

Tidal Energy in Electric Power Systems

Shabana Sheth, *Member, IEEE* and Mohammad Shahidehpour, *Fellow, IEEE*

Electric Power and Power Electronics Center

Illinois Institute of Technology

Chicago, Illinois 60616

Abstract--This paper discusses the uses and advantages of tidal energy in restructured power systems. The paper defines the resources as well as the ways in which tidal energy is converted into electricity. The paper also reviews a few tidal power projects around the world. It also shows the working of hydro tidal power plant. A comparative review of renewable energy sources is presented and conclusions are outlined.

I. Introduction

The earth is filled with almost 75% water and it is conceivable that tides based on this pollution free source of energy would be very cost-effective for generating electricity. Tides are originated from the motions of the earth, the moon and the sun. Tidal energy exploits the natural rise and fall of coastal tidal waters caused mainly due to interaction of gravitational fields of the sun and the moon. Figure 1 shows how the gravitational attraction of the moon and the sun affect tides on earth. The magnitude of this attraction depends on the mass of the object and its distance away [1]. The moon has the greater effect on earth despite of having a smaller mass than the sun because it is so much closer.

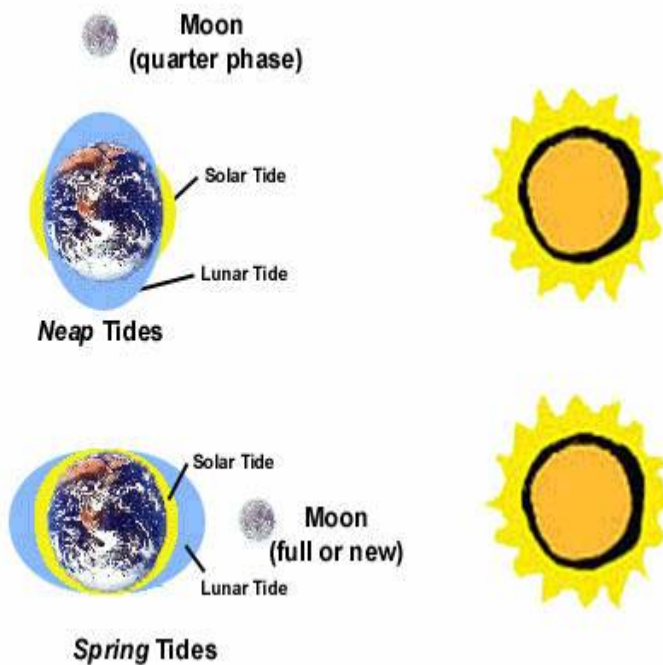


Figure1. Gravitational effect of the sun and the moon on tidal range (Adapted from Boyle, 1996)

The gravitational force of the moon causes oceans to bulge along an axis pointing directly at the moon. The rotation of the earth causes the rise and fall of tides. When the sun and the moon are in line their gravitational attraction on the earth combine and cause a "spring" tide. When they are positioned as in the Figure 1 at a right angle from each other, their gravitational attraction pulls water in different directions, causing a "neap" tide. Some coastlines may have high tides up to 11 meters and in some cases such as those in the Bay of Fundy located in Atlantic Canada, tides could reach as high as 17 meters.

II. Tidal Energy Resources

The technology required to convert tidal energy into electricity is very similar to that used in traditional hydroelectric power plants. The first requirement is a dam or "barrage" across a tidal bay or estuary. Building dams is an expensive process. Therefore, the best tidal sites are those where a bay has a narrow opening, thus reducing the length of dam. At certain points along the dam, gates and turbines are installed. When there is an adequate difference in the elevation of water on two different sides of the barrage, the gates will be opened and the hydrostatic head causes water to flow through turbines, turning electric generators to produce electricity.

Electricity can be generated by water flowing both into and out of a bay. There are two high and two low tides each day. Electricity is generated from tidal power plants every twelve hours, with no electricity generation at the six hour mark in between [2]. Alternatively, the turbines can be used as pumps to pump extra water into the basin behind the barrage during periods of low electricity demand. This water can then be released when demand on the system is greatest, thus allowing the tidal plant to function with some of the characteristics of a pumped storage hydroelectric facility.

Tidal power is a relatively unexplored resource. Sites that add up to 12,500 MW (48 TWh per year) in Europe alone have been noted. Many sites have average capacity factors (e.g., average output versus rated peak output) of 40 to 60 percent. Since tides are predictable, energy extraction times for planned base load power can be scheduled and energy capture rates could be much better than that of other intermittently available resources.

A. Environmental Impact

Energy from water is used for many centuries in water mills and water pumps. Water is a free resource and tidal plants are highly efficient (80%) as compared to fossil fuel plants

(coal/oil efficiency = 30%. Tidal energy is an abundant renewable resource and is pollution free. It can be produced every day and 365 days a year. Tidal energy's peak output coincides with peak energy demand which makes it a useful source of energy [3]. Use of tidal energy could also decrease the need for nuclear power with its associated radiation risks.

Tidal power is an attractive energy resource, not only because it is clean and available in unlimited quantities, but also because the vagaries of weather, unlike solar or wind power, do not affect its production. Tidal energy site can also offer improved transportation due to the building of rail bridges. Perhaps the largest disadvantages of tidal barrages are the environmental and ecological affects on local inhabitants. Making a dam at the bay or estuary can change the flow of tidal waves and affect the aquatic and shoreline life and even navigation. Creating a dam may cause flood in the region as the water level changes, and this could affect the vegetation around the coast as well as the aquatic life. Tidal energy barrages could modify existing estuarine ecosystems to varying degrees. Some pre-barrage intertidal areas could become permanently inundated and, although the intertidal zonation could change by time, it could still be present and capable of supporting an estuarine ecosystem. The post-barrage upstream intertidal range could be reduced to approximately a half.

Changes to the hydraulic regime will invariably change patterns of sedimentation, eventually leading to a shift in sediment (particle size) distribution. The sediment levels change in turn can affect the animals like fish and birds. To protect the fish, provisions are made to pass them through the barrage without being captured by turbines blades. All this can force the birds to migrate to other favorable areas. These effects are not all bad as they may allow different species of plants and creatures to flourish in an area where they are not normally found. There would be some sediment accumulation in the upstream of the barrage. The amount will depend on the position of the barrage. In estuaries like the Severn, with high sediment loads, this is an important consideration. For this reason the proposed downstream alignment offers an advantage because it would be less vulnerable to sediment accumulation [3]. As sites are not the same, it is difficult to generalize the environmental impact of tidal energy.

III. Generating Electricity from Tides

Tidal power production applies the same principles as hydroelectric power generation, except that tides flow in both directions and generators are designed to respond to two directional water flows [1].

The simplest generating system for tidal plants is the ebb generating system (Figure 2), which involves a dam, known as a barrage across a bay or estuary. Sluice gates on the barrage allow the tidal basin to fill on the incoming high tides and to exit through the turbine system on the outgoing tide (known as the ebb tide). Two way generation systems, which generate electricity on both the incoming and ebb tides are also possible. Accordingly, flood generating systems generate power based on incoming tides which are less favored than ebb generating systems.

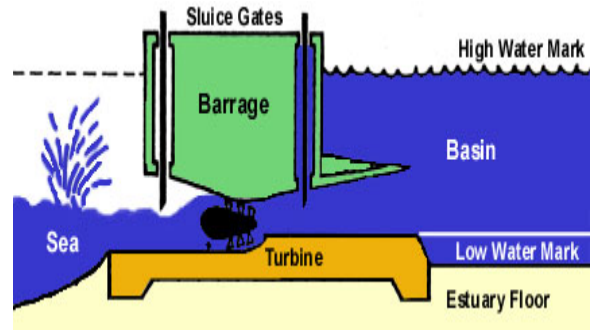


Figure 2. Ebb generating system with a bulb turbine (Energy Authority of NSW Tidal Power)

The following types of turbines are used for tidal power generation [1].

- **Bulb Turbine:** water flows around the turbine (Figure 3), which makes the maintenance difficult, as the water must be prevented from flowing past the turbine and into the generator. The La rance tidal plant near St Malo on the Brittany coast in France uses a bulb turbine.

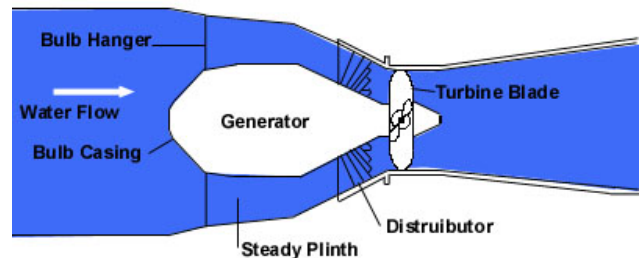


Figure 3. Bulb Turbine (Boyle, 1996)

- **Rim Turbine:** Rim turbines (Figure 4), also known as the Straflo turbine, reduces the problems encountered by bulb turbine as generator is mounted on the barrage at right angles to turbine blades. Despite that, it is difficult to regulate the performance of Rim turbines which are not unsuitable for pumping either. This turbine is used in Annapolis Royal in Nova Scotia.

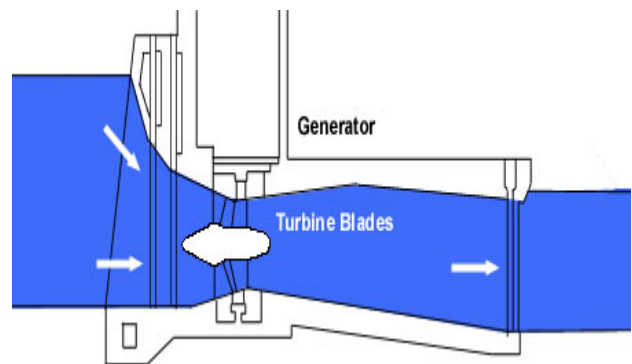


Figure 4. Rim Turbine (Boyle, 1996)

- **Tubular Turbine:** In this turbine (Figure 5), the generator is on the top of the barrage and the blades are connected to a long shaft. Tubular turbines are proposed for the Severn tidal project in the United Kingdom.

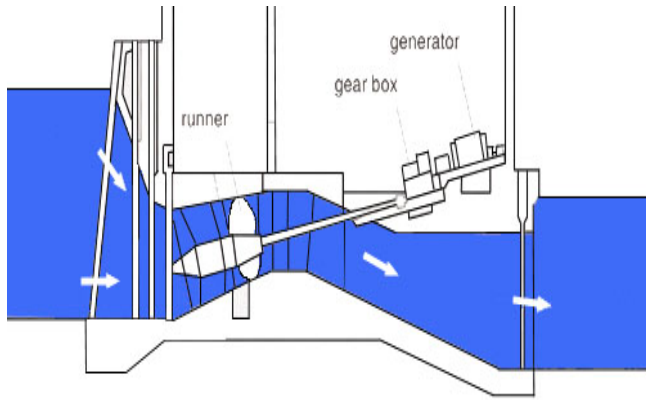


Figure 5. Tubular Turbine (Boyle, 1996)

IV. Tidal Projects Around the World

Annapolis Tidal Generation, Bay of Fundy, Canada:

The Annapolis Tidal Generating Station was completed in 1984. It was a pilot project sponsored by the provincial and federal governments designed to explore the potential of harnessing energy from the sea [4]. This facility has the distinction of being the first and only modern tidal plant in North America. Bay of Fundy is the home to the world's highest tides. Tides, which can sometimes reach 21 feet in height, rise and fall every 12 hours and 25 minutes in harmony with the gravitational forces of the sun, the earth, and the moon. Annapolis Tidal shown in Figure 6 utilizes the seawater of the Bay of Fundy. Twice a day, the tide comes in and out. Twice a day the turbine turns. Twice a day electricity is generated which is supplied to the provincial electric grid. Annapolis uses the largest straflo turbine in the world to produce more than 30 million kWh/year - enough to power 4,000 homes.



Figure 6. Annapolis Tidal Project

La Rance Project, France: The Rance tidal power plant, generating 240 MW, is the largest operating tidal facility in the world, far bigger than the next largest, the Annapolis facility (20 MW) in Canada [1]. The enclosed estuary of the Rance River in Brittany has a surface area of 22 km² (see Figure 7) and very large tides with 13.5 meter difference between high and low tides during the equinox. Detailed studies began in 1954 when the generating equipment available was not suitable for the project. Hence, new

horizontal 10 MW turbines were designed with all the electromechanical components fitting into the structure. These gave the plant enough power and also made it possible to build a four-lane road on top of the dam, which reduced the distance from St Malo to Dinard from 45 km to 15 km. There are 24 units of 10 MW which can run during both incoming and outgoing tides.

The Rance plant is a major tourist and educational attraction receiving around 400000 visitors a year, including many school parties and engineering study groups. However, it is only one of the many hydroelectric plants operated by Electricité de France (EDF). In total, EDF operates some 479 hydroelectric power plants ranging in size from a few dozen kW up to a massive 1800 MW in the Alps. With a combined installed capacity of 23300 MW, these hydroelectric plants produced 15 per cent of all the electricity generated in France in 1995 [5,6].



Figure 7. La Rance Tidal Power Station (Image courtesy of Popular Mechanics)

Severn Estuary Project, England: The Severn Estuary is located between Wales and England in south-west Britain. It is a very large estuary with mud-flats, rocky platforms, and islands. The seabed is rock and gravel with sub-tidal sandbanks. Due to its classic funnel shape which is unique in UK, Severn has the second largest tidal range in the world after Bay of Fundy in Canada. This tidal regime helps the inhabitation of plant and animal communities even though there are extreme physical conditions of liquid mud and tide-swept sand and rock [8]. The effect of tidal energy on environment has always been recognized as a significant factor. The main environmental risks include changes of water levels which modify currents, and sediment transport and deposit. Industrial infrastructure is unlikely to restrain the development of tidal energy. However, a very large scheme on the scale of the UK's Severn Barrage would require substantial supply from EU turbine-generator manufacturers to provide the estimated quantity of generation equipment [9].

New access roads and grid strengthening would also be required to accommodate a project on this scale. Barrages offer new opportunities for improvements or additions to existing transport networks. Risks are associated with the size of civil engineering works required and delays to the construction schedule, with the eventual effect on interest rate charges for this construction. The work would modify the flow of water in an estuary, involving substantial civil engineering and electromechanical equipment. The proposed project could have a generating capacity of 8640 MW.

V. Economics of Tidal Energy

One of the main barriers to the increased use of tidal energy is the cost of building tidal generating stations. The prime cost of the La Rance project was 617 million in 1967 French francs (FF) equivalent to about 3.7 billion FF today. However, in 160000 hours of operation, the plant has generated 16 billion kWh of electricity with 90 per cent reliability. It is estimated that the Severn River in England would have a construction cost of \$15 billion. Operation and maintenance costs of tidal power plants are very low because the seawater is free. The major factors in determining the cost effectiveness of a tidal power site are the length and height of the barrage and the difference in height between high and low tide. These factors can be expressed in the Gibrat ratio. The Gibrat ratio is the ratio of the length of the barrage in meters to the annual energy production in kWh. The smaller the Gibrat site ratio, the more desirable the site. The Gibrat ratios are La Rance 0.36, Severn 0.87 and the Bay of Fundy 0.92 [2].

VI. Proposed Sites For Tidal Projects

There are many sites on which tidal energy studies are going on around the world. In the following, we discuss a few of the ongoing projects around the world [7].

China: The southeastern coastal areas of Zhejiang, Fujian and Guangdong Provinces are considered to have substantial potentials for tidal energy. China has been utilizing tidal energy with modern technologies since 1956. Since then several small scale tidal plants were built for pumping irrigation water. Later tidal energy was used for power generation which were supplemented around 1970 by larger stations of which the 3 MW Jiangxia and the 960 kW Baishakou schemes were the largest. Currently there are seven tidal power stations in China with a total capacity of 11 MW.

Korea: The potential sites are in the west coast with an average tidal ranges of about 6 m. Two prospective sites are Garolim Bay, which was studied in detail, and the Gulf of Asam. The Korean Ocean Research and Development Institute (KORDI) reviewed the schemes in the mid-1980's with the help of British companies, but no projects have resulted yet from those studies.

Argentina: The southern coast between Tierra del Fuego and Golfo San Matias has a mean tidal range of about 7.5m. An assessment of the country's tidal energy potential identified

five sites with an estimated potential of 37 TWh/year. The development of tidal energy resources is dependent on the further expansion of hydroelectric resources and the construction of a transmission system that could connect tidal power plants with a suitable distribution network. An investigation has been carried out in the San José Gulf, which has a basin area of 780 km² and is connected to the sea by a 7 km long strait. A barrage at this location would be approximately 13.4 km long, have an installed capacity of 5 040 MW and could produce an estimated 9.4 TWh/year.

Russian Federation: After several studies performed since the 1930's, a small pilot plant with a capacity of 400 kW was constructed at Kislogubsk near Murmansk and commissioned in 1968. The success of this installation led to a number of design studies for much larger tidal plants at sites in the north and east of the country including Lumbov (67 MW) and Mezen Bay (15,000 MW) in the White Sea, Penzhinsk Bay (87,400 MW) and Tugur Bay (6,800 MW) in the Sea of Okhotsk. Eventually the Tugur station emerged as the only feasible major scheme at the present time.

Mexico: Two areas in the Gulf of California have been examined, one near Isla Montague at the mouth of the Río Colorado, the other at the island of Tiburón further down the Gulf. They each have a tidal range of 6-7 m. The potential output of one site in the Colorado estuary is estimated at 5.4 TWh/year.

India: The main potential sites for tidal power generation are the Gulf of Kutch and the Gulf of Khambat (Cambay), both in the western state of Gujarat, and Sunderbans area of West Bengal, in eastern India. The tidal ranges of the Gulf of Kutch and the Gulf of Khambat are 5 m and 7 m respectively with theoretical capacities of 900 MW and 7,000 MW respectively.

Australia: Tidal energy has a lot of potential mainly in the northwestern coast of Australia where tides are among the largest in the world. In the late 1990's, Tidal Energy Australia, a Western Australian company, proposed a combination of double basin/double flow design for the Doctor's Creek, which would be on King Sound near the Kimberley town of Derby. If installed, the plant with a capacity of 48 MW would have been the second largest tidal power station in the world and the only one providing continuous power output. The government of Western Australia was in favor of using fossil fuel for generating power. After much debate, the tidal plant was rejected for the time being.

VII. Other Types of Ocean Energy

Tidal energy can also be exploited directly from marine currents induced by the combined lunar and solar gravitational forces responsible for tides. These forces cause semi-diurnal movement in water in shallow seas, particularly where coastal morphology creates natural constrictions, for example around headlands or between islands. This phenomenon produces strong currents, or tidal streams, which are prevalent in places like the British Isles and other parts of the world where there are similar conditions. These currents are particularly

prevalent where there is a time difference in tidal cycles between two sections of coastal sea. The flow is cyclical, increasing in velocity and then decreasing before switching to the opposite direction. The kinetic energy within these currents could be converted to electricity, by placing free standing turbo-generating equipment in offshore areas. The following discussions further explore these ideas for generating electricity.

A. Energy from Tidal Stream

As discussed above, tides ebb and flow, tidal currents are often generated in coastal waters and quite often in areas far from bays and estuaries. In many places, the shape of the seabed forces water to flow through narrow channels, or around headlands (much like the wind howls through narrow valleys and around hills). However, seawater has a much higher density than air, meaning that currents of 5-8 knots generate as much energy as winds of much higher velocity. In addition, unlike the wind rushing through a valley or over hilltops, tidally-generated coastal currents are predictable. The tide comes in and out every twelve hours, resulting in currents which reach peak velocity four times every day. Two rival technologies -- tidal fences and tidal turbines -- are now being developed to catch the energy of these currents.

Coastal currents are strongest at the margins of the world's larger oceans. A review of likely tidal power sites in the late 1980s estimated the energy resource was in excess of 330,000 MW. South East Asia is one area where such currents could be exploited for tidal energy. In particular, the Chinese and Japanese coasts and the large number of straits between the islands of the Philippines are suitable for development of power generation from coastal currents. Marine Current Turbines (MCT), Ltd is running a program of tidal wave development. Figure 8 depicts the proposed development project in Lynmouth, UK. It is planned that some 300 MW of installations will be completed by 2010 [10].

B. Electricity From Ocean Waves

Wind generated by the differential heating of the earth pass over the open bodies of water, transferring some of its energy to the water in the form of waves. The energy of a wave is proportional to the squared of its height. The significant wave height is roughly that which an observer could estimate with a clock. The wave effect is usually described in kW per meter front. This energy transfer results in a concentration of the energy involved: the initial solar power level of about 1 kW/m² is concentrated to an average wave power level of 70 kW/m of crest length. This figure rises to an average of 170 kW/m of crest length during the winter, and to more than 1 MW/m during storms.

However, wave power cannot be harnessed everywhere. Wave-power rich areas of the world include the western coasts of Scotland, northern Canada, southern Africa, Australia, and the northeastern and northwestern coasts of the United States. In the Pacific Northwest alone, it is feasible that wave energy could produce 40 to 70 kW/m of western coastline. The US West Coast is more than a 1,000 miles long with potential applications for wave energy. In general, World Energy Council 2001 Survey stated the potential exploitable

wave energy resources worldwide is 2 TW. The potential wave energy in Europe alone could supply more than 50% of the total power consumption in the region.

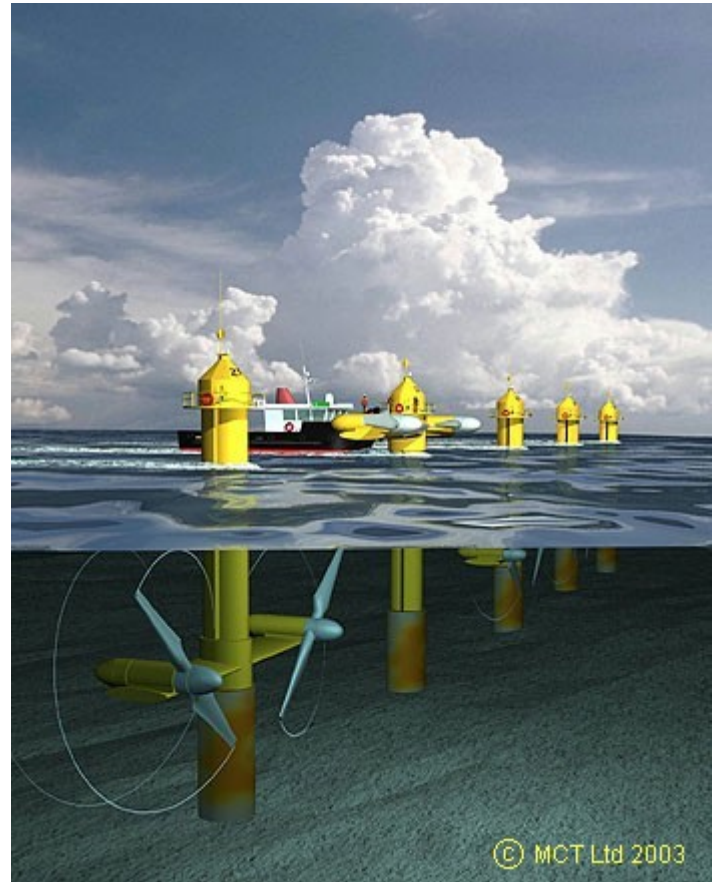


Figure 8. Tidal Wave Turbine Project

Figure 9 depicts a power generating facility based on wave energy in which water is stored in an above-sea-level reservoir and led out through the turbines. This principle is the same technique as that of hydro power plants [11]. These floating platforms create electricity by funneling waves through internal turbines and then back into the sea.

The Japan Marine Technology Center has developed a prototype wave power vessel that carries three air turbine generator units. Called the Mighty Whale in Figure 10, the vessel is designed to be anchored to the seabed and remotely controlled from shore [12].

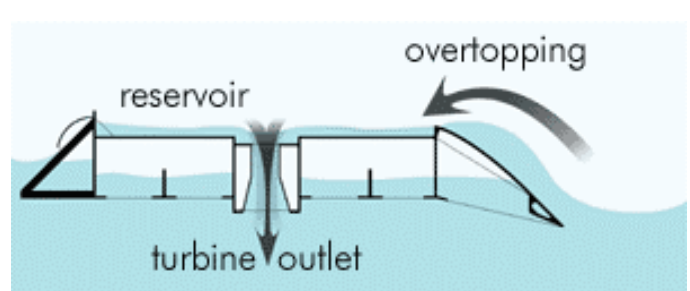


Figure 9. Ocean Wave Turbine

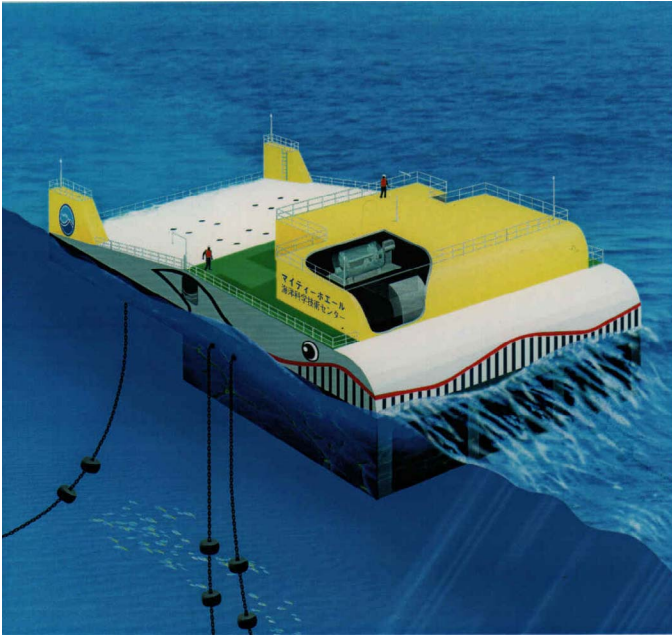


Figure 10. Mighty Whale

VIII. Summary and Conclusions

There is enough potential in tidal power to generate large amounts of electricity though it may not be able to support the entire needs of the world. The higher the tides, the more electricity can be generated from a given site and the lower the cost of electricity produced. Tidal energy is regarded as a prominent energy prospect among renewable resources and USDOE is taking measures towards this objective.

There are environmental disadvantages which could make tidal power less attractive. The largest disadvantage of tidal power is the effect on plants and animals which live within the estuary. Building of barrages can affect the quality of water also due to sediments in the water. The barrages can also flood the near by vegetation.

The available tidal energy is approximately proportional to the square of the tidal range. Extraction of energy from the tides is considered to be practical only at those sites where the energy is concentrated in the form of large tides and the geography provides suitable sites for tidal plant construction. Such sites are not commonplace but a considerable number have been identified in the UK, France, eastern Canada, the Pacific coast of Russia, Korea, China, Mexico and Chile. Other sites have been identified along the Patagonian coast of Argentina, Western Australia and western India. Some very ambitious projects are currently being studied including those of Severn and Mersey, UK (8600 MW and 700 MW respectively), Bay of Fundy, Canada (5300 MW), San José, Argentina (5000 MW), Kutch, India (900 MW) and Garolim, Korea (480 MW). Some of these projects could come to fruition during the next few years. Australia has the right sort of tides on its northwestern coast, but neither an obvious site for such a plant nor a nearby energy market.

Tidal power is a natural source of energy with many benefits. The planet's tidal capability greatly exceeds that of the world's entire coal and oil supply. It is an ideal source of energy with great potential. However, to make tidal energy our

main source of energy supply, it needs to be developed fully. It is believed that the technology required for tidal power is fairly well developed and the main barrier to increased use of the tides is that of construction costs. Worldwide, approximately 3,000 GW of energy is continuously available from tides. Due to the constraints outlined in this paper, it has been estimated that only 2% or 60 GW can potentially be recovered for electricity generation. The future costs of other renewable and non-renewable sources of electricity, and their impact on the environment, could ultimately determine whether or not tidal energy generation can be used on large scales.

References

1. The Australian Renewable Energy (acre.Murdoch.edu.au/ago/ocean/tidal.html).
2. Energy fact sheet, Energy Educators of Ontario, (www.iclei.org/efacts/tidal.htm), 1993
3. Tidal energy (www.geology.wisc.edu/~pbrown/g410/tidal/tidal.html.)
4. Annapolis tidal power plant, Nova Scotia power, (power.about.com/gi/dynamic/offsite.htm).
5. French science and technology no.29, the Rance tidal power plant (www.ambafrance-au.org/fst/pages/fst29/fst29p15.en.htm).
6. Tidal Hydroelectric power plant (www.elgersmad.homestead.com/Files/Tide/index.html).
7. Survey of energy resources, Tidal energy, World energy council (www.worldenergy.org/wec-geis/publications/reports/ser/tide/tide.asp).
8. JNCC adviser to government (<http://www.jncc.gov.uk/UKSPA/sites/England/UK9015022.htm>)
9. Tidal energy- Market barriers, (europa.eu.int/comm/energy_transport/atlas/htmlu/tidalmark.html).
10. MCT project (www.marineturbines.com/projects.htm).
11. Wave energy project (www.wavedragon.net/technology/wave-energy.htm).
12. Mighty Whale (www.jamstec.go.jp)
13. www.poemsinc.org/links.html

Biographies

Shabana Sheth was employed with Consolidated Construction Co. in Muscat, Oman as an Assistant Electrical Engineer. She completed in 2004 her MS degree in Electric Power Systems at IIT and is currently a consulting engineer to the electric power industry.

Mohammad Shahidehpour is a professor in the Electrical and Computer Engineering Department and Director of Electric Power and Power Electronics Center at IIT.