Tidal Energy

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Introduction

As a brief introduction, the authors would like to explain their interests in studying Tidal Power as a means for generating reliable, carbon-free electricity.

Lauren Kologe

Why Tidal Energy? Aside from my fascination with the Norfolk Tides minor league baseball team, I knew nothing about this renewable source of energy and wanted to discover the science behind it, and the potential of harnessing the crash of the ocean. Both old school and cutting edge, tidal power is always offered as an alternative energy source, but is largely ignored in favor of wind and solar power. However, renewable energies are like Slim-fast cookies: using less polluting technologies to produce our power does not mean we can over-consume. As a replacement to traditional fossil fuels, tidal power can make a significant contribution on a local and regional scale to the power grid of several countries. Although there are significant environmental impacts from large-scale tidal schemes, there are also existing environmental impacts from coal power plants, oil refineries, etc. so I believe we should educate ourselves about the costs and benefits of a wide variety of energy sources. Different localities will be impacted in unique ways, so what is true for one community may not be true for another. We should not let indecision over environmental concerns stagnate possibilities for cleaner energy, but let it urge us to look for the best solution available to us at the current level of technology and society. Cooperative and democratic governing structures will enable clear communication between the various stakeholders: from citizens to cabinet members, we will be more flexible and willing to work together not only to create new power schemes, but also to allocate resources more equitably.

Pete Clark

Both the United States and United Kingdom are surrounded by copious amounts of tidal water. The periodic differential water leveling created by lunar/earth interactions creates a predictable system capable of generating respectable amounts of kinetic energy through artificial damming. Meanwhile, offshore, strong underwater currents are potential sources for copious amounts of energy through the use of ocean floor turbines. Interestingly, the UK has major advantages in both systems over the US; the waters around the UK have substantially greater tidal differences between low and high tide levels and a variety of cool water channels that house persistent ocean currents. Ironically, at the same time, the US embraces the idea of renewable energy through such systems much more firmly than the UK. Not to be taken less seriously is the potential for wave energy to one day be the leader in renewable energy systems in both countries. This document will explore the possibilities of all three energy systems while keeping in mind the relatively different general attitudes toward each nation's waterways.

Rebecca Klossner

Throughout the paleotechnic period many technological advances were made because of the abundance of cheap, readily available energy. Today, society is facing the consequences of the industrial revolution. In recent years there has been a push to find more environmentally sound methods of producing energy. One proposal uses this basic Roman tidal technology on a much larger scale. The proposed Severn Barrage could potentially create 8,640 MW of electricity, supplying about 6% or the UK's present energy needs. We determined on our research trip that a "technological society boils down to turning a wheel". If society is unable to think "outside of the box", it is inevitable that we will return to ideas that have worked in the past. Using the same basic idea, we will apply these ancient schemes to the needs our society has today.

Basic Science of Tides

Lunar Tidal Dynamics

The constant interaction between earth and its moon make for one of the most complex yet overlooked scientific phenomena: the tidal system. For our purposes, we will explore the coastal tidal system which includes such structures as inlets, rivers, and bays. Although vital in the understanding of these smaller scale structures, the open ocean dynamics will be avoided as these systems are relatively futile in terms of pertaining to energy systems.

Dynamically speaking, the earth and the Moon are two masses that display centrifugal forces on one another. First, we must consider a particle of mass *m* which is located on the earth's surface. Given Newton's law of gravitational state we introduce the equation:

$$F = G\,\frac{m_1 m_2}{R^2} \qquad (1.1)$$

where the F is the force created between $mass_1$ and $mass_2$, G is the universal gravitational constant whose value depends only on the chosen units of mass, length, and force (typically 6.67×10^{-11} N m^2 kg^{-2}). If we then take the difference between the force towards the moon and the force necessary for earth's rotation (1.1) we generate the tidal producing force (Pugh 62):

$$\text{Tidal Force} = \frac{2Gmm_1a}{R^3} \qquad (1.2)$$

where m is the mass of the earth, *a* is the mean radius of the earth and R is the distance between earth and the lunar surface. The net effect of this equation is to displace particle m1 away from the center of the earth. Thus, we can conclude that diurnal tides are generated because the maxima and minima in each daily rotation are unequal in amplitude. (Pugh 64) This is ultimately, in its simplest form, the process behind the half-day cycle which results in a period of 12 hours 25 minutes between successive high waters. (Johansson 515) Figure 1.3 demonstrates Tidal Force and its tendency to create bulging at the water's surface; thus making for the differential sloshing effect.

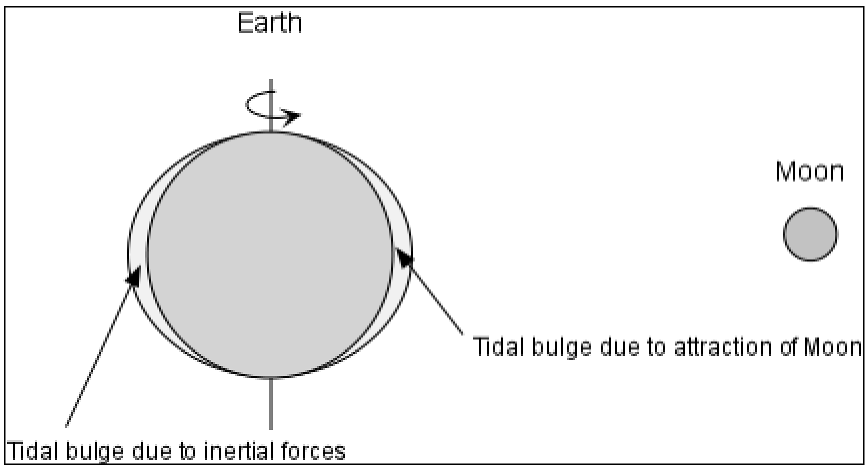


Figure 1.3:

Spring-neap tides are a second significant tidal pattern type. The fortnightly modulation in semidiurnal tidal amplitudes is due to the various combinations of lunar and solar semidiurnal tides. The minimum ranges occur at the first quarter and last quarter. This is because at times of spring tides the lunar and solar forces combine together, but at neap tides the lunar and solar forces are out of phase and tend to cancel. (Pugh 82) Figure 1.4 illustrates the difference between Neap and Spring ellipses; notice during the Spring Tide, the ellipse is drawn outward toward the Sun, allowing for increases tidal activity in terms of range. During the Neap Tide, one gets a significant decrease in tidal activity due to the gravitational strain at the poles instead of at the Equator. Unfortunately, although predictable, this tidal pattern makes for increased variation in terms of expected power output; if tidal power produced 25% of a large city's power peak load, the city would be forced to find another source of power during times of Neap Tide. This has always been a significant factor when considering tidal energy schemes as a significant portion of a population's energy requirement.

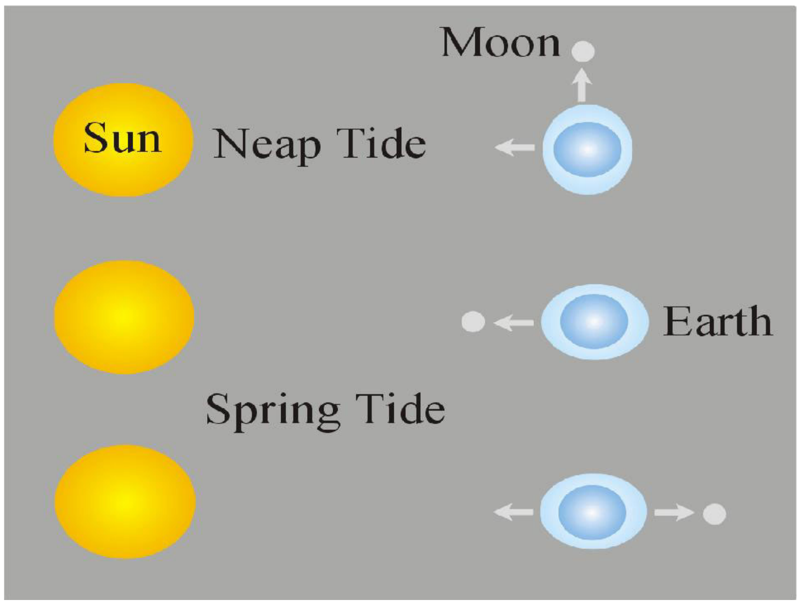


Figure 1.4

Tidal Energy Logistics

Harnessing energy from such an extremely predictable source seems rather practical and ingenious. However, significant tidal range, the one crucial component of the system, can only be found in isolated areas of the world. Figure 1.5 illustrates five of the most promising sites for tidal energy due to their extreme tidal range. Several, including La Rance, already have tidal energy systems through the use of barrage structures. The mean tidal range, which is found by simply doubling the value of the tidal amplitude, is the distance between the highest water level at high tide and the lowest water mark at low tide. Interestingly, these amplitudes are only means. In fact, tidal ranges in the order of eight to nine meters are not uncommon during full moon periods. Noticeably, there are two areas which are noteworthy in terms of their tidal range; Southeast Canada and the Western Shore of Great Britain. Determining potential tidal energy systems for both of these locations will be discussed in greater detail later in this document.

	Mean Tidal Amplitude(m)	Basin Area (km2)
La Rance, France	4	17
Bay of Fundy, Canada	5.5	240
Annapolis, Nova Scotia	3.2	6
Severn Estuary, England	4	420
Garolim Bay, South Korea	2.5	85

Figure 1.5 (Source: Pugh)

Oceanic topography and local resonance effects play vital roles in the tidal range of a given waterway. Observing the topography of the Bay of Fundy we notice that, unlike the United States' Coastal Plain, Southeast Canada consists of a ridge/valley system. Along the US Coastal Plain, the water depth gradient is rather minimal; depths gradually decrease as one heads west of the Continental Shelf. In comparison, the water depths in and around the Bay of Fundy consists of several significant drop offs and eddies of deep water that are relatively close to the coastline. Deep water within a structure works in a twofold manner towards increasing tidal range; it minimizes the effects of water current friction due to bottom structure while also causing a surge effect in which incoming water quickly rises due to the extreme water depth gradient.

There are several other factors which play key roles in determining the feasibility of engineering an expensive tidal energy system at a given location. The ideal site for tidal power generation is a basin of large area with a relatively narrow entrance. (Pugh 296) Such waterways allow for the least expensive construction of barrage structures and hence, keep the bottom line in mind. Another important factor is the proximity of the site to an area in demand for power. For example, the Minas Basin scheme has the disadvantage of being distant from major areas of power demand and hence is not seen as being as successful of a scheme as La Rance due to the very small population to which it serves.

More importantly is taking into account how the waterway will be affected both ecologically and commercially by a damming structure. In the Severn Estuary, although major cities of Cardiff and Bristol are close by, they are major ports whose commercial interests would be affected if access for shipping were restricted. (Pugh 296) At the same time, numerous species of fish use Severn Estuary as spawning grounds. Therefore, preventing certain marine species from swimming upstream may have detrimental effects on the fish population in the entire region.

The demands for power are also closely linked to the 24-hour diurnal cycle, with weekly and strong annual cycles superimposed. (Pugh 298) Tidal power is available during the five to six hour window after a high tide phase. However, this phase advances by fifty two minutes each day. Therefore, tidal power becomes problematic when the high tide phase does not occur until peak usage hours (after 11 pm). Seasonal variation, however, is a much greater risk in terms of tidal energy schemes. Unlike available wave power, which reaches a maximum during the winter months, coinciding with the maximum seasonal demand, tidal power has its greatest variation over the spring-neap cycle. (Pugh 298) Due to the fact that available power pertains to the square of the tidal range, the difference between spring and neap tides can often make for a drastic difference in available power between winter and summer. The mismatch between supply and demand has led to the development of several schemes which sacrifice optimum total power generation in favor of a more controlled supply; this method produces what the industry coins ‘firm power.’ (Pugh 298) Several examples that examine the effect tidal range has on power output will be discussed in later sections.

Historical Aspects

Ancient Tide Mills

During the Roman occupation of England, several tide mills were built in order to grind grain and corn. These tide mills operated by storing water behind a dam during high tide. As the tide receded the water was slowly let out from behind the dam in order to power the mill. One of these ancient mills is located at the Nendrum Monastic Site on Mahee Island in Ireland. In 1999, archeologists funded by the Environmental Heritage Service uncovered what they thought to be a stone tidal pond used for catching fish. What they unveiled was a stone built tidal mill and evidence of an ancient tidal mill dating back to 787 A.D. The picture above shows the millstone being excavated. Paddle blades from the wheel were also found at the site. Mills such as these operated in the same manner until the time of the Industrial Revolution.

Eling Mill

History

The Eling Mill, located in the south of England, is an excellent demonstration of how tidal mills may have worked over a thousand years ago. Eling Mill is a tidal powered flour mill and has been for many centuries. The mill was included in the

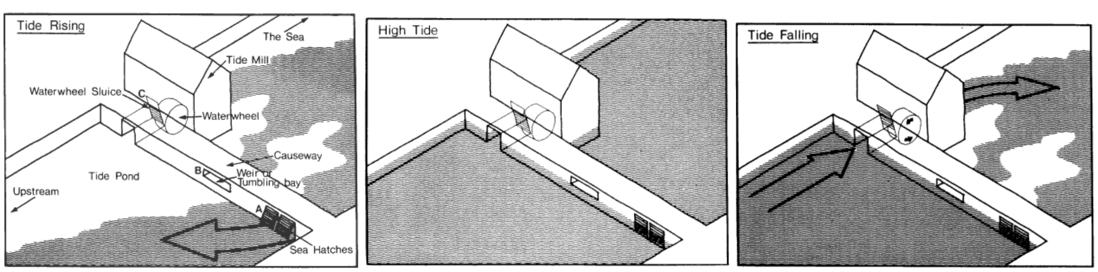
Domesday Survey in 1086, which took an inventory of who owned what throughout the country on England. Originally the Mill was owned by the King because Eling was a royal manor, but King John sold the mill in the early 13th century. Historically, a tide mill was built on the site of a former mill in 1419 by Thomas Mydlington. Most of the grain that was milled at the site was not locally produced. Oftentimes, grain from several hundred miles around the coast was brought to the Mill by ship. At maximum output the mill would have produced four tons of flour each day.

The Mill that currently occupies the site was reconstructed in the 1770s after several floods damaged the millhouse and the dam. It has two separate wheels, each with its own machinery which allows two different milling operations to occur in the same mill. In 1382, the Mill was purchased by the Bishop of Winchester and was given to Winchester College as a means to fund the college. Winchester College owned the Mill for over five hundred years, until 1975 when the New Forest District Council purchased it. Although the Eling Mill has been rebuilt quite a few times, it has basically operated in the same manner for over 900 years.

In the late 1800s, large steam-powered roller mills were built throughout the country to mill imported grain, usually from Canada. Many of the tidal mills were forced to close, and only several of these historic sites remain today. The local governing body, the New Forest District Council, restored the mill and reopened it in 1980. Eling is unique in that it remains a functional mill that produces flour.

How the Mill Works

The basic schematic diagrams below show how the mill is run generally. When the tide comes in, one way gates are pushed open and the tide pond is filled. At Eling, the tide pond is over 3 km long. At high tide, the mill can not work because the water high in the tide pond is equal to that on the sea side of the mill, and no water flows to cause the wheel to turn. Also, the wheel is under water, so there is too much drag for the wheel to even turn. As the tide starts to fall, called the ebbing tide, the gates are forced close, and the water is trapped in the tide pond at its high tide level. A waterwheel sluice is regulated the amount of water which is allowed to turn the blades of the wheel. When the water level falls completely below the wheel, milling is started by opening the sluice several centimeters allowing water from the tide pond to turn the wheel. From this point, the tide then gets to its lowest height, and again starts to rise. Milling continues through this until the water rises to the bottom of the wheel. At Eling, the time of milling is approximately five hours. Because tides change twice a day, there are two milling periods each day of five hours each with the later milling period occurring twelve and a half hours after the first.



Diagrams from : Eling Tide Mill Trust Ltd. 2000

Letter A designates the sea hatches, or gates. B represents the Weir or Tumbling bay, which automatically maintains the head of water required to work the mill machinery. It can also act as a spillway for flood control. C corresponds to sluices that control the amount of water from the tide pond contacting the wheel.

The picture below shows the Eling site, and each of the components for the tidal scheme.

The Eling Tide Mill provides an excellent example of how tidal scheme technology had remained unchanged for thousands of years.

New Technology from an Old Idea

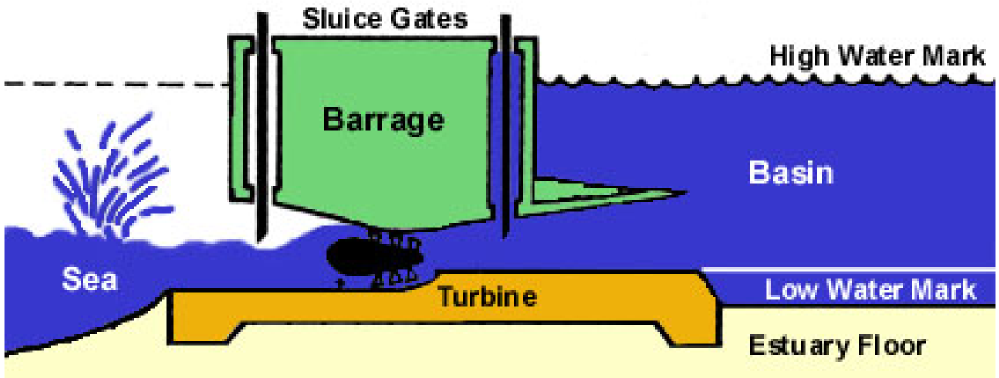
As stated in the previous section, the industrial revolution brought about enormous changes in the way almost everything was done. The need for small tidal mills that milled relatively local grain diminished with the invention of large steam-powered roller mills. The industrial revolution also brought cheap energy in the form of electricity, ushering in the paleotechnic period. The period is characterized by the invention of the steam powered machine, which allowed a time of technological advancement that was unprecedented. The rapid pace of this era did not leave enough time to consider the consequences of using fossil fuels, such as the effect of this new fuel on the environment. Through the latter part of the twentieth century the world seemed to finally see some of the consequences of the reckless progression mankind made for over 150 years.

Global warming, air pollution, water pollution, and acid rain are just some of the problems faced when using the fossil fuels that the paleotechnic period popularized. Throughout most of the twentieth century, many people had creative ideas for renewable energy resources, to take the place of burning fossil fuels to create energy. These resources are naturally replenishable, and nearly inexhaustible, but they are limited in the amount of energy that is available per unit of time National (Association of Regulatory Utility Commissioners, 2001). Therefore, using renewable energy for large scale power generation has been limited.

If energy from the sun, wind, earth and sea could be harnessed economically and efficiently, the use of fossil fuels could be greatly diminished. If tidal energy could be used hundreds of years ago to create the energy needed to mill grain, then perhaps it could be used to create electricity that humans have become so dependant on. This thought was actually put to work in France in 1967 when the first large-scale tidal scheme to produce electricity was constructed. There have been considerable changes in the technology used to grind grain into flour and that used to barrage produce 240MW of electricity.

From Milling to Electricity

In order to create enough electricity to be economically feasible, the size and configuration of the structure has to be increased tremendously. Tidal Energy consists of generating kinetic energy from potential energy. If falling water is forced through ducts with rotators attached to them, the rotors will turn driving electric generators (Mc Gown 182). Generating electricity from tides is very similar to hydroelectric generation, except the tides flow in two directions rather than one. For tidal power, the most common generating system is the ebb generating system. In the scheme, a dam, or barrage is constructed across an estuary. The tidal basin is allowed to fill when the sluice gates are opened and high tide is in. The gates are then closed when the tide turns trapping the water behind the gates. Once low tide is reached, the gates are opened the water flows through the turbines located underneath the water generating electricity. The basic concept for this type of scheme is extremely similar to that used at the Eling Mill. The schematic below shows the basic concept used in an ebb generation scheme.



Ebb generating system with a bulb turbine (Adapted from Energy Authority of NSW Tidal Power Fact Sheet)

In some cases, double effect turbines are used, which are able to generate electricity when then basin is filling. In this scheme, sluice gates located on either side of the turbine are opened, when the tidal basin is low, and the sea is at high tide level. Water will rush into the tidal basin, turning the turbines and generating electricity. This occurs until the water level on either side of the barrage is equal. At this point, the sluice gates are closed until the sea is at its low tide height. When this occurs, the gates are opened and water flows from the basin to the sea, generating electricity a second time.

Construction

In terms of construction, caissons, which are large units of concrete or steel that, are manufactured at shore-based construction yards are delivered to water sites by barges and then positioned by cranes to allow for the structures to correctly settle on the marine floor. Overall, this is an extremely expensive process. Another method calls for constructing diaphragm walls of reinforced concrete within a temporary sand island. But the approach offers no significant cost advantages over caissons and studies for the proposed Mersey Barrage in the United Kingdom indicate that the use of diaphragm walling could prolong construction time by about two years. (Johansson 519)

Location

Historically, tidal mills were usually built on inlets branching off tidal estuaries. An estuary is a wide part of a river where it meets the sea. It creates a unique environment because both freshwater and saltwater are present. Tidal estuaries are characterized by narrow, shallow channels with a relatively constant width and depth. Tides are greatly amplified in these areas of smaller volume, which causes the tide to travel up the river. Tidal ranges vary greatly from once place to another because of the geography of the land, but the most suitable tidal ranges are between five and ten meters.

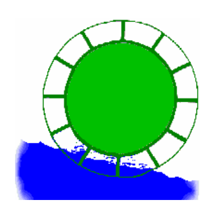
Tidal Barrage

The tidal barrage is similar to a dam, which creates a tidal basin used for electricity generation. The structure is extremely large, spanning the entire width and height of the estuary. The bottom of the barrage is located on the sea floor and the top is above the highest level that the water can get at high tide.

Evolution of Turbine Types

Waterwheel Turbines

Waterwheels were used from the invention of the tidal mill until the industrial revolution.

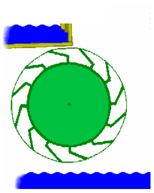


Undershot Wheel

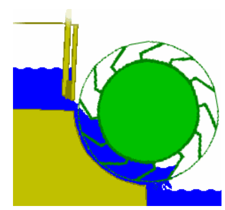
The first turbine used was the basic undershot waterwheel. This is probably the oldest type of waterwheel dating back over two thousand years. It is mounted vertically on a horizontal axle and it has flat boards located radially around a rim. It is turned by water flowing under the wheel and striking the boards.

The second type of turbine used was an overshot waterwheel. The overshot wheel is much more efficient than the undershot wheel. Again, this turbine is mounted vertically on a horizontal axle, but the overshot wheel has buckets mounted around the rim. Water from above flows into the buckets causing one side of the wheel to be heavier. Gravity then acts on the heavier side causing the wheel to turn.

Overshot Wheel



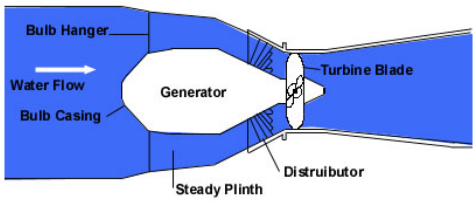
The third type of turbine used was a breast-shot waterwheel. This type of wheel was developed in the late middle ages and combines the previous two waterwheels. It has buckets on a rim that face the opposite direction of the buckets on the overshot wheel. Water then fills the buckets at the middle of the wheel. Again, gravity acting upon the water in the buckets causes the wheel to turn.



Breast-shot Wheel

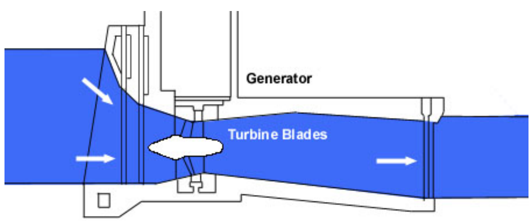
Recent Turbine Developments

Bulb turbines incorporated the generator-motor unit in the flow passage of the water. These turbines are used at the La Rance power station in France. The main drawback is that water flows around the turbine, making maintenance difficult.



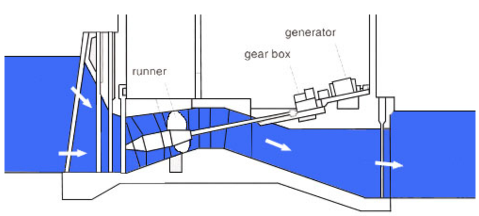
Bulb Turbine (Copyright Boyle, 1996)

Rim turbines allow the generator to be mounted in the barrage, at right angles to the turbine blades. It is difficult to regulate the performance of these turbines and it is unsuitable for use in pumping.



Rim Turbine (Copyright Boyle, 1996)

Finally, in tubular turbines, the blades are connected to a shaft which is oriented at an angle that allows the generator to be located on top of the barrage. These types of turbines have been proposed for the Severn Barrage which is discussed in subsequent sections.



Tubular Turbine (Copyright Boyle, 1996)

Once the development of more tidal schemes occurs, additional types of turbines will be tested and implemented.

La Rance – A Working Case Study

La Rance Tidal Power Plant is the only full scale power station of its type in the world, located in northern France on the La Rance River. The power plant was completed in 1967, with 24 bulb turbines, each capable of producing ten megawatts of power. The dam itself is 2460 feet (750 meters) long, and 43 feet (13 meters) high. In order to build such a unique plant, twenty-five years of studies and six years of construction were needed. The site was chosen because it has one of the greatest tidal ranges in the world, at 13.5m.

The turbines used in La Rance are bulb turbines that are capable of generating power when the basin is filled and emptied at high and low tide. The blades of the turbine can change directions depending on the current flow. The turbines weigh 470 tons and have a blade diameter of over seventeen feet. The plant is also equipped with pumps that allow water to be pumped into the basin when the sea is close to basin level at high tide. This allows for more electricity to be generated if there is an anticipated increase in demand.

La Rance has been successful as the first full scale tidal power plant. Some of the environmental impacts potentially caused by such schemes are discussed in other sections. La Rance has not had an adverse impact on the local environment. Flooding as a result of daming the river has not occurred either. In this case, the barrage was large enough to create a road with two double lanes, saving local citizens an eighteen mile drive. The unique nature of the power station has also increased tourism in the area. La Rance attracts over 300,000 visitors every year. The initial cost, which deters many similar projects from ever being constructed, was 617million in 1967 French francs, equivalent to about FF 3.7 billion today, which is approximately $66 million (Technologies 'France', 1996). Despite the high initial cost, the power station has been working for over thirty years, generating enough electricity for around 300,000 homes.

Severn Project – Will There Ever Be a Barrage?

History

Proposals to dam the Severn have existed for over one hundred years. The Severn offers one of the largest tidal ranges in the world with an average of 23 feet (7 meters) with spring tides reaching 36 feet (11 meters). The Severn River has over eighteen ports, and historically was one of the major trading routes in England. When the Severn Barrage concept was originally proposed in the 1840s, it was to improve shipping and prevent flooding. In addition, the barrage would create a roadway and railway across the river.

Proposals for a tidal power plant on the River Severn have dated back to 1918. However at the time of the proposal, the low cost of coal used to generate electricity did not make the project economically feasible. In 1943, the rising cost of coal constituted the formation Brabazon Commission to reinvestigate the barrage. The proposal called for a single basin operating on discharge only that would produce 800,000 kilowatts of output (UN, 1957). Again, the plan was abandoned, because of poor economic feasibility. In this case, if the amount saved on coal is allotted to the power plant, coal would have to cost £4.65 per ton in order to warrant the building of the plant. At the time of the study, coal only cost £3.90 per ton (UN, 1957).

The Severn Barrage Committee was organized in 1978 in order to advise the government on whether or not to proceed with the Severn Barrage for a means of producing electricity. The committee spent two and a half years deciding that a barrage across the Severn would be technologically feasible, but not economically feasible.

The Proposed Scheme

When completed, the Severn Barrage would be almost 10 miles in length, located between Brean Down in Somerset and Lavernock Point in Glamorgan. This location is thought to have the less of an impact on the environment and less engineering risks, while being the most cost effective. The tidal basin would be over 190 square miles (500 square kilometers). The proposed barrage would be comprised of concrete units, which had been prefabricated, to house the turbines and sluices. The 216 tubular turbines would be located in the central portion of the barrage, and each would drive a 40 megawatt generator, resulting in an estimated 17TWh each year (Tidal Files). The proposed scheme has a lifetime of at least 120 years (Taylor, 2002). Ship locks were also included in the scheme because the Severn has many important ports that would be located in the tidal basin if the barrage was built.

The proposed scheme would be an ebb generating system (Taylor, 2002). At high tide sluice gates are closed and the tidal basin is kept to the height of the seawater at high tide. The gates are then opened as the sea level falls. Water from the tidal basin will then flow through the turbines in order to generate electricity. The proposal also includes a pumping mode, which allows more water to be pumped into the basin at high tide. With the increased development of double effect turbines, it may be possible to generate even more electricity from the Severn.

New Light on an Old Subject?

In early 2002, a definition study for a new appraisal of the Severn Barrage was released. The study was carried out under a contract with the Energy Technology Support Units' (ETSU) Sustainable Energy Programmes. The last formal study was concluded in 1989, to asses the technical and financial aspects of the Severn Barrage. The study completed in 2002 investigated whether the changed and changing circumstances since 1989 justify a reappraisal of the Project. The proposal was abandoned in 1989 because of economic problems, and opposition from environmental groups and local citizens.

Governmental Policy and the Environment

One of the most significant changes in Energy Policy for the UK since the 1989 study is the Renewables Obligation. This policy is the main method of encouraging the use of renewable energy in the UK. It mandates that all licensed electricity suppliers in England and Wales supply a specific proportion of their electricity from renewables (DTI, 2002). It also provides a goal for the UK to obtain ten percent of its electricity need from renewables by 2010, and twenty percent by 2020. Currently renewables only provide three percent of the total electricity supply. In order to meet the Renewables Obligation, the UK needs to greatly increase electricity production from non-fossil fuels. The proposed Severn Barrage could provide a peak capacity of 8,640 megawatts of power, representing six percent of the present electricity requirements. Unfortunately, the Barrage would not be able to contribute to the 2010 goal, because the plant would not be fully constructed and online until at least 2014.

The Kyoto Protocol has also altered the energy policy for the UK. The Protocol calls for developed nations to reduce their greenhouse gas emissions. A market based permit system was used to create incentive for greenhouse gas emission reductions. Creating six percent of the countries energy needs using a renewable resource would reduce the number of permits needed by the country. The electricity from the barrage would avoid the emission of eighteen million tons of carbon dioxide every year.

Another point to consider is the effect of global warming on the average height of the water in the Severn Estuary. If predictions are correct, and the sea level does rise many of the low lying areas around the estuary could be flooded and costal erosion would significantly increase. The annual average flooding damage cost risk currently totals £40-200 million, and this is expected to rise. These costs and costs of potentially installing flood mitigation could be avoided if the Severn Barrage was constructed.

Economics

The cost of the proposed barrage would be between £10.3 – 14 billion, and the project could take up to nine years to construct. The initial investment in this structure is usually the deterring factor when the proposals are rejected. However, if the broader social and economic benefits, beyond the scope of the market, are taken into account the project becomes competitive with the current cost of electricity. If the cost of the saved carbon credits and the avoidance of flooding is taken into account the electricity generated by the barrage is actually more cost effective than that of a coal fired power plant (McAlpine, 2002). In addition, the Barrage could create jobs in the area and boost tourism. Finally, if the Barrage functions for its entire estimated lifetime of 120 years, then the initial costs incurred are not substantial in comparison.

Environmental Impacts

The Severn Estuary is a unique ecosystem, where freshwater and saltwater meet. The range of the tides inside the tidal basin would be reduced which could have an adverse affect on the mud flats and silt in the river. The environmental impact of the La Rance barrage has been negligible, but this may not be the case for all tidal barrages. The environmental impacts are very site specific and cannot be entirely predetermined. The various possible environmental impacts are discussed at length in other sections.

Recommendations

The first recommendation made by the report is for further studies on the subject, costing no more than £500,000. The second recommendation is for the government to sanction a full re-appraisal of the project, including competitive bids for the construction. Finally, the government could decide to promote the project and seek active partners to develop this technology. This suggestion would also require the proper legislation to be passed in order to implement such a project.

Proposition: Long Island Sound Barrage

There are only a handful of tidal sites inside the United States that consist of a large tidal range. The Passamaquoddy site is characterized by a tidal range in the order of six to seven meters. However, located on the US/Canada border in a desolate area does not bode well for the harnessing of appreciable energy to any respectable population or city. On the other hand, one of the most overlooked potential sites that not only lies relatively close to one of the world's largest population centers, but can be characterized as having a sufficient tidal range for energy harnessing is the Long Island Sound.

Long Island Sound is located in the Northeast quadrant of the United States and border's New York State's Long Island and the state of Connecticut and Massachusetts. In terms of tidal range, as one heads west in the sound, the tidal range increases dramatically. Many sources, including the United State Coast Guard and the National Oceanic and Atmospheric Administration, which is responsible for tidal predictions, claim that tidal ranges of three to four meters is not uncommon. For our purposes, we will use a mean tidal range value of 3.5 meters at a location Mount Sinai, NY. The surface area of the sound is an impressive 2,092 km^2. (NURC) The major decision pertaining to the construction of the potential barrage would be the location. Due to the fact that the Long Island Sound is a heavily traveled waterway, lending entrance into the New York City Harbor, and the fact that tidal range is greatest on the western extent of the sound, we chose to position the barrage approximately halfway into the sound. Therefore, a 16 mile structure would be necessary to span from Little Danbury, CT to Mount Sinai, NY.

Figure 1.7 illustrates the expected placement of the barrage. In terms of biological effects and reasoning, we will discuss those matters sufficiently in later context.

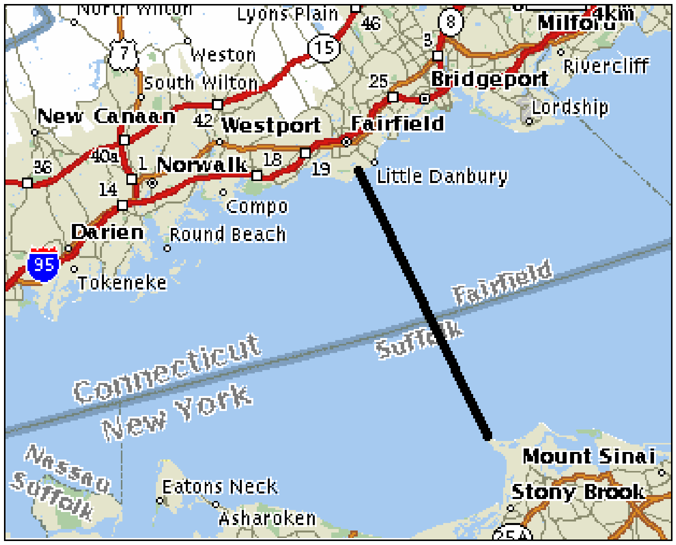


Figure 1.7

Since we are practically slicing the Sound into thirds, we must also cut off two thirds of the given surface area to a value of 697.3 km^2. The Severn Barrage, one of the largest potential sites, is estimated to cover a surface area of only 420 km^2. (Pugh 292) Hence, we can conclude that the Long Island Sound has a significant advantage over most tidal schemes in terms of surface area, a major component to the mean theoretical power output equation. Given these estimated measurements, we can now explore the potential amount of energy that could possibly be harnessed through such a system. The potential energy contained in a basin of area, filled at high tide, and discharging into the open sea at low tide is:

$$S \int \rho g dz \qquad (1.8)$$

where H is the tidal amplitude, ρ is the water density and g is the gravitational acceleration, which gives (Pugh 293):

$$2S\rho gH^2 \qquad (1.9)$$

Note that the theoretical mean power relies heavily on the square of the tidal amplitude. Using equation 1.9, we find that the maximum theoretical mean power output for Long Island Sound would be 2,135 Mw. This would be about one third the amount of theoretical mean power output expected from the Severn Barrage (6,100 Mw). (Pugh 296) Also keep in mind that the theoretical mean power output is only 250 Mw at La Rance. Therefore, even if calculated value was more than 85% inaccurate, the Long Island Barrage would still be producing more power output than the La Rance scheme. Mathematically speaking, such a proposition as the Long Island Barrage would be extremely feasible. However, there are several other factors that must be explored before sufficiently claiming a warranted design.

Long Island Sound has had an awful past in terms of ecological concerns. Extremely high levels of toxins including mercury, have been found deposited in it sediments. According to the EPA/NOAA-sponsored Long Island Sound Study, 40% of the bottom area of Long Island Sound is marginal to unusable habitat for many marine animal species during the summer months due to oxygen depletion. (Soundkeeper) Nitrogen from sewage systems and runoff catalyzes the excessive growth of algae, which ultimately decompose and rob the water of oxygen needed by marine life. Population increases over the last 50 years near the coastal areas of New York and Connecticut have generated quantities of nitrogen laden sewage beyond the capabilities of current technology-based strategies to treat it before it enters Long Island Sound. A vital water quality goal in the Sound is the attainment of dissolved oxygen levels that will support all marine life. (Soundkeeper) The effects of placing a barrage in the middle of the Sound are truly unknown. Theoretically, the barrage would have a straining effect on the waters coming from the New York Bight area. The build up of sediment close to the barrage would act as a buffer between the incoming clean oceanic waters and the highly polluted Hudson River waters. In fact, the state of the Long Island Sound is so horrific that it would likely be achievable to get a decent amount of local support and potentially legislative support.

One major factor that would likely prevent the proposal of a Long Island Sound barrage scheme from getting far into legislation is the fact that the striped bass, the most vital East Coast fishery both commercially and recreationally, uses the Sound for spawning during the spring and migration during the fall. Typically stripers lay massive amounts of roe late in the spring then leave for the open waters during the summer months when the waters warm to levels that are uncomfortable for the species. Once fall establishes itself, the striped bass enters the east entrance of the Sound, following massive schools of menhaden, which they prey on. Most researches believe that there are two major wintering grounds on the East Coast; the Chesapeake Bay and Hudson River Watershed. Preventing the striped bass from entering and leaving the barrage system with ease would likely disrupt the entire migration process of the stock. The outcome of such a scenario could be disastrous. Therefore, this is a serious factor to take into account when deciphering the level of feasibility of this potential project.

In conclusion, the engineering of a Long Island Sound Barrage is quite feasible on paper, especially mathematically and physically speaking. However, after considering the effects that such a scheme would have on the habitat and fisheries, it quickly becomes apparent that such a feat would not be practical in a humane sense.

The Bay of Fundy: Case Study of a Potential Tidal Power Site

Experiencing one of the highest tidal ranges anywhere in the world, the Bay of Fundy on the border of Southeast Nova Scotia and Northern Maine has been a gleam in the eye of tidal power developers since 1910. This site has many interesting environmental, political, and economic concerns that make it an excellent case study for tidal power development.

Environmental Impacts

Renewable sources of energy such as tidal power offer an alternative to fossil-fuels because they do not pollute the environment as much with carbon dioxide and other emissions. Tidal power creates no air or water pollution from its operation. However, any proposed large-scale energy project has environmental impacts that must be weighed and considered.

Although tidal barrage and tidal current schemes do not emit pollutants, they may cause changes in tidal patterns, vertical mixing, sedimentation, and water salinity and temperature (Rieser et al. 24). Increased sedimentation requires more frequent dredging, but may be counterbalanced by erosion. Erosion is a major concern in itself for citizens of Maine's beaches: sand dunes that were protected tooth and nail are at risk for major erosion, and coastal dwellings are at risk for major storm surges if this erosion is increased by a tidal barrage scheme (United States Cong. S. Hrg. 98-233 270). Drainage basins and groundwater sources might be at risk for saltwater intrusion, which must be controlled as part of the tidal power plant's daily operations (Watson and Adkins).

Another major concern is the boundary layer stresses of water flow in a tidal scheme: shear stresses at peak flow simulate friction against a wall, and disturb the benthos, or ocean floor (White 45). Until recently, the benthos was too deep to be examined closely by instrumentation, so changes in these environments over time could not be ascertained. We now have underwater rovers to scan the ocean floor, so we must note carefully the existing condition of such areas as a baseline to compare future natural or man-made changes to the benthic ecosystem (Boudreau). One possible concern with tidal pattern disruption by barrage schemes is that pollutants that would normally be carried away by the tide may lodge in the ocean floor and concentrate in higher levels than would be expected (Boudreau). The complexity of these benthic systems still cannot be modeled, however, and the changes that may result in the ecosystem may be caused by factors other than a tidal barrage (National Research Council 76).

Red tide has been a problem around the Bay of Fundy area, an ideal site for tidal power that has been proposed for development since 1910. "Red tide" is the common name for harmful algal blooms which form under certain oceanic or freshwater conditions. Single-cell algae species overrun the waters and reduce dissolved oxygen levels, sometimes resulting in a mass suffocation of fish. These organisms produce toxic poisons that do not affect primary producers, but collect in the digestive tracts of fish, and the meat of shellfish. Larger marine mammals and humans may eat these shellfish and become sick with paralytic shellfish poisoning, and even die. Red tide was a particular problem in the Bay of Fundy even before any tidal barrages were constructed, possibly due to the vulnerability of its native organisms, and the tides which carry and diffuse algae species throughout the region (Offshore/Inshore Fisheries Development and Technologies).

Fish migration is also affected heavily by tidal barrages: diadromous fish such as the American shad and salmon must migrate from saltwater to freshwater to spawn. If tidal barrages by their design do not make it impossible for these fish to migrate, the fish may be killed by passing through the turbines sometimes multiple times in their lifespan (United States Cong. S. Hrg. 98-233 181). Designs are in the works which are fish-friendly, with wider gaps between the blades of the turbines, but any impact on the fishing industry is met with hostility by the communities where the potential for tidal energy is greatest, because the fisheries constitute their livelihood (United States Cong. S. Hrg. 98-233 268). Marine mammal migration may also be affected in some regions, one example being seal migration off the coast of Scotland in the area of a proposed tidal current energy scheme.

Inter-tidal zones would also be affected by a proposed barrage scheme: some of these schemes would raise the water level to make the tidal range always above sea-level. Presently, the Bay of Fundy ranges from around 26 feet below sea level to 25 feet above sea level. The proposed Minas Basin energy scheme would constrain the range to 1 foot above sea level to 25 feet above sea level. Diverse organisms that function in the inter-tidal zone would be "swept away" and this unique ecosystem would change in ways that we cannot predict.

Ecological modeling can only predict certain consequences or patterns that may emerge if certain processes dominate the landscape. As with "Silent Spring," we realize that we cannot predict with any certainty the environmental effects of a plan, especially a new type of construction. A fallacy with environmental impacts is in comparing the plan's environmental effects with a static or historical context: the world is dynamic and will not be tomorrow what it is today. How would the area be affected ultimately by coal, oil, nuclear, hydropower, geothermal, wind, solar, or tidal power? A comprehensive life-cycle analysis of each system must be compared to tidal power, on a local/regional and also national/international scale to determine the best-case scenario for each power plant.

Economics

We have seen that tidal energy has many environmental impacts, both positive in reducing carbon and particulate emissions, and negative in causing change to the shore ecosystem. Economic factors also play a major role in negotiating energy choices, whether the decisions ultimately made are logical or not.

Short term costs of changing to any substitute good or service are always high. Classical economics tells us this, and clearly the capital costs will be high to build all new infrastructures immediately. However, the long-term costs may be lower, especially in the case of renewable energies as an alternative to fossil fuel sources of electric power. The Gibrat ratio is a term invented to describe the cost of a tidal barrage: it is the ratio of the length of the barrage in meters to the annual energy production in kilowatt hours of the tidal scheme. A small Gibrat ratio implies less cost in relation to the benefit of increased energy output. The Severn Estuary has a Gibrat ratio of 0.87, the Bay of Fundy of 0.92, and the operating La Rance tidal scheme has a Gibrat ratio of 0.36 (Baird). These ratios do not, however, take into account the cost of distribution to energy markets.

Another concern for economists is the dwindling supply of fossil fuel resources. Production cannot always increase to meet demand, as the supply of oil and coal is finite and will one day refuse to yield to our growing appetites for energy consumption. When resources are scarce, prices rise, and the argument made for cheap energy from coal and oil will no longer hold true when our poor and perhaps even middle class citizens cannot afford electricity from the grid. It may be a case of the grasshopper versus the ant, but we must look into renewable energies if for no other reason than the "invisible hand". Even if everything is fine today while we are driving our Mercedes, we need to look several moves ahead.

Energy futures trading is a hot "commodity"; just like wheat or corn, you can speculate on the price of oil and coal. Such commodities trading is thought of as "price exploration": it takes an agreed upon quality of product and provides price knowledge to the global market so a fair price may be upheld. Dealing in buying or selling commodities is a risky business, especially in the case of oil, whose exploration costs are high and resources are running low. "Hedging your bets" takes on new meaning as you can place options to buy or sell on the future price of goods, letting speculators or brokers absorb the price fluctuation risk (Commodities Futures Trading Commission). Protection against price risks may enable farmers to keep going, and supply our cars with gasoline and our homes with lights. But tidal power would also bring tourists and media attention to Washington County, Maine, which has the lowest median income of all counties in Maine (Udall 44). This begs the question of why we continue to miss the point of our “energy futures”: the loss of health and environment is no tradeoff to a bit more cheap energy now.

Policy Concerns

We can fill a stadium with engineers and environmentalists and build a tidal power scheme, but it would serve no purpose unless the laws regulating its construction, maintenance, and function were agreed upon by all jurisdictions. What is frustrating about energy policy is that no one body has jurisdiction over what goes on with a power plant: citizens, landowners, local, county, state, and national governments are all involved, and with the case of the Bay of Fundy, both the United States and Canadian national governments must agree and act in concert. The details of projects may become quagmired in bureaucratic red tape in our current system; tomorrow’s challenge is to connect various stakeholders to obtain the best possible situation financially and environmentally.

It is difficult to see the worldwide effects of a small tidal project (or oil refinery) but the problem with making decisions on a local scale is that energy projects in particular have consequences for far-removed locales. Chernobyl’s nuclear disaster, for example, contaminated sheep a continent and sea away in Wales. The Kyoto Protocol and other supranational regulatory bodies suggest using “credits” for countries that are cleaner so that others may continue their destructive practices. This is ridiculous, because it imposes a “lowest common denominator” on world energy prices. If a country only competes for energy sources with others in, say, the European Union, then its new system of credits would not affect prices (Ilex Energy Consulting). However, if a country like the United States competes for the lowest oil prices, it may be knowingly or unknowingly making emissions and pollution worse.

What is worse, the United States has strict guidelines over energy exports, but not over imports, stated in the National Energy Policy Act of 1969 (. Although we may not be polluting in our backyards, in our codified law we could not care less how Canada pollutes, as long as we receive their energy. In the case of a large tidal barrage in the Bay of Fundy, New England would receive much of the power generated, so this disconnect must be solved.

Other Tidal Power Schemes

I took the Bay of Fundy as an example of an excellent source of tidal power generation, but there are other sites that are also favorable, and unlike Nova Scotia, have a large population that would benefit from the close proximity of renewable energy. San Francisco is one such site: the bay waters that pass under the Golden Gate every day may foretell a new Gilded Age for the city. California has realized that it is "short on energy" since 1970: a convention of petroleum geologists concerned that they could not provide enough energy to meet demand actually recommended looking into renewable energies and reducing energy consumption (Weaver et al. 312). A tidal project in San Francisco would consist of a "box" that would create a pressure differential when ocean water moves into the box, that would then spin turbines on land. This unique design, proposed by the British company HydroVenturi, has the benefit of even less maintenance of the system (McCarthy).

For a power plant that lasts over seventy-five years, one and a half times as long as a coal plant and twice as long as a nuclear plant, this makes good economic and environmental sense (Gray and Gashus). Only time (and possibly the administration) will tell when tidal power schemes will become a part of the grid.

A More Futuristic Approach – Artificial Reef Turbine Program

Current-driven fences and turbines have excellent potential within the ecological constrains of marine life, particularly pertaining to fish populations. If we set up a scenario in which we have fields of current fences or turbines under the water's surface, we have the potential to produce respectable amounts of power for coastal communities. However, one major aspect of these structures that must not be ignored is their capability to create more than adequate living structure for species such as cod, black sea bass, tautog, and ling. By simply placing a grate structure over the fences or turbines, a safe habitat for these species is created. Figure 2.1 illustrates the expected outcome of such a scheme.

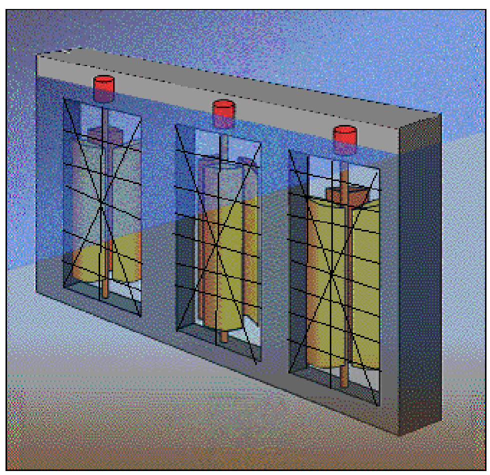


Figure 2.1

Presently, there is extremely high demand for inshore artificial structures. In 2000, the state of New Jersey purchased over fifty abandoned New York City subway cars that were to be sunk in various locations about one to two miles offshore. These cars would act as safe havens for most all inshore species. At the same time, recreational divers and anglers look highly upon such programs as they concentrate fish in a small area, making for excellent fishing/observation environs. Meanwhile, these structures also help conserve certain species as they prevent trawlers, shown in Figure 2.2, from netting fish in densely populated areas. Trawlers simply do not want to risk getting their expensive gear or nets caught on the bottom structure, and thus, they avoid such areas.

Figure 2.2

Conclusions

As with the introduction, each author included their own conclusions based on their research.

Lauren Kologe

When making a choice between several alternatives, it is not good enough just to hear the benefits and disbenefits of one of the options. In comparing tidal power to the already existing infrastructures for coal-fired and nuclear power plants, we must weigh the environmental and economic impacts for each technology, on a local and global scale, and in the long term. Only by understanding these considerations may we come to an informed decision over our energy choices. Another choice is how many resources to use. Cutting our energy consumption now would delay the fearsome consequences of ignoring the dwindling base of fossil fuels. Either way, there is a difference between working effectively and perfection: any energy scheme has inherent costs and benefits, we just need to take our heads out of the sand and start dialogues about our energy choices for a better tomorrow.

Peter Clark

Hydroelectric power is a totally feasible proposition where the necessary conditions intersect with a populous. The only major fallback is the lack of human control over the ocean and its associated tributaries. Although we can build around it and on it, we have yet to invent a method of building through the depths. At the same time, the marine ecosystem is fluidous; it is one of the few ecosystems that man has yet to devise a way of controlling.

Rebecca Klossner

The evolution of tidal energy from a primitive means of grinding grain, to a power station generating over 8,000 megawatts is fascinating. Today it is sufficient to say that in most parts of America electricity is almost a basic human need. This is in direct competition with human biological needs for clean water and air. The fossil fuels we used today are causing these two needs to conflict. In the future we look to renewable energy for a means of providing us with energy, as well as not damaging the air and water that we need for survival. Tidal energy can offer this, but only if we are willing to pay the price for a clean environment.

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