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Tidal Energy Update 2009

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Abstract

Tidal energy has the potential to play a valuable part in a sustainable energy future. It is an extremely predictable energy source, depending only on the gravitational pull of the moon and the sun and the centrifugal forces created by the rotation of the earth-moon system. Tidal energy has been exploited on a significant scale since the construction of the La Rance tidal barrage in France in 1967. A tidal barrage utilises the potential energy of the tide and has proven to be very successful, despite opposition from environmental groups. Kinetic energy can also be harnessed from tidal currents to generate electricity and involves the use of a tidal current turbine. This is the more desired method of capturing the energy in the tides. However, tidal current turbine technology is currently not economically viable on a large scale, as it is still in an early stage of development. This paper provides an up-to-date review of the status of tidal energy technology and identifies some of the key barriers challenging the development of tidal energy. The future development of tidal current devices and tidal barrage systems is discussed as well as examining the importance of a supportive policy to assist development.

Keywords: Tidal energy, tidal current turbine, tidal barrage

Contents

1. Introduction

The global energy requirements are primarily provided by the combustion of fossil fuels. In 2007, the global share of energy from fossil fuels was 88% of the total primary energy consumption. This primary energy consumption consists of 35.6 % oil (3952.8 million tons of oil equivalent (mtoe)), 23.8 % natural gas (2637.7 mtoe), 28.6 % coal (3177.5 mtoe), 5.6 % nuclear (622 mtoe) and 6.4 % hydroelectricity (709.2 mtoe)[1]. The consequence of this heavy dependence on fossil fuels is becoming increasingly concerning. Fossil fuels have limited potential and, at the current rate of

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exploitation, it is expected that these resources will deplete within the coming decades.

The security of supply issues are not the only concerning factors from an over-reliance on fossil fuels to meet energy demand. The CO_2 released into the atmosphere from burning fossil fuels restricts the earth from radiating the heat from the sun back into space, resulting in the rise in global temperature. This global issue known as the greenhouse effect causes dramatic climate change and, inevitability, a rise in sea level[2]. The increased exploitation of coal and nuclear energy to alleviate the oil dependence has resulted in acid rain and public concern over nuclear waste.

Renewable energy technologies are becoming an increasingly favourable alternative to conventional energy sources to assuage these fossil fuel related issues[3]. Since renewable energy technologies are indigenous and non-polluting, they can deal with both security of supply concerns and environmental issues. The development of renewable energy technologies is largely influenced by energy policy[4]. Solar and wind energy technologies have gained the greatest attention recently and consequently have developed considerably. The main disadvantage of most renewable energy technologies are their intermittent availability and variation in energy intensity.

Tidal energy offers a vast and reliable energy source[5]. Currently, the harnessing of tidal energy from the rise and fall of the tides has been exploited on a commercial scale using tidal barrage systems. Recent efforts to exploit this predictable energy source have been directed towards the kinetic energy in tidal currents[6]. This method of energy extraction is approximately fifteen years behind the wind technology industry. However, having started its development later, tidal current energy technology can benefit from the advances in engineering and science resulting from the development of wind energy technology.

This paper presents the current status, issues and future developments of tidal energy technology. The effect of policy on the development of the technology is also discussed.

2. Basic Physics

Tidal energy is the energy dissipated by tidal movements, which derives directly from the gravitational and centrifugal forces between the earth, moon and sun[7]. A tide is the regular rise and fall of the surface of the ocean due to the gravitational force of the sun and moon on the earth and the centrifugal force produced by the rotation of the earth and moon about each other[8]. The gravitational force of the moon, due to it being closer to the earth, is 2.2 times larger than the gravitational force of the sun.

The tidal phenomenon occurs twice every 24 hours, 50 minutes and 28 seconds[9]. A bulge of water is created by the gravitational pull of the moon, which is greater on the side of the earth nearest the moon. In parallel the rotation of the earth-moon system, producing a centrifugal force, causes another water bulge on the side of the earth furthest away from the moon illustrated in Figure 1. When a landmass lines up with this earth-moon system, the water around the landmass is at high tide. In contrast, when the landmass is at 90° to the earth-moon system, the water around it is at low tide. Therefore, each landmass is exposed to two high tides and two low tides during each period of rotation of the earth[10]. Since the moon rotates around the earth, the timing of these tides at any point on the earth will vary, occurring approximately 50 minutes later each day[11].

The moon orbits the earth every 29.5 days, known as the lunar cycle[11]. Tides vary in size between spring tides and neap tides. Spring tides occur when the sun and moon line up with the earth, whether pulling on the same side of the earth or on opposite sides, resulting in very high spring tides. Neap tides occur when the sun and moon are at 90° to each other, resulting in low neap tides.

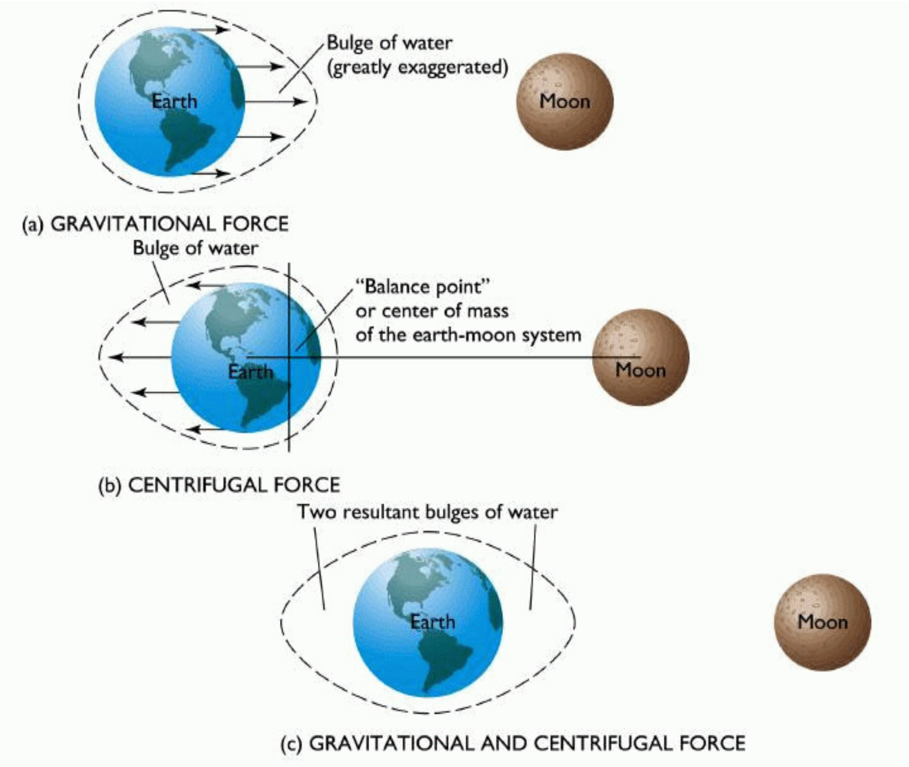

Figure 1. The Effect of the Moon on Tidal Range[12]

Tidal currents are experienced in coastal areas and in places where the seabed forces the water to flow through narrow channels. These currents flow in two directions; the current moving in the direction of the coast is known as the flood current and the current receding from the coast is known as the ebb current. The current speed in both directions varies from zero to a maximum. The zero current speed refers to the slack period, which occurs between the flood and ebb currents. The maximum current speed occurs halfway between the slack periods[11].

These tidal variations, both the rise and fall of the tide and the flood and ebb currents, can be utilised to generate electricity.

3. Tidal Energy Status

Tidal energy consists of potential and kinetic components. Tidal power facilities can be categorised into two main types: tidal barrages and tidal current turbines, which use the potential and kinetic energy of the tides respectively[13].

3.1. Tidal Barrages

3.1.1. Principles of Operation

Tidal barrages make use of the potential energy of the tides. A tidal barrage is typically a dam, built across a bay or estuary that experiences a tidal range in excess of 5 m[14]. Electricity generation from tidal barrages employs the same principles as hydroelectric generation, except that tidal currents flow in both directions. A typical tidal barrage consists of turbines, sluice gates, embankments and ship locks. The turbines that are used in tidal barrages are either uni-directional or bi-directional, and include bulb turbines, straflo or rim turbines and tubular turbines (for more information see [11]). Tidal barrages can be broken into two types: single-basin systems and double-basin systems. These are described below[15].

3.1.1.1. Single-Basin Tidal Barrages

Single-basin systems consist of one basin and require a barrage across a bay or estuary. There are three methods of operation for generating electricity within a single basin [16]:

- *Ebb Generation*- The basin is filled with water through the sluice gates during the flood tide. At high tide, the sluice gates are closed, trapping the water in the basin. At this point extra water can be pumped into the basin at periods of low demand, typically at night when electricity is cheap. The turbine gates are kept closed until the tide has ebbed sufficiently to develop a substantial hydrostatic head across the barrage[17]. The water is let flow out through low-head turbines, generating electricity for several hours until the hydrostatic head has dropped to the minimum level at which the turbines can operate efficiently.

- *Flood Generation*- During the flood tide the sluice gates and turbines are kept closed until a substantial hydrostatic head has developed across the barrage. Once the sufficient hydrostatic head is achieved, the turbine gates are opened allowing the water to flow through them into the basin. Flood generation is a less favourable method of generating electricity due to effects on shipping and the environment. These effects on shipping and the environment are caused by the average decrease in sea level within the basin.

- *Two-Way Generation*- This method of operation utilises both flood and ebb phases of the tide to generate electricity. The sluice gates and turbines are kept closed until near the end of the flood cycle. After this point the water is allowed to flow through the turbines, generating electricity. When the minimum hydrostatic head for generating electricity is reached the sluice gates are then opened. At high tide, the sluice gates are closed and the water is trapped behind the barrage until a sufficient hydrostatic head is reached once again. Water is then allowed to flow through the turbines to generate in the ebb mode. Two-way generation has the advantage of a reduced period of non-generation and a reduction in the cost of generators due to lower peak power[16].

3.1.1.2. Double-Basin Tidal Barrages

Double-basin systems consist of two basins. The main basin is basically the same as that of an ebb generation single-basin system. The difference between a double-basin system and a single-basin system is that a proportion of the electricity generated during the ebb phase is used to pump water into the second basin, allowing an element of storage; therefore this system can adjust the delivery of electricity to match consumer demands.

The major advantage double-basin systems have over single-basin systems is the ability to deliver electricity at periods of high electricity demand. However, double-basin systems are unlikely to become feasible due to the inefficiencies of low-head turbines. High construction costs of double-basin systems due to the extra length of the barrage may also restrict the development of this system.

3.1.2. Current Status of Tidal Barrages

Generating electricity using tidal barrages is mature and reliable. Numerous tidal sites worldwide are considered suitable for development; however there are only four tidal barrage power plants in operation at present. The four operational power plants and other tidal barrage sites subjected to feasibility studies are described below.

3.1.2.1. La Rance, France

The largest operating tidal barrage power plant is the La Rance power facility in France, with a generating capacity of 240 MW. The La Rance power facility illustrated in Figure 2 was constructed between 1961 and 1967, and is situated on the river Rance in Brittany[18]. The barrage is 720 metres long which encloses a surface area of 22 km^2 of the estuary. The barrage contains 24 reversible 10 MW bulb turbines operating with a typical hydrostatic head of 5 m[11, 19]. The mode of operation of the La Rance tidal power facility uses a combination of two-way generation and pumped storage. Pumping from the sea to the basin is carried out at certain tides to enhance generation on the ebb. The facility produces a net power output of approximately 480 GWh per year[11].

Figure 2. The La Rance Tidal Power Station in France[20]

3.1.2.2. Annapolis Tidal Generation, Bay of Fundy, Canada

The Annapolis Tidal Generation facility illustrated in Figure 3 was constructed between 1980 and 1984 and is located in the Bay of Fundy, Canada. Its construction was a government pilot project to explore the potential of harnessing tidal energy[21]. The facility has a generating capacity of 20 MW, which is connected to the national grid. The Bay of Fundy has the highest ocean tidal range worldwide with a maximum tidal head of 16 m[22]. This tidal facility uses one turbine, the largest straflo (rim) turbine in operation in the world, producing 30 GWh of electricity per year[21]. There is great potential for further development of tidal power in the Bay of Fundy. Two other potential basins have been identified: the Minas Basin and the Cumberland Basin. The proposal for the Minas Basin could have an installed capacity of over 5 GW.

Figure 3. The Annapolis Tidal Power Facility[23]

3.1.2.3. Kislaya Guba Power Facility, Russia

The Kislaya Guba power facility was constructed in 1968 as a government pilot project with a generating capacity of 400 kW[20]. Kislaya Guba is a fjord on the Kola Peninsula near Murmansk in Russia and is the smallest tidal power facility in operation worldwide[24]. The success of this installation has led to feasibility studies to develop much larger sites in the north and east of Russia[25], including Mezen Bay in the White Sea with a potential power capacity of 15 GW and Tugar Bay with a potential power capacity of 6.8 GW.

3.1.2.4. Jangxia Creek, East China Sea

The Jangxia Creek power facility was constructed about the same time as the La Rance power facility. This tidal power facility has a generating capacity of 500 kW and is situated on the East China Sea.

3.1.2.5. Other Tidal Barrage Sites

There are many potential tidal barrage sites worldwide. Some of the larger sites currently undergoing feasibility studies include the Severn Estuary in the UK[26], Bay of Fundy in Canada, Mezeh Bay and Tugar Bay in Russia, and the Wash, the Mersey, the Solway Firth, Morecambe Bay and the Humber Estuary in the UK. In addition to these large sites there are numerous small scale sites such as estuaries and rivers that could be utilised. The small scale sites of interest from feasibility studies include Garlolim Bay in Korea, the Gulf of Kachchh in India, Secure Bay in Australia and Sao Luis in Brazil.

3.1.3. Applicable Resource

There are many sites worldwide that have been identified as suitable for tidal barrage construction and these are listed in Table 1. The difference in water height varies from location to location, depending on various conditions.

Location	Mean Range (m)	Basin Area (km^2)	Potential Mean Power (MW)	Potential Annual Production (GWh/year)
North America				
Passamaquoddy	5.5	262	1800	15800
Cobscook	5.5	106	722	6330
Bay of Fundy	6.4	83	765	6710
Minas-Cobequid	10.7	777	19900	175000
Amherst Point	10.7	10	256	2250
Shepody	9.8	117	520	22100
Cumberland	10.1	73	1680	14700
Petitcodiac	10.7	31	794	6960
Memramcook	10.7	23	590	5170
South America				
San Jose, Argentina	5.9	750	5870	51500
United Kingdom				
Severn	9.8	70	1680	15000
Mersey	6.5	7	130	1300
Solway Firth	5.5	60	1200	10000
Thames	4.2	40	230	1400
France				
Aber-Benoit	5.2	2.9	18	158
Aber-Wrac'h	5	1.1	6	53
Arguenon	8.4	28	446	3910
Frenaye	7.4	12	148	1300
La Rance	8.4	22	349	3060
Rotheneuf	8	1.1	16	140
Mont St Michel	8.4	610	9700	85100
Somme	6.5	49	466	4090
Ireland				
Strangford Lough	3.6	125	350	3070
Russia				
Kislaya	2.4	2	2	22
Lumbouskii Bay	4.2	70	277	2430
White Sea	5.65	2000	14400	126000
Mezen Estuary	6.6	140	370	12000
Australia				
Kimberley	6.4	600	630	5600
China				
Baishakou	2.4	No data	No data	No data
Jiangxia	7.1	2	No data	No data
Xinfuyang	4.5	No data	No data	No data

Table 1. Major World Tidal Barrage Sites[27]

3.1.4. Current Issues

The current issues restricting the development of tidal barrage systems are the high construction costs and the environmental impact, with no major technical issues requiring resolution.

The construction of a tidal barrage requires a vast quantity of materials to withstand the huge loads produced from dammed water. The resulting high construction costs are considered one of the greatest issues when deciding whether or not a site is economically viable for tidal energy extraction. Due to the developments in turbine design, routine repair can now be conducted at greater ease; therefore maintenance is no longer considered a development issue.

The decision to utilise tidal energy technologies must be made with the awareness that imminent changes will be made to the surrounding environment. The greatest disadvantage of tidal barrages is the environmental impacts. Building a dam across an estuary or bay may change the flow of the tidal currents, affecting the marine life within the estuary. The impact of a tidal barrage varies from site to site; however, there are very few projects available for comparison. Water quality within the basin may also be affected, such as sediment transportation, resulting in changes to water turbidity. The effect on fish and other marine animals may also be detrimental, due to them passing through the turbines. The presence of a barrage will also influence maritime traffic. This maritime traffic problem is easier solved for an ebb generating system, where the basin is kept at a much higher water level than the water level of a flood generation system. The changes in sediment transportation are not all negative and, as a result, marine life may flourish at sites where they are not normally found.

3.1.5. Future Developments

Tidal barrage technology is mature, reliable and has excellent potential. However, the high capital cost associated with the construction of a tidal barrage system is the biggest barrier restricting its development. The future development of tidal barrage systems depends specifically on an increase in the cost of electricity generated from conventional sources and on no alternative method of electricity generation materialising in the mean time[28]. The major advantage this technology has over other renewable energy technologies is the fact that it is already available and reliable[29].

3.2. Tidal Current Turbines

3.2.1. Principles of Operation

Tidal current turbines extract the kinetic energy in moving water to generate electricity. Tidal current technology is similar to wind energy technology[30]. However there are several differences in the operating conditions. Under similar conditions water is 832 times more dense than air and the water flow speed generally is much smaller[31]. Since tidal current turbines operate in water, they experience greater forces and moments than wind turbines. Tidal current turbines must be able to generate during both flood and ebb tides and be able to withstand the structural loads when not generating electricity.

The following two methods of tidal current energy extraction are the most common[32]:

- Horizontal axis tidal current turbines. The turbine blades rotate about a horizontal axis which is parallel to the direction of the flow of water.
- Vertical axis tidal current turbines. The turbine blades rotate about a vertical axis which is perpendicular to the direction of the flow of water[33].

In its simplest form a tidal current turbine consists of a number of blades mounted on a hub (together known as the rotor), a gearbox, and a generator. The hydrodynamic effect of the flowing water past the blades causes the rotor to rotate, thus turning the generator to which the rotor is connected via a gearbox. The gearbox is used to convert the rotational speed of the rotor shaft to the desired output speed of the generator shaft. The electricity generated is transmitted to land through cables.

These three parts are mounted to a support structure that is required to withstand the harsh environmental loadings. There are three main support structure options when considering installing a tidal current turbine. The first of these is known as a gravity structure which consists of a large mass of concrete and steel attached to the base of the structure to achieve stability[34]. The second option is known as a piled structure which is pinned to the seafloor using one or more steel or concrete beams. The third option is known as a floating structure. The floating structure is usually moored to the seafloor using chains or wire. The turbine in this case is fixed to a downward pointing vertical beam, which is fixed to the floating structure.

3.2.2. Current Status

Tidal current turbine technology is still in its infancy[35]. Currently the spotlight is on the work reliability of the technology[36]. Recent advances have translated into down-scaled models and full-scale prototypes[37] and also the first dedicated test centre, The European Marine Energy Centre (EMEC), based in Orkney, Scotland is operational since May 2005 for the testing of tidal current turbines. This centre was set up to offer marine-based renewable energy technology developers the opportunity to test full-scale grid-connected prototype devices in excellent marine energy conditions. Below, listed in alphabetical order, are some of the most promising tidal current turbines including two “non-conventional” devices that are still considered turbines.

3.2.2.1. DeltaStream Turbine

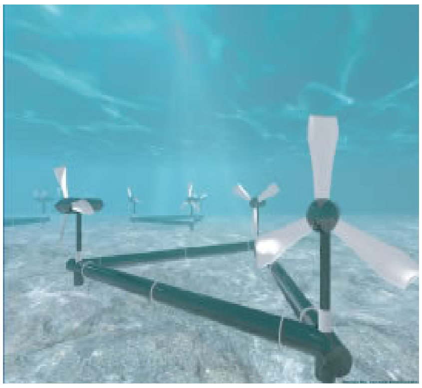

Figure 4. DeltaStream Turbine[38]

The DeltaStream Turbine device (Figure 4) was developed by a company called Tidal Energy Ltd based in the UK. The 1.2 MW device consists of three, three-bladed, horizontal axis tidal turbines each with a diameter of 15 m, mounted on a triangular frame, producing a low centre of gravity for structural stability. This device has yet to undergo testing, after which full production has been planned for summer 2009[38].

3.2.2.2. Evopod Tidal Turbine

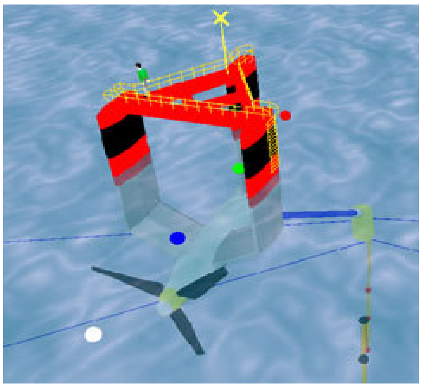

Figure 5. Evopod Tidal Turbine[39]

The Evopod Tidal Turbine (Figure 5) was developed by a company called Ocean Flow Energy Ltd based in the UK. The device is a five-bladed, horizontal axis, floating structure which is moored to the seafloor. The mooring system allows the device to maintain optimum heading into the tidal stream. A 1/10th scale model is currently being tested in Strangford Lough in Northern Ireland[39].

3.2.2.3. Free Flow Turbines

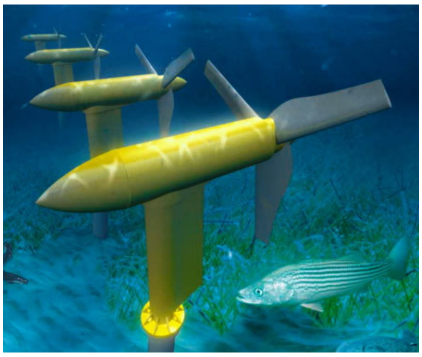

Figure 6. Free Flow Turbine[41]

The Free Flow Turbine (Figure 6) was developed by Verdant Power Ltd based in the USA and Canada. This three-bladed horizontal axis turbine has a diameter of 4.68 m and a prototype is being tested in New York City’s East River, generating 1 MWh of electricity per day. Late in 2008 Verdant Power Ltd were awarded a $1.15 million contract from Sustainable Development Technology Canada to develop phase one of the Cornwall Ontario River Energy Project[40].

3.2.2.4. Gorlov Helical Turbine

The Gorlov Helical Turbine (Figure 7) is a vertical axis tidal current turbine based on the Darrieus Windmill concept and was developed by a company called GCK Technology Inc based in the USA. The Gorlov Helical Turbine utilises three twisted blades in the shape of a helix, and has proven to be efficient and reduces vibration. A scale model of diameter 1 m was built and commenced testing on July 10th 2002.

Figure 7. Gorlov Helical Turbine[42]

3.2.2.5. Lunar Energy Tidal Turbine

The Lunar Energy Tidal Turbine (Figure 8) is a horizontal axis tidal current turbine and was developed by Lunar Energy Ltd based in the UK. The structure consists of a gravity base, a 1 MW bi-directional turbine 11.5 m in diameter, a duct of length 19.2 m and diameter 15 m, and a hydraulic motor and generator. This tidal turbine is at the development stage, and to-date nothing has been built. The ducting is included to maximise the energy extraction from the current water flow. Lunar Energy Ltd has recently agreed a £500 million deal to install 300 tidal current turbines off the coast of Korea[43].

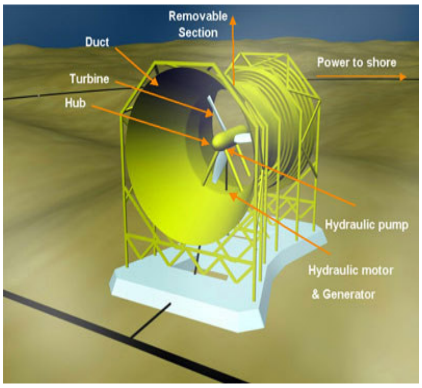

Figure 8. Lunar Energy Tidal Turbine[43]

3.2.2.6. Neptune Tidal Stream Device

The Neptune Tidal Stream Device (Figure 9) was developed by a company called Aquamarine Power Ltd based in the UK. The device is said to have a generating capacity of 2.4 MW. It consists of twin, three-bladed, horizontal axis turbines mounted on a monopole structure. The device can generate electricity in both the ebb and flood tides. Aquamarine Power Ltd has set plans to test their device within the next three years at the EMEC. On January 12th 2009 it was announced that ABB Ltd, an automation group, will commission the electrical system of the device[44].

Figure 9. Neptune Tidal Stream Device[44]

3.2.2.7. Nereus and Solon Tidal Turbines

The Nereus and Solon Tidal Turbines (Figure 10) were developed by Atlantis Resource Corporation Ltd based in Singapore. The Nereus Tidal Turbine is a shallow water, horizontal axis turbine and has been grid connected in Australia. The 400 kW rated device was successfully tested in July 2008. The turbine is robust and has the ability to withstand flow with large amounts of debris. The Solon Tidal Turbine is a deep water, ducted, horizontal-axis turbine, developed in 2006. The 500 kW turbine was successfully tested in August 2008.

Figure 10. Nereus Turbine is shown on top, and below is the Solon Turbine[45]

3.2.2.8. Open Centre Turbine

Open-Hydro Ltd based in Ireland has developed the Open Centre Turbine (Figure 11). The technology consists of a slow moving rotor 6 m in diameter, a stator, a duct and a generator. Recently, Open-Hydro Ltd became the first tidal current energy company to connect to the UK national grid and commence electricity generation. The 250 kW Open Centre Turbine was installed at the EMEC. The company has invested €5 million in the design and construction of a specialist barge to install their tidal turbine[46]. On October 21st 2008 Open-Hydro Ltd were chosen by the electricity suppliers in France (EDF) to develop a demonstration farm there[47].

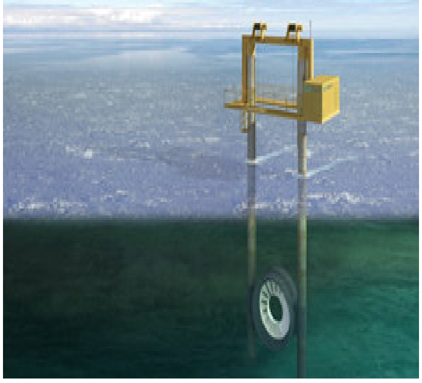

Figure 11. Open Centre Turbine[48]

3.2.2.9. Pulse Tidal Hydrofoil

Pulse Tidal Hydrofoil (Figure 12) was developed by a company called Pulse Generation Ltd based in the UK. This design has the ability of operating efficiently in shallow water. In April 2008 permission was granted to deploy a prototype in the Humber estuary in Northern England[49]. Currently this device is at the design stage of development, and to-date nothing has been built.

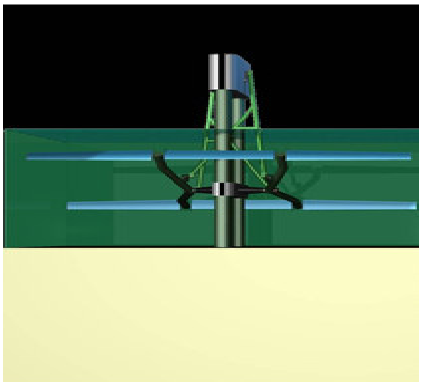

Figure 12. Pulse Tidal Hydrofoil[49]

3.2.2.10. SeaGen

SeaGen (Figure 13) is a 1.2 MW tidal current turbine, developed by Marine Current Turbines Ltd based in the UK, after the successful installation of the 300 kW device called Seaflow off the coast of Devon in the UK in 1993. A trial model of SeaGen was installed and grid connected in May 2008 in Strangford Lough, Northern Ireland[50]. The technology consists of a pair of two-bladed horizontal axis rotors, 16 m in diameter. The rotor is connected to a gearbox which increases the rotational speed of the shaft to drive a generator. The rotor blades are pitch controlled to allow for operation in both ebb and flood tides. The pitch control is also used as a braking mechanism in order to facilitate maintenance requirements of the rotor. On January 18th 2009, this device successfully operated at full power (1.2 MW)[51].

Figure 13. Seagen[52]

3.2.2.11. Stingray Tidal Energy Converter

The Stingray Tidal Energy Generator (Figure 14) is a tidal current energy converter developed by Engineering Business Ltd based in the UK. The concept transforms kinetic energy from the moving water into hydraulic power. It consists of a parallel linkage holding several large hydroplanes. The 150 kW prototype was successfully deployed in September 2002, in Yell Sound, off Shetland in the UK. However the device was removed several weeks later and development has stalled.

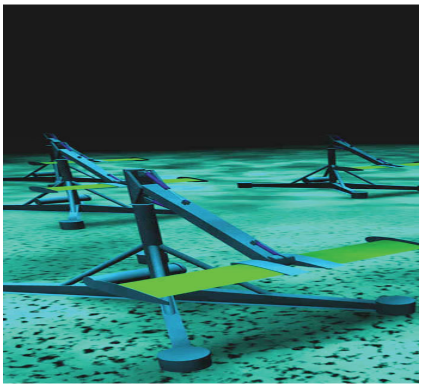

Figure 14. Stingray Tidal Energy Converter[53]

3.2.2.12. Tidal Fence Davis Hydro Turbine

The Tidal Fence Davis Hydro Turbine (Figure 15) was developed by Blue Energy Ltd based in Canada. The tidal fence technology consists of an array of vertical axis tidal current turbines. The Davis Hydro Turbine consists of four fixed hydrofoil blades, connected to a rotor that drives a generator via a gearbox. This system offers the capability of tidal energy extraction from any site, including river applications from 5 kW to 500 kW, and ocean applications from 200 MW to 8000 MW. No prototypes have been tested to date.

Figure 15. Tidal Fence Davis Hydro Turbine[54]

3.2.2.13. TidEl Stream Generator

The TidEl Stream Generator concept (Figure 16) was developed by SMD Hydrovision Ltd based in the UK. The TidEl system consists of two contra-rotating 500 kW rotors of 15 m diameter. The company have successfully tested a 1/10th scale model of the device. The complete assembly is buoyant and is tethered to the seafloor with the use of mooring chains. The mooring system allows the turbines to align to the tidal current flow direction quite easily.

Figure 16. TidEl Stream Generator[55]

3.2.2.14. Tidal Stream Turbine

The Tidal Stream Turbine is a 300 kW three-bladed horizontal axis tidal current turbine (Figure 17) developed by Hammerfest Strom AS, a Norwegian company. The turbine was installed in September 2003 in the Kvalsundet, which is situated on the north coast of Norway and it was the world's first grid connected tidal current turbine when it became operational in November 2003. The company has started developing a new 1 MW device, called HS1000[56]. Scottish Power has an agreement with Hammerfest Strom AS to build and install a full-scale model in Scottish waters[57].

Figure 17. Tidal Stream Turbine[58]

3.2.3. Applicable Resource

There are many promising tidal current sites worldwide. The practical energy resource available at each site is the theoretical resource minus the effects of limitations such as technology status, water depth, wave exposure and seabed exposure. Tidal current sites with water flow speed greater than 2.5 m/s are generally considered to have significant practical resource and to be economical viable[59-61].

The most desirable locations for harnessing the energy in tidal currents are generally sites where narrow straits occur between land masses or are adjacent to headlands where large tidal currents develop. The major tidal currents are encountered in the following locations[62]:

- Arctic Ocean
- English Channel
- Irish Sea
- Skagerrak-Kattegat
- Hebrides
- Gulf of Mexico
- Gulf of St Lawrence
- Bay of Fundy
- Amazon
- Rio de la Plata

- Straits of Magellan
- Gibraltar
- Messina
- Sicily
- Bosporus

3.2.4. *Current Issues*

The current issues restricting the development of tidal current turbines are installation challenges, maintenance, electricity transmission, loading conditions and environmental impacts.

The installation of tidal current turbines offers challenges some of which have been addressed from other off-shore energy technologies. These devices must be designed for ease and speed of installation. Construction of foundations and installation during tidal currents will be challenging, with only a few minutes of slack time between tides. Some devices may require mooring systems which are subject to biofouling and corrosion, affecting the survivability of the system. Several methods have been identified to prevent biofouling and corrosion, particularly around seals, welds, bearing surfaces and electrical insulation materials. These methods include antifouling paints and the use of sonic and ultra-sonic systems.

Easy access to the turbine is required for maintenance. The use of a ship will be required for routine maintenance and repair of tidal current devices, making it hazardous and difficult. At the design stage, it is crucial to set out measures to reduce the frequency and difficulty of maintenance. There are several concepts proposed for ease of maintenance, most of which include the rising of the turbine above the water level to allow for maintenance from a platform or ship. Replacement of large parts will be a difficult operation requiring calm waters and good weather.

Electricity transmission is another issue and in some cases transmission to shore over longer distances may be required. If so the use of higher voltage transmission will be required. Generators should be developed to operate at higher voltages, preventing the need to install transformers at, or below, the sea surface. Tidal current energy resource is often in energy dense areas, where grid access is limited. Upgrading the grid network may be required so that it doesn't restrict the amount of tidal generated electricity connected; this may be costly and cause public discontent.

In comparison to wind turbines, tidal current turbines generate a much larger thrust due to the density of seawater[63]. Resisting these large thrusts will involve the use of greater amounts of materials or stronger materials, which will result in greater capital costs. The fluctuations in the velocity of the flow around a tidal current turbine rotor can lead to several severe problems, such as blade vibrations, which may lead to fatigue failure. When designing a tidal current turbine turbulence levels must be taken into account to reduce its damaging effects. The use of computer software to model the water flow and prototype testing will play an important part in blade design.

The environmental impacts of tidal current devices are believed to be minimal in comparison to tidal barrages. The energetic conditions at which tidal turbines will be located are areas where marine species are not commonly found. Capturing the kinetic energy of the tidal flow has been identified as possibly the greatest environmental impact. This impact is also site specific and without appropriate assessments it is unknown how great an impact tidal current turbine may have on the surrounding environment.

3.2.5. Future Developments

The extraction of tidal energy using tidal current turbines is becoming an increasingly favourable method of electricity generation. Several companies have installed demonstration devices, both full-scale and down-scaled. If testing continues to be successful full-scale tidal farms are expected to materialise within the next decade. However, it should be noted that only a few of the devices discussed above have been built and successfully tested in harsh tidal currents. The Delta Stream Turbine, Lunar Energy Tidal Turbine, Neptune Tidal Stream Device, Pulse Tidal Hydrofoil and Tidal Fence Davis Hydro Turbine are all at the design stage, and to-date nothing has been built. Several scale-models have been built and tested including the Nereus and Solon Tidal Turbines, Evopod Tidal Turbine, Gorlov Helical Turbine, TidEl Stream Generator and Stingray Tidal Energy Converter. The Stingray Tidal Energy Converter was installed and removed and is no longer under development. The SeaGen and Seaflow, Open Centre Turbine, Tidal Stream Turbine and Free Flow Turbines are the only full scale operational tidal current turbines, which are generating electricity. All of these demonstration devices operate with a horizontal axis of rotation, which suggests that this may be the optimum configuration for tidal current turbines. At the rate at which tidal current turbine technology is developing, it is expected that other high potential tidal current sites will become available which were previously uneconomical for energy extraction.

4. Tidal Energy Policy

Tidal energy policy has been the main driver for tidal energy development as demonstrated by countries such as Canada, France, Portugal, the UK and the USA. Internationally tidal energy policies now form a key component of most governmental sustainable energy policies. The principle objective of these sustainable energy policies is to increase security of energy supply, while reducing costs and environmental effects. This objective can be achieved by diversifying the sources of energy, increasing renewable energy deployment, reducing reliance on fossil fuels, and reducing CO_2 emissions[64].

Tidal energy is becoming increasingly favourable as an alternative to conventional energy sources. Tidal energy has the advantage of predictability over other renewable energy sources, increases security of supply due to the fact that it helps create diversity of supply, reduces CO_2 emissions, offers innovation potential and broadens industrial capabilities and assists with economic development through employment and manufacturing [65-67]. Tidal energy policies generally consist of mechanisms to assist the development of technology such as:

- *Financial and Tax Incentives*- Financial and tax incentives provide the cost reductions tidal energy technologies require to become competitive with conventional energy systems. These incentives include tax credits, reduction in income tax and value added tax, loans, rebates and production payments. Production payments reward electricity suppliers with a subsidy payment per unit of electricity produced, hence reducing the risk of investment in tidal energy technologies.

- *Research and Development Funding*- It is well understood that sustained R&D for tidal energy technologies is critical to their successful utilisation. R&D has often been the most cost effective method to develop renewable energy. R&D is regularly carried out between universities and public institutions or private companies. For tidal current technology in particular, demonstration programs can play a crucial role in testing the performance and reliability of new immerging technologies.

- *Feed-In Tariffs*- Feed-in tariffs essentially are an incentive structure to encourage the application of renewable energy technologies. The electrical suppliers are required to purchase renewable electricity at above market prices set by the energy policy of that country. This support mechanism is generally the best method to develop renewable energy technologies as it provides a stable and profitable market. This tariff level varies from country to country. If well structured, feed-in tariffs can prove to be extremely valuable in future market stability for tidal energy companies looking to invest in long-term tidal energy technology innovation[68].
- *Carbon Tax*- This support mechanism is an environmental tax on CO_2 emissions and other greenhouse gas emissions. Tidal energy technologies are considered carbon neutral. Carbon tax is effectively a tax on the combustion of fossil fuels[69]. The principle purpose of carbon tax is to protect the environment and delay climate change. However, implementing this tax serves as an incentive for all renewable energy technologies.
- *Mandatory Renewable Energy Targets*- Mandatory renewable energy targets are becoming increasing popular in most developed countries worldwide. This support mechanism requires a fixed percentage of electricity to be generated from renewable energy. The implementation of this mechanism worldwide has shown exceptional development so far. There is considerable support for the long term view to maintain the current rate of development beyond the target dates.
- *Improvements in Planning Process*- Companies have encounted problems relating to the planning process which is a barrier to the development of tidal energy. In this mechanism regional authorities are made aware of the importance of renewable energy and strategic energy planning is conducted at local, regional and national level to insure that planning issues are dealt with swiftly and in a consistent manner.

5. Discussion

Tidal energy is a clean and renewable source of energy and has the advantage of predictability over other renewable energy sources. There is great potential to generate large amounts of electricity from tidal energy technologies.

The large construction cost of tidal barrages is likely to restrict their development. However, with the probability of increased fossil fuel prices, tidal barrage schemes may prove to play a major part of worldwide electricity production. A considerable number of potential tidal barrage sites have been identified for large scale electricity generation, although only four tidal barrages have been constructed to date. Tidal barrages have several environmental impacts, such as effects on water quality and marine life. Tidal energy extraction using tidal barrages is mature and reliable with no major technical issues requiring resolution.

Tidal current devices have lesser impact on the environment than tidal barrages. However the full extent of the environmental impacts is still unknown. As tidal current devices are still in an early stage of development, a lot of technical issues require resolution. Some of the main technology development issues identified are installation and maintenance, electricity transmission and loading conditions. All these issues will have to be fully resolved if tidal current energy is to be made a major source of electricity supply.

Canada, China, France, India, Korea, Norway, Russia, the UK and the USA appreciate the technical viability of their tidal energy resource. However, even though tidal energy is developing more quickly in these countries, meaningful incentives to further develop tidal energy have not materialised. Also, a robust resource assessment must be undertaken for all continents. Currently only a small minority of countries have conducted their own assessment of the potential for harnessing tidal energy within their waters.

Effective tidal energy policies are critical to the development of tidal energy. With such policies tidal energy can play a vital role in a sustainable energy future.

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