12

Marine Tidal Current Electric Power Generation: State of Art and Current Status

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1. Introduction

Tidal power is a form of renewable energy generated by the periodic change in the ocean envelope of the Earth while interacting with Sun and the Moon via gravitational forces. The gravitational force of the Earth and the Moon attracts the ocean towards it. The motion of Earth around the centre of mass of the Earth-Moon system develops a bulge on the side of Earth opposite the Moon. The net effect of the two phenomena is two tidal bulges. The rotation of the Earth-Moon system cause the two bulges to rotate, making the sea level to rise and fall periodical to coastal observers. The tides created by the Earth-Moon system are known as lunar tides (Tom, 2007).

The gravitational force of the Earth-Sun system has the same influence on the ocean. It creates bulges that tend to follow the Sun through the day. The influence of the Sun is about 46 % of that from the Moon. The positions of the solar bulges change much more slowly than the position of the lunar bulges. The lunar and solar tides will be additive, resulting in higher high tides and lower low tides. However, if the Moon, Earth and Sun form a right angle, the solar tide will tend to diminish the lunar tide, which is known as neap tides. This is because the moon's contribution is more than twice that of the sun, the solar tide will not completely cancel the lunar tide. During neap tides, the high tides are not very high and low tides not very low. Neap tides occur at two week intervals.

The large tides are caused by the linear alignment of the sun, Earth and moon which is also called spring tides. During spring tides, high tides are very high and low tides very low. Spring tides occur in two week intervals. Neap tides arrive a week after the spring tide.

As Earth turns, landmasses obstruct the tidal crests, diverting, slowing and otherwise complicating their movements. This interference produces different patterns in the arrival of tidal crests at different places. The shape of the basin itself has a significant influence on the patterns and heights of tides. For these and other reasons, some coastlines experience semidiurnal tides: two high tides and two low tides of nearly equal level each day. Others have diurnal tides: one high and one low daily. The tidal pattern is called mixed if successive high tides or low tides are of significantly different heights throughout the cycle. This pattern is caused by blending diurnal and semidiurnal tides.

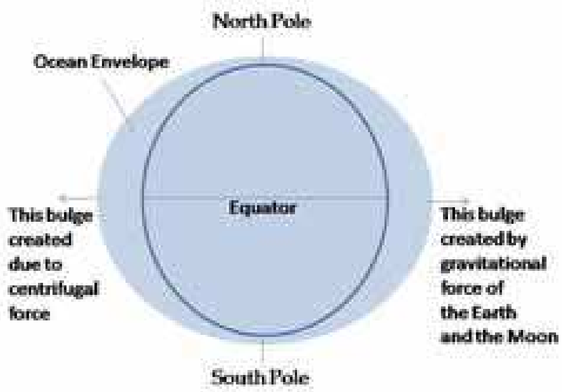

Fig. 1. Lunar tide created by the Earth-Moon System

Humans have found ways to use the tides. As early as the eight century, the Spanish, French and British built tidal storage ponds behind dams that were filled by the incoming tidal through sluice gates. These gates were closed at high tide and the trapped water then released to the sea through a water wheel to mill grain. The Eling Tide Mill in the United Kingdom has been producing flour with tidal power since 1418 (Eling, 2009).

A few tidal power electrical generation plants have been built that operate on the similar principle, in that a dam or barrage is constructed to impound the water at high tide and then releasing the water through openings with conventional hydroelectric turbine-generators when the water in the dam has sufficient potential energy. Although tidal power has not been widely used, tidal power is more reliable and predictable than wind energy and solar power. The Earth's tides are caused by the tidal forces due to gravitational interaction with the Moon and Sun, and the Earth's rotation, tidal power is practically inexhaustible and classified as a renewable energy source.

Numerous techniques have been proposed to extract energy from tidal current energy. The kinetic energy present in marine and tidal currents can be converted to electricity using relatively conventional turbine technology. There are several sites of the global ocean have the potential tidal energy that can be harnessed economically. Some of those sites are Pembrokeshire in Wales, River Severn between Wales and England, Cook Strait in New Zealand, Bay of Fundy in Canada, East River in New York City, Golden Gate in the San Francisco Bay, Piscataqua River in New Hampshire, and The Race of Alderney and The Swinge in the Channel Islands. Those sites can make a significant contribution to electricity supply. This is the reason why the marine renewable sector is currently the focus of much industrial and academic research around the world. There are generally three categories of tidal energy technologies as described in the following.

2. Categories of tidal energy technologies

Tidal power can be classified into three main types:
Barrage tidal power: A physical barrier, namely the Barrage, is constructed within the sea with Sluice Gates to control the flow of sea water. The Sluice Gates are to be closed at high tide so that the water level inside the barrage is held at its highest level. As the tide recedes, a difference in water level in between the barrage and the sea is created. The potential energy from the water level difference can then drive turbines to generate electricity.

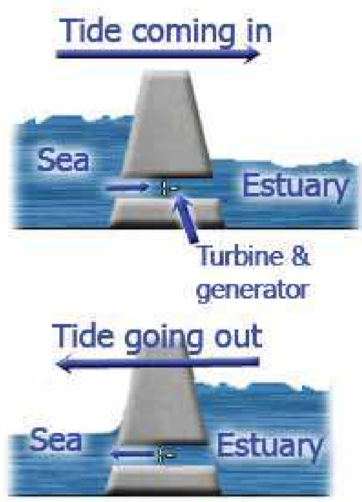

Fig. 2. Barrage tidal power for electricity generation (Source: http://home.clara.net/darvill/altenerg/tidal.htm)

Tidal stream system: A horizontal axis turbines are placed in the path of tidal currents to generate electricity, similar to the operation of wind turbine. This method is getting popular because the cost and ecological impact of tidal turbines is much lower than that of the barrage system.

Fig. 3. Tidal stream turbine (Source: http://www.altdotenergy.com/2008/12/seagen-achieves-maximum-capacity-of-12-mw/)

Tidal lagoons: These approaches are similar to barrages, but can be constructed as self contained structures, not fully across an estuary, and are claimed to incur much lower cost and impact overall. Furthermore they can be configured to generate electricity continuously which is not the case with barrages.

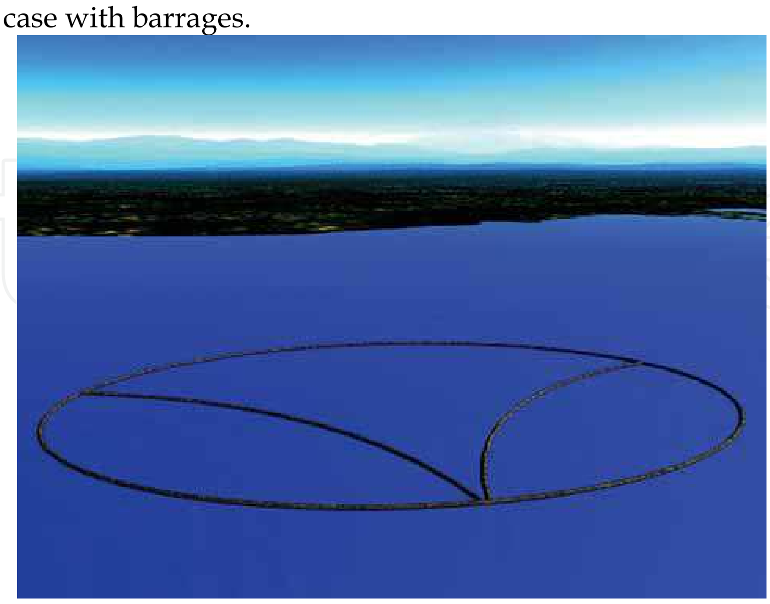

Fig. 4. Tidal lagoon with 3 pools configuration (Source: http://www.tidalelectric.com/technology.html)

3. Barrage tidal power

There are only a few barrage tidal power plants operating globally. The largest one is 240 MW plant on the Rance River in France, and two small plants on the Bay of Fundy and across a tiny inlet in Kislaya Guba Russia. The Rance tidal power plant has been operating since 1966 with the annual production of 600 GWh (Charlie, 2007).

The barrage system consists of caissons, embankments, sluices, turbines, and ship locks. Caisson is a very large concrete blocks used to house the sluices, turbines, and ship locks. Embankments seal a basin where it is not sealed by caissons. The sluice gates used in tidal power are the flap gate, vertical rising gate, radial gate, and rising sector.

Fig. 5. Barrage tidal power plant on Rance River (Source: http://www.britannica.com/EBchecked/topic-art/595132/118418/Tidal-power-generation-station-on-the-Rance-River-in-Saint)

The barrage system generates electricity using the difference in water level in between the barrage and the sea. The difference in water level is created by a process known as outflow or ebb generation where the basin is filled through the sluice gates during high tide while the turbine gates are closed as shown in Figure 6. Then the sluice gates are closed when a significant difference in water level is achieved. The turbine gates are opened to let the water to flow out, hence generating electricity. This cycle repeats itself. If the difference in water level is not great enough, pumping may operate where turbines are powered by the grid electricity to pump water from the sea into the basin in order to raise the height by, say, another 2 ft (61 cm). The cost for creating the extra 2 ft rise can be returned by the total electricity generation as a result of the pumping.

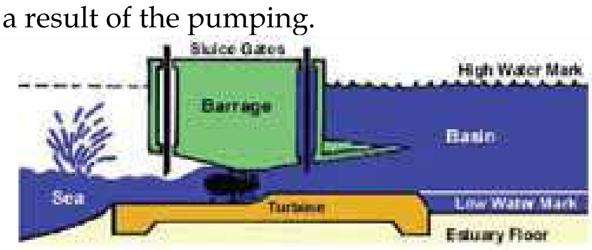

Fig. 6. Ebb generation scheme

Electricity can also be generated through inflow generation where the basin is filled through the turbines instead of sluice gates during high tide. However, this approach is generally less efficient than outflow generation, because the volume contained in the basin is less than the volume contained through outflow generation. Therefore the amount of electricity generated using this method is less than that of outflow generation.

3.1 Environmental impact

Barrage systems have not been widely used because it may create several environmental issues. The placement of a barrage into an estuary alters the flow of saltwater in and out of estuary which eventually change the hydrology and salinity, hence creating negative effects on the marine mammals that use the estuaries as their habitats (Pelc et al., 2002). During the construction of the tidal barrage, the estuary was isolated from the sea water, hence damaging flora and fauna. Some species lost their habitat due to La Rance's construction. Also as a result of the construction, sandbanks disappeared, the beach of St. Servan was badly damaged. (Charlie, 2007).

Estuaries often have high volume of sediments moving through them, from the rivers to the sea. The introduction of a barrage into an estuary may result in sediment accumulation within the barrage, affecting the ecosystem and also the operation of the barrage.

Another environmental impact of barrage system is fish kill. Fish may move through sluices safely, but when these are closed, fish will seek out turbines and attempt to swim through them. If the turbines are moving slowly enough, such as low velocities of 25-50 rpm, fish kill can be minimised. However, some fish will be unable to escape the water speed near a turbine and will be sucked through. Fish can be killed by pressure drop, contact with blades, cavitation, etc. The most fish-friendly turbine design has fish mortality per pass of approximately 15%. Various passage technologies (fish ladders, fish lifts, etc.) have so far failed to overcome this problem for tidal barrages. Research in sonic guidance of fish is ongoing (Peltier, 2003). The Open-Centre turbine may minimise this problem by allowing fish to pass through the open centre of the turbine.

Fig. 7. Open centre tidal turbine (Source: http://www.greentechmedia.com/articles/photos-clean-power-at-the-edge-of-the-world-5723.html)

3.2 Economics

Tidal barrage power schemes have a high capital cost and a very low running cost. Governments may be able to finance tidal barrage power, but many are not willing to do so because they need to wait for many years before investment return and may face high irreversible environmental and social issues. For example, the energy policy of the United Kingdom (European Commission, 2008) realises the potential role of tidal energy and expresses the need for local councils to understand the possible contribution of tidal projects to meeting the national goal of renewable energy. The UK government itself appreciates the technical viability, but has failed to provide meaningful incentives to move these goals forward.

4. Tidal stream generators

Tidal stream generators draw energy from currents, which is the same way as wind turbines. The higher density of water, 832 times the density of air, means that a single generator can provide significant power at low tidal flow velocities as compared with wind speed. In another words, water speeds of nearly one-tenth of the speed of wind provide the same power for the same size of turbine system. The total kinetic power in a marine current can be expressed by the following equation.

$$P = \frac{1}{2}\rho A v^3 \tag{1}$$

Where ρ is the seawater density (kgm^{-3}), A is the swept area of turbine blades (m^2) and v is the velocity of seawater (m/s).
However, a marine energy converter or turbine can only harness a fraction of this power due to losses and Eq. (1) is modified as follows.

$$P = \frac{1}{2}\rho C_p A v^3$$

Where C_p is the power coefficient and the percentage of power that can be extracted from the fluid stream taking into account losses due to Betz's law and the internal mechanisms within the converter or turbine. For wind generators, C_p has typical values in the range 0.25-0.3. The upper limit is for highly efficient machines with low mechanical losses. For marine turbines, C_p is in the range of 0.35-0.5.
Tidal stream generators are not fully mature because, at present, there is no commercial scale production of tidal generators and no standard technology being recognised as the clear winner. A variety of designs are being experimented. Several prototypes have been developed. Some are very close to large scale deployment. However, their efficiencies and feasibility have yet to be independently verified.
At present, there are several prototypes, namely horizontal axis turbine, vertical axis turbine, oscillating devices and tidal turbine with venturi shroud as described in the following.

4.1 Horizontal axis turbines

These horizontal axis turbines have the similar concept to traditional windmills operating under the sea and have the most prototypes currently operating.
A prototype of a 300 kW horizontal axis turbine was installed in Kvalsund, south of Hammerfest, Norway (Penman, 2009) and connected to the grid on 13 November 2003.

Fig. 8. Tidal turbine in comparison with offshore wind turbine

A 300 kW horizontal axis turbine, also known as Seaflow, was installed by Marine Current Turbines off the coast of Lynmouth, Devon, England, in 2003 (Fraenkel, 2004). The turbine has a diameter of 11m being fitted to a steel pile which was driven into the seabed. It was connected to a dump load.

Fig. 9. Seaflow Turbine

A prototype project was installed in the East River between Queens and Roosevelt Island in New York City in the United States in April 2007 (Verdant Power, 2009). However, the blades broke off due to the strong tidal currents. Therefore, new reinforced turbines were installed in September 2008. (Urbina, 2004) (Galbraith, 2008).
A prototype, called SeaGen, was installed by Marine Current Turbines in Strangford Lough in Northern Ireland in April 2008. The turbine began to generate at full power of about 1.2 MW in December 2008 and was reported to feed 150kW into the grid for the first time on 17 July 2008. It is currently the only commercial scale device to have been installed anywhere in the world (MCT, 2008).

Fig. 10. Seagen Farm

A prototype has been developed by OpenHydro, an Irish company (The Renewable Energy Centre, 2008). Its performance is being studied at the European Marine Energy Centre (EMEC), in Orkney, Scotland.

Fig. 11. Seagen installed by Marine Current Turbine in Strangford Lough in Northern Ireland (Source: http://www.iconocast.com/00001/G1/News4.htm)

4.2 Vertical axis turbines

The Gorlov helical turbine (GHT), evolved from the Darrieus turbine design by altering its blade to become helical blades. This cross-flow turbine was developed in 1994. The turbine consists of one or more long helical blades that run along a cylindrical surface like a screw thread that has 'airplane wing' profile. The blades provide a reaction thrust that can rotate the turbine. The turbine shaft (axis of rotation) should be perpendicular to the water current, and the turbine can be positioned either horizontally or vertically. Due to its axial symmetry, the turbine always develops unidirectional rotation, even in reversible tidal currents. This project has been proposed for the Uldolmok Strait in Korea, where a very strong reversible tidal current up to $6ms^{-1}$ (Cascio, 2005).

Fig. 12. Gorlov turbine (Source: http://www.oce.uri.edu/oce311/)

Neptune Renewable Energy has developed Proteus (Neptune, 2009). The Neptune Proteus is a vertical axis turbine mounted within a symmetrical Venturi diffuser duct and beneath a very simple steel deck and buoyancy chambers. The Neptune Proteus is designed for estuarine sites that have high tidal currents, yet have the advantages of lower access, cabling and maintenance costs than in offshore environments. The vertical shaft connects to the 1:200 gearbox and generator in the deck housing. The device is moored in the free stream, minimising environmental impact and operates equally efficiently for both flood and ebb currents. The rotor is maintained at optimal power outputs by sets of computer controlled shutters within the duct and by the variable electrical load. The overall efficiency of the system suggests to be greater than 45%.

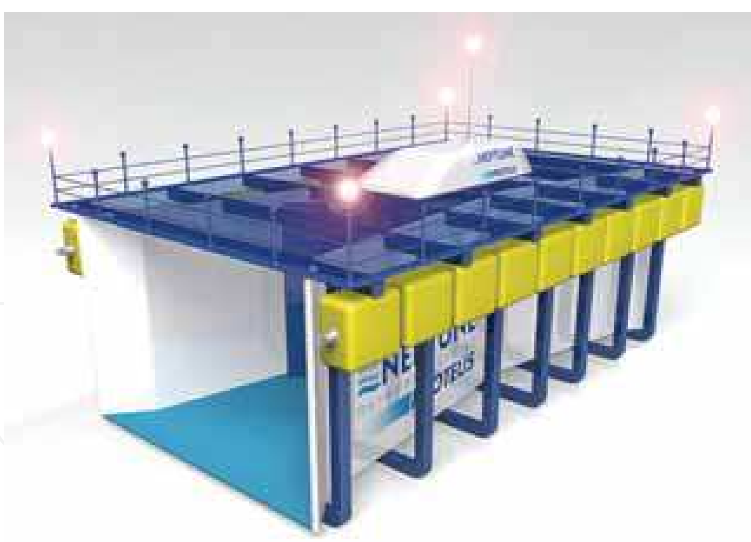

Fig. 13. The Neptune Proteus

The Enermar Project developed Kobold turbine (Ponte, 2009) that can provide very high starting torque, hence providing instant power once loaded. A pilot plant is moored in the Strait of Messina, Sicilian shore in Italy with the average tidal current of 2 m/s. A floating platform is above the surface of the water and is readily accessible for maintenance and repair of the turbine. The system can produce power of 20 kW.

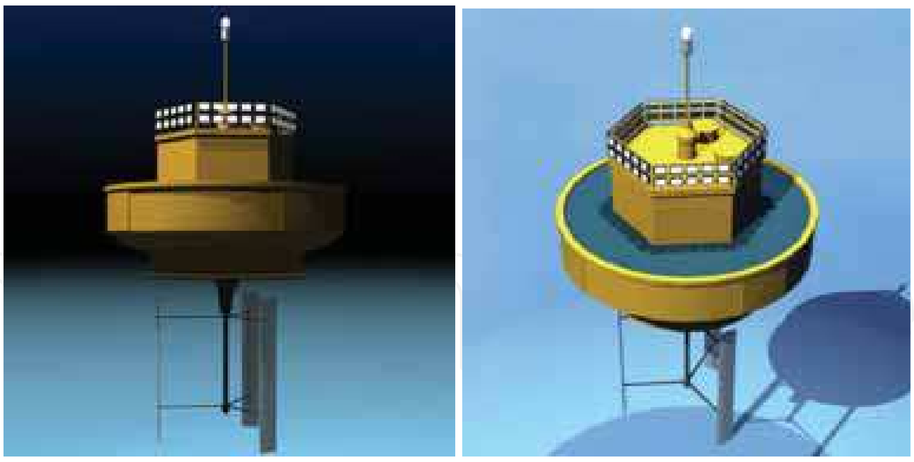

Fig. 14. Kobold turbine (left side) and floating platform (right side)

Blue Energy tidal turbine consists of four fixed hydrofoil blades connected to a rotor that drives an integrated gearbox and electrical generator as shown in Fig. 15. The turbine is mounted in a durable concrete marine caisson which anchors the unit to the seabed. The platform is above the surface of the water and is readily accessible for maintenance and repair. The rotation of the turbine is unidirectional on both the ebb and the flow of the tide. A unit turbine is expected to be about 200 kW output power. For large scale power production, multiple turbines are linked in series to create a tidal fence across an ocean passage or inlet.

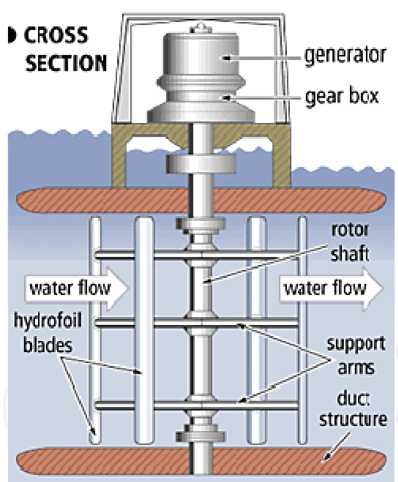

Fig. 15. Blue Energy tidal turbine

4.3 Oscillating devices – Stingray tidal turbine

Stingray uses the flow of the tidal stream over a hydroplane to create an oscillating motion that operates hydraulic cylinders to drive a motor that, in turn, drives an electrical generator. This device is a seabed mounted machine, to be situated typically in any water depth up to 100m. During 2003, a 150kW Stingray was tested off the Scottish coast, including a flexible control system to allow the performance of the generator to be accurately controlled and recorded over a longer period (IHC, 2009).

Fig. 16. Stingray tidal energy conversion device using oscillating hydroplane (Source: http://www.engb.com/services_09a.php)

4.4 Shrouded Tidal Turbines

A Patented tidal stream turbine invented by Aaron Davidson and Craig Hill of Tidal Energy Pty Ltd, Australian company, uses a venturi shaped shroud to increase the flow rate through the turbine, hence increasing the turbine efficiency as much as 3.84 times compared to the same turbine without the shroud. The Tidal Energy installed and tested such shrouded tidal turbines on the Gold Coast, Queensland in 2002. Tidal Energy has installed another shrouded turbine for a remote Australian community in northern Australia, providing 3.5 MW of power to the community. Another larger 5 meter diameter turbine, capable of 800 kW in 4 m/s of tidal flow, is planned for deployment as a tidal powered desalination showcase near Brisbane Australia in October 2008 (Hirch, 2009). Another device, the Hydro Venturi, is to be tested in San Francisco Bay (Hammons, 2008).

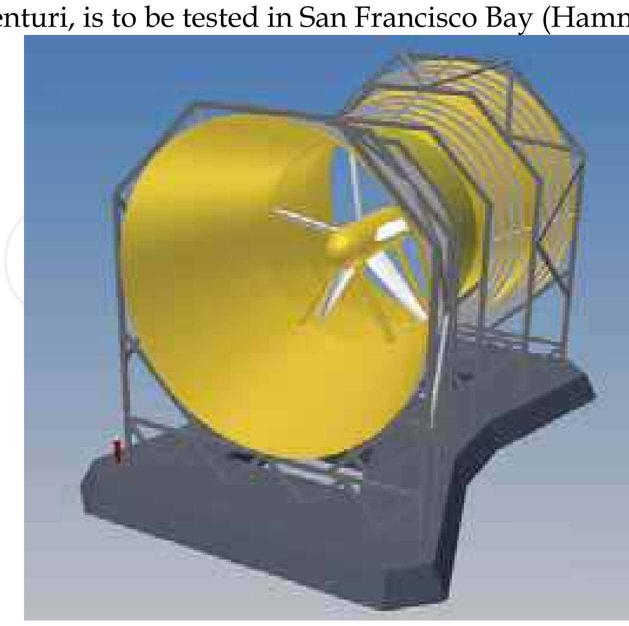

Fig. 17. Tidal turbine with venturi shroud (Source: http://www.reuk.co.uk/Lunar-Energy-Tidal-Power.htm)

In late April 2008, Ocean Renewable Power Company, LLC (ORPC) (EMEC, 2009) successfully completed the testing of its turbine-generator unit (TGU) prototype at ORPC's Cobscook Bay and Western Passage tidal sites near Eastport, Maine (Viscarolasaga, 2008). The TGU makes use of cross-flow (ADCF) turbines to drive a permanent magnet generator located between the turbines and mounted on the same shaft. This technology can be used for generating power from river, tidal and deep water ocean currents.

4.5 Current Activities for Commercial Developments of Tidal Technologies

RWE's npower announced that it is in partnership with Marine Current Turbines to build a tidal farm of SeaGen turbines off the coast of Anglesey in Wales (MCT, 2008).

In November 2007, British company Lunar Energy announced that, in conjunction with E.ON, they would be building the world's first tidal energy farm off the coast of Pembrokshire in Wales. It will be the world's first deep-sea tidal-energy farm and will provide electricity for 5,000 homes. Eight underwater turbines, each 25 metres long and 15 metres high, are to be installed on the sea bottom off St David's peninsula. Construction is due to start in the summer of 2008 and the proposed tidal energy turbines, described as "a wind farm under the sea", should be operational by 2010.

British Columbia Tidal Energy Corp. plans to deploy at least three 1.2 MW turbines in the Campbell River or in the surrounding coastline of British Columbia by 2009 (Alternative Energy Press, 2007).

An organisation, named Alderney Renewable Energy Ltd, is planning to use tidal turbines to extract power from the notoriously strong tidal races around Alderney in the Channel Islands. It is estimated that up to 3GW could be extracted. This would not only supply the island's needs but also leave a considerable surplus for export (Alderney Renewable Energy, 2009).

Nova Scotia Power has selected OpenHydro's turbine for a tidal energy demonstration project in the Bay of Fundy, Nova Scotia, Canada and Alderney Renewable Energy Ltd for the supply of tidal turbines in the Channel Islands. Open Hydro.

5. Conclusion

Tidal energy is a promising renewable energy source available to the world. Since the past one decade, numerous research and development efforts have been carried out hoping that tidal energy can become a realistic renewable energy source one day. At present, tidal current technologies are still in the developing stage. A large variety of tidal designs have been developed and experimented. Several prototypes have been claimed to be promising. Some companies are planning for large scale manufacturing and deployment of tidal turbine. Any commercial tidal plants are still in the planning stage.

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Renewable Energy is energy generated from natural resources-such as sunlight, wind, rain, tides and geothermal heat-which are naturally replenished. In 2008, about 18% of global final energy consumption came from renewables, with 13% coming from traditional biomass, such as wood burning. Hydroelectricity was the next largest renewable source, providing 3% (15% of global electricity generation), followed by solar hot water/heating, which contributed with 1.3%. Modern technologies, such as geothermal energy, wind power, solar power, and ocean energy together provided some 0.8% of final energy consumption. The book provides a forum for dissemination and exchange of up-to-date scientific information on theoretical, generic and applied areas of knowledge. The topics deal with new devices and circuits for energy systems, photovoltaic and solar thermal, wind energy systems, tidal and wave energy, fuel cell systems, bio energy and geo-energy, sustainable energy resources and systems, energy storage systems, energy market management and economics, off-grid isolated energy systems, energy in transportation systems, energy resources for portable electronics, intelligent energy power transmission, distribution and inter-connectors, energy efficient utilization, environmental issues, energy harvesting, nanotechnology in energy, policy issues on renewable energy, building design, power electronics in energy conversion, new materials for energy resources, and RF and magnetic field energy devices.