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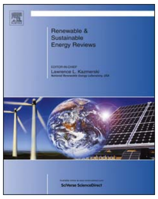

Turning of the tides: Assessing the international implementation of tidal current turbines

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ABSTRACT

The excessive combustion of fossil fuels for energy provision have altered natural planetary functions, resulting in adverse biophysical and societal implications. Such implications have prompted many governments globally to advocate for the adoption of renewable energy systems in order to reduce GHG emissions. While renewable energy technologies such as solar and biogases have been thoroughly researched and deployed, tidal current turbines (TCTs) that harness kinetic energy from the lateral movement of the tides are a comparatively emerging renewable energy technology, and thus has received relatively less attention with respect to their potential to supplement the renewable energy transition. This paper examines the physics behind tidal movements and cycles, and the technological operation of TCTs. Environmental impacts and economic barriers are analyzed. Best practices of MSP from world leading nations are examined, along with current deploy-andmonitor-consenting regimes of TCT test facilities. An optimal TCT design is suggested based on a synthesis of information from proceeding sections. Finally, an analysis of the implementation of TCTs in Canada, China, and Norway is presented, the results of which demonstrate that harnessing the accessible and sustainably extractable resource of each nation can result in an aggregate installed capacity of 9076 MW through the deployment of 7564 TCTs at a cost of $5,740,964,430, thereby creating 14,467 jobs. This would produce 29,829,711 MW h/yr of electricity sold at approximately 22 cents/kWh, eliminating a total of 14,914,855,258 kg of CO2e, approximately 0.1%. of the projected global electricity demand for 2016.

1. Introduction

Concerns regarding the rapid pace at which the global climate is warming, the associated negative implications, and the necessity of adopting adaptive and mitigative measures to combat such atmospheric disruption have become an underlying discourse in the 21st century. Historically, environmental concerns resulting from anthropogenic activities have remained localized. As Emperor Nero's tutor, Seneca, first argued, the smoke produced from the excessive burning of wood had negative health implications. A literature review suggests that air pollution had become a concern in England as early as 1352, resulting in a ban on the burning of coal [92].

Changes in the global environment had only become a concern in the late 20th century, which is attributed to the dawn of the Industrial Revolution two centuries prior. In the late 18th century, a remarkable feat of human ingenuity saw the exploitation of fossil fuels for purposes of energy provision. Due to the intrinsic nature of fossil fuels, energy could be disseminated to a large geographical base in a short period of time and at a relatively low cost [100]. This energy transition led to an explosion in the sizes of human population, particularly in large urban centers, and provided the impetus for the communal structuring of modern society. However, such excessive exploitation of fossil fuels has resulted in an enormous release of (GHG) emissions into the Earth's atmosphere. Consequently, the rate of global atmospheric concentrations of CO2 from the Industrial Revolution to now has been accelerating at a pace comparable to the 20,000 years proceeding it [86], while the amount of atmospheric methane, a GHG with 20 times the warming potential of CO2, has approximately doubled [63].

In 2007, fossil fuels constituted 88% of global primary energy consumption; 35% oil (3952.8 mtoe), 23.8% natural gas (2637.7 mtoe), and 28.6% coal (3177.5 mtoe) [65]. In the same year, in light of these numbers, the Intergovernmental Panel on Climate Change [64] called for a 50–85% reduction in GHG emissions in order to avoid the projected adverse implications perpetuated by climate change. Progressive governments responded by setting legislative GHG emissions reduction targets, such as British Columbia's *Greenhouse Gas Reduction Targets Act*. This statute signals how the province as a whole aims to achieve a 33% reduction in GHG emissions relative to the 2007 baseline by 2020 and an 80% reduction in GHG emissions

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relative to the 2007 baseline by 2050 [79]. Moreover, in order to meet legislative GHG emissions reduction targets, many governments have looked towards the large-scale adoption of indigenous, non-polluting renewable energy systems. An example is the EU Directive to produce 20% of their energy from renewable sources by 2020 [109].

Approximately three centuries ago, the only energy source that society had utilized were renewables, ranging from solar energy to grow crops, biomass to feed populations and provide heat, and wind and hydro energy to mill grain and pump water [58]. Today, due to the threat of climate change, modern society is attempting to revert back to such a model while simultaneously aiming to uphold an urbanized, high-tech lifestyle. This ideal has resulted in attention being focused on renewable energy technologies (RETs) such as solar (PV), wind turbines, and biogases. However, comparatively less attention has been paid to the use of renewable energy from the ocean to help meet global energy demands.

In theory, harnessing less than 0.1% of the energy from the oceans waves, thermal capacity, and tides has the capability of meeting the worlds energy demands five times over [17]. The utilization of ocean energy, however, is not a new concept, as tidal mills designed to employ tidal current movements to grind cereals were used in medieval times. The Eling Tidal Mill was constructed in the Roman era and fully restored to activity in 1980 [16] (Fig. 1). However, the utilization of tidal energy for the purposes of electricity generation is a new and emerging concept.

When considering the different ocean energy technologies available, as well as all renewables, the development and deployment of tidal current turbines (TCTs) is of particular interest to nations with suitable tidal resources. It is important to replace environmentally detrimental energy sources such fossil fuels with an energy source that is not only carbon neutral, but also maintains the ecological integrity of the site in which it is operating. However, TCTs require greater environmental assessment and monitoring in order to verify this estimation as baseline environmental reports are limited to particular sites, a product of the pre-commercial phase in which TCTs currently lie [85]. However, TCTs are set to realize large-scale commercial implementation off the shores of Scotland this year in 2016 [66].

This paper will provide an overview of TCTs, exploring the physics behind tidal movements, their technological operation, perceived environmental impacts, the economic and policy implications of facilitating TCT adoption, the MSP context for implementation, and optimal technological design and deployment. Finally, an assessment of the implementation of TCTs within Canada, China, and Norway's coastal boundaries will be examined, offering installed capacity, systems efficiency, and annual electricity generation figures, purchasing, installation, and grid connections costs, subsequent CO2e reductions figures, and employment projections.

Fig. 1. “Eling Mill, Eling, Hampshire” by nick macneill/CC BY-SA 2.0 [35].

2. Tidal physics

Philosophies surrounding the movement of the tides date back to Aristotle, with theories put forth since then by Claudius Ptolemy, Nicolaus Copernicus, Tycho Brahe, and others [56]. Many Eastern cultures believed that water was the blood of the Earth and the rising and falling of the tides was the Earth breathing. In the late 16th century, Johannes Kepler put forth a theory of tidal movements being a product of gravitational and centrifugal forces of the moon and sun enacted upon the Earth's oceans, a theory that is known today to be correct.

Such gravitational and centrifugal forces work in conjunction to create a bulge in the Earth's oceans, one closest to the moon, and one on the other side of the planet [103]. These bulges result in daily tidal movements comprised of flood tides (where water is flowing towards a coastline,) ebb tides (where water is receding away from a coastline) and slack tides (where water is transitioning from flood to ebb or vise versa and therefore there is no tidal movement). These daily flood and ebb tidal movements vary across different sites, with some geographical areas experiencing flood and ebb tidal movements twice every 24 h and 48 min, known as a semi-diurnal cycle, or only once every 24 h and 48 min, known as a diurnal cycle [7].

Every tidal cycle, whether semi-diurnal or diurnal, operates within a lunar cycle consisting of conjunction, first quartile, opposition, third quartile, and back to conjunction, repeating approximately every 28 days [16]. At conjunction and opposition, where the moon and sun are oriented parallel to one another with respect to the position of the Earth, spring tides occur, which are periods characterized by higher velocity tidal flows [90]. At first and third quartile, where the moon and sun are oriented perpendicular to one another with respect to the position of the Earth, neap tides occur, which are periods characterized by lower velocity tidal flows. It is essential to understand all of these relationships in order to grasp the appeal of TCTs. Tidal movements are predictable down to the very second, as more than 100 harmonic constituents and cyclical components characteristic of each tidal movement repeat themselves every 18.6 years [103]. Thus, tidal current energy is the most reliable renewable energy source. It can be modelled decades in advance, allowing grid operators to accommodate electricity generated from TCTs and match it to societal demand.

While lunar cycles contribute greatly to the overall movement of the tides, this only constitutes 40% of the tidal energy system [16]. Tidal currents occurring in the deep open ocean are generally very slow. However, as tides begin to approach land, site specific shoreline geometry and bathymetry amplify tidal velocity [98]. This is an important characteristic for siting the suitability of TCT implementation, as TCTs are only economically viable when operating under conditions where mean spring tides have a velocity of 2 m/s or greater [46]. Typically, the more drastic the difference between the vast depth and breadth of an open ocean relative to the shallow, narrow conditions of an estuary and/or loch opening or a headland, the higher the tidal velocity will be at that site [16].

3. TCT technology

3.1. Current status

The first recorded attempt at harnessing kinetic energy from tidal currents in order to produce electricity took place in the early 1990s at Loch Linnhe, in the Western Scottish Highlands [38]. Although progress has continued since then, most research and development (R & D) has been focused on emulating sea conditions in test tanks. Test tanks allow for the scaling up of 1/100-sized models incrementally