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TIDAL ENERGY: OPPORTUNITIES AND CHALLENGES FOR RENEWABLE POWER GENERATION

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ABSTRACT

Diminishing fossil fuel reserves combined with concerns of environmental damage and climate change provide a strong motivation toward the development of practical and renewable energy sources. Of the available mix of renewable energy sources, tidal energy offers significant advantages. Tidal energy is highly predictable (unlike wind energy), is available night and day (unlike solar energy) and does not require expensive and environmentally damaging infrastructure (unlike hydroelectric energy).

This paper examines tidal energy technology and its role as a renewable energy source. The particular opportunities and challenges associated with tidal energy are summarized to provide a template for further research.

A novel hydrodynamic test facility has been developed to provide experimental evaluation of proposed theoretical models, and to assess the performance of proposed turbine systems. The test facility is fully instrumented and consists of a road-transportable, motorized pontoon.

Keywords: Tidal energy, design for environment hydrodynamic testing.

1 INTRODUCTION

Fossil fuel reserves are diminishing due to the effects of peak oil [4]. Concurrently the world's energy demand increases continuously, for example [5]:

- The annual primary energy consumption rate increased by 2.4% in 2007, the fifth consecutive year of above average growth.
- Annual coal consumption rose by 4.5% in 2007 with a 10-year average growth of 3.2%.

In addition to the supply deficit associated with fossil fuels, the environmental consequences of fossil-fuel use are significant and potentially irreversible. The extraction, production and combustion of fossil fuels results in harmful pollutants, in particular carbon dioxide (CO_2). Anthropogenic CO_2 emissions upset the natural levels of atmospheric CO_2 and contribute to global warming [6]. Current levels of atmospheric CO_2 are approximately 360 ppm as opposed to the natural occurring density of 200-250 ppm [7]. To mitigate the environmental impact of fossil-fuel use, governments are implementing emissions restrictions, for example the Kyoto Protocol, which mandates greenhouse gas reductions [8].

This combination of supply deficit and environmental impact requires the urgent development of technologies that utilize renewable energy sources. Such alternatives include: solar, wind and hydro energy. One form of hydro energy is tidal energy, which uses the energy of tidal flows to generate useful energy. Tidal energy, is a promising element of the available mix of renewable energy sources as:

- the available tidal energy is periodic and highly predictable (unlike wind energy)
- tidal energy is available throughout the diurnal cycle (unlike solar energy)
- may be implemented without impeding natural tidal flows (unlike traditional hydroelectric energy)

Despite the potential benefits of tidal energy there remain a series of challenges to their robust implementation. This paper reports on the associated opportunities and challenges of tidal energy and presents a novel hydrodynamic test facility that has been developed to evaluate proposed turbine systems.

2 THEORY OF TIDAL ENERGY

The celestial relationship between then Earth, Moon and Sun is fundamental to the nature of the tides. Depending on the relative position of the Moon, Sun and Earth, the tides will experience fluctuations in amplitude, thereby creating potential and kinetic energy that can provide a renewable energy source for many applications.

2.1 Gravitational Attraction

Tidal flow is due to fractional differences in gravitational force over the Earths surface. The gravitational force between celestial bodies is given by Newton's law of gravitation; which states that the gravitational force is directly proportional to the product of the masses and inversely proportional to the square of the distance between them [10].

$$F = G\frac{Mm}{r^2} \tag{1}$$

Where:

M = mass, kg, of the primary body, i.e. Sun or Moon
m = mass, kg, of the secondary body, i.e. Earth
r = distance, r, of the water molecule from the Sun or Moon
G = gravitational constant = 6.67×10^{-11} Nm^2/kg^2

The gravitational force applied by the Sun and the Moon on the closest, relative surface of the Earth is F_{S1} and F_{M1}, respectively.

Where the [11]:

- mass of the Moon is 7.34×10^{22} kg with a mean orbital radius of 3.84×10^{8} m about Earth
- mass of the Sun is 2×10^{30} kg while the orbit of Earth is 1.496×10^{11} m about the Sun
- radius of the Earth is 6.378×10^{6} m while the mass of the Earth is 5.97×10^{24} kg

Therefore:
$F_{S1} = 3.5585 \times 10^{22}$ N
$F_{M1} = 1.9821 \times 10^{20}$ N

Tidal amplitude is caused by the large fractional difference of gravitational attraction between the Moon and the Earth. The surface of Earth that is furthest from the Sun experiences a gravitational force, $F_{S2} = 3.5579 \times 10^{22}$ N, 0.00017% less that experienced by the surface closest to the Sun, F_{S1}. The surface of the Earth that is furthest from the Moon experiences a gravitational force, $F_{M2} = 1.8563 \times 10^{20}$ N, 6.35% less that the surface closest to the Moon.

The tidal period is influenced by the geometry of the water body which typically results in either diurnal or semi-diurnal frequencies [12]. Tides on the coast of the Atlantic Ocean are typically semi-diurnal, i.e. two local maxima occur per day with a period of approximately 12.42 hours [12, 13]. The larger Pacific Ocean responds to semi-diurnal and diurnal frequencies where the period of diurnal tides is approximately 24.814 hours [12, 14].

Due to the interaction of lunar and solar attractions, tidal amplitude alters with each lunar month, Spring tides are the largest and take place during a full or new moon period when the Earth, Moon and Sun are in alignment [10]. In this celestial arrangement the gravitational forces of the Moon and Sun combine to attract the water bodies of the Earth [15]. Neap Tides are the lowest tides and occur when the Earth, Moon and Sun are perpendicular to each other. In this celestial arrangement the gravitational forces of the Sun and the Moon on the Earth , counteract one another. [15].

Tidal amplitude is affected by the waterway geometry and also by the Coriolis force which forces the water currents eastwards as the Earth rotates about its axis [17]. Therefore, the highest tidal ranges generally occur in west facing waterways [16]. The cyclical nature of the tides creates a tidal amplitude or range between the maximum and minimum tidal level. Tidal amplitude is generally less than 1m in the open ocean, approximately 2m across continental shelves, and increases significantly in the constrained bodies of water such as estuaries, passages and straits [16].

2.2 Energy Extraction Methods

The variation in tidal range provides energy that can be extracted by potential or kinetic energy methods.

Potential energy methods

In traditional hydroelectric systems, a barrage is used to create an artificial water basin in a tidal waterway. The basin retains water after high tide, resulting in a tidal head that can be used as a source of renewable energy. Hydraulic gates are used to control the flow of water through turbines, which generate useful mechanical energy. The turbines can either generate power from one direction of flow (single action) or from the rising and lowering tide (double action). The maximum potential energy, P_{PE}, can be found from [14]:

$$P_{PE} = \tfrac{1}{2}\, dgAh^2 \quad (2)$$

Where:

d = water density ≈ 1000 kg/m^3
g = gravitational acceleration = 9.81 m/s^2
A = surface area of basin, m^2
h = mean tidal range, m, of the two water bodies

System type and location have a significant impact on the energy available to a barrage type system. For example, a double acting system in a semi-diurnal flow, can provide four times the energy as a single acting system in a diurnal flow location [14]:

Table 1. Current, large-scale hydroelectric plants [18]

Site	Country	Capacity (MW)	Operating since
La Rance	France	240	1966
Annapolis Royal	Canada	18	1984
Jangxia Creek	China	0.5	1980

Kinetic energy methods

Energy extraction methods that harness the kinetic energy of a fluid are most suitable in scenarios where fluid flow is constricted, such as straits, estuaries and artificial obstructions, as the constriction results in a local increase in fluid velocity. The theoretical mean power of a fluid flow through a constrained area is given in Equation 3 [19]. The kinetic energy of the fluid, P_{KE}, is proportional to the cube of the fluid velocity, u, i.e. an increase in fluid speed by factor of 2 will increase the kinetic energy by a factor of 8, (Figure 1).

$$P_{KE} = 1/2\ Edu^3 \quad (3)$$

Where:

d = water density ≈ 1000 kg/m^3
E = cross sectional area the restricted flow (m^2)
u = depth averaged, upstream fluid velocity (m/s) perpendicular to the cross section area

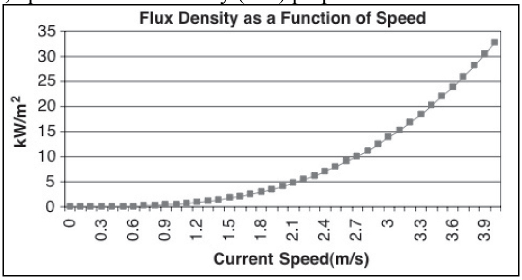

Figure 1. Energy Flux density as a function of speed [20]

2.3 Potential Sites

The selection of a suitable tidal energy site depends on the tidal amplitude and local electricity demands. Figures 2 and 3 indicate global tidal amplitudes using satellite based altimetry analysis, which can be used to calculate the potential and kinetic energy of a site to assess feasibility. The World Energy Council has identified feasible sites in the UK, France, Canada, the Pacific Coast of Russia, China, Mexico, Western India and Western Australia [21]. Potential sites are subject to feasibility issues, including: sea floor stability and site accessibility. The disadvantage of developing in regions of high tidal stream velocities is that installation and maintenance of the turbines is difficult, and anchoring methods may be prohibitively expensive. To improve the feasibility of these sites, there is a need for improved methods of anchoring and construction (Section 5).

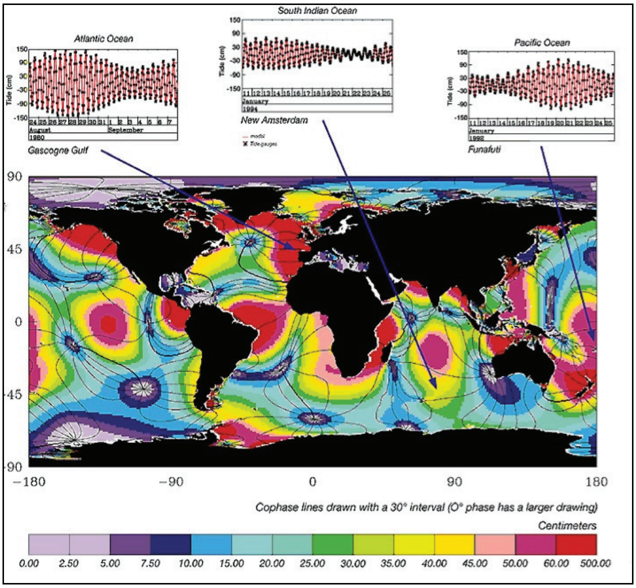

Figure 2. Global amplitudes and phases of semi-diurnal tides, in centimeters [22]

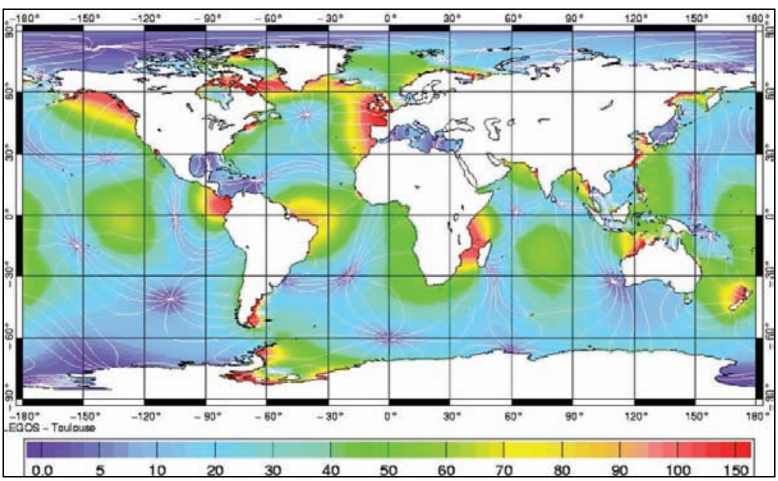

Figure 3. Global amplitudes of semi-diurnal tides, in centimeters.

A current development project in Wando Hoenggan, South Korea will utilize the kinetic energy of tidal flows with the installation of 300 individual turbines, intended to provide electricity to power

200,000 homes by 2015 [3]. These turbines are to be anchored to the sea floor to avoid interference with local shipping channels. An engineering study estimated the Kimberley region in Australia to have 3,000 MW of available tidal power due to tidal ranges of up to 12m [23]. Also, Pentland Firth in Scotland has a resource of approximately 10,000 MW, the equivalent of 3 large coal power plants and could power a million homes [3].

2.4 Hydrofoil characteristics

A hydrofoil is a section or shape that generates a net lift force as a fluid passes over it. The pitch angle of the blade is the angle between the chord line (a straight line connecting the leading and trailing edges of the hydrofoil section) and the direction of hydrofoil motion. The Angle of Attack (AoA) is the angle between the chord line and the direction of fluid flow. Variation in the AoA determines the magnitude of the lift and drag forces for a blade section. A range of hydrofoils has been proposed to optimize turbine performance (Figure 5).

Darrieus Turbine

The Darrieus turbine is a cross flow turbine, i.e. the direction of fluid flow is perpendicular to the turbine's axis of rotation (Figure 4). The direction of rotation is determined by the hydrofoil orientation. An advantage of the Darrieus turbine is due to the symmetric hydrofoil, which allows each blade to generate useful lift during both upstream and downstream passes. However, as a consequence of this symmetry, the associated hydrofoil geometry may be a non-optimal compromise between upstream and downstream conditions. As the Darrieus turbine rotates about its axis, variations in the blade AoA result in torque variations that can causes vibration and reduce the associated fatigue life. Strategies to reduce these effects include: limiting peak angular velocity, increasing stiffness and the use of high strength materials. However, these strategies may reduce the available output power and increase costs.

A disadvantage of a Darrieus turbine is that the turbine may not be self-starting, i.e. the turbine requires an external force to initiate rotation. This is due to regions of rotation where the starting torque values are negative during one revolution [24]. For a Darrieus turbine with 4 or more blades, these regions of rotational angle do not have negative values, thereby allowing self-starting. Further increasing the number of blades assists self-starting [25]. However, the associated solidity is non-optimal, and the turbine efficiency is reduced due to turbulence [24].

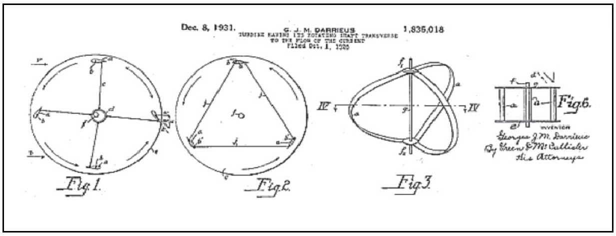

Figure 4. Darrieus turbine as filed for US patent [9]

Helical Turbine

An innovative strategy to reduce vibration is to curve the blades around the circumference of the turbine thereby creating a helical hydrofoil. A helical turbine presents an element of the hydrofoil at each possible AoA to the fluid flow, thereby minimizing torque variation and associated vibration. A particular variant of a helical turbine is the Gorlov Helical Turbine (GHT), which is reported to have a maximum efficiency of 35% (Figure 5). The GHT consists of 3 hydrofoil blades in a helical configuration [26]. A helical turbine implementation has been tested in the novel facility presented in this work (Section 6, Figure 7).

Cycloturbines

Helical turbines are more expensive than turbines with straight hydrofoils due to manufacturing complexity, and although the vibration issues are addressed, the issue of non-optimal hydrofoil geometry remains. Variable pitch turbines, known as cycloturbines, can continuously vary the AoA to optimize power generation. Despite the benefits of cycloturbines, the variable pitch requirements increase the system complexity and cost and may reduce the associated system service life [27].

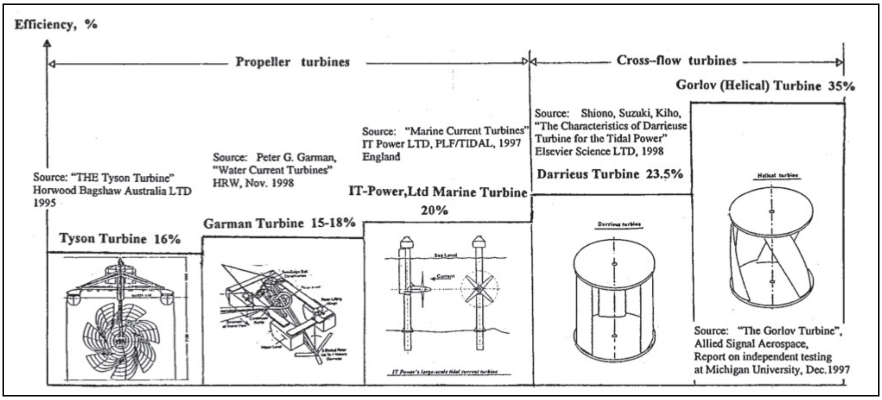

Figure 5. Comparison of turbine efficiencies [9]

3 OPPORTUNITIES

The kinetic energy of tidal flows may be converted into useful energy, which is typically used to supply electricity to the local grid. In addition, tidal energy provides opportunities for hydrogen production and water desalination. Each application has positive and negative aspects that must be understood in the development of a robust renewable tidal energy strategy.

3.1 Hydrogen Production

Hydrogen is the most abundant terrestrial element [29], consisting of 11.1% of water by mass [30]. The simplest method for extracting hydrogen from water is Electrolysis, an electrochemical reaction that separates water molecules into its oxygen and hydrogen. A direct electric current (DC) is passed through two electrodes, an anode and cathode. The hydrogen is separated from the oxygen and collects on the cathode where it can be stored and used as a non-polluting energy carrier. Electrolysis requires large amounts of electrical energy. If this electrical energy is sourced from polluting technologies, for example coal fired generators, the associated emissions adversely effects the environmental impact of hydrogen use. Renewable electrical energy sources, such as tidal energy, provide an opportunity to combine with hydrogen transport technologies to provide a zero-emission energy carrier.

3.2 Desalination

Currently, there are 400 million people living in urban areas without drinking water [31]. Tidal turbines can be used to power desalination systems to provide additional drinking water supplies. A particular advantage of tidal turbines is that the input energy can be mechanical or electrical as is preferred for the particular desalination system. Two types of desalination systems exist.

Mechanical Vapour Compression (MVC) is a distillation process that uses a mechanical compressor to purify seawater by vaporization. The primary energy demands in the system are for the compressor motor, which typically requires 8 to 12 kWh to purify 1m^3 of saltwater [32].

A Reverse Osmosis (RO) desalination plant uses the membrane process and is one of the most efficient methods for filtering seawater to create fresh water. The pumps need to operate at a pressure above the osmotic pressure (60-90 bar) to force the saline water molecules through a semi-permeable membrane [33]. The RO process requires 3 to 10 kWh of electrical energy to create 1m^3 of fresh water.

3.4 Motor Technologies

Innovative motor technologies under development for the automotive industry can be applied to improve the cost effectiveness and overall efficiency of tidal energy systems. For example, brushless, ironless motors have almost zero no-load losses and regarded as the most appropriate option for direct wheel drive automotive applications [34]. These motors can produce extremely high torque per unit mass and provide high efficiency at low torques and varying speeds [34].

4 CHALLENGES

Despite the associated opportunities, there remain challenges to the implementation of tidal energy technologies, including:

- environmental impact
- anchoring methods
- simulation complexity

4.1 Environmental Impact

Regulating tidal flow using a barrage requires high capital costs for the construction of the system [31]; and may result in the blocking of marine life and the interruption of shipping. Investigations at the Annapolis tidal Plant, Canada, show that the use of acoustic devices eliminated the occurrence of fish passing through the turbines [36]. The greatest ecological impact of the La Rance tidal plant, France, occurred during the construction phase when the estuary was completely closed for 2-3 years [10].

4.2 Anchoring Methods

A potential challenge of significance to tidal energy systems is the requirement of a secure anchor to the sea floor. For example, a company withdrew their tender to develop a tidal energy system in Collier Bay, Australia, in due part, to the unstable sea floor, which would make civil engineering and construction efforts excessively costly [23]. Innovative anchoring methods are required to accommodate the specific requirements of tidal energy systems, and thereby reduce system cost and increase the number of feasible sites.

A novel approach to anchoring tidal turbines could be the application of additional hydrofoils. These could be integrated with the support structure at various angles to create a down-force to assist in grounding the system to the sea floor [18].

MIT is developing a robotic device that replicates the Razor Clam in its ability to secure itself into silt and sand. The clam burrows by loosening the sea floor with a muscular foot, resulting in a very high anchoring efficiency. A mechanical analog to the clam is under development with the intent of significantly reducing anchoring costs. These developments could be used to increase the feasibility of the available tidal energy sites.

Existing structures may be used to minimize the cost and complexity of securing tidal turbines. For small to medium-scale projects a wharf or water drain may provide a structural base to which turbines could be mounted, thereby reducing costs.

4.3 Simulation complexity

Theoretical simulation of turbine performance is problematic and includes inherent uncertainties [37]. Experimental testing is required to validate and enhance theoretical models. This paper reports on a novel hydrodynamic test facility that has been developed to provide this requirement (Section 5).

5 INSTRUMENTED PONTOON

To respond to the identified challenges associated with tidal turbine development, a novel hydrodynamic test facility has been developed (Figures 6 and 7). The test facility provides a robust basis for the experimental validation and optimization of turbine performance. Furthermore, the facility is road-transportable allowing rapid deployment to a variety of candidate sites. A reinforced opening allows in-situ access to the turbines and generators when operating offshore. A pivoting, cantilevered beam is mounted under the deck and can be lowered, to deploy test turbines, or retracted to permit road transportation.

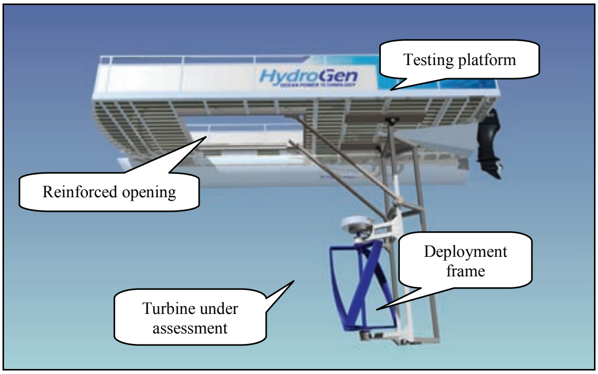

Figure 6. CAD model of test facility

The test facility is equipped with navigation aids, including a depth sounder, electronic chart and GPS. Sophisticated instrumentation is used to provide robust experimental data including: shaft encoder, accelerometers, submersible load-cell, water current meters (Faraday effect and impeller types), heat sensors and power electronics. The test facility has been successfully applied to experimentally assess the performance of:

- Darrieus, helical and cycloturbine designs
- proprietary turbines for developers and Universities in the USA, Canada and Australia

The knowledge gained from these experiments will be used to assess a range of turbine prototypes, including alternative blade profiles with variable lift characteristics.

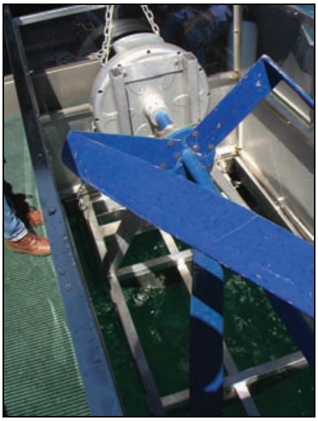

Figure 7. Helical turbine and submersible generator ready for testing.

6 CONCLUSION

This combination of peak oil and anthropogenic environmental impact requires the urgent development of technologies that utilize renewable energy sources. Tidal energy system offers many advantages which are able to compliment other renewable energy sources. Tidal energy can be used to provide renewable grid electricity. In addition, tidal energy can assist in the generation of sustainable hydrogen without the environmental impact of methane reformation or non-renewable electricity supplies. Tidal energy may provide opportunities for salt water desalination.

Despite the opportunities of tidal energy, there remain some challenges that require development to ensure the overall system is robust and feasible. Innovative anchoring methods are required that can accommodate the specific requirements of tidal energy systems, thereby reducing system cost and increasing the number of feasible sites. Recent motor technologies can be applied to increase efficiency and improve cost effectiveness.

A novel road-transportable hydrodynamic test facility has been developed to respond to the challenges associated with tidal turbine development. The facility provides a robust experimental laboratory for the evaluation and validation of theoretical models and proposed turbine variants. In particular, the facility provides access to the turbine and generator during testing, allowing in-situ system optimization. The facility has been successfully deployed to assess a range of turbine variants. Future experimental programs scheduled for assessment include: alternative blade profiles with variable lift characteristics, and the experimental optimization of the vibration characteristics of vertical axis tidal turbines.

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