1980 by an experimental plant, named OTEC-1, mounted on a converted tanker off Hawaii, and rated at 1 MW thermal. Experiments in both projects lasted only for a few months, with overall Rankine cycle efficiencies over 2.5% for a temperature difference of 21°C. More recently, in 1992, an open cycle land-based OTEC experimental plant was installed at the Natural Energy Laboratory of Hawaii (NELH), with the objective of verifying the feasibility of the open cycle. Its generator nominal output is 210 kWe, and the net output is approximately 50 kWe.

Two pilot plants were built by Japan, one on the island of Kyushu, with a gross power output of 50 kWe, and another one on the island of Nauru, with a gross power output of 100 kWe.

3.5 Economics and Environmental Impacts

Like some other renewable energies, high capital costs continue to plague OTEC. Proof of economic viability remains to be shown. Economic analysis indicated the early market for OTEC to be islands and near-shore communities requiring 15 MWe or less. Cost analyses showed that the closed cycle OTEC would be cost effective for only very large-sized plants (greater than 40 MWe) (Trenka, 1993). The simpler and cheaper heat exchangers of the open cycle system, coupled with the fact that the open cycle produces large volumes of fresh water, helped to change the emphasis to the development of the open cycle OTEC.

The major environmental concerns are the potential change in the oceanographic properties of seawater due to pumping. Others relate to chemical pollution arising from working fluid leaks and corrosion. Structural effects promoting artificial reef formation, entailing nesting and fish migration can be positive.

4. MARINE CURRENTS

Kinetic energy from the sea can be harnessed using relatively conventional techniques, which are similar in principle to those for extracting energy from the wind, by using submarine converters similar to “underwater windmills”. This option is still relatively undeveloped, however. A number of studies have been completed on the energy potential of marine currents but there have been few on the engineering requirements for utilisation of this resource. Countries where theoretical studies and experimental projects took place are the UK, Italy, Canada, Japan, Russia, Australia and China in addition to the European Union. In Europe two prototypes are being developed partially funded by the European Commission.

The start up of the exploitation of the marine currents energy can make use of conventional engineering components and systems but development is required to achieve reliability and durability of the equipment at low operational and maintenance costs. Further research will be necessary to develop more efficient converters at lower electrical energy unit costs.

4.1 Resource

The fastest oceanic no tidal currents are derived by a complex process involving the adsorption of solar radiation in the ocean and atmosphere, followed by its transformation and redistribution from the Equator towards the poles by moving currents of air and water, and finally a focusing of the oceanic currents on the western edges of ocean basins (or the eastern coasts of continents) by the Earth’s rotation. The Gulf Stream in the Atlantic, the Kuroshio off Japan and the Agulhas-Somali system on the eastern African coast form the main current system. Tidal currents are the consequent flow of ocean water due the rise and fall of tides (see 2.1). Other factors such as salinity and local temperature differences also make a contribution to the movement of ocean water. This can be magnified by underwater topography, particularly in the vicinity of land or in straits between islands and mainland.

The total power of ocean currents is estimated to be about 5 TW (Isaacs and Seymour, 1973) which is of the same order of the global electricity consumption. However, energy extraction is practical only in a few areas where the currents are concentrated near the periphery of the oceans or through straits and narrow passages between islands and other landform. Thus only a small part of the total energy can be converted to electrical or other useful form of energy.

The power of a current is given by

$$P = \frac{1}{2} \rho \, A V^3$$

where A is the cross section of flow intercepted by turbine, ρ is water density and V is current velocity. For tidal currents that occur close to the shoreline in estuaries and in channels between mainland and islands, V varies sinusoid ally in time as a function of period of the different tidal components (see 2.1).

In the case of tidal flows, it has been considered that its exploitation should be interesting at sites where the maximum sinusoidal current velocity exceeds 1.5 m/s and should be evaluated on a site-by-site basis for $1.0<V<1.5$m. For constant currents, the maximum current velocity should exceed 1.0 m/s, and is dependent on site evaluation for $0.5<V<1.0$m.

Studies to assess the marine currents resource have been recently carried out in the UK (DTI, 1993), European Union (CEC, 1996) and in far-eastern countries (CEC, 1998). In Europe this resource is of special interest for the UK, Ireland, Greece, France and Italy. In this area 106 promising locations were identified and it was estimated that, using present day technology, these sites could supply 48TWh/yr to the European electrical grid network. In China it has been estimated that 7000 MW of tidal current energy are available. Locations with high potential have also been identified in the Philippines, Japan, Australia, Northern Africa and South America.

The predictability of marine currents and the high load factor (20-60%) are important positive factors for its utilisation. Sites with pure tidal flow in most cases offer capacity factors in the 40-50% range. For non-tidal flows this range increases to the order of 80%.

There still remains uncertainty with regard to the detailed characteristics of this marine resource. The available marine current data are limited and not fully consistent. The further development of efficient 3D numerical flow models in addition to long-term data collection will enable to produce a comprehensive accurate assessment of this resource.

4.2 Technology

The technique that has been mostly considered for the exploitation of marine currents is to use a turbine rotor, set normal to the flow direction, that is mounted on the seabed or suspended from a floating platform. As with wind energy exploitation, there are two conventional rotor concepts having adequate efficiency to be considered: the axial flow rotors (propeller-type, horizontal axis) and the cross-flow rotors (Darrieus-type). Figure **5** illustrates the basic configuration of each rotor type. Both axial flow and cross-flow rotors can be of fixed geometry, or either type can have the blades pivoted so as to allow the pitch of the blades to be adjusted. Support structures to hold the turbine in position, can either be fixed to the seabed, or float with a suitable mooring system. The first type should be used for installation in shallow waters (20-30m water depth) while the floating structures should be adopted for deep water sites (50m or more) but can also be used in lower depths.

First generation systems will be based on the use of conventional engineering components and systems in order to achieve reasonable reliability at low costs. A medium-sized turbine, of 10-15 m diameter and 200-700 kW rated power, deployed in as shallow water as possible (i.e. 20-30 m water depth), is likely to be the most economic overall solution for the first generation machines (CEC, 1996). The greatest technical problems are likely to arise from the need for adequate operational life and low maintenance costs from machinery operating in a harsh environment.

Second generation systems can follow from this by introducing specialised components, such as low speed multi-pole electrical generators, hydraulic transmission systems, etc. Novel concepts to be developed within R&D programmes will be the *third generation* systems.

4.3 Demonstration plants

The first two prototypes are being developed by SME´s in Italy and in the UK with the support of the European Commission.

In Italy, the 130 kW prototype using a cross-flow three blade turbine mounted on a floating platform of cylindrical shape has been built and deployed in the Strait of Messina, close to the Sicilian shore (Ponte di Archimede, 2000; see Fig. 6.). In that site the mean (tidal) current velocity is about 1.5 m/s and the water depth 20m. The Kobold© turbine maximum efficiency is 42% being practically invariant with respect to the current velocity.

Fig. 5. Schematic representation of the axial-flow and cross-flow rotors.

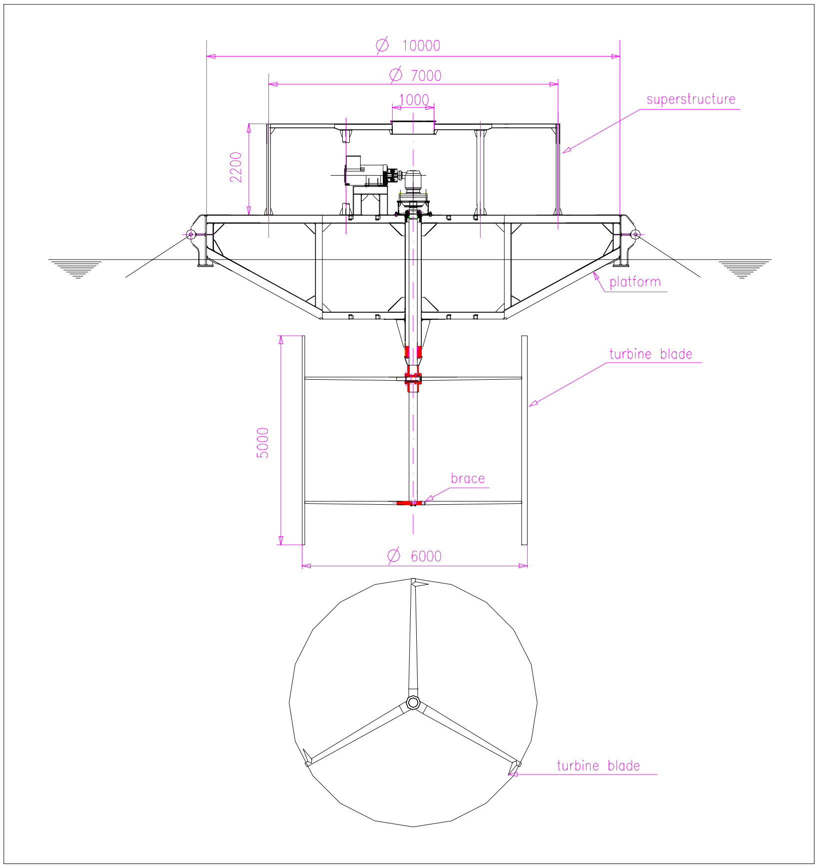


Fig. 6. General arrangement of turbine, platform and superstructure of the ENERMAR system.

In the UK the 300 kW system being developed will use axial-flow rotor(s) and will be installed on a mono-pile socketed into the seabed in a current velocity of about 2.5m/s in 2001 in the Channel of Bristol, south-west of England.

The construction of a 75 kW device is planned for China also with support by the European Commission and in collaboration with Italy.

4.4 Economics and Environmental Impacts

The prediction of electricity cost is dependent upon the size of machine, the choice of economic parameters, the running costs in addition to the load factor that is especially critical.

Preliminary estimates of unit costs of electrical energy vary between 0.05 and 0.15 ECU/kWh depending on the studies. The assessment described in CEC (1996b) has estimated that costs of less than 0.10 ECU/kWh would be achievable with first generation machines in a good current regime (current velocity of 3m/s) with load factor larger than 30%.

The environmental impact of submerged marine current turbines will be minimal; the main conflicts are expected to be with shipping, navigation and fishing. Significantly large amounts of energy extracted continuously, with a consequent reduction of the velocity of the current, could have the potential of modifying climatic conditions downstream and the transport of sediments. Hence, an environmental impact assessment should be performed on a site-by-site basis.

5. WAVE ENERGY

The power present in ocean waves has been recognised for millennia although mostly in terms of its destructive potential. However, the possibility of obtaining useful energy from ocean waves has been considered for some centuries. The first patent of a wave energy device was registered in France by the Girards father and son at the end of 18th century and since then more than one thousand patents have been filed in various countries.

The conversion of ocean wave energy requires new technology to an extent larger than for most of other ocean energy sources. It can be said that research on wave energy conversion based on adequate scientific background started in the 1970s when the oil crises provoked the exploitation of a range of renewable energy sources, including waves. Based on various energy-extracting methods a wide range of systems has been proposed but only a few reached the demonstration stage, with in two cases commercial viability being claimed.

5.1 Resource

Wave energy can be considered a concentrated form of solar energy. Winds are generated by the differential heating of the earth, and, as a result of their blowing over large areas of water, part of their energy is converted into waves. The amount of energy transferred and hence the size of the resulting waves depends on the wind speed, the length of time for which the wind blows and the distance over it blows (the “fetch”). Energy is concentrated at each stage in the conversion process so that the original solar power levels of typically ~100 W/m^2 can be converted into waves with power levels of typically 10 to 50 kW per metre of wave crest length. Within or close to the generation area, the storm waves known as “wind sea” exhibit a very irregular pattern. These waves will continue to travel in the direction of their formation even after the wind turns or dies down. In deep water (i.e. when their wave length is smaller than half of the water depth), waves lose energy only slowly so they can travel out of the storm areas with minimal loss of energy, progressively becoming regular, smooth waves or “swell”. These can persist at great distances (i.e. tens of thousands of kilometres) from the origin. Therefore, coasts with exposure to the prevailing wind direction and long fetches tend to have the most energetic wave climates, i.e. the western coasts of the Americas, Europe and Australia/New Zealand as shown in Fig. 6.

An idealised description of ocean waves is given by a sinusoid (Fig. 7a) characterised by its height H, length, L, and period T (the inverse of frequency f). Another important parameter is the water depth h. Real seas exhibit an irregular pattern, however (Fig. 7b). Assuming linear theory, they can be described as a sum of individual waves that are random in height, period and direction. Within a length of time (generally 3h, except in stormy conditions) the characteristics of real seas remain constant thereby comprising a sea state that can be described by a directional wave spectrum $S(f,\theta)$ which provides the distribution of energy density in the frequency f and direction θ domains. This spectrum can in turn be summarised by parameters of wave height, period and direction. For wave height, the standard parameter is the significant wave height H_S that is computed as $H_s=4m_0^{1/2}$; in wave energy utilisation, a widely used period parameter is the energy (mean) period defined as $T_e=m_{-1}/m_0$, the n-th spectral moment being computed by $\int_0^{2\pi}\int_0^{\infty} f^n\, S(f,\ \theta)\ \mathrm{d}f\ \mathrm{d}\theta$. The power available in real seas is usually expressed in terms of power per unit length along the wave crests. In deep water it can be estimated as

$$P \cong 0.5\, H_s^2\, T_e$$

where P is given in kW/m, H_s is expressed in metres and T_e in seconds. There is great variation in power levels, with the passage of each wave, from day to day and from month to month. The seasonal variation however is in general favourable in temperate zones, since wave energy (like wind power) is at its largest in the winter months coinciding with the greatest energy demand.

The global wave power potential was estimated to be 10^{12}-10^{15} J (1-10 TW) that is the same order of magnitude of the world consumption of electrical energy (Isaacs and Seymour, 1973; WEC,1993). The best wave climates, with annual average power levels between 20 and 70 kW/m or higher, are found in the temperate zones (30 to 60 degrees latitude) where strong storms occur (Fig. 7). However, attractive wave climates are still found within ±30 degrees latitude where regular trade winds blow, the lower power level being here compensated by the smaller wave power variability.

Resource assessments have been undertaken at national level and at the European level through the development of WERATLAS, the European Wave Energy Atlas (Pontes et al., 1998) which contains a detailed description of the European Atlantic and Mediterranean offshore resource and wave climate (Fig. 9). This enabled to accurately estimate the total annual European deepwater resource that amounts to about 320 GW.

As waves approach the shore travelling through waters of decreasing depth they are modified through a number of phenomena when $h<L/2$ (which for most areas occurs where $h < \sim 100$m). Refraction, diffraction and reflection of ocean waves are conservative phenomena (i.e. the total energy remains constant) similar to the optical waves ones. They promote the redistribution in the space and frequency domains of wave energy density. Refraction promotes the turning of crests, which tend to become parallel to depth contours and shoreline. As a consequence energy is concentrated in convex bathymetries as in headlands and submarine ridges areas, and is dispersed in concave sea bed areas as bays. Even in the absence of focussing or defocusing, the change of direction that refraction promotes can be of great importance to wave energy extraction in near shore and at the shoreline because the capture efficiency of devices used here is orientation-dependent. Due to the action of indented coastlines, diffraction can promote the increase of wave energy concentration. Wave breaking and bottom friction are dissipative phenomena. Wave breaking causes the dissipation of most of the wave energy. However this can also have a positive effect in the near shore /shoreline wave energy extraction because the largest storm waves break before reaching the plant thus avoiding the extreme loads of waves breaking upon its structure. Bottom friction, that can be only important when a wide continental platform exists, increases with seabed roughness.

In assessing how much power can be converted into electricity (the technically achievable resource), account must be taken of limitations on device deployment and losses in the energy conversion and transmission scheme. In Europe, the conversion of the available resource could supply the whole or a substantial part of the electrical energy demand in several countries as e.g. Ireland and Portugal (CEC, 1992b) whereas in isolated islands and remote areas and the conversion of a small fraction of the available resource could meet the whole electrical energy demand.

5.2 Technology

The large number of different concepts under investigation at present in various parts of the world suggests that the best technology has not yet been identified. Prototypes of just a few types have been tested at sea, and the first power plants claiming commercial viability have recently been or are being built. The first device to attain widespread commercial application in the 1960s is a navigation buoy developed in Japan based on the oscillating water column device (see below).

Several ways of classifying wave energy devices have been proposed, based on energy extraction method, size of the device, etc. As in CEC (1992b), the method adopted here uses the location of the device with respect to the shoreline: *shoreline devices, bottom-*

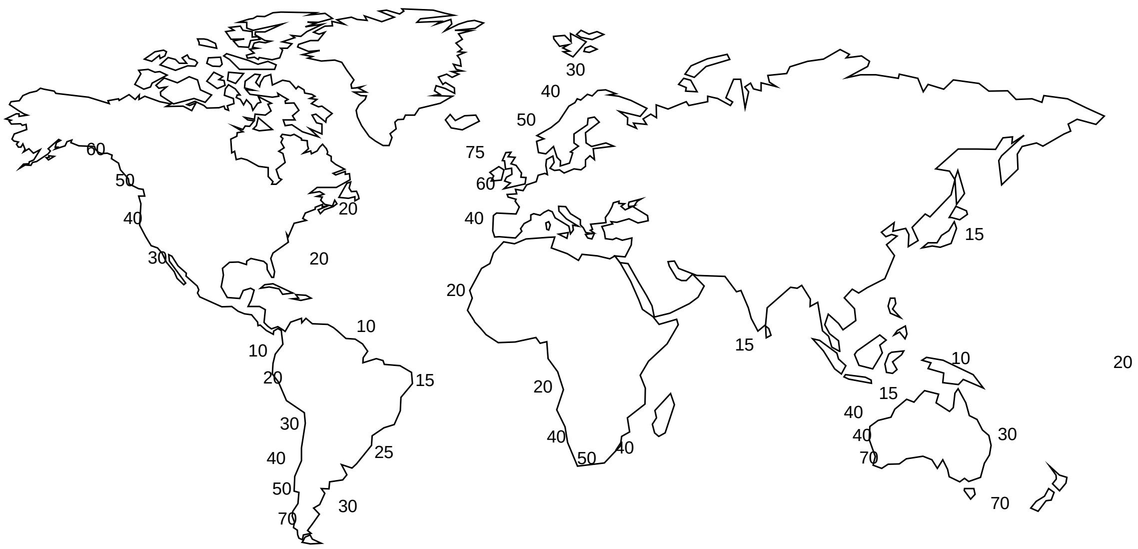
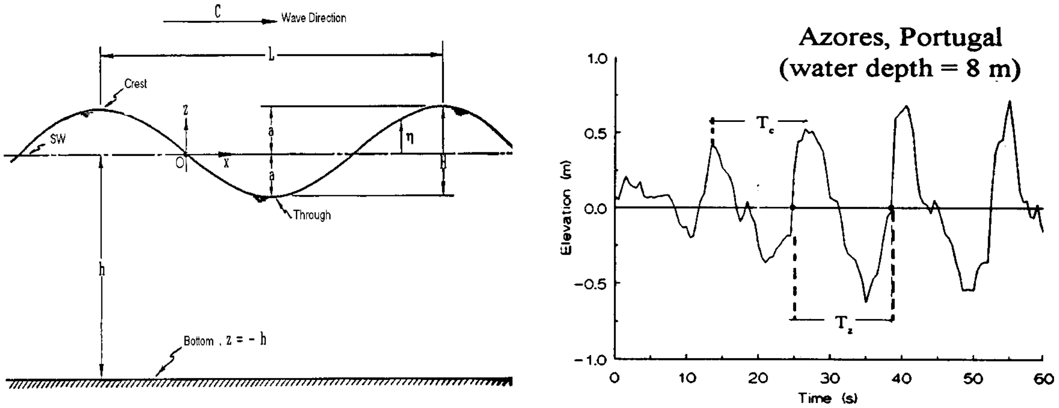


Fig. 7. Global distribution of offshore annual wave power level in kW/m .



a) b)

Fig. 8. Sea surface elevation a) ideal sinusoidal wave; b) real sea.

fixed near shore devices and *offshore devices*. Only devices that have been demonstrated or are near the demonstration stage will be considered here.

Shoreline devices have the advantage of easier maintenance and installation and do not require deep-water moorings and long underwater electrical cables. The less energetic wave climate at the shoreline can be partly compensated by natural wave energy concentration due to refraction and/or diffraction. The main devices are the oscillating water column (OWC) and the convergent channel (TAPCHAN). The Pendulor is another shoreline (or bottom-fixed near shore) device.

The OWC device comprises a partly submerged concrete or steel structure, open below the water surface, inside which air is trapped above the water free surface. The oscillating motion of the internal free surface produced by the incident waves makes the air to flow through a turbine that drives an electric generator. Figure 10 shows a schematic diagram of this device**.** The axial-flow Wells turbine, invented in the late 1970s, has the advantage of not requiring rectifying valves. It has been used in almost all the prototypes.

The TAPCHAN comprises a gradually narrowing channel with wall heights above mean water level as shown in Fig. 11. As the waves propagate down the channel, the wave height is amplified until the wave crests spill over the walls to a reservoir which provides a stable water supply to a conventional low-head turbine. This is considered a relatively mature technology.

A shoreline or near shore device named “Pendulor” (Fig. 12), based on a pendulum or oscillating flap acted upon directly by the waves, has been under development (including models tests at sea) for a number of years in Japan (Watabe et al., 1999). Plans for construction of a 150 –250 kW system in Sri-Lanka have been developed

Bottom-fixed near shore devices would be situated in shallow waters (typically 10 to 25 m water depth). The OWC is again the main type of bottom-fixed near shore device. A way of building the power plant at marginal costs consists in incorporating it into a breakwater whose primary purpose is harbour or coastal protection. This approach was adopted in the port of Sakata, Japan and in Trivandrum, India. In both cases, the structure of the air chamber was built of concrete as a floating caisson, which was towed and sunk in position on a prepared seabed.

Offshore devices exploit the more powerful wave regimes available in deep water (typically more than 40 m water depth). Although some floating devices have shown good prospects to be competitive with conventional electricity production, no offshore device has yet been demonstrated at full scale but reduced models of some have been temporarily deployed in the sea.

In order to extract energy from the waves, the device needs to be at or near the water surface and requires flexible moorings and underwater electrical transmission cables. In most cases, its main element is an oscillating body that either floats or is submerged near the surface. Several ways have been proposed to convert the oscillating motion of the body into useful mechanical energy. These may involve hydraulic pumps or rams incorporated into, or acted upon by, the moorings. Examples of such devices are the Swedish hose pump device (Fig. 13) described by Sjostrom (1993) and the Danish Wave Power device (e.g Nielsen and Plum, 2000).

Another type is the Archimedes Wave Swing that consists of a cylindrical, air-filled chamber (Fig. 14) (Rademakers et al., 1998) in which the oscillating motion of a “floater” (an air-filled chamber which ensures buoyancy) with respect to the bottom fixed basement, is directly transmitted to a linear electrical generator. The up and down movement of the floater is caused by the change of its buoyancy due to the alternate compression and decompression of the air inside it as waves pass.

The Pelamis device is composed of cylindrical sections linked by hinged joints which move with respect to each other in the waves. Energy is extracted at the joints by hydraulic rams which drive electrical generators (Yemm et al, 2000). A device rated 375kW is being developed for Scotland.

Another floating system is the “Mighty Whale” based on an OWC device that also makes use of hull motion for wave energy absorption. It was developed in Japan (Hotta et al., 1995).

Alternately floating devices may involve the use of a gyroscope to provide an inertial reference frame for a hydraulic power take-off mechanism, as in the famous Edinburgh duck, **(**e.g. Thorpe, 1992).

The above devices are intended for electricity production but desalination is another important use of wave energy devices. The floating McCabe wave pump (see Fig.15) was designed for fresh water (by reverse osmosis) and/or electrical energy production for remote communities. Energy is extracted from the rotation of the pontoons about the hinges by linear hydraulic pumps, which pressurise a closed loop oil hydraulic system that drives generators, and/or an open loop sea water system that drives a turbine and generator. A 40m-long prototype has undergone sea tests in Ireland (Kraemmer et al., 2000).

5.3 Demonstration Plants

Full scale prototypes of shoreline and near shore devices have been tested in the sea since 1985.

A 500 kW shoreline OWC prototype was installed at Toftesfallen, in Norway, but was destroyed by storm three years later (White, 1989)**.** A prototype rated 75 kW was operational from 1991 to about the end of this decade at the island of Islay, Scotland (Whittaker at al, 1993). This was followed by the construction in a nearby location of the same island of a commercial 500 kW plant OWC (LIMPET) that was also partially supported by the European Commission. A different in situ construction method was used for this plant (Heath et al, 2000) that started operation in late 2000. At the island of Dawanshan, in South China Sea, a 20 kW plant stated operation in 1991 (Yu at al., 1993)**.** Following this, another shoreline plant rated 100 kW is being constructed at Zhelang Town, Guangdong Province. Under the sponsorship of the European Commission, a prototype rated 400 kW connected to the local grid was constructed at the Azores islands, Portugal (Falcão, 2000).

Two near shore breakwater OWC devices have been built and tested in Japan and India. The Japanese one incorporated in the breakwater of Sakata, which became operational in 1989, was equipped with an undersized Wells turbo generator module of 60 kW used for experimental and monitoring purposes. The Indian plant was commissioned in 1991 and was equipped with a Wells turbo generator rated 150 kW (Raju et al., 1993).

A demonstration Tapchan device with rated output of 350 kW operated from 1985 to the mid-1990s in Norway. The construction in Java, Indonesia, of a 1.1 MW commercial plant (Tjugen, 1993) has started but was halted shortly after due to non-technical difficulties.

The construction of a 2 MW Archimedes Wave Swing prototype is underway and its deployment off Portugal is planned for summer 2001.

In Japan a 50m-long, 30m-wide Mighty Whale prototype, with three air-chambers equipped with 10 kW, 50 kW and two 30 kW turbo-generators, was tested from 1998 to 2000 at Gokasho Bay, Mie Perfecture.

5.4 Economics and Environmental Impacts

It is difficult to realistically estimate the unit costs of electrical energy produced from the waves since the few existing schemes have been prototypes with the additional costs incurred by such a stage of development. However the estimated costs have shown a steady decrease with time, despite the little financial support received in recent years. It should be noted that the cost of energy produced is a function of local wave climate and, in the case of shoreline devices, is site specific. The costs of a number of devices have been evaluated in the last UK review of wave energy, as reported by Thorpe (2000). This review shows that there have been significant reductions in the predicted generating costs of devices. It appears that several devices have already the potential to provide cheaper electrical energy for small islands and remote coastal communities that depend on expensive Diesel generation.

Wave power generation is generally considered environmentally benign. For shoreline power plants, the main negative impacts are visual intrusion and noise from air turbines. Nearshore and offshore plants may constitute obstacles to coastal marine traffic and, when deployed in large numbers, may promote modifications to coastal dynamics. Other impacts, namely on the ecosystems, on fishing and on recreation and tourism may occur. Most of these burdens can be minimised and, in some cases, eliminated.

A detailed environmental cause-and-effect study of any intended deployment should be required. A strategy for the assessment and quantification of environmental impacts needs to be developed.

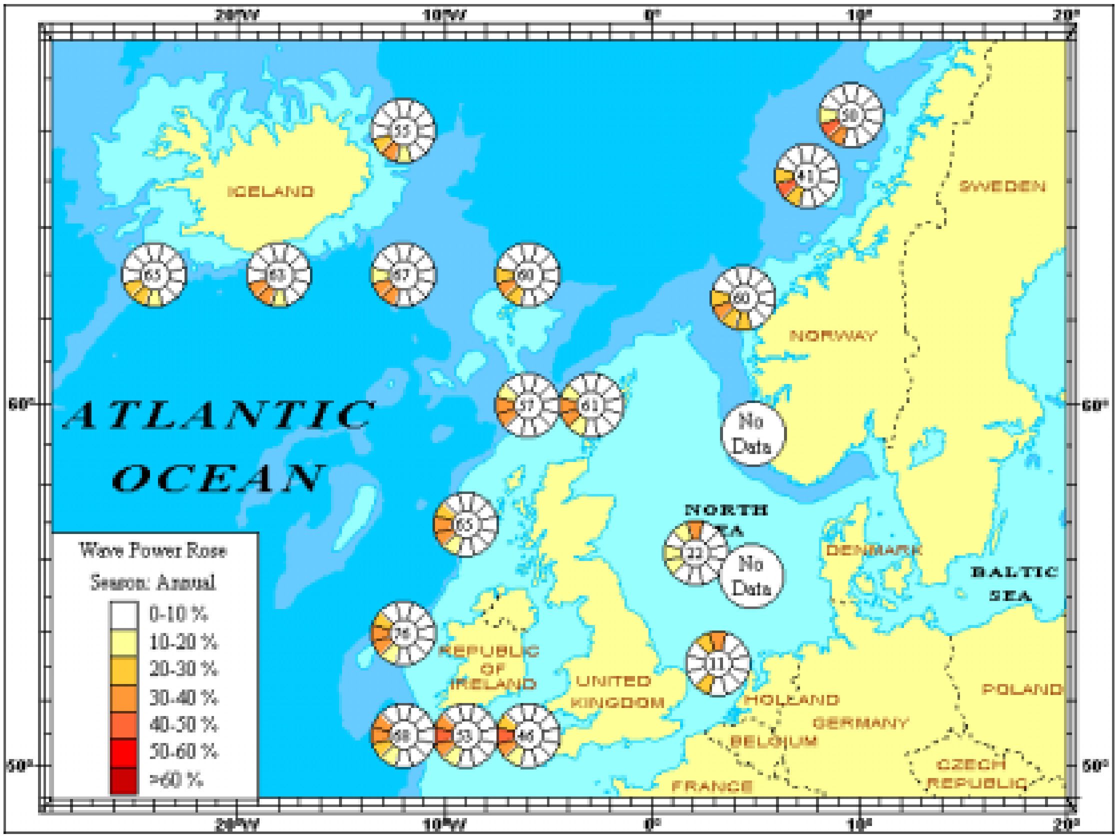


Fig. 9. Annual power level and its directional distribution off Europe´s Northeastern Atlantic coasts (from WERATLAS, Pontes et al. 1998).

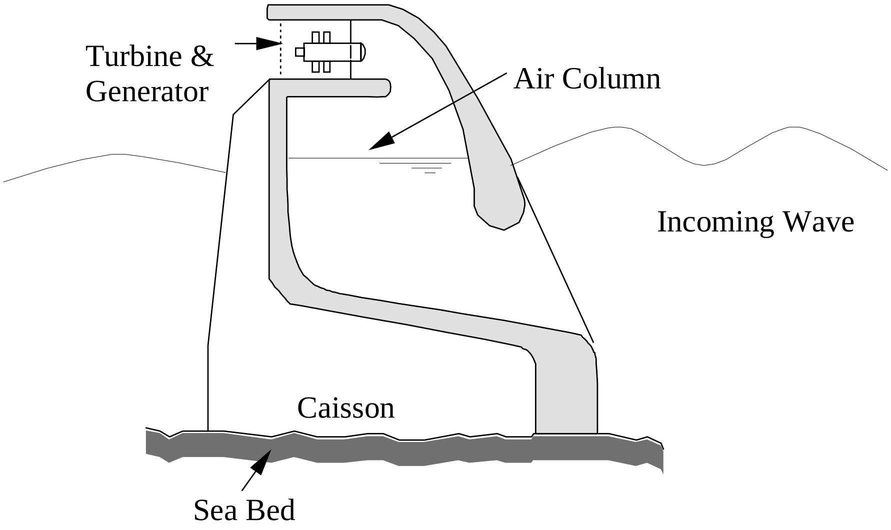


Fig. 10. Oscillating Water Column device.

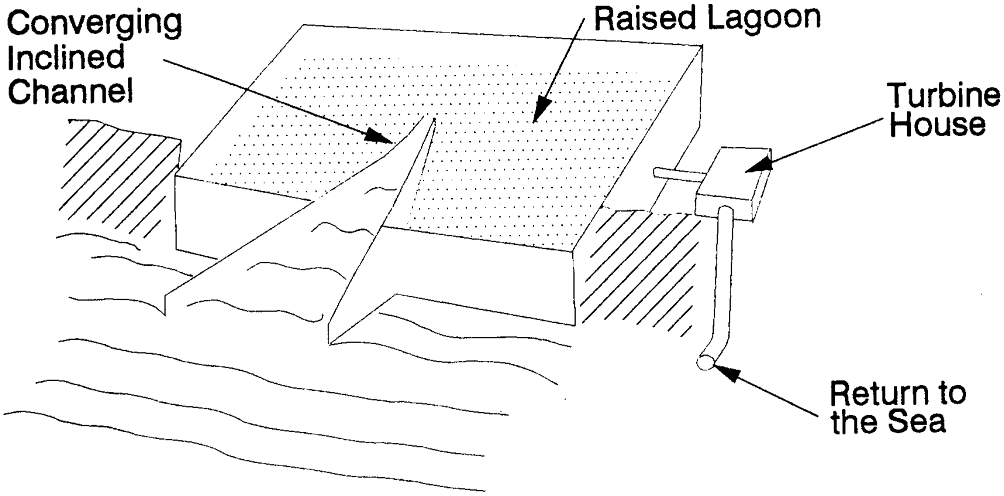


Fig. 11. TAPCHAN device.

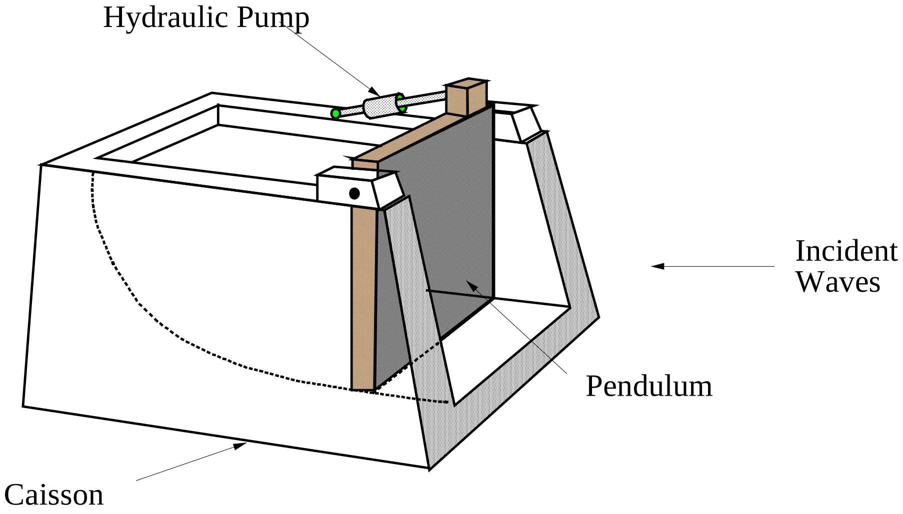


Fig. 12. Pendulor.

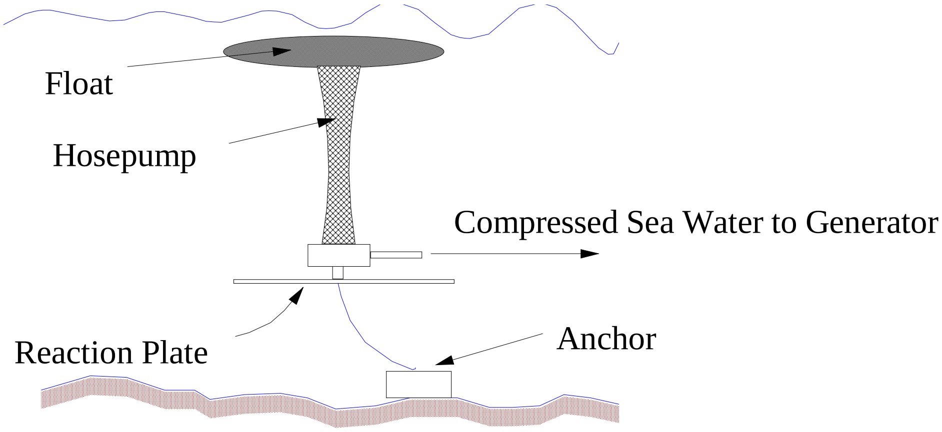


Fig. 13 Hose Pump.

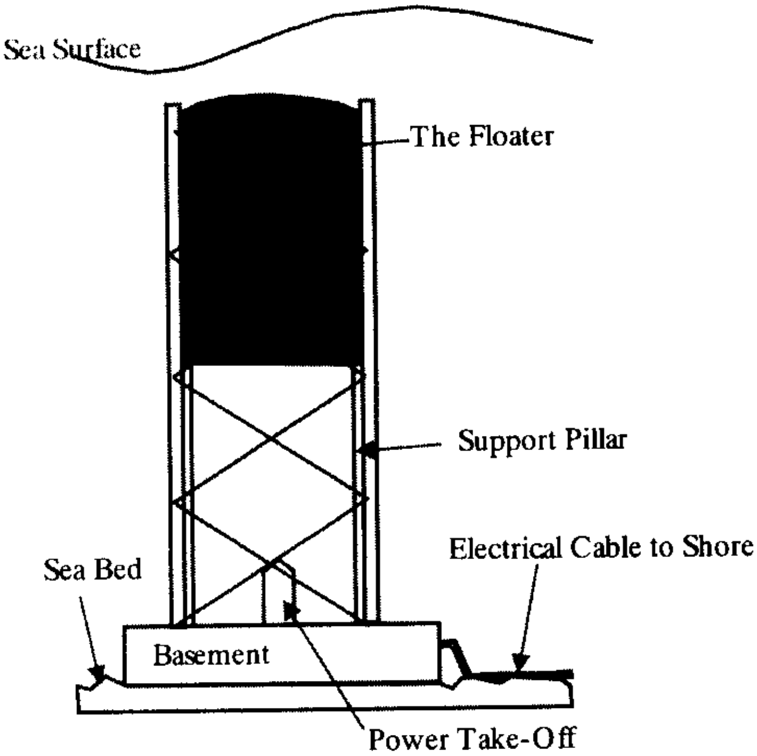


Fig. 14 Archimedes Wave Swing.

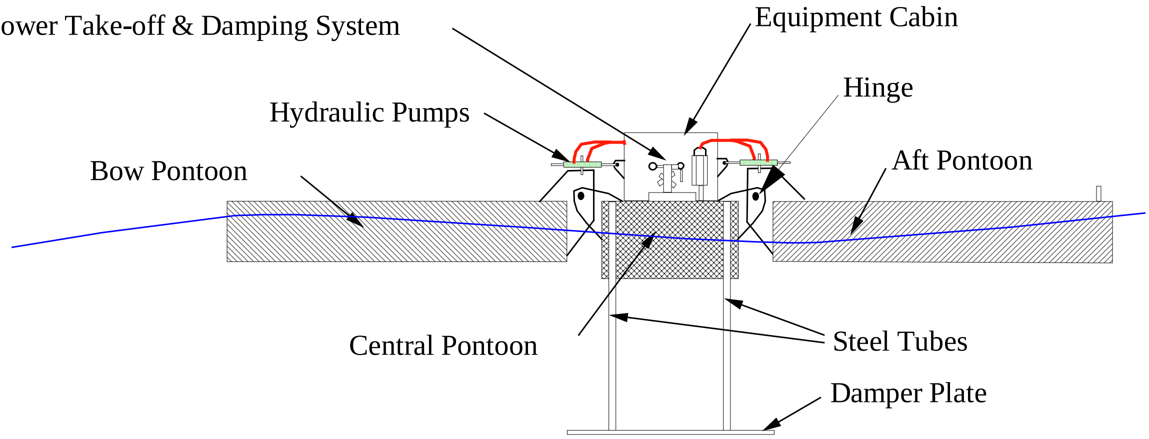


Fig. 15. McCabe wave pump.

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