A REVIEW ON THE STATUS OF TIDAL ENERGY TECHNOLOGY WORLDWIDE

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ABSTRACT: *Demand for energy resources is significantly increase over the years in line with the fast economic development. However, with the decline of fossil fuels and stringent policies on pollution issues it has influence the development trend to look for renewable energy such tidal energy. Tidal energy is formed from a change in the gravitational field caused by relative motion between moon and earth. Energy of the tides is converted to electricity using various technologies and approaches. This paper reviews the status of tidal energy technology worldwide and discusses the factors affecting its successful implementation.*

Keywords: Tidal Energy, Tidal Barrage, Tidal Current Turbine, Renewable Energy

1. INTRODUCTION

The global energy requirements nowadays are primarily provided by the combustion of fossil fuels. In 2013, the total energy consumption by the worldwide is 13,583 million tons of oil equivalent (Mtoe) which is increases 2.3% per year from year 2000 to year 2013 [1]. From this data, it shows that the consequent of the dependency on the fossil fuels is becoming increasing continuously as the fossil fuels constitutes about 88% of the total primary energy consumption [2]. Continuous usage of fossil fuels will lead to the increment of cost and energy. Dependencies on the fossil fuels in the world wide neither effective nor consistent anymore as it will give negative impact as well as create other problems if not well managed. Fossil fuels such as coal, oil and natural gas can give negatives impact to the environmental degradation and the burning of oil and coil will produce greenhouse emission and causes global warming, acid rain, water pollution affects to the human health problems. Renewable energy sources could be provide as a solution to the problem caused by the fossil fuel as they are inexhaustible and have less adverse impacts on the environment [3]. Currently, ocean energy considered as a potential green and renewable source of energy. Tides and currents are the ocean energy source. Ocean energy tapped in multiple forms such as energy from waves, kinetic energy from tidal and marine currents, potential energy from tides and energy form salinity and thermal gradient. The basis of the ocean energy resources can be classify such as tides, currents, waves, salinity gradient and Ocean Thermal Energy Conversion (OTEC) systems. The tidal energy is highly predictable over a long time scales compared to other renewable energy source, as it is a conversion of gravitational energy [4]. Thus, it has the potential to be a reliable renewable energy source.

2. BACKGROUND

Basic Principle of Tidal Energy

Tidal energy defined as the energy formed by tidal flows. The tidal flows generated from the gravitational and centrifugal forces between the earth, moon and sun [5]. A tide is the regular rise and fall of the surface of the ocean caused by the gravitational force of the sun and the moon on the earth and the rotation of the earth and moon to each other will produce centrifugal force [6]. The moon create gravitational force about 2.2 times higher than the gravitational force of the sun due to the facts that the distance of moon to the earth is less compared with the sun [2]. The gravitation creates tidal with two "bulges" in the earth envelope which one on the side of the earth facing the moon while the other is on the opposite side. A maximum of two tides can be observed by depending on the location relative to the axis of the earth rotation [7].

Tidal ranges classified as spring tide and neap tide. The spring tide occurred during the time of new and full moon where the earth, moon and sun positioned closely on the same line as seen in Figure 1. This explains why tidal ranges are greater than the average during spring tide [8]. Meanwhile, the neap tide occurred when the sun's gravitation act at right angles to the moon on the earth as illustrated in Figure 2. During the neap tide, tidal ranges are less than the average [8].

Figure 1: Gravitational effect of the sun and the moon on tidal range during the spring tide [9]

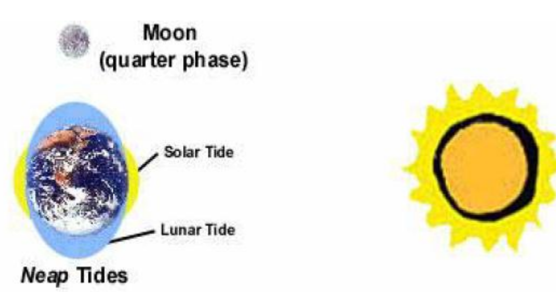

Figure 2: Gravitational effect of the sun and the moon on tidal range during the neap tide [9]

A tidal phenomenon is periodic [8]. The tide phenomena can be categories into three main types, which influenced by different locations on the earth namely semi – diurnal tides, diurnal tides and mixed tides [10].

Semi – diurnal tides has a period that matches the fundamental period of the moon (12 hour 25 min). During this period, ocean normally will experience two high tides per day. The amplitude of the tide will varies through the lunar month, with tidal range being greatest during as mentioned previously. Diurnal – tides has a period corresponding to a full revolution of the moon relative to the earth (24 hour 50 min). This type of tide has only one high tide per day. It is subject to the variations of arising from the axis of rotation of the earth being inclined to the planes of orbit of the moon around the earth and the earth around the sun. The mixed tide is the combination of the characteristics of semi diurnal tides and diurnal tides. They may be display monthly and bimonthly variation.

Tidal Energy Status

The potential and kinetic components are two forces that form a tidal energy. Based on these two components, two main approaches used to generate power from the tidal energy, tidal barrage approach and tidal current turbines approach. Tidal energy can utilize in the form of potential energy, kinetic energy and current energy [11].

Tidal Barrage Approach

The basic principle of tidal barrage is exploiting power from potential energy of the tides. A tidal barrage is typically a dam look like structures and used to capture energy from the water channel through a bay or river that have a tidal range in excess of 5m [12]. Compared to conventional damn which is water is control on one side, a tidal barrage allows water to flow into the bay at high tide and releasing the water back during low tide. It seems that a tidal barrages share the same principles as hydroelectric power plant for the electricity generation, except that tidal currents flow in both directions. A typical tidal barrage normally consist a caissons, sluices, turbines, embankments and ship locks. The turbines that used in tidal barrages can be directional or bi – directional and include bulb turbines, straflo or rim turbines and tubular turbines [13]. Tidal barrage divided into two types that are single – basin system and double – basin system [14].

Single – basin system

Single – basin system has only one basin by constructing barrages across a bay or estuary [2]. Under single – basin system, there are several type of method used to generate electricity [15] is the ebb generation, flood generation and two – way generation.

- Ebb generation – Ebb generation uses the energy of falling tide or known as ebb tide where the water flow out back to the sea. Initially, during flood tide, the water allowed to flow into the basin through the sluices gates and when water level in the basin is sufficient to achieve hydrostatic head then sluices gates are closed. At this point, the extra water pumped into the basin to raise the level further. At this condition, when the different of water level inside the basin and water level of actual sea becomes sufficient enough to form sustainable hydrostatic head[16]. Then, after fall of tide, sluices gates are open to allow the water flow back to sea, the entrapped potential energy inside the water will flow out through the turbines and generate electricity until the water level inside the basin has dropped to the minimum level [2]. Then, the basin is filled again by opening back the sluices gates and the cycle keep continue along the process. The example of ebb generating system is shown in Figure 3.

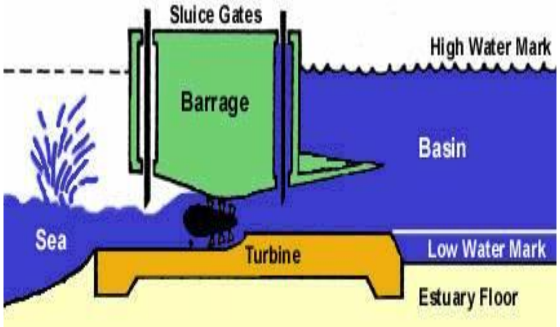

Figure 3: Ebb generating system [17]

- Flood generation – Flood generation uses the energy of rising tide or flood tide. At low tide, the basin emptied through sluices gates. Then, when the tide turns and flood tide start coming, the sluice closed until a substantial hydrostatic head has developed across the barrage. The sluices gates opened when there is a sufficient head height achieved and allowing the water to flow through the turbine and generate the electricity. However, the flood generation system is less efficient if compared to ebb generation. This is caused by river flowing into basin side that created insufficient hydrostatic head and reducing the turbine power produced.
- Two – way generation – This type of method generates power using both ebb and flood phases of the tides. The sluice and turbines kept closed until near the end of flooding cycle. At this point, the water allowed to flow through the turbines. When the minimum hydrostatic head reached, the sluice gates are then opened. During the high tide, the sluice gates closed making the water trapped behind the barrage until a sufficient hydrostatic head reached once again. Then, the water allowed to flow back through the turbines to generate in the ebb mode. The advantages of this method of operation are extending the generation period and thus reducing the cost of generators caused by lower peak power [15].

Double – basin system

Double – basin system consist of two basins and the main basin same with the ebb generation single – basin system. The difference between a double – basin and a single – basin system is the proportion of the electricity generated during the ebb phase that is used to pump the water into the second basin. This shows that this double – basin system allowing the effective control of storage capacity and enhance the productivity.

That strengthens the facts why in the case of high electricity demand, double-basin systems still able to supply electricity as per demand. However, this method suffers a drawback of high construction cost and less efficient of low – head turbines.

Current Status of tidal barrage approach

Previous study has shown the reliability of tidal barrage to generate electricity and potential of tidal sites worldwide for the development. This is noticeable when there are various tidal barrage power plants in operation nowadays. The following section discusses several of popular tidal based power plants that currently in operation and in construction.

Sihwa Lake Tidal Power Plant, South Korea.

The Sihwa Lake tidal power plant is the South Korean first tidal power plant located on Lake Sihwa as shown in Figure 4. It is about 4km from the city of Siheung and known as the world's biggest tidal power plant with capability to produce power output of 254MW [18]. The main structure of this plant was the 12.5km long seawall constructed in 1994 for the purpose of flood mitigation and agricultural. The power of this plant come from it 30km^2 basins and ten 25.4MW submerged bulb turbines [19]. The sluice gates used are culvert type and eight sluice gates used for controlling the water flow of the barrage [19]. This tidal power station cost about $355.1m and the construction process take place from 2003 to 2010 [19]. The Daewoo Engineering & Construction is the responsible contractor for this project [18]. In August 2011, Korea Water Resources Corporation is owner of this project start it operation. This power plant reported was capable to generate power output of 552.7GWh annually [18].

Figure 4: Sihwa Lake Tidal Power Plant, South Korea [19]

La Rance Tidal Power Plant, Frane

La Rance is the first tidal barrage in operation as can be seen in Figure 5. It is the first tidal power plant that has been operate since 1966 and is the biggest tidal power plant [20] after Sihwa Lake tidal power station and exhibits a peak rate of 240MW capacity [20] .Currently, this tidal power plant are being operated by Electricité de France (EDF) and able to generate power output of 540GWh annually [20]. The construction of this tidal power plant started in 1961 and took 6 years comprising the construction of a 145.1m long barrage and a 163.6m long dyke with six wheel gates [22]. The basin area covered by the plant is 22km^2 and producing power rated capacity of 10MW through each of the 24 reversible bulb turbines [19]. The average tidal range in the plant site was recorded, as 8.2m is the highest in France [22]. This tidal power plant provide electricity approximately 130,000 households every year through 225kV national transmission network [19].

Annapolis tidal power generating station illustrated in Figure 6 is located in the Annapolis Basin, a sub – basin of the Bayof Fundy in Canada, has an installed capacity of 20MW making it the world's third biggest operating tidal power plant [19].

Figure 5: The world's oldest tidal power station, La Rance, France [19]

Annapolis Royal Generating Station, Canada

The plant utilises a causeway built in the early 1960s, which was originally designed to serve as a transportation link and also as a water control structure to prevent flooding [19]. This tidal power station generates 50GWh of electricity annually to power over 4,000 homes [19]. It started the operation in 1984 and the project was undertaken primarily to demonstrate the application of a particular type of turbine generator (trade – name, Straflo) for tidal and other low – head hydro applications [23]. The Straflo machine differs from the conventional hydroelectric turbine – generator installation because the turbine and generator integrated rather than in separate unit [23].

Figure 6: The Annapolis tidal power facility [19]

Jiangxia Pilot Tidal Power Plant, China

Power plant has 6 bulb turbine generator units and operating in both ebb and flood tides with the producing an annual power output of 7MWh is illustrated in Figure 7 [25]. The power station feeds the energy demand of small villages at a 20km distance through a 35kV transmission line and the maximum tidal range in this estuary is 8.39m [25]. This power station started the construction from 1974 and the project investment was 1,130 million Yuan [26]. The first generator sets of 500kW of its generation in 1980 and the first project was completed in 1985 which installed one set generator of 500kW, one set of 600kW and three sets of 700kW with the total capacity of 3.2 MW [25]. In June 2007, the 6th set generator was successfully developed and connected to the grid and making the total installed capacity reached 3.9MW [25].

Figure 7: Jiangxia Tidal Power Station is located in Wenling City, China [27]

Current Construction Tidal Power Project- Swansea Bay Tidal Lagoon, United Kingdom.

The 240MW Swansea Bay Tidal Lagoon project will be built at Swansea Bay in UK and the planning application for the £850m ($1.4bn) project approved in March 2013 [28]. The plant's site has an average tidal range of 8.5m and involving the construction of 9.5km long of sea wall or breakwater facility to create a lagoon cordoning off 11.5km^2 of sea [19]. The structure of the plant will use suitable hydraulic conditions for bi – directional generation [29]. The reversible bulb turbines also used in this plant to generate power as water passes in and out of the lagoon with the rise and fall of tides [19]. The ground breaking for this project scheduled in 2015 while the full commissioning is expected in 2018 [19]. This tidal lagoon will power over 120,000 homes for 120 years with an estimated annual power generation capacity 400GWh [19].

Challenges and barriers

The high construction costs and the environmental impact are some barriers that limiting the development of tidal barrage system. It became the challenge particularly when the construction of a tidal barrage requires a large quantity of materials to withstand the huge loads that being produced from the water in dammed. The high construction costs considered as one of the critical factors that influence the economic viability of the system. However, the advancement in turbine design has contribute to the effort of reducing the maintenance cost and ease the routine repair works thus improve the process of system development. The adverse effects of this system such influence to environmental impacts could be a major barriers for the tidal barrage system because building a dam along a bay or an estuary can cause flow instability of tidal currents. Apparently, this will affect the marine life around estuary or bay as it leads to disruption in movement and growth of fishes and other marine life. Water quality in the basin may also affect due to the sediment transportation that will change the water turbidity.

Tidal Stream Generator Approach

Tidal stream generator or also referred as tidal current turbines is a device that generate electricity by extracting the kinetic energy from the moving. Technology of tidal current basically shared the same concept with the wind energy technology [30] but with difference operating conditions. Seawater is 832 times denser than air, and the speed of water flow is much lower than air [31]. This condition shows the tidal current turbines require a greater forces and moments compared to the wind energy technology. There are two most common methods used for the tidal current energy extraction which are [32]:

- Horizontal axis tidal current turbines. The turbine blades rotate at a horizontal axis which is parallel to the direction of water flow.

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

In the simplest form of tidal stream generator, it consists a number of blades mounted on a hub (together known as rotor), a gearbox and a generator. The flowing water that passes through the blades is known as hydrodynamic effect. The force created from hydrodynamics effect causes the rotor to rotate and turning the generator to which the rotor is connected via a gearbox. The gearbox is function to control the rotational speed of the rotor shaft to the desired output speed of the generator shaft [2]. The tranmission of electricity from generator to the land are connected using a underwater cable. The support structure of the tidal stream generator is important to ensure it can withstand with the harsh environmental loadings in the water. There are several type of support structure options which can be fall into three main main structures as explained in the following.

- A gravity structure: It consists of a large mass of concrete and steel attached to the base of the structure to achieve stability.
- A piled structure: The structure is pinned to the seafloor using one or more steel or concrete beams.
- A floating structure: It is usually moored to the seabed using chains and wire. The turbine is mounted to a beam is vertically extended downward from the floating structure [2].

Current status of tidal current turbine approach

Tidal current turbine technology is still in its early development. Recent advances have translating into down – scaled models and full – scale prototypes [7]. The first that dedicated test centre is The European Marine Energy Centre (EMEC), based in Orkney, Scotland started its operational since May 2005 for testing the tidal current turbines [34]. The centre was set up with an excellent oceanic wave regime, strong tidal currents and with 14 full – scale test berths which having more grid – connected marine energy converters [34].

Tidal Energy Ltd.

This company develop the Delta Stream Turbine (Figure 8a). The 1.2MW devices consists of three, three – bladed, horizontal axis tidal turbines with each diameter of 15m and mounted on a triangular frame that producing a low centre og gravity for structural stability. It is fully submerge on the seabed, typically from 30m to 60m depths of water. Raw power at 6.6kV is being transmit to shore via a submarine cable. The device currently being commissioned at Pembroke Port and the company will shortly installing and testing Delta Stream in the water of Ramsey Sound [35].

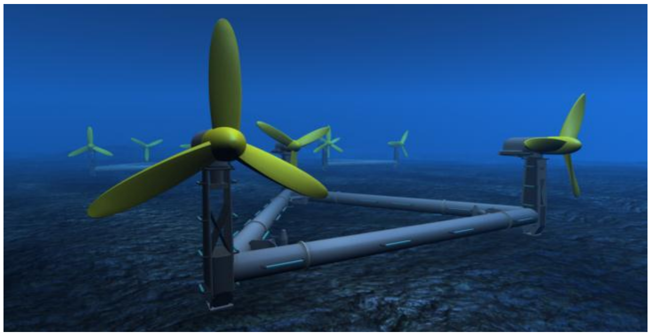

Figure 8a : 1.2MW Delta Stream Turbine [35]

Figure 8b : 400kW Delta Stream model at Pembroke Port [35]

Ocean Flow Energy Ltd

This company develop the Evapod Tidal Turbine and it based in the UK. The device is a five – bladed, horizontal axis and having a flooting structure which is moored to the seafloor. The mooring system allowing the device to maintain optimum heading into the tidal stream. Ocean Flow currently commissioning a 1/4th scale mono – turbine Evopod which follows the successful operational of 1/10th scale project in Strangford Narrows, Northern Ireland. A 1/4th scale – mono turbine consists of an Evopod with a rated output of 35kW E35 – 01 that is connected into the 11kV grid at Southend, South Kintyre. The E35 was successfully installed onto its mooring at Sanda Sound on 7th of August 2014 [36].

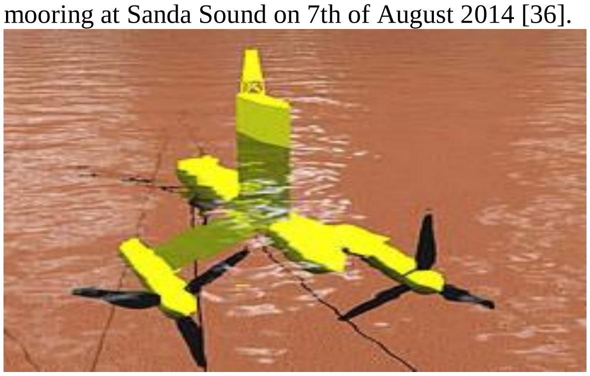

Figure 9a: Evopod Twin Tidal Turbine [36]

Figure 9b: E35 successfully installed into Sanda Sound [36]

Verdant Power Ltd.

The company that base in the USA and Canada developed the Free Flow Turbines. The central component of the device is a horizontal – axis turbine equipped with an open three bladed rotor with the diameter of 4.68m. Since 2002, Verdant Power has conducted prototype and pre – commercial testing of its device at the Roosevelt Island Tidal Energy (RITE) Project which is located in the East Channel of the East River in New York Harbour. During 2006 to 2009, Verdant Power completed a grid – connected demonstration of its device (Gen4) at the RITE project (Figure 10) with the demonstration included the operation of six full – scale tidal turbines and representing as the world's first operation of a grid – connected tidal turbine array [37].

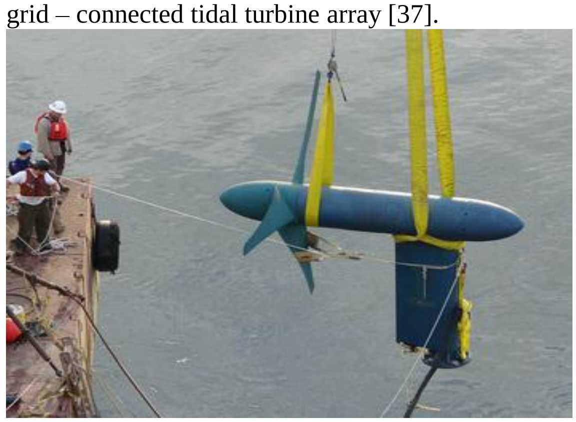

Figure 10: Free Flow Turbine (Gen4) for RITE Project [37]

GCK Technology Gorlov

Helical Turbine is a vertical axis tidal current turbine (Figure 11) based on the Darrieus Windmill concept and was develop by this company based in USA. This device utilises three twisted blades in the shape of a helix and has proven being efficient and reducing the vibrations. A scale model of 1m diameter was built and being commissioning for the testing on 10th July 2002 [38].

Figure 11: Gorlov Helical Turbine [38]

***Lunar Energy Ltd*.**

Lunar Energy Ltd developed the Lunar Energy Tidal Turbine is a horizontal axis tidal current turbine. The structure consists of a gravity base, a 1MW bi – directional turbine 11.5m in diameter, a duct length 19.2m with the diameter of 15m and a hydraulic motor with the generator. In 2011, the installation methodology had been re – design and a 2.4MW turbine need to be design [39].

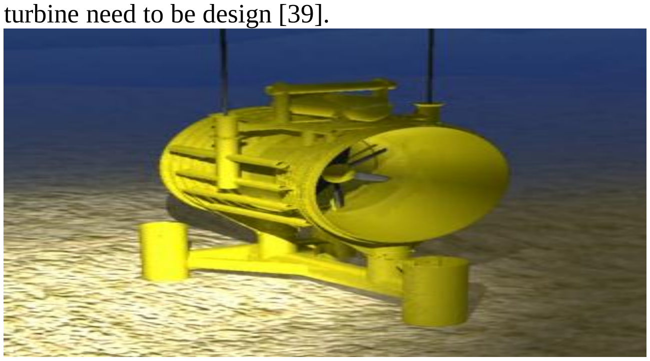

Figure 12: Lunar Energy Tidal Turbine [39]

Atlantis Resources Corporation Ltd.

This company had developed many tidal turbines such as Nereus Tidal Turbine, Solon Tidal Turbine, AR 1000 and the latest is AR 1500 [40].

- The Nereus Tidal Turbine is a shallow water turbine, a horizontal axis turbine tested, and grid connected in Australia. The 400kW device successfully tested in July 2008 and the turbine is robust. It also can withstand water flow with large amounts of debris [40].

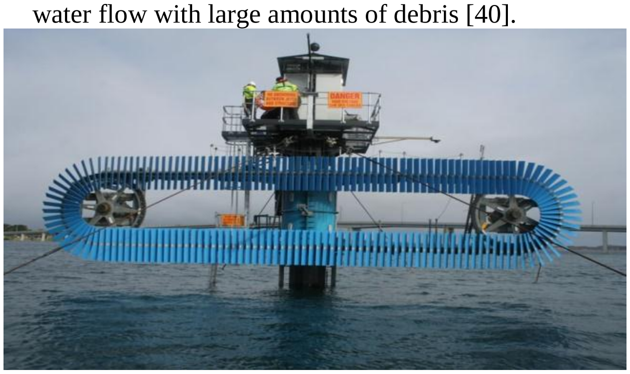

Figure 13a: Nereus Tidal Turbine [40]

- The Solon Tidal Turbine is deep water, ducted and horizontal axis turbine developed in 2006. The 500kW device successfully tested in August 2008.

Figure 13b: Solon Tidal Turbine [40]

- The AR 1000 is a commercial scale 1MW horizontal axis turbine, designed for Open Ocean and having a single rotor set with highly efficient fixed pitch blades. It successfully deployed and commissioned at the EMEC facility in 2011 and now the fixed pitch AR 1000 system installed on CECEP's Daishan demonstration site in China in 2014.

Figure 13c: AR 1000 [40]

- The AR 1500 is the latest tidal turbine under development at Atlantis and it will have a rated capacity of 1.5MW at 3.0m/s with the ability to withstand extreme environment in Pentland Firth, Scotland and the Bay of Fundy, Canada. The detailed designed had been completed by Lockheed Martin Corporation in 2014. The first unit now is due for pre – delivery on shore acceptance testing at end of 2015.

Figure 13d: AR 1500 [40]

Open Hydro Ltd.

Open Hydro Ltd is based in Ireland and has developed the Ocean Centre Turbine. This turbine consists of a slow moving rotor with the diameter of 6m (Figure 14a), a stator, a duct and a generator. In 2006, Open Hydro installed the turbine (Figure 14b) at the EMEC for testing and in May 2008, it successfully generating electricity to the Scottish grid. The first project for Ocean Centre turbine is at France (EDF) and the project featuring a 16m, 2.2MW rated turbine and was successfully installed in 2011/2012 and also in 2013/2014 [41].

Figure 14a: A 6m Open Centre Turbine [41]

Figure 14b: Open Centre Turbine being prepared for deployment in Orkney (EMEC) [41]

Pulse Generation Ltd.

This company is based in the UK has developed the Pulse Tidal Hydrofoil. It has a simple access the machine is buoyant allowing it to be fully assembled and commissioned onshore before floating out for the installation. It also can generate four times the power of competing 'horizontal axis' and can generate the same power in shallow depth while others do in deep water. It also use the oscillating hydrofoils which lie horizontally in the water and sweep up and down. It shows that the length of hydrofoils (blades) is not limited with the depth of water. The company had deployed a 100kW Pulse – Stream 100 (Figure 15a) into the River Humber in the UK in 2009 and began generating electricity in May in the same year. The electricity generated being exporting to Millenium Chemicals (a large plant on the South bank of estuary) [42].

Figure 15a: A complete unit of Pulse Tidal Hyfrofoil [42]

Figure 15b: The blades from above (exposed during low tide) [42]

Marine Current Turbines Ltd.

SeaGen – S 2MW (Figure 16) device was developed by this company and consists of twin 1MW power strains, delivering 2MW of grid conditioned electricity to the substation. The technology consists a pair of two – bladed horizontal axis rotors with 20m of diameter and connected to a gearbox increases the rotational speed of the shaft to drive a generator [2]. It is suitable in the marine environments with the water depth up to 38m and achieves rated power in tidal currents greater than 2.4m/s. The SeaGen – S 2MW is actually has incorporated a few of design changes from the following testing system in Strangford Lough with the rated power from 1.2MW to 2MW and the increment of rotor diameter from 16m to 20m. In 2013, with 8GWh generation, the system continuing in 24 – 7 operation [43].

Figure 16: SeaGen - S 2MW [44]

Current Issues

The development on the tidal current turbines having many issues especially on the installation challenges, maintenance, transmission of electricity and the environmental impacts.

The tidal current turbines designed to be easy, ease and speed for the installation process. The construction of bases or foundations and installation process will be very challenging during tidal currents as there will be only a few minutes of slack time between tides. Other devices may need mooring systems can be exposed to bio fouling and corrosion that can affect the survivability of the system. There are several methods can be used to prevent bio fouling and corrosion which are antifouling paints and ultrasonic system. These methods could be applied especially around welds, seals, bearing surfaces and the electrical insulation materials.

For the maintenance, it is required to have an easy access to the turbine. During the maintenance routine and repairing stage, it is required to use a ship making it hazardous and difficult. The rising of turbine above the water level is one of several concepts proposed for ease the maintenance while for the replacement of large parts which is a difficult operation, requiring calm water and good weather.

The transmission of electricity is also one of the highlight issues in some cases transmission to shore will required a longer distances. This will cause a higher usage of voltage transmission. To prevent the installation of transformers below the sea or at sea surface, generators used should be developed to operate at higher voltages.

The environmental impacts of tidal current turbines are minimal compared to tidal barrages. Tidal turbines will be located usually in a rough condition where marine species are not commonly found. Toxity of paints, lubricants and antifouling coatings also will give the impacts to the ocean and marine life [45].

3. DISCUSSION

Tidal energy is a renewable and clean energy source. It is a predictable energy compared to other renewable energy such as solar and wind energy. High and low tide develop with the well– known cycles which making it easier to construct the system with the right dimensions.

The large construction cost for the tidal barrages may be a main reason to restrict their development. However, tidal barrage scheme may be a major part for the electricity production worldwide as the price of fossil fuels increases nowadays. Tidal barrages have several environmental impacts such as effects on marine life and the quality of water. Tidal barrages extracted tidal energy is mature and more reliable as there are no major technical issues requiring resolution.

Tidal current turbines have lesser environmental impacts compared to the tidal barrages, but the full extent is still unknown. Many technical issues require resolution as the tidal current turbines are still in early stage of their development. The main issues identified for the technology development are the installation challenges, maintenance routines, electricity transmission and loading conditions. If the tidal current turbines being as a major source of electricity supply, all these issues above will have to be fully resolved.

4. CONCLUSION

Continuous development of tidal energy technology indicates that as a one of importance renewable energy resources nowadays. Despite of its barriers and challenges, which made some gap if comparing with fossil fuel energy, the future development of this energy is yet to be exploring to fill the gap and obtained more achievements in the near future.

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