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# WAVES, CURRENTS, TIDES—PROBLEMS AND PROSPECTS

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**Abstract**—A quantitative estimation of the energy potential of ocean surface waves, ocean currents and tides and a review of the techniques for utilizing these renewable energy sources, their present state of development and their economic and environmental aspects are presented. The potential of wave power, which is in the order of 1–10 TW, could become a significant source of energy in regions of the world with favorable wave conditions, such as the United Kingdom and Japan. All wave-power schemes investigated today are in an early stage of development, and require more research to become commercially available. The prospects for utilizing ocean currents are relatively unattractive due to the small resource base and the possible environmental effects. Although tidal mills have been used since the eleventh century, today only one sizable tidal power plant has been built, the 240 $MW_e$ Rance Tidal Power Station in France. The overall potential of tidal energy is about 3 TW, but only in certain locations of the world do the natural conditions promise technical and economic viability.

## 1. INTRODUCTION

Energy sources and the frightening prospect of a strife-torn world with severe energy deficiencies together form one of the major concerns of mankind today. Although energy derived from oil and gas will play a vital role in meeting a growing demand for many years to come, the rising price of oil and the realization of the exhaustive nature of the world's oil and gas resource base have focused a lot of interest and effort on harnessing unconventional energy sources such as geothermal, tidal, and solar energy. The last of these includes energy derived directly from sunlight as well as indirectly from wind, waves, ocean currents, running water, ocean thermal gradients, or as fuel from biomass. The theme common to these potential sources of energy is that they are renewable sources. They are virtually inexhaustible energy flows and not depletable energy stocks. Another feature they have in common is that they are not now in widespread commercial use (except the running water source) and that, in the public energy discussion, they are often referred to as the only ultimate energy resources for mankind.

This paper is concerned with the prospects and problems of three of these renewable energy flows, that is, waves, ocean currents and tides. In order to estimate the impact these resources may have on the world's energy supply within the next several decades, it is necessary to discuss the potential supply of these sources, the technologies and systems that are currently being considered as means for utilizing them, their economics and their environmental effects.

As a point of reference, one should bear in mind that today's world energy consumption is in the order of 9 TW-years/yr, which corresponds to nearly $10.10^9$ tonnes coal equivalent (tce)/yr. As the world's population continues to increase and as a higher standard of living leads to increasing per capital demand for energy, it is estimated that world energy demand will rise to $30.10^9$ tce/yr in the year 2020.

## 2. WAVE POWER

Although only recently the subject of serious investigation, wave power is by no means a new concept. Hundreds of wave machine designs have been invented during the last 200 yr. It is estimated that since 1856 over 340 patents were granted in the

United Kingdom and 59 U.S. patents had been given on wave power utilization by 1972.[1,2] Devices for harnessing wave energy may be classified into four groups:

- propulsion schemes,
- buoy power supply devices,
- offshore power plants, and
- shore-based power plants.

Today wave energy is only used on a small scale to power buoys. The average power output of these systems ranges from 70 to 120 W. The engineering challenge for harnessing wave energy in power plants of several hundred kilo- and megawatts is to find a cost-effective way to convert a fraction of the large amount of energy contained in wave motion under the inhospitable conditions existing in the open sea. Of the hundreds of schemes which have so far been proposed for utilizing wave power, three of these devices are briefly described next.

Salter proposed a specially contoured rocking device to extract as much as 80% of the wave power contained in the band of water above its depth of immersion.[3,4] The Salter device (Fig. 1) consists of a number of "duck-shaped" segments rotating about a common backbone. The rear surface of each duck is a cylinder coaxial with the center of rotation so that when the vane moves there is no displacement of the water behind it. The front curve is designed to match the displacements of water in approaching waves. The natural "nodding" period coincides with the wave period. The oscillation of the vane is used to provide high pressure water to power a hydraulic turbine by means of a specially designed pump. A common backbone for about 40 vanes is provided by a composite cylindrical tube containing the hydraulic network. The ends of the tubes are joined to vertical plies which house trim tanks, ballast and machinery. Since the Salter device is designed to operate in a free-floating mode, the power transmission systems presents some problems to be solved.

A number of wave power devices work on the principle that the wave motion inside an inverted box can force air into and out of an orifice at the top of the box. The displacement of air is then used to drive an air turbine. Masuda proposes use of this mechanism in very large, floating buoys.[5] The principle design is shown in Fig. 2. The air in the two separated air chambers is expanded with a falling wave and compressed with a rising wave. In both cases, the turbine is driven by the flow of air between the two air chambers. Japan has recently built a large-scale wave power test facility of this pneumatic type. It is a boat-shaped buoy, 18 m long, 12 m wide and houses 22 pneumatic chambers, each about 25 m$^2$ in area.

Figure 3 shows the construction principle of a hydroelectric wave generator proposed by Kayser.[6] In this concept, a taut line mooring keeps a buoy in position below the wave surface and fluctuating wave pressure acts on a large piston which drives a small piston. Thereby the large volume low-pressure water is reduced into a small volume

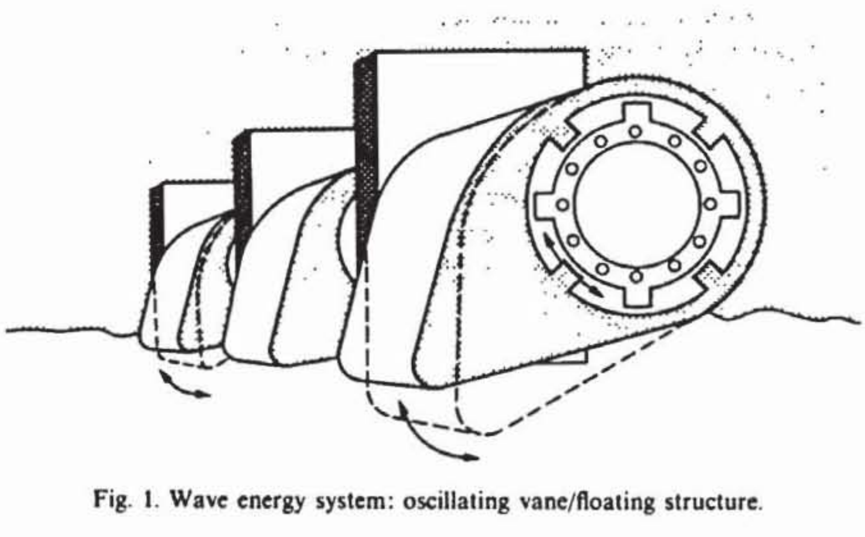

Fig. 1. Wave energy system: oscillating vane/floating structure.

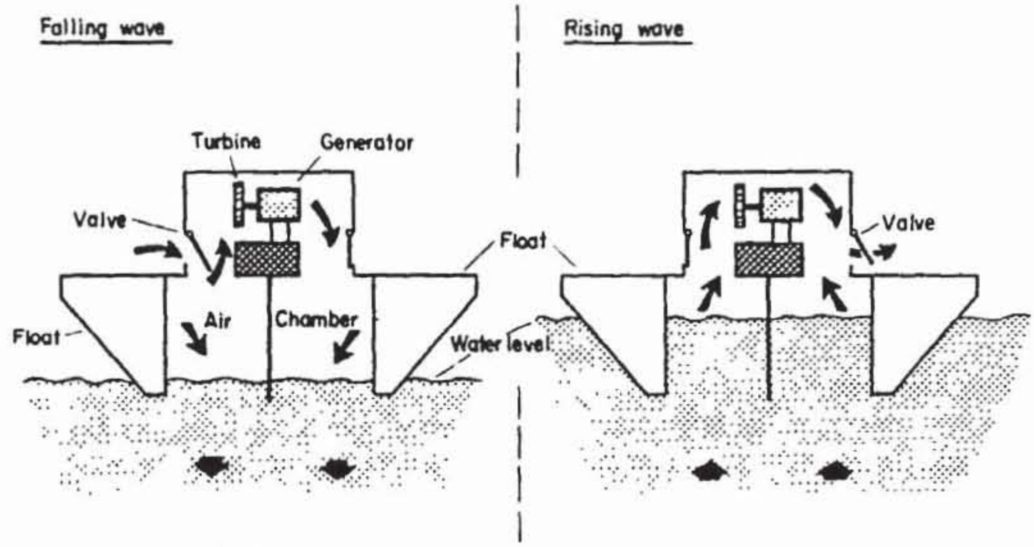


Fig. 2. Wave energy system: pneumatic wave converter.

of high-pressure water. That small volume of water can be stored in a high-pressure water supply reservoir to be converted to electric power through a pelton turbine. The reservoir allows a continuous running of the turbine. A wave generator of this type with a diameter of 2 m can produce an electric output of about 1 KW.

The characteristic of wave power to vary with time poses several design optimization problems to ensure a constant power output of the device over periods of time. Another challenging engineering problem is the occasional occurrence of very high waves, which the power plant must be able to survive. Generating power from sea waves seems technically feasible and a broad variety of different devices have been proposed, but they all require research and development before they can become commercially available.

Since, for most wave power schemes, neither detailed designs are available nor demonstration projects are in operation long enough, reliable cost estimates cannot be given. An assessment study on the economic and technical feasibility of the large-scale generation of electricity from ocean wave in the United Kingdom, completed in 1976, concluded:

The (cost) estimates produced by this study and others indicate that wave-generated

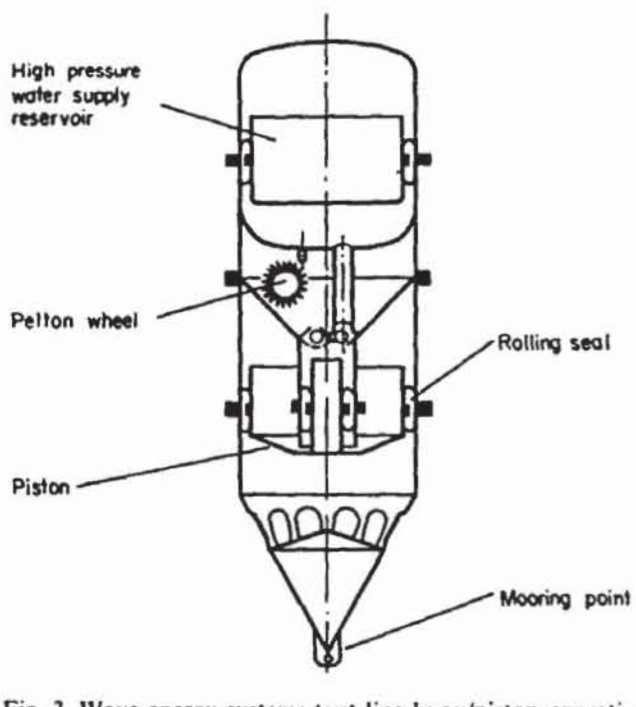


Fig. 3. Wave energy system: taut line buoy/piston operation.

electricity is likely to be more expensive than nuclear-generated electricity but possibly by no more than a factor of 3, not by an order of magnitude. Without further design and development work it is not possible to be more precise than this.[1]

Because there are no large-scale wave power stations existing today it is very difficult to assess the environmental effects of harnessing this energy source. In significant numbers, wave power stations could cause problems in existing fishing operations but might provide the benefit of drawing fish to them. There are possibilities that such structures, not far from the shore, could have significant effects on coastal erosion, deposition and seawater turbidity.

Waves are generated by large-scale wind systems which, in turn, are derived from solar energy. The sea acts as a large collecting area and the inertia of the water provides short-time storage which dampens the effects of variations in the speed of the wind. The total wave energy of the world's oceans has been estimated to be $27.3.10^9$ tce, which is nearly three times today's world energy consumption. The energy input rate from the sun by waves due to wind is estimated to be in the order of 1–10 TW, compared with the present world energy consumption of about 9 TW. The energy in a train of seawaves can be calculated by considering the potential and kinetic energy of the waves. Based on observed wave data, Panicker calculated the wave energy and power for the northern hemisphere.[2] He found that the longitudinal distribution of wave energy and wave power has two main peaks, one in the Atlantic and one in the Pacific, both at the eastern end of the ocean basin. Detailed analysis of wave energy available at various locations off the coast of the United Kingdom have shown remarkable differ-

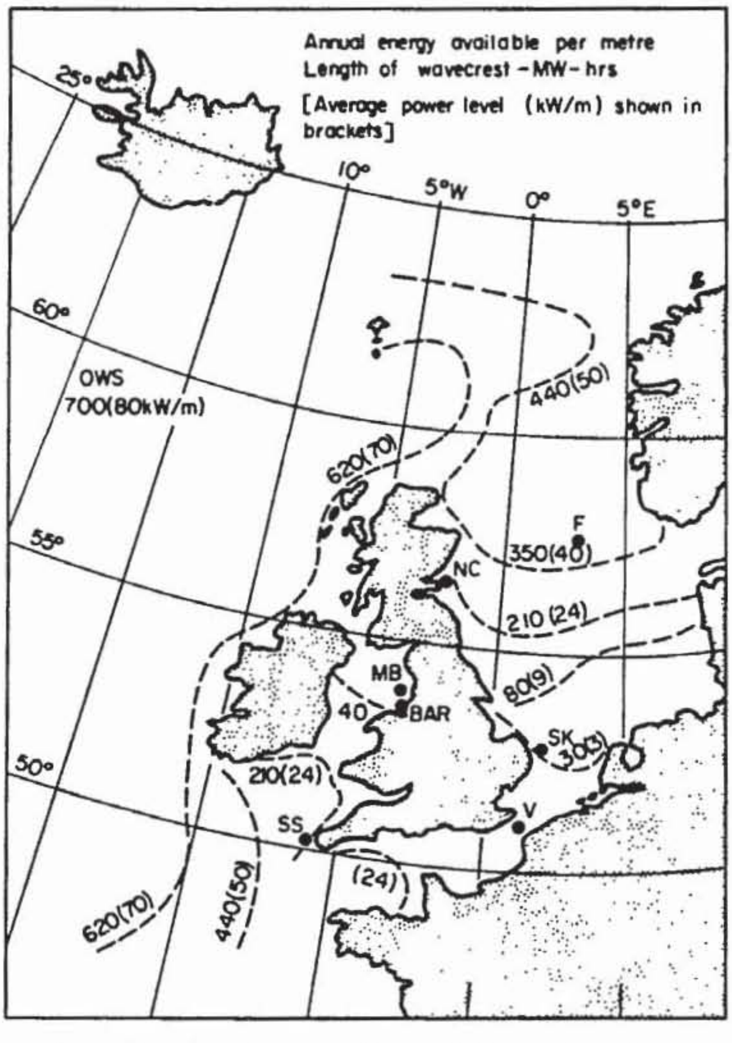


Fig. 4. Annual energy availability in British coastal water.

ences due to location. Figure 4 shows isoquants of annual energy available per meter length of wavecrest in different areas around the British Isles. The figures given in brackets are the average wave power level in kW/m of wavecrest.

The highest wave energy levels occur where the Atlantic approaches the British Isles, excluding south-west England. Here the average energy available per meter length of wavecrest is more than twice as high as in the North Sea. The levels of wave energy in the U.S.A., Canada, Japan, and Australia are roughly the same as in the North Sea.

As already mentioned, the available wave energy has a great variation over the year, with a maximum in winter when consumption is also at its highest. There is, however, a greater variation in wave energy available than energy demanded. The result is that there would either be a shortfall of energy in summer or a theoretical excess in the winter. Therefore the wave power systems either require a backup or must be integrated into the interconnected supply grid.

The energy contained in ocean waves is enormous and, if suitably harnessed, wave power can be shown to be technically feasible, it could become a significant renewable source of energy in certain regions of the world with favorable wave conditions, such as the United Kingdom. For the time being, large-scale devices are not available, but major research and development programs are under way in the United Kingdom and Japan.

## 3. OCEAN CURRENTS

Ocean currents arise as a result of temperature differences between the poles and the equator and as a result of the rotation of the earth. The kinetic energy of these currents may be harnessed in a similar way to wind energy. Of the large number of ocean currents which are present, the Gulf and Mozambique currents have the largest velocities and would thus be the most suitable for energy production.

In order to assess the energy production capabilities of ocean currents, it is necessary to examine their energy potential. Since the Gulf Stream has the highest velocity, it is taken as an example. The central region of the Gulf stream is 50 km wide and has an average depth of 120 m. For velocities of 2 m/s, calculations show the current power to be 24 GW.[7] Part of this energy could be used to drive water turbines. Assuming the turbine has a 40% efficiency and that 20% of the energy content of the Gulf Stream is an upper limit to that which may be extracted on ecological grounds, only about 2 GWe electrical power could be produced. This estimate clearly serves to show that ocean currents could not provide us with a solution to the energy problem. In addition, the disruption of the ocean currents may have drastic consequences on the climate. In this way, the Gulf Stream, for example, is particularly important for North Europe.

## 4. TIDAL ENERGY

As early as the eleventh century, there were tidal mills operating in Europe. Such mills were used for mechanical power only to work grain mills and to pump water. Tidal mills also existed in the United States. The National Park Service recently restored one in Massachusetts.[8] Slade's Mill, built in 1734 and still in existence, provided up to 375 kW and was used to grind spices.

Tidal mills draw on a complex energy system involving the rotation of the earth and the gravitational pull of moon and sun. The tides rise and fall twice every 24 hr and 50 min, which is the approximate period of rotation of the moon. Because of these 50 min, the maximum water level will not occur at the same time on consecutive days.

Moreover, the tidal amplitude varies daily. It reaches a maximum every 2 weeks when the moon and the sun are in conjunction. This event is called a "spring" tide. When the sun and the moon are at right angles with the earth the tide has a minimum amplitude and is called a "neap" tide. The actual local amplitude of the tide, however, is mainly determined by coastal geography which can set up an acute resonance that acentuates the tidal amplitude. Under favorable conditions (which are found only at a few locations on earth) the "spring" tide range may exceed 15 m. In the open sea the tidal range is usually less than 1 meter. The energy of the tides is dissipated as heat due to friction. It is derived from both slowing down the earth's rotation and increasing the distance of the moon from the earth. Currently, the length of the earth day is increasing by approximately 20 $\mu$sec per yr and the moon's orbit is expanding by about 3 cm per yr.[9] From these figures, the energy dissipated through the tide is calculated to be 2.6–3 TW, which is one third of today's world's power consumption.

Only a small fraction of this tidal energy potential can be harvested at a relatively limited number of locations in the world where the tide amplitude is large enough to permit practical and economic use of tidal power. Figure 5 shows coastal regions with an average tidal range greater than the 3 m, which is required to assure technical feasibility, and regions with a tidal range of more than 5 meters.

In the past, several possible sites for tidal power stations have been investigated in greater detail. Figure 6 lists the most important of them.[10] All sites listed in Fig. 6 represent an average hydraulic power of about 0.06 TW, of which only a maximum of 25% could be converted to electricity.

On several occasions since World War 1, consideration has been given to potential tidal power development and sites in the Bay of Fundy bounded by the Provinces of New Brunswick, Nova Scotia, and Maine on the Atlantic coast of Canada and the United States. The most recent assessment of tidal power in the Bay of Fundy[11] was carried out in the period 1975 to 1977. Thirty potential sites were investigated and the study has led to the conclusion that the development of tidal power sites in Cumberland Basin is economically feasible. Cook Inlet, Alaska, is another possible site for harnessing tidal power in North America.

German engineers have studied the San José Gulf in Argentina as a potential site for a productive tidal plant. At this time all schemes remain in the blueprint stage.

In Europe, France has a remarkable number of possible tidal power plant sites. The only sizable tidal installation in the world today is in France, on the estuary of the River Rance near Saint Malo. Other sites have been considered but there are no concrete

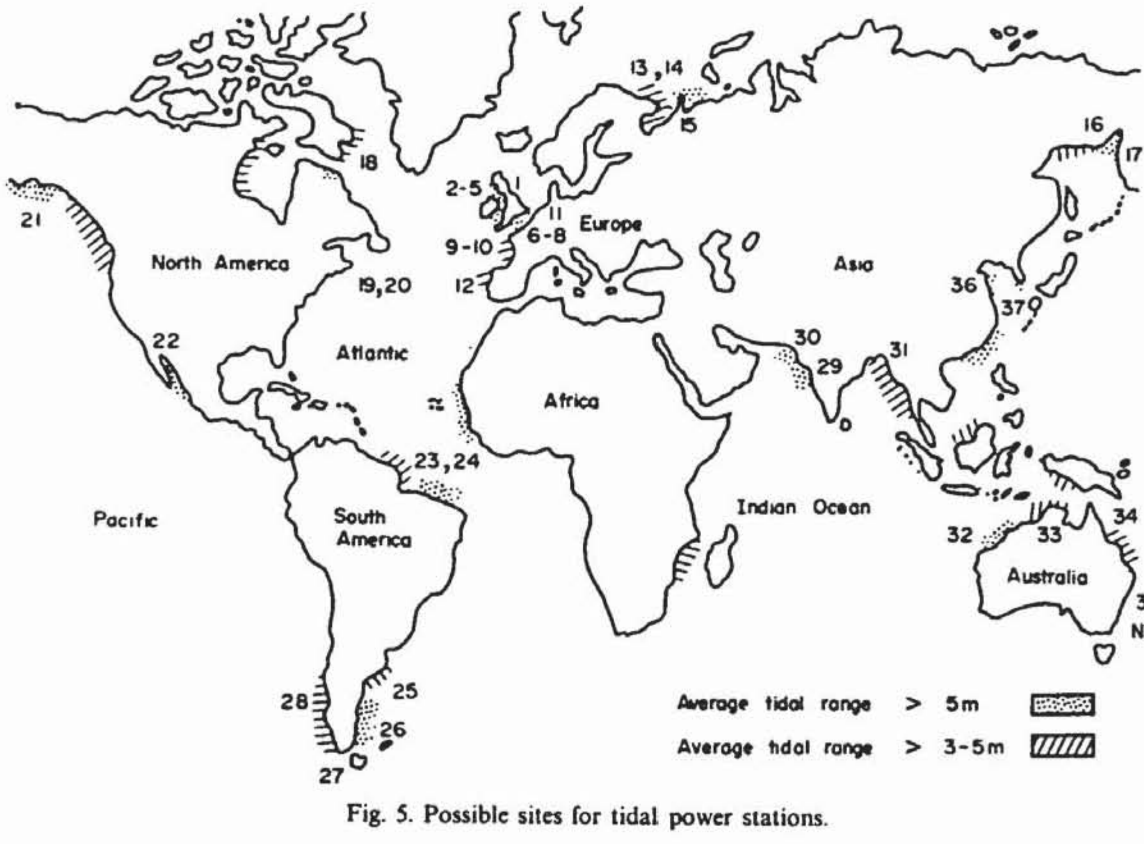


Fig. 5. Possible sites for tidal power stations.

| Location | Average Tidal Range m | Hydraulic Energy ($10^9$ kWh/yr) |
|---|---|---|
| North America | | |
| Bay of Fundy | | |
| Passamaquoddy | 5.5 | 15.8 |
| Cobscook | 5.5 | 6.3 |
| Annapolis | 6.4 | 6.7 |
| Minas-Cobequid | 10.7 | 175.0 |
| Amherst Point | 10.7 | 2.25 |
| Shepody | 9.8 | 22.1 |
| Cumberland | 10.1 | 14.7 |
| Petitcodiac | 10.7 | 7.0 |
| Memramcook | 10.7 | 5.2 |
| Cook Inlet, Alaska | | |
| Knik Arm | 7.5 | 6.0 |
| Turnagin Arm | 7.5 | 12.5 |
| South America | | |
| Argentina | | |
| San Jose | 5.9 | 51.5 |
| Europe | | |
| England | | |
| Severn | 9.8 | 14.7 |
| France | | |
| Aber-Benoit | 5.2 | 0.16 |
| Aber-Wrach | 5.0 | 0.05 |
| Arguenon/Lancieux | 8.4 | 3.9 |
| Frenaye | 7.4 | 1.3 |
| La Rance | 8.4 | 3 1 |
| Rotheneuf | 8.0 | 0.14 |
| Mont St. Michel | 8.4 | 85.1 |
| Somme | 6.5 | 4.1 |
| USSR | | |
| Kislaya Inlet | 2.4 | 0.02 |
| Lubovskii Bay | 4.2 | 2.4 |
| White Sea | 5.7 | 126.0 |
| Mezen Estuary | 6.6 | 12.0 |
| Σ | | 578.02 |

Fig. 6. Tidal power sites.

plans for a second plant. Russia also has a remarkable tidal power potential. The White Sea alone has a hydraulic energy potential of 126 billion kWh/yr.

As already mentioned, the period of the tide is 12 hr and 25 min. As a result, the output of a tidal plant is constantly shifting in and out of phase with the demand for electric power. Another obvious problem is the irregularity of the tides caused by the rising and setting of the sun. There are two operating principles for tidal power plants. In a single way operation, the sluices are opened on the flood tide to fill the basin (see left part of Fig. 7). At high tide, the sluices are closed and the ebbing sea level gives rise to a head between the basin and sea level. Energy is produced when the basin is emptied into the sea. By pumping when the basin and sea levels are about the same, relatively little energy is needed to lift the water level of the basin. This added water, during the subsequent operating cycle, falls through a greater head and produces more energy than was consumed in pumping. Pumping therefore improves the operation of a tidal plant. If generation is permitted on both the ebb and the flood tide, the operating mode is "double effect". This requires a reversible turbine which, in the case of pumping, must also be able to pump in both directions. The double effect operation scheme is illustrated in Fig. 7.

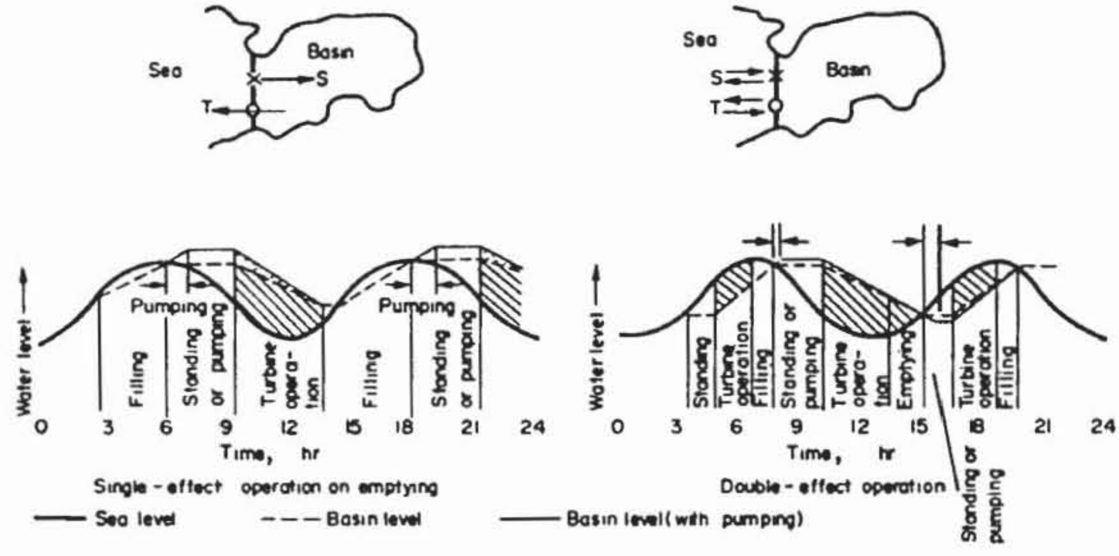


Fig. 7 Double and single acting cycles-operation mode.

Two tidal stations operate commercially at this time, one small experimental unit of 800 kW at Kislogubsk in the U.S.S.R. and a 240 $MW_e$-installed power plant at La Rance in France. The Rance Plant is located in the north-western part of France near St. Malo and has been operating at full capacity since 1968.[12] With the excellent natural conditions an equinoctial spring tide reaches an amplitude range of 13.5 m.

The Rance dam, which retains a water volume of about $184.10^6$ $m^3$ and is 750 m long, forms a basin with an area of 22 $km^2$. The three essential elements of the Rance Tidal Power Plant can be seen from Fig. 8. On the left is a lock for fishing boats. Next to this is the power station with 24 units each of 10 MW capacity, followed by a dike and a sluice section. The power station consists of a hollow concrete structure, acting as a dike. Fig. 9 shows a cross section of the power station. The unit consists of a horizontal-shaft Kaplanturbine connected to a generator and housed in a metal bulb-shaped casing which is supported by fixed-stay vanes in a 53 m long horizontal conduit. The set may be operated for pumping as well as for power generation, and for each case in both directions. The net output of the power plant is about 500 GWh per yr. This results in a full capacity load factor of 2000 hr per yr.

Although two tidal power plants are now in operation, general cost estimates cannot be given because the costs are site-dependent. The final construction cost of the Rance project was 470 million Francs (1968 value), i.e. 2375 Francs/$kW_e$. For the Cumberland Basin in the Bay of Fundy the latest cost estimates are 1140\$/$kW_e$, plant capacity (1976 dollars). Two environmental side effects are caused by tidal power plants. Usually they reduce the maximum level of the tide amplitude and, by damming off water ways, they affect fish life.

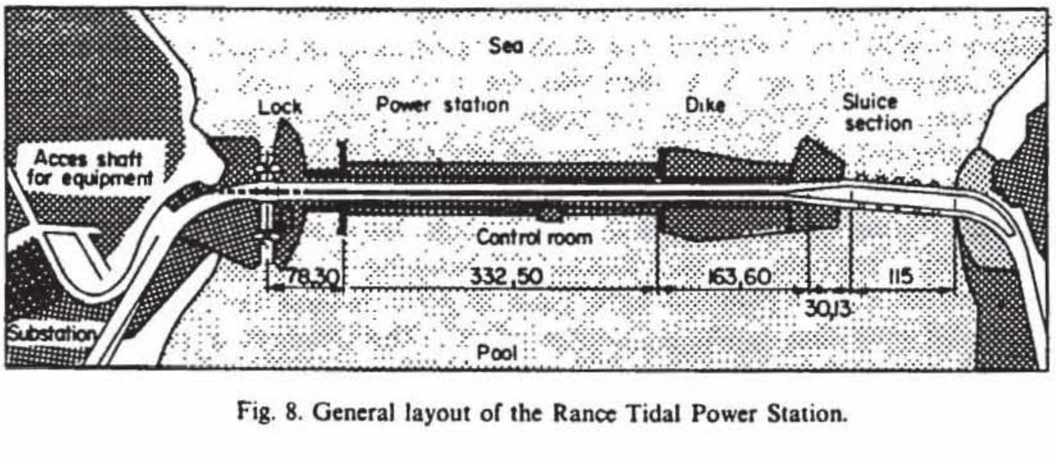


Fig. 8. General layout of the Rance Tidal Power Station.

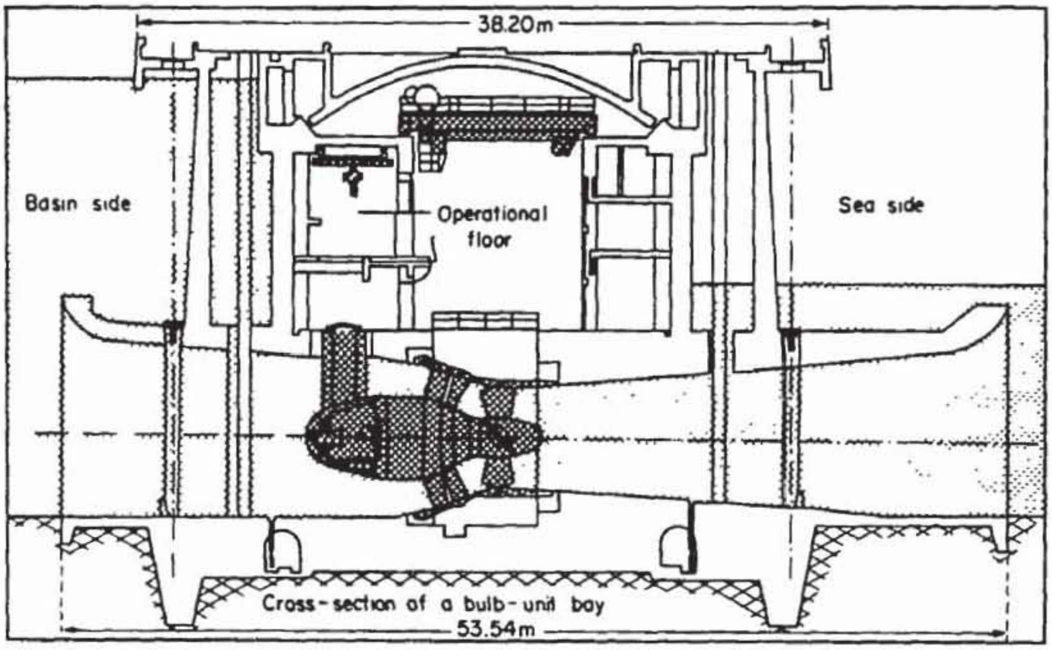


Fig. 9. Cross-section of the Rance Tidal Power Station.

## 5. CONCLUSIONS

The overall tidal energy potential of 3 TW, and the potential of locations where the necessary technical conditions of tidal amplitude to utilize tidal power are met, are too small to take over a major share of the needs for electricity. In certain favorable geographic locations, however, tidal power offers at least a modest potential for development beyond its present scope.

The prospects for utilizing ocean currents are relatively unattractive due to the small resource base and the possible environmental effects.

The energy potential of wave power is in the order of 1–10 TW and, if the continuing research efforts show that converting the energy in the waves into electricity is technically and economically feasible, it could become a significant source of energy in certain regions of the world with favorable wave conditions, such as the United Kingdom and Japan.

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