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

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A B S T R A C T

The excessive combustion of fossil fuels for energy provision introduced during the Industrial Revolution of the late 18th century and proceeding through to the 21st century have perpetuated global climate change, thereby altering natural planetary functions and resulting in adverse biophysical and subsequent societal implications. Such implications have alerted many governments within the international scene to advocate for the adoption of renewable energy systems in order to reduce greenhouse gas (GHG) emissions produced through fossil fuel-derived electricity generation. While renewable energy technologies such as solar photovoltaic (PV), onshore wind turbines, and biogases have been thoroughly researched, developed, 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, the technological operation of TCTs, and how these factors function to make tidal current renewable energy advantageous by comparison to other renewables due to its intrinsic predictability, reliability, high capacity factors, favorable overall systems efficiency, and ability to easily accommodate energy storage or provide base-load power via matching tidal phase shifting. Environmental impacts concerning the installation and operation of TCTs on benthic and pelagic habitats, hydrology, sediments, and marine wildlife are analyzed. The paper's conclusion is that TCTs are essentially environmentally benign if sited and scaled appropriately within local and regional marine ecological contexts. Economic barriers due to the high capital costs associated with TCTs are examined, and it is suggested that a combination of renewable energy subsidies and the incorporation of environmental and social externalities into fossil fuel prices are required to make TCT implementation economically feasible. Best practices of marine spatial planning (MSP) from world leading nations such as Belgium are examined, along with current deploy-and-monitor-consenting regimes of TCT test facilities such as the European Marine Energy Centre (EMEC). This paper calls for the dissemination of information amongst such test facilities in order to provide a standardized baseline assessment criterion to inform the zoning processes of nations constructing comprehensive MSPs, and it advocates for the development of integrated plans amongst bordering nations that better suit natural oceanographic boundaries. An optimal TCT design based on a rimmed horizontal axis rotor secured by a gravity base 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 tidal current resource of each nation can result in a total aggregate installed capacity of 9.072GW through the deployment of 7,519 TCTs at a cost of $8,218,144,984, thereby creating 15,516 jobs. This would produce 29.93TWh/yr of electricity sold at approximately 22 cents/kWh, eliminating a total of 14,965,000 tonnes 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 negative implications arising from such accelerated warming, and the necessity of adopting proper adaptive and mitigative measures into order to combat such atmospheric disruption have become a dominant underlying discourse for generations 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 (Owen, 2004).

Changes in the global environment had only become a concern in the late 20th century, the instigating timeline of 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 (Rose, 1998). 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 form 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 carbon dioxide (CO2) from the Industrial Revolution to now has been accelerating at a pace comparable to the 20,000 years proceeding it (NOAA, 2004), while the amount of atmospheric methane, a GHG with 20 times the warming potential of CO2, has approximately doubled (IPCC, 2001).

In 2007, fossil fuels constituted 88% of global primary energy consumption; 35% oil (3952.8 million tons of oil equivalent - mtoe), 23.8% natural gas (2637.7 mtoe), and 28.6 % coal (3177.5 mtoe) (International Energy Agency, 2007). In the same year, in light of these numbers, the Intergovernmental Panel on Climate Change (IPCC, 2007) 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 that found in 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 relative to the 2007 baseline by 2050 (Ministry of Environment, British Columbia, 2014). 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 in order to combat climate change. An example is the EU Directive to produce 20% of their energy from renewable sources by 2020 (Union, 2009).

Approximately three centuries ago, the only energy source that society had utilized was renewable energy, 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 (Heal, 2009). Today, due to the threat of global 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 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, a testament to how the development and implementation of such technologies is still in its infancy.

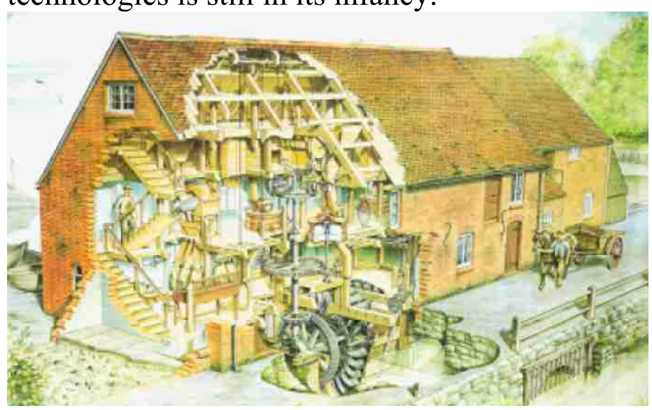

Figure 1: Eling Tide Mill, Totten, Southampton, England (Hazen, 1999)

In theory, harnessing less than 0.1% of the energy from the oceans waves, thermal capacity, and tides via wave energy converters (WECs), ocean thermal energy convertors (OTECs), tidal barrages, and TCTs, has the capability of meeting the worlds energy demands five times over (Caillé, Al-Moneef, de Castro, Bundgaard-Jensen, Fall, de Medeiros, Jain, Kim, Nadeau, Testa, Teyssen, Garcia, Wood, Gaubao, & Doucet, 2007). 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 the medieval times. For example, the Eling Tidal Mill was constructed in the Roman era and fully restored to activity in 1980 (Bryden & Melville, 2004). 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 TCTs is of particular interest to nations that have the resources required to host the technology due to their estimation of being the most environmentally benign renewable technology (Pelc & Fujita, 2002). 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 more environmental assessment and monitoring in order to verify this estimation because baseline environmental reports are limited to particular sites, a product of the pre-commercial phase in which TCTs currently lie (Myers, Keogh, & Bahaj, 2011). However, TCTs are set to realize large-scale commercial implementation off the shores of Scotland this year in 2016 (Johnson, Kerr, & Side, 2012).

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 TCT 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.

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 (Hardisty, 2009). 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.

Figure 2: Johannes Kepler (Hardisty, 2009)

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 (Tarbotton & Larson, 2006). 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 hours and 48 minutes, known as a semi-diurnal cycle, or only once every 24 hours and 48 minutes, known as a diurnal cycle (Ben Elghali, Benbouzid, & Charpentier, 2007).

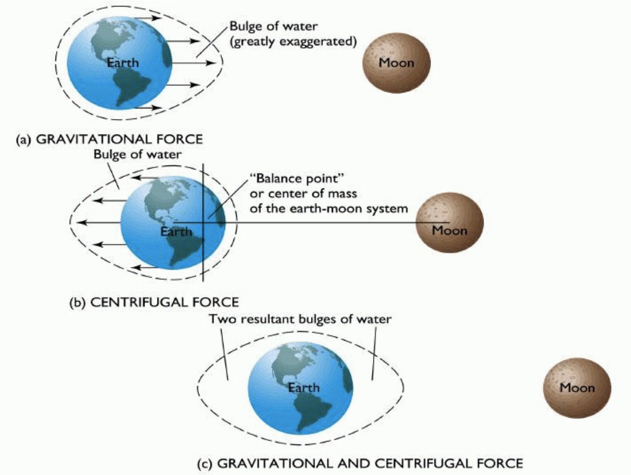

Figure 3: Lunar induced gravitational and centrifugal tidal fluctuations (O'Rourke, Boyle, & Reynolds, 2010b)

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, with the cycle repeating approximately every 28 days (Bryden & Melville, 2004). 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 accelerated by gravitational and centrifugal forces (O'Rourke, Boyle, & Reynolds, 2010b). 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 attributes in order to understand the provision of energy from the tides, and therefore 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 (Tarbotton & Larson, 2006). Thus, tidal current energy is the most reliable renewable energy source. It can be modelled decades in advance in order for 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 (Bryden & Melville, 2004). 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 (Ramos & Iglesias, 2013). 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 flow velocity of 2 meters per second (m/s) or more (Fraenkel, 2006). 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 (Bryden & Melville, 2004).

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 (Esteban & Leary, 2012). Although progress has continued since then, most research and development has been focused on emulating sea conditions in test tanks. Test tanks allow for the scaling up of 1/100-sized models incrementally in order to ensure structural stability and operational reliability prior to investing the large capital costs needed to deploy full-scale TCTs in real marine environments (Mueller & Wallace, 2008). Thus, the estimated extractable 788.4 TWh/yr of electricity that can be generated from TCTs currently remains untapped due to the early stages of planning, consenting, development, and deployment that TCTs currently reside in (Esteban & Leary, 2012).

Most of the information known about TCTs is provided from pre-commercial test centers, the first and largest of which is EMEC, located in the Orkney Islands, northeastern Scotland, which has been operational since May of 2005 and hosts five grid connected TCTs (O'Rourke, Boyle, & Reynolds, 2010b). Two notable TCT devices that have been implemented in real marine environments are SeaFlow and SeaGen, both of which were developed by Marine Current Turbines Ltd. (MCT). Considered to be the world's first full-sized TCT, the 300kW SeaFlow was installed in 2003 off the coast of the village of Lynmouth, Devon, England (Fraenkel, 2006). The turbine was implemented 1.1 km from the shoreline in a depth of 25 m, has a single 11m diameter rotor, and is currently not grid connected. The project cost totaled £3.5 million and has yielded a vast amount of comprehensive data concerning commercial implementation procedures ranging from construction to operation to maintenance.

Figure 4: 300kW SeaFlow turbine off the coast of North Devon, England (by Fundy)

Another benchmark in TCT deployment was the implementation of the first full-scale grid connected TCT, SeaFlow's successor, the four-times more powerful twin 16m rotor 1.2MW SeaGen TCT, deployed in the Strangford Narrows off of the coast of Northern Ireland in July of 2008 (Fraenkel, 2010). The next and much anticipated milestone in TCT development is the large-scale commercial implementation scheduled this year of 2016 in Scotland (Johnson, Kerr, & Side, 2012). If scheduled deployment carries foreword as announced, there is expected to be over 1000 TCT generating 1.6GW of electricity by 2020.

3.2. Technological operation

Typically, TCTs function by harnessing kinetic energy dissipated by the movement of tides via a bladed propeller mounted on an axis hub, with a rotor connecting to a gearbox, which turns a generator in order to produce electricity (other technologies designed to harnessed tidal current energy will be discussed in greater depth in section 3.3.) (O'Rourke, Boyle, & Reynolds, 2009). In order to secure the turbine in place, three distinct anchoring methods are used, including pile driving a cylindrical monopole into the seabed, attaching the turbine to a large enough concrete base to stabilize it to the seabed, known as a gravity base, and connecting it to a floating buoy and mooring anchoring cables to the seabed. The electricity produced is then either transmitted to an offshore or onshore generator, in the latter case via under water cables that can be attached to the seabed or buried beneath it, and connected to the grid.

The ideal depths at which the first generation of commercially deployed TCTs are excepted to operate are around the 30-40m mark (Myers & Bahaj, 2005), although shallower and greater depths can be achieved dependent on TCT design (O'Driscoll, 2012). Jack-up-barges are suitable to undertake installation and maintenance work on TCTs and are more maneuverable and less costly than the use of conventional vessels, although costs for installation and routine maintenance will increase relative to the greater depths and further offshore distances at which a TCT is deployed. While TCT installation and maintenance may be costly and time constrained due to the energetic areas in which TCTs are required to operate (velocities of 2m/s or greater), especially when employing divers, MCT reported that it only took 30 minutes to position and install SeaGen (Fraenkel, 2010). Furthermore, MCT is planning on achieving a 95% level of operational reliability, thereby limiting the necessity for routine maintenance. This is extremely advantageous, considering that TCTs are expected have operational lifespans of 20-30 years, thereby offering another advantage of a 6-

month energy return on energy investment (ERoEI) and an energy payback approximately 40 times greater than the energy invested to install and operate it over its lifespan (Fraenkel, 2006).

A theoretical upper limit on the ability of turbine technology to convert raw energy into useful output energy was developed by Albert Betz's actuator disk theory in 1919, referred to as a power coefficient (Cp), and is estimated to be 59.3% (Duncan, Thorn, & Young, 1970). Testing from MCT's SeaGen revealed that the TCT's Cp fluctuated between 45% and 52% dependent on the tidal cycle, thereby resulting in an average Cp of 48%, achieving 81% of Betz's theoretical maximum (Fraenkel, 2010).

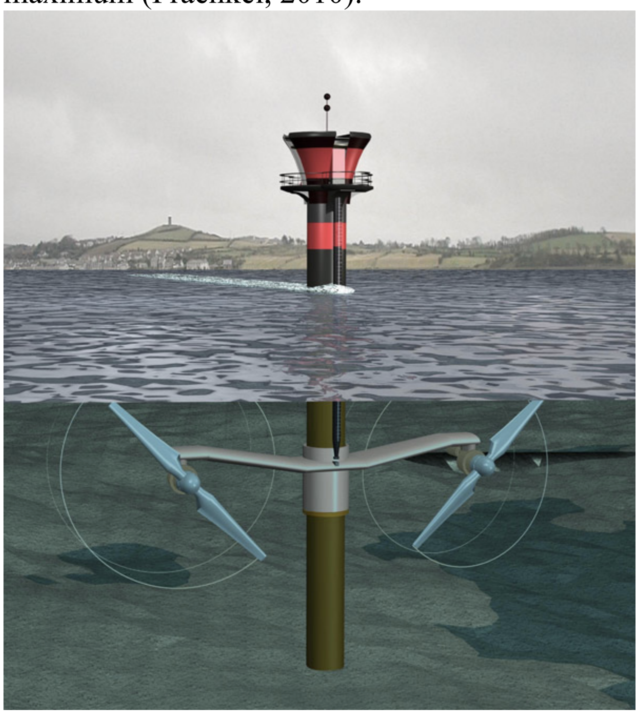

Figure 5: SeaGen 1.2MW TCT (Fraeknel, 2010)

Due to the intrinsic predictability characteristic of tidal movements, TCTs can provided energy to a grid that can be planned for better than most other renewables. Furthermore, the nearly constant movement of the tides provides TCTs with a capacity factor (Cf - the ratio of output over a period of time over the potential maximum output if operating 100% of the time) that is significantly higher than other renewables, which is essential for any renewable energy system in order to be economically viable (Grabbe, Lalander, Lundin & Leijon, 2009). Results from SeaGen operation demonstrated a Cf of well over 60%, and, when combined with an average Cp 48%, the total system efficiency was found to be 45% (Fraenkel, 2010), a great deal higher than solar PV (13%), wind (39%), and geothermal (20%) (Evans, Strezov, & Evans, 2009). Another advantage that TCTs have is that they do not require the utilization of valuable terrestrial land, which is important in a rapidly urbanizing society so that more urban space can be conserved for other societal uses.

3.3. Overview of different technologies

Given the UK's status as a world leader in potential tidal current energy resources available to the island, which is estimated to hold 47.7% (25.7GW) of Europe's resource (Charlier, 1997), the UK's Department of Trade & Industry (DTI) launched a research and development (R&D) program directed towards TCTs in 2001, thereby igniting competition amongst numerous developers (Fraenkel, 2006). Essentially, this program resulted in the development of five distinct categories of TCT technologies; horizontal axis turbines, vertical axis turbines, venturi-type shrouded turbines, oscillating hydrofoil devices, and free-range suspension turbines.

Horizontal axis turbines are characterized by a bladed propeller mounted on a horizontal axis hub, as is the case with MCT's SeaFlow and SeaGen devices. The former employs a single duel bladed propeller and the latter a pair of duel-bladed propellers. Both TCTs utilize a monopole structure to anchor the TCT to the seabed, with the ability to raise the turbine above the ocean surface in order to preform maintenance in a more cost-efficient way than other structural designs such as gravity bases and floating buoys (Fraenkel, 2002). However, this option means that the tip of the monopole is never fully submerged, thereby possibly leading to public resistance due to visual pollution. Another notable horizontal axis TCT developments include the 1MW E-Tide TCT developed by Hammerfest Strøm in Kvalsund, Norway since 2003, which is fully submerged, can be implemented near shore or offshore depending on tidal velocities and the local bathymetry characteristic of a site, and is stabilized to the seabed through mooring three separate legs (Ben Elghali, Benbouzid, & Charpentier, 2007).

Vertical axis turbines are characterized by a bladed propeller mounted on a vertical axis hub, much like the Darrieus wind turbine. One of the most notable developments is the Kobold turbine of the Enermar Project, moored to the seabed in the Strait of Messina off the coast of Sicily, Italy. This turbine produces 20kW in current speeds as low as 1.8m/s (Ben Elghali, Benbouzid, & Charpentier, 2007). Vertical access turbines have the flexible advantage of holding a drivetrain either on the seabed or a surface vessel, whereas horizontal axis designs require that drivetrains be housed entirely in the rotor hub, but a vertical axis configuration is at a disadvantage regarding the rotor structure, which takes up a much greater area than the horizontal configuration while producing the same power, thereby making them pricier (Fraenkel, 2002). Furthermore, vertical axis TCTs cannot self-start and therefore require additional mechanisms to facilitate energy generation, attributing to a more complex system with higher costs and greater potential for mechanical deficiencies. Vertical axis TCTs are also more difficult to stop, which can be hazardous in an emergency situation, and they have greater potential to induce cavitation (the formation of air pockets around rotor tips), which may cause detrimental ecosystem impacts.

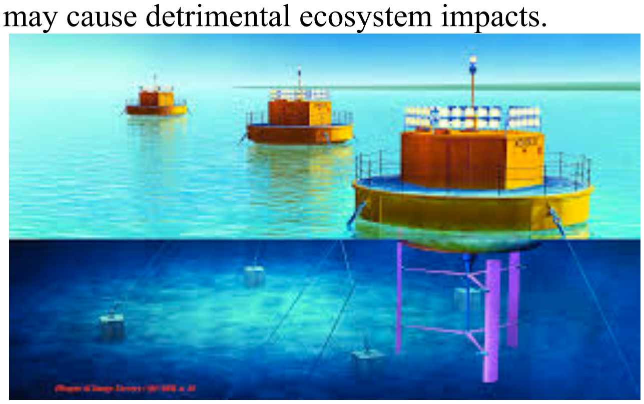

Figure 6: Kobold turbine of the Enermar Project (Calcagno, G., & Moroso, 2007)

A more exotic oscillating hydrofoil device produces high-pressure oil to drive a generator, as is the case with the 150kW Stingray device developed by Engineering Business Ltd. and deployed at Yellsound in Shetland, northeastern Scotland (Bryden & Couch, 2006). The venturi-type shrouded design utilizes a duct in order to narrow the tidal flow past the rotor and therefore produce more energy per square inch of propeller employed, as is the case with the 1MW HydroHelix gravity base turbine of the Lunar Energy Project in France (Ben Elghali, Benbouzid, & Charpentier, 2007). However, venturi devices, like vertical axis turbines, are more sensitive to cavitation due to the high rpm of rotor tip speeds, are generally pricier, and, as in the specific case of the HydroHelix which employs a gravity base, are limited to more shallow waters (Fraenkel, 2002).

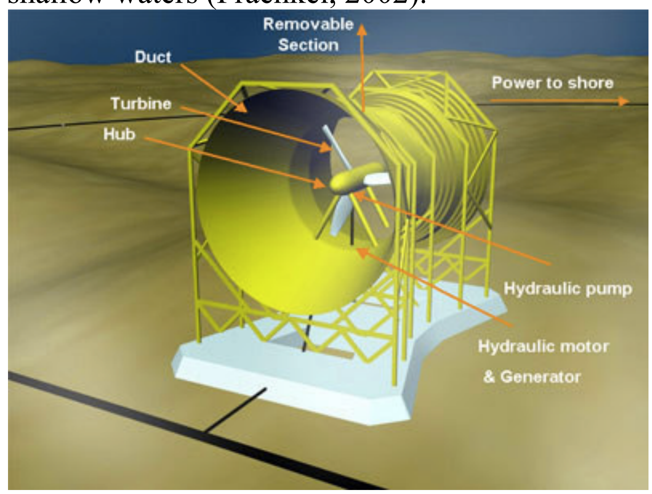

Figure 7: Lunar Energy HydroHelix (Lunar Energy Ltd., 2008)

Free motion suspended TCTs, such as Minesto's Deep Green turbine that is undergoing testing in Strangford Narrows off of the coast of Northern Ireland, acts as a turbine attached to an underwater kite, tethered by a cable to the seabed (O'Driscoll, 2012). The TCT has advantages such as the ability to operate at much greater depths and at considerably lower tidal velocities then the standard 2m/s, thereby negating the requirement to compete with other developments for tidal hotspot locations. But the device has a significantly greater spatial footprint as a result of its flight path, thereby increasing the possibility of marine species collision. One more notable distinct TCT design is the rimmed turbine, such as the OpenHydro turbine in Ireland. The rimmed turbine is characterized by a single moving part with no seals, a self-contained rotor, and a magnet generator encapsulated within the outer rim, which reduces mechanical complexity and associated maintenance requirements and subsequent costs (Ben Elghali, Benbouzid, & Charpentier, 2007).

It is important to understand the dynamics of each TCT as local site conditions differentiate greatly from one to another. The advantages of each TCT design should be utilized according to the characteristics of the site being proposed for implementation. For example, in water depths greater than 40m, the rimmed OpenHydro turbine would be ideal for implementation as there are reduced maintenance requirements and, therefore, the increased costs associated with maintenance procedures in deep waters is balanced. Shallower waters lend themselves better to the HydroHelix due to its gravity base design and relatively inexpensive shallow water maintenance, balancing additional material costs associated with the venturi-type shroud. The Deep Green kite design can be employed at sites with lower tidal current velocities currents than the standard economically viable 2m/s.

3.4. Dynamics of TCT array configuration

While currently there are only a small number of individual TCTs operating at various sites across the globe, eventual large-scale commercial implementation will require the deployment of TCTs in large arrays in order to provide vast quantities of energy to an electrical grid and make TCTs an economically viable renewable energy option (Myers & Bahaj, 2012). There are several demonstrator arrays in Europe currently in the planning and consenting stage, including Sound of Islay in Scotland, Anglesey Skerries in North Wales, and Paimpol Brehat in Brittainy, Northern France (Myers, Keogh, & Bahaj, 2011). Understanding the dynamics of TCTs operating individually is much different than comprehending how TCTs will act in an array, as issues such as structural loading, spatial usage, and output efficiency will arise.

If TCTs are located too close to each other within an array, exceptional thrust forces many compromise the structural integrity of the device (Myers, Bahaj, Retzler, Ricci, & Dhedin, 2010), reducing mechanical reliability, increasing maintenance costs, and decreasing temporal power output. Moreover, while spacing TCTs very close too one another within an array may reduce electrical cable costs, it will also limit access for maintenance vessels and reduce energy output of adjacent turbines due to excessive structural drag, resulting in the blockage of flow and a subsequent decrease in tidal velocity to a degree that would place limitations on the overall acceptable size of the array (Vennell, 2012). However, if turbines are spaced too far apart, their spatial footprint may have negative effects on habitat disruption, result in increased cable costs, and limited access to marine space for other uses such as commercial shipping and fishing (Myers & Bahaj, 2005).

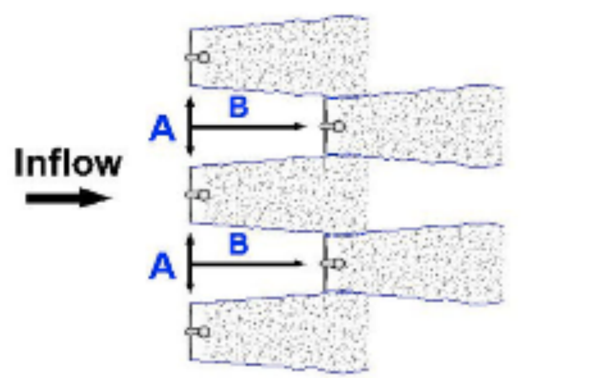

Figure 8: Optimal layout configuration of a TCT array (Myers and Bahaj, 2012)

Taking all of these factors into consideration, Myers and Bahaj (2012) from the Sustainable Energy Research Group of the University of Southampton, UK, conducted a model experiment to determine the optimal layout configuration of an array of TCTs. Their results demonstrated that a 1.5 diameter lateral separation between parallel turbines oriented perpendicular to the tidal flow was optimal. Such a layout did not result in excessive thrust forces enacted upon either turbine, as the turbines' respective wakes (an area of flow immediately behind an object, caused by the flow of surrounding fluid on either side of the object) did not mix. The simultaneously decreased the amount of cable costs required by not separating the TCTs further apart. The experiment then accounted for the optimal spacing of a downstream TCT in order to take advantage of the accelerated flow velocity produced from the combining of the wakes of both upstream TCTs with the faster moving flow of the undisturbed fluid passing between them. An optimal placement for a downstream TCT was calculated to be 3 diameters downstream, positioned in the centerline of the two upstream TCTs. This placement resulted in a 22% increase in power available to the downstream TCT. Myers and Bahaj's experiment generated mathematically modelled research that suggested that the geometric manipulation of TCTs within an array can provide an increase in flow velocity and a subsequent increase in Cp beyond the Betz limit of 59.3% maximum turbine efficiency (Vennell, 2012).

Although Myers and Bahaj's (2012) optimal array layout configuration may not be feasible in all implementation scenarios due to local geology and bathymetry conditions specific to different sites, as demonstrated in their assessment of a large TCT array deployed in the Alderney Race between France and the UK (Figure 9: Myers & Bahaj, 2005), this configuration should be taken advantage of within large arrays wherever permitted in order to enhance power output, reduce cable costs, promote the structural integrity of individual TCTs, and reduce the array's spatial footprint to the greatest extent possible. The configuration limits potential environmental impacts and allows for a more diversified use of marine space within the given site. Although it is suggested that first generation commercial TCT arrays that are expected to be installed at depths between 30-40m will limit access to the area for other uses such as recreational and commercial (Myers & Bahaj, 2012), further analysis should be undertaken to determine the feasibility of implementing second generation commercial TCTs at great enough depths (possibly 70m) in order to permit the use of surface sea space above the installed TCT array.

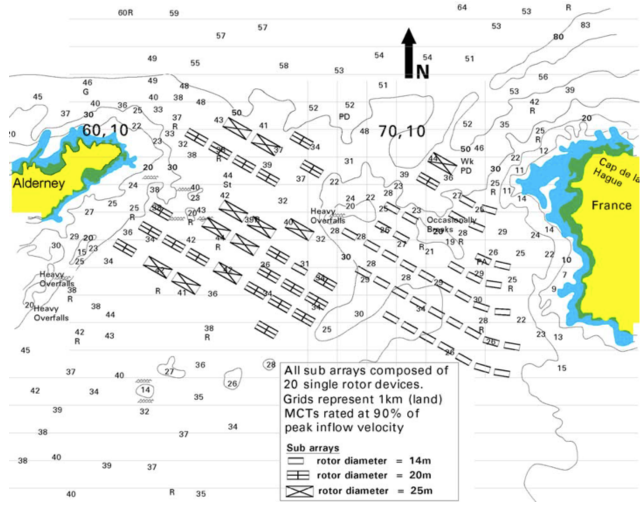

Figure 9: Race of Alderney TCT array layout (Myers & Bahaj, 2012)

3.5. Storage capability

The production of energy from all renewable energy technologies is inherently intermittent due to the fluctuating and cyclical natural planetary functions on which they rely to harness their energy; simply put, the sun does not always shine and the wind does not always blow. It is due to this inherent intermittency that renewables are unable to provide base load power to grids and therefore cannot yet replace detrimental and controversial fuel sources such as fossil fuels and nuclear energy, which can be instantly manipulated for purposes of energy generation. This fact has perpetuated the development of technologies that store energy produced by renewables when the grid does not need it and release it to the grid when it is required either in larger amounts than usual or when the renewable energy technology is not currently generating any energy.

As discussed in depth in section 2., the movement of the tides on which TCTs rely to harness energy are nearly constant and predictable for decades into the future. These characteristics make TCTs an incredibly attractive candidate for the utilization of energy storage technology as costly storage systems would have to be built to a lesser capacity than that of solar and wind (Bryden & Macfarlane, 2000). TCTs have been estimated to operate for approximately 90% of their lifespan (Myers & Bahaj, 2005), and storage systems can be tuned in phase with tidal fluctuations for years, allowing a reliable supply of energy to a grid. However, TCTs have the capacity to provide constant base load power to a grid where site characteristics permit, thereby negating the necessity of implementing expensive storage systems, a feature shared by no other renewable energy other than geothermal. If two or more TCT arrays are build in locations where daily tidal cycles are out of phase with one another, then one array would be able to supply power to the grid, for instance, while experiencing flood tide, while the other is at slack tide and thus producing no power, and vise versa. The British Isles are one such example where tidal flows possess such flow patterns (Hardisty, 2008).

4. Environmental Impacts

Although TCTs do not emit GHGs into the atmosphere during operation, and hence are an excellent replacement for fossil fuels in order to combat climate change, the environmental impacts of TCTs during their lifecycle of installation, operation, maintenance, and decommissioning must be as benign as possible in order to uphold ecosystem integrity and compete with the implementation of other renewable energy technologies. Pelc and Fujita (2002) suggest that TCTs are the most environmentally benign renewable energy technology, and while attention must be paid to possible stressors (features of the environment that may be altered during the TCTs lifecycle) and receptors (elements of the ecosystem that have the potential to respond, either negatively or positively, to such stressors), harnessing the power of tidal currents can be accomplished without significantly impacting the marine environment if developments are sited and scaled appropriately relative to the site specific conditions targeted for implementation. Potential stressors include TCT installation, the physical presence of the device occupying seabed and water column space, potential for rotor blade strike, lifecycle acoustic emissions, electromagnetic fields (EMFs) from electricity cables, and potential pollutants. Potential receptors include benthic and pelagic habitats, marine wildlife such as fish, diving birds, and marine mammals, local hydrology, and seabed sediments.

4.1. Benthic habitats

A benthic habitat is the ecological region at the base of the ocean floor. The installation of TCTs on the seabed will intrude upon benthic ecology and local species communities. It has been theorized that the presence of TCT structures will produce an artificial reef effect that may result in some benthic species populations flourishing at the detriment of others (Langhamer & Wilhelmsson, 2009). For example, the introduction of man-made structures within a benthic habitat could result in enhanced biodiversity which could be nullified via the greater accumulation of predatory fish species, thereby altering the natural functioning of the ecosystem (Langlois, Anderson, & Babcock, 2005). Such artificial reef effects have been observed in offshore oil and gas and wind installations off of European coastline (Boehlert & Gill, 2010). However, preliminary environmental assessments undertaken by the Fundy Ocean Research Center for Energy (FORCE, 2013), Canada’s largest TCT test center located on the coast of the Minas Passage, Nova Scotia, revealed a considerably low level of macrofauna biodiversity characteristic of the high velocity tidal flow site suitable to accommodate TCTs, which typically host more hazardous flow conditions than offshore oil and wind developments. The assessments concluded that, due to such low levels of benthic biodiversity, it is unlikely that TCTs will have a negative impact on benthic communities.

4.2. Pelagic habitats

Pelagic habitats are marine ecosystems that are located at a point between the seabed benthic region and the ocean surface region. A concern for pelagic ecosystems is similar to that of benthic ecosystems, in that the introduction of a man made structure into the region may result in an artificial reef effect, thereby altering natural ecosystem functions by increasing certain pelagic species such as fish and resulting in a higher order of predatory species aggregation (Inger, Attrill, Bearhop, Broderick, James Grecian, Hodgson, Mills, Sheehan, Votier, Witt, & Godley, 2009). However, high tidal velocity regions suitable for TCT implementation have been assessed to host low levels of species biodiversity in benthic habitats (FORCE, 2013). Given that tidal flow velocities are not uniform through different ocean depths, as 75% of available energy is located in the top 50% of flow (Fraeknel, 2002), thereby providing for even faster currents within the pelagic zone, it can be estimated that it is unlikely that TCTs will have negative impact on pelagic communities.

4.3. Marine wildlife

4.3.1. Interactions with turbines

4.3.1.1. Fish

There have been concerns surrounding fish species colliding with TCT rotor blades, thus inducing high levels of fish mortality, as has been the case with tidal barrages, emulating a hydroelectricity dam that takes advantage of the rising and falling of tides to funnel ocean water through many turbines, such as the 240MW system in La Rance, France (Esteban & Leary, 2012). However, unlike tidal barrages, TCTs do not block entire cross sections both laterally and vertically and thus do not interrupt mass fish migration patterns (Pelc & Fujita, 2002). Moreover, TCT rotors spin slowly enough to minimize fish mortality, with MCT's SeaFlow rotor operating at 15rpm (Fraenkel, 2006). Tests conducted for SeaFlow demonstrated that 17 out of 18 randomly drifting objects of an average cross section of 20cm passed through the rotor without contact, and when contact did occur it was not direct but rather glancing, off of the smooth, slowly rotating blade. It is expected that fish, as well as any marine species able to exist in flow conditions ranging from 2-14m/s would be agile enough to navigate past rotor blades, at the very least, much more so than randomly drifting objects. Furthermore, the risk of collision from TCTs is miniscule in comparison to ship propellers, as TCTs absorb the energy from flow regimes while ship propellers apply energy into the marine environment, occurring suddenly in previously still waters, and creating a suction force.

Other interactions that TCTs may have with fish populations may be present in the form of creating fishing exclusion zones where TCT arrays are implemented (DOE, 2009). While some believe this to be a positive effect via increasing the amount of fish species through providing a de facto habitat protection zone (Defne, Haas, & Fritz, 2011), others believe that this may attract a greater amount of larger predatory fish species to the zone and subsequently increase mortality rates amongst smaller local prey fish species, thereby altering the ecological makeup of the natural habitat (Boehlert & Gill, 2010). Regardless, rigorous monitoring must be undertaken in commercially deployed large-scale TCT arrays.

4.3.1.2. Birds

Much like concerns surrounding blade strike induced fish mortality, there are concerns regarding diving sea birds such as diving ducks, cormorants, terns, gannets, and auk species colliding with TCTs (Fraenkel, 2006). If TCT arrays are packed to densely and fill an excessive portion of the cross section of a site, habitat alterations could occur which would magnify the number of seabird prey inhabiting the site, subsequently increasing seabird foraging and heightening the risk of seabird collision with TCTs (Boehlert & Gill, 2010).

Figure 10: Common Murre, a diving seabird species found off the coast of Newfoundland and Labrador (The David Suzuki Foundation, 2014)

However, Fraenkel (2006) suggests that the risk of diving seabird collision is miniscule, if not non-existent, as it is partially dependent on the number seabirds foraging in a given TCT site. Baseline data collected at the FORCE (2013) operations center in Minas Passage through standard seabird observation protocols for their Environmental Effects Monitoring Program (EEMP) concludes that annual seabird sightings were very low, especially when compared to other sites within the Bay of Fundy. This suggests that, if diving seabird collision with TCTs were to be a problem, it could easily be negated through strategic siting. Another concern is that underwater lighting coming from TCTs in order to deter marine mammals from encountering devices (Fraenkel, 2006), as well as above water TCTs structures, such as that of the SeaGen design, could potentially result in collisions (Boehlert & Gill, 2010). However, SeaGen has been deemed to have no significant adverse impact on seabird populations (O'Driscoll, 2012).

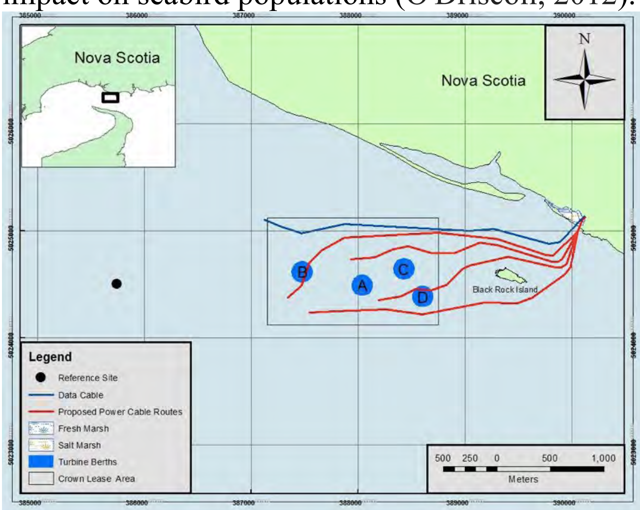

Figure 11: FORCE (2013) monitoring and control site

4.3.1.3. Mammals

Of perhaps greatest concern when it comes to the potential for blade strike to induce marine species mortality is the possibility of marine mammal collision due to their often-protected status around the globe, such as the harbor seal (Fraenkel, 2006). However, once again such concerns are more perceived as opposed to real. As alluded to in section 4.3.1.1., TCT rotors spin at low speeds and the edges of blades are blunt, thereby negating serious damage to a marine mammal if impact were to occur. In any event, marine mammals who live in such high tidal velocity conditions are expected to possess the agility required to navigate through and around these slow spinning TCTs.

Figure 12: Harbour seal, Race Rocks, British Columbia (Race Rocks Ecological Reserve)

Moreover, studies have shown that marine mammals such as toothed whales that possess echolocation sensory have the ability to detect and avoid submerged structures, while finless porpoises can use sonar sensory to detect objects 250ft ahead of them (Akamatsu, Wang, Wang, & Naito, 2005). Another concern has to do with whether the presence of underwater structures such as TCTs will have an impact on the inhabitation of areas surrounding TCT arrays. Although during the installation phase of pile driving for offshore wind turbines off the coast of Denmark exhibited a reduction in foraging behavior of harbor porpoises and overall echolocation activity up to 15km from the installation site (Tougaard, Carstensen, Damsgaard Henriksen, & Teilmann, 2003), such effects were short lived and conditions returned to their baseline almost immediately upon completion (Carstensen, Henriksen, & Teilmann, 2006).

4.3.2. Noise

The installation and decommissioning phases of a TCT's lifecycle are projected to produce significant noise levels that may exceed protection threshold levels and therefore have a significant negative impact on marine wildlife, particularly when employing pile-driving techniques (Frid et al., 2012). While installation and decommissioning are expected to be very quick, and therefore subsequent impacts to be short lived, it is essential to undertake such procedures during times where marine wildlife are absent from the area in order to avoid any negative implications (Bryden et al., 2007).

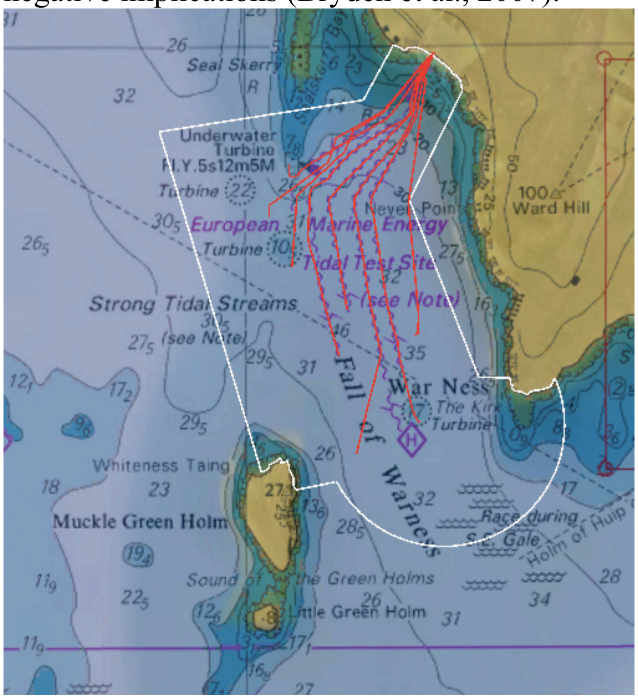

Figure 13: EMEC's Fall of Warness TCT test site in the Orkney Islands, Scotland (Harland, 2013)

The operational noise of TCTs is expected to be low and therefore unlikely to cause any considerable negative impacts on marine wildlife (Bryden et al., 2007). Acoustic monitoring tests undertaken at EMEC's Fall of Warness TCT test site in the Orkney Islands, Scotland, demonstrated that, while TCTs increase overall noise levels, the energy put into the water is below 1 kHz, significantly lower than that of a ship propeller, which also induces cavitation unlike TCTs, thereby further raising noise levels (Harland, 2013). The acoustic monitoring program at the TCT test site concluded that operational noise has little impact on marine mammal echolocation unless species are extremely close to the TCT, and with no possibility of physiological damage. While individual TCT operational noise may pose no threat to marine wildlife, as TCT implementation reaches commercial status, monitoring programs will be required to discern the cumulative acoustic levels of a large TCT array.

4.3.3. EMFs

EMF emissions produced from offshore wind turbines result from the same technologies utilized for TCTs, and thus lessons can be learned from offshore wind installations (OSPAR, 2008). When studying the movement patterns of sea turtles, Lohmann, Putman, and Lohmann (2008) determined that the impacts of EMFs could range from minor, inducing temporary disorientation when situated in close proximity to an electricity cable, to major, altering permanent nesting patterns. Moreover, Westerberg and Lagenfelt (2008) found evidence that eels can be temporarily diverted off of their migratory path and along the stretch of electricity cables. However, Bochert and Zettler (2004) found evidence that benthic organisms are not effected by long-term exposure to EMFs, while FORCE's (2013) EEMP acknowledged that migration routes for EMF-sensitive marine species may be effected but only in the very near field, and are expected to be of little impact, thereby suggesting that the siting of large TCT arrays should take into consideration marine species that rely on EMFs for migration, foraging, and reproduction purposes (Boehlert & Gill, 2010).

Figure 14: Green sea turtle (Aquaworld, 2015)

4.3.4. Pollution

As mentioned previously, TCTs are a clean renewable energy technology proposed to replace fossil fuels, as they produce electricity without emitting GHGs into the atmosphere. However, there have been concerns regarding the possibility of TCTs to release pollutants such as lubricating oil and antifouling paints into the ocean (Fraenkel, 2006). This impact has been considered negligible. The amount of lubricating oil required is miniscule and well contained, with no known leaks detected during SeaFlow's operation. Regardless, any antifouling paints used for the TCTs are proposed to be of the most environmentally friendly kind due to environmental regulations, are present in much lesser amounts in comparison to ships, and may not even be required at all in practice.

4.4. Hydrology

Given that wind turbines extract energy from the lowest vertical levels of the vast atmosphere, it is almost impossible that even the largest of wind farms, either onshore or offshore, can significantly alter the up or downstream wind flow regime (Vennell, 2012). In contrast, TCT arrays must displace a certain fraction of a tidal flow regime that is bounded by the seabed and the ocean surface (Vennell, 2010). Large TCT arrays that are packed too closely together will increase turbulence in the water column, altering natural mixing properties and possible wave properties, which may negatively effect the reproduction and recruitment processes of marine species (Frid, Andonegi, Depestele, Judd, Rihan, Rogers, & Kenchington, 2012), as well as compromise the optimal array layout configuration developed by Myers and Bahaj (2012) in section 3.4.

However, if sited and scaled appropriately, taking into consideration the distance of the cross section of a given site, it is very unlikely that a TCT array could have negative impacts on local hydrology (Pelc & Fujita, 2002). A one dimensional flow model developed by Bryden, Couch, Owen, and Melville (2007) demonstrated that 25% of the kinetic energy flux could be extracted from a cross section with less than a 7% reduction in flow speed, which has been deemed unlikely to cause any negative effects to regional hydrology.

4.5. Sediment deposition

Increased water column turbulence and subsequent mixing of flow properties resulting from the implementation of a TCT array ultimately reduce overall tidal current velocities in both the near and far field, thereby resulting in sediment deposition (Engineering Business Ltd., 2005). However, as with the case for hydrology alteration, significant sediment deposition is predominantly an issue of siting and scaling. For example, in theory, at 15rpm TCT rotors turn slowly enough so that negative effects regarding sediment transport is essentially negligible (Pelc & Fujita, 2002). However, if TCTs within a large array are packed to closely together and/or fill too great a portion of a given cross section, sediment concentrations can be reduced significantly upstream, downstream, and within the array. This is demonstrated in Ahmadian, Falconer, and Bockelmann-Evans' (2012) Severn Estuary, Britain model, where 25% of the tidal flow velocity was reduced within the array, considerably greater than the Bryden et al. (2007) model of a 7% reduction considered to be environmentally benign.

4.4. Strategic environmental assessment

Site-specific environmental assessments (EAs) and EEMPs undertaken by MCT, EMEC, and FORCE can help disseminate information pertaining to environmental conditions pre- and post-TCT implementation. Nevertheless, there must be a transformation of information gathering on TCT environmental interactions from ad hoc deploy and monitor scenarios to standard baseline bodies of knowledge. The objective of such a transformation would be to properly plan for large-scale commercial deployment of TCT arrays, via the facilitation of regional and integrated ecosystem assessment and monitoring approaches of offshore developments that better fit natural oceanographic boundaries and habitation and migratory patterns of marine species. This transformation would symbolize a strategic environmental assessment (SEA) approach (Fidler & Noble, 2012). Thus far, there has been little dissemination of information amongst international agencies with regards to offshore energy systems development, and, therefore, few opportunities for transferable learning have been provided.

The cumulative impacts of TCT arrays will pose different environmental interactions than the operation of individual TCTs that are currently being assessed. Thus, rigorous SEA is required in order to streamline TCT deployment and meet Scotland's commercial implementation schedule of 2016 (Johnson, Kerr, & Side, 2012). However, there must be a suitable median for the strictness of EA regulations; if EAs are too soft, then undermined environmental degradation may ensue, whereas if EAs are too strict, then commercial deployment of TCTs may not be realized to a scale which provides an international opportunity to replace climate change-inducing fossil fuel energy systems (Boehlert & Gill, 2010).

5. Economic and policy transitions incentivizing TCT implementation

It has been proposed that the largest hindrance to the large-scale implementation of TCTs, as well as any renewable energy system of a substantial capacity, is the economic framework inherent in renewable technologies, particularly the high capital costs associated with implementation, high energy prices, and the uncertainty of operational costs due to intermittency, or as is the case for TCTs, the lack of modelling of operational and maintenance costs as a result of their pre-commercial status (Li & Florig, 2006). In order to facilitate a rapid energy transition away from fossil fuels and towards renewable energy, thereby streamlining the implementation of TCTs, renewable energy costs must decrease, fossil fuel prices must climb, and strong supporting energy and financing policies must be put in place (Timmons, Harris, & Roach, 2014).

5.1. Reducing TCT costs

Due to the low energy prices of fossil fuels in relation to renewable energy, 80% of the global energy supply is provided by fossil fuels (Timmons, Harris, & Roach, 2014), which, as alluded to in the introduction to this paper, has perpetuated the global climate change dilemma (IPCC, 2001). However, this is mostly a result of the high capital costs associated with renewable energy system implementation. Essentially, when a renewable energy power plant is build, or an array of TCTs is implemented, the magnitude of upfront expenditures in constructing the plant can be compared to amassing a fossil fuel station and purchasing all of the fuel the station will require over its lifecycle (Timmons, Harris, & Roach, 2014). While this is indeed the case for tidal current energy, unlike fossil fuels, there are no associated fuel costs, and therefore fluctuations in unstable international fuel markets and an unreliable energy supply are not a factor. Governments could therefore provide fiscal incentives for utilizes to acquire a mandated portion of their electricity supply from renewable energy technologies, as is the case in the UK (Fraenkel, 2002).

When compared to other renewable energy technologies, TCTs have several inherent advantages that, in theory, should incentivize their adoption over other renewables. Considering that the materials required to construct a TCT are similar to that of wind turbines (Fraenkel, 2006), and accounting for tradeoffs between higher capacity factors for TCTs over wind turbines (Timmons, Harris, & Roach, 2014) with lower installations costs for wind turbines over TCTs (Fraenkel, 2010), ERoEI for TCTs is expected to be comparable to wind turbines, at a duration between 4-6 months (Danish Wind Industry Association, 1997). With TCTs expected to have operational lifecycles of 20-30 years, this would mean the an ERoEI of 4-6 months would result in an individual TCT producing 40 times the energy required to construct, install, and operate it (Fraenkel, 2006). The similarities between TCT ERoEI to that of wind turbines would suggest a net energy ratio of 18 (Kubiszewski, Cleveland, & Endres, 2010), higher than that of natural gas at a ratio of 10 (Hall, 2008), shale oil at 5, nuclear at 5-15 (Murphy & Hall, 2011), PV at 6.8 (Battisti & Corrado, 2005), sugarcane ethanol at 0.8-10 (Goldemberg, 2007), corn-based ethanol at 0.8-1.6 (Farrell, Plevin, Turner, Jones, O'hare, &

Kammen, 2006), and biodiesel at 1.3 (Hall, Cleveland, & Kaufmann, 1986).

Moreover, as has been witnessed for nearly all disruptive technologies within energy transitions, as the maturation of engineering and scale of manufacturing increases, capital and energy costs will decrease accordingly (Mueller & Wallace, 2008). This can be demonstrated through an analysis of the timeline of wind turbine technologies. Wind power had cost 30 cents/kWh in the 1980s, which was too expensive to be economically feasible for large-scale implementation. However, with the further development of technology, in conjunction with the accumulative adoption of the technology on smaller scales, costs had dropped to 5 cents/kWh in 1999, thereby making wind energy competitive with fossil fuels (Herzog, 1999). O'Rourke, Boyle, & Reynolds (2010b) estimate that TCT technology is approximately 15 years behind wind energy. However, having begun R&D at a later stage than wind turbines, TCTs have the added benefit of drawing upon advances in science and engineering, which may therefore speed up the maturation process and subsequent cost reductions.

The purchase, installation, and grid connection of a 20MW TCT array currently underway in Hammerfest, Norway, is expected to reach $18,216,800 (converted from $US to $CAN and including inflation) (Charlier, 2003). These figures suggest a cost of $910,840/MW of installed capacity. However, it is worthy to note that where TCT arrays are sited have a considerable impact on their capital costs, as deploying larger arrays closer to shore and in shallower waters reduces installation, operation, maintenance, and electricity cable costs (Li & Florig, 2006). The introduction of a feed-in tariff in Portugal has priced electricity provided from ocean energy at 34 cents/kWh (converted from Euros to $CAN and including inflation) (Soerensen & Naef, 2008). But Esteban and Leary (2012) calculated that this is supposed to plummet to 10 cents/kWh by 2021, similar to the timeline of wind energy, thereby making TCTs cost competitive with fossil fuels. It has been estimated that up to 1 million jobs could be created in the ocean energy sector (TCTs, tidal barrages, offshore wind turbines, OTECs, and WECs) by 2030, providing 7% of the world's electricity, which is expected to be 29.750TWh/yr.

Furthermore, due to the resulting high capacity factors of TCTs, coupled with the predictability of TCT electricity generation that lends itself well to energy storage, as well as site differentiated tidal cycle phase shifting facilitating the possibility of base load power provision discussed in section 3.5., TCTs are one of the only renewable energy technologies that can overcome intermittency issues and subsequently enter various electricity markets. Essentially, there are four distinct electricity markets; the base load market, where long-term contracts are granted to provide continuous energy in the amount that demand never drops below base load demand; the installed capacity market, where the grid operator pays for capacity to be consistently brought online for purposes of peak fluctuations in demand; the spinning reserve market, where the grid operator pays a generation station in case additional output is needed beyond typical base load and peak demand; and the spot market, where the grid operator takes bids for electricity provision for the following day in anticipation of excessive peak demand (Heal, 2009). Generally, renewable energy technologies only compete in the spot market. However, due to the several significant operational advantages that TCTs have in relation to other renewables, particularly the potential to eliminate intermittency issues, strategic implementation can allow TCTs to participate in all four electricity markets. For example, the tidal cycle phase shifting option of solving intermittency would eliminate capital cost externalities of energy source redundancy induced by the construction of additional storage capacity.

Regardless, due to the high capital costs of renewable energy systems, implementing a plethora of policy tools that subsidize renewable energy generation is essential in order to overcome current economic barriers and fast track the renewable energy transition. Recommended financial policy tools include mandatory renewable energy targets as mentioned in the UK, where failure to meet mandates result in financial penalties (Owen, 2004), feed-in tariffs, such as those existing in Portugal, which guarantee renewable energy electricity producers fixed long-term sales contracts at or above current market prices (Timmons, Harris, & Roach, 2014), financial tax incentives, tax credits, and R&D funding allocation (O'Rourke, Boyle, & Reynolds, 2010b). Such policy implementation has proven to be a great contributor to TCT development in Canada, France, Portugal, UK, and the USA. Some countries have taken to the construction of policies to facilitate the adoption of TCTs one step further. An example is Ireland's Department of Communications, Marine and Natural Resources white paper document entitled *Delivering a Sustainable Energy Future for Ireland*, released on March 12th, 2007, which states that 500MW of ocean energy capacity is to be installed by 2020 in order to reach the nation's 33% renewable energy electricity target by 2020 (O'Rourke, Boyle, & Reynolds, 2010a).

R&D expenditures specifically tend to speed up the maturation of renewable energy technologies, thus facilitating implementation in necessary economies of scale and subsequently driving down capital costs (Timmons, Harris, & Roach, 2014). Johnstone, Haščič, and Popp (2010) discovered that R&D programs have a direct positive correlation on patent account activity, specifically with regards to ocean energy, with Italy, Sweden, and the UK leading the way, which has a direct positive correlation with technological maturation. Although there are relatively few ocean energy patents, the number is steadily increasing as continual technological maturation paves the way for large-scale commercial implementation of TCTs.

5.2. Increasing fossil fuel costs

While policies that endorse renewable energy subsidies are essential to facilitate the adoption of renewable energy technologies such as TCTs in order to fast track the energy transition away from climate change-inducing fossil fuel energy, the low prices of polluting technologies must at the same time witness an increase in costs to make large-scale implementation of renewables feasible. A primary way to do this is to internalize external damages caused by biophysically and socially detrimental energy technologies into the marketplace. Owen (2004) suggests that such environmental externalities can be divided into two main encompassing categories; costs regarding damage to human health and the natural environment that are not directly associated with climate change (such as industry accidents), and costs associated with GHG emissions that perpetuate climate change (such as flood damage).

The non-climate-change-inducing externalities were calculated for coal to be 67 cents/kWh and for gas to be 16 cents/kWh. If these environmental adders were injected into the market, while current trends of decreasing renewable energy generation costs persist, coal and gas would become more expensive than the majority of renewables by 2020 based on societal costs alone, which only account for the material and energy flow within their life cycle. The concept of putting a price on climate change inducing externalities is not a new one, as British economist Arthur Cecil Pigou noticed in the early 20th century during the infamous London fogs that costs imposed on society resulting from pollution were not included in the market, and suggested that a Pigouvian tax based on a polluter pays principal be internalized into the market.

When considering the consequences of environmentally detrimental and controversial fuel sources such as fossil fuels and nuclear energy, a temporal price tag should also be implemented in order to fully account for the externalities incurred throughout the fuel source's life cycle (Owen, 2004). For example, the release of GHG emissions from fossil fuels could have impacts present in excess of 100 years, while storage of hazardous nuclear waste can be tracked for centuries, and should therefore be priced accordingly. Since such externalities are essentially a market failure, government intervention must occur, imposing carbon taxes that delegate the financial burden of environmental degradation to those who perpetuate it. Examples of countries that have adopted this principal include Denmark, Finland, Germany, the Netherlands, Norway, Sweden, and the United Kingdom.

Another means of increasing fossil fuel prices is to eliminate government granted fossil fuel subsidies. Although in the short term this can result in increased energy costs and limit economic growth (Timmons, Harris, & Roach, 2014), the finances that governments will retain can be allocated to renewable energy subsides and R&D funding, which, where implemented, has demonstrated an increase in patent activity and therefore renewable energy maturation which is likely to speed up the large-scale adoption of renewable energy technologies such as TCTs (Johnstone, Haščič, & Popp, 2010).

6. MSP

The global marine environment is facing an increasing demand in spatial use, both from conventional applications such as commercial fishing, shipping, dredging, aquaculture, mineral extraction, recreation and tourism industries, as well as emerging initiatives to harness renewable energy from the marine environment (Douvere & Ehler, 2009). The management of such issues is complicated by emerging costal population growth and legislative obligations to protect identified marine environments and promote overall marine ecosystem biodiversity, which is currently in decline (Foley, Halpern, Micheli, Armsby, Caldwell, Crain, Prahler, Rohr, Sivas, Beck, Carr, Crowder, Duffy, Hacker, McLeod, Palumbi, Peterson, Regan, Ruckelshaus, Sandifer, & Steneck, 2010). The implementation of comprehensive MSP is essential in order to effectively coordinate the use of marine space to accommodate the estimated 382 existing and emerging marine activities (Lester, Costello, Halpern, Gaines, White, & Barth, 2013), while meeting environmental, social, and economic objectives, such as the commercial deployment of TCTs (Ehler & Douvere, 2006).

6.1. Regulatory approaches

MSP is essentially an extension of terrestrial land use planning. To coordinate a defined area of space to accommodate multiple and often conflicting uses, proper zoning, consenting, licensing, and permitting measures must be taken, organized by national policy and backed by legislation. Due to the current absence of MSP implementation and the comparatively uncoordinated structuring of marine spatial use relative to mature terrestrial land use planning practices, the majority of the ocean can be seen as an enormous greenfield site (Johnson, Kerr, & Side, 2012). Since MSP is the main regulatory conduit to facilitate the deployment of TCTs, which are an emerging concept in their own right, a thorough understanding and strict regulatory process must be put in place in order to achieve competing and conflicting environmental, economic, and social goals.

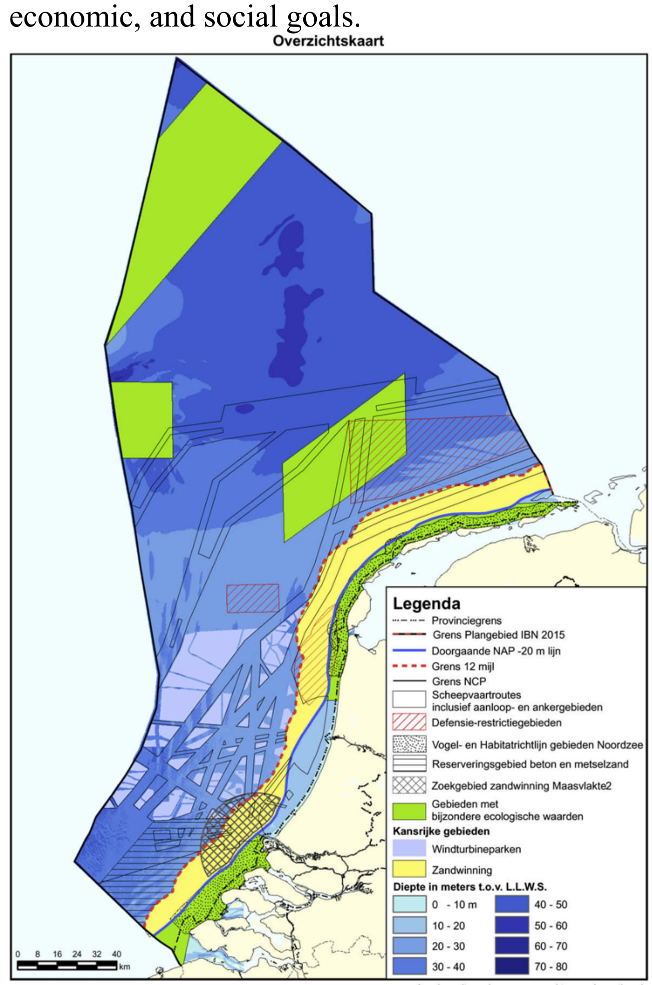

Figure 15: BPNS MSP (Douvere & Ehler, 2009)

Several European nations have taken a global initiative in developing MSPs, including the Netherlands' Integrated Management Plan for the North Sea 2015 (IMPNS2015, 2005), Germany's coastal La¨nder, Territorial Sea Plan and Exclusive Economic Zone (EEZ) plan (Gee, Kannen, Glaeser, & Sterr, 2004), the UKs Marine Bill MSP (Douvere & Ehler, 2009), the Scottish Government's non-statutory Pentland Firth and Orkney Waters (PFOW) pilot spatial plan (Marine Scotland, 2011), and Belgium's Master Plan for the Belgium Part of the North Sea (BPNS), which is the first MSP to apply land use planning tools to their plan and begin to implement it incrementally (Douvere, Maes, Vanhulle, & Schrijvers, 2007). A factor that all of these nations have in common is the potential to accommodate ocean energy, with the shores of the UK, particularly Scotland, possessing vast tidal current resources (Hardisty, 2009).

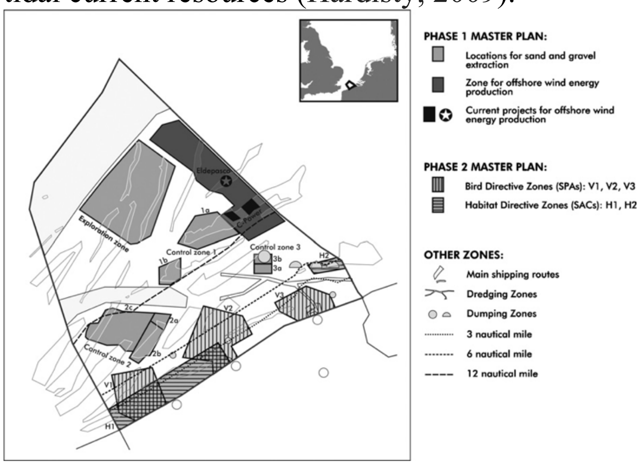

Figure 16: Phases 1 and 2 of the sustainable Master Plan for the BPNS (Douvere et al., 2007)

Within the North American and European context, land use planning practices have evolved from an incremental, ad hoc, individual permit granting process to the development of comprehensive official plans with strict zoning regulations and a streamlined permit allotment system (Douvere & Ehler, 2009). However, due to the infancy MSP, such comprehensive planning practices and tools have yet to be developed. Therefore, best practices upon which to draw from have yet to be consolidated, thereby leaving the implementation process of TCTs in a state of regulatory limbo. Regardless, while the development and implementation of MSPs in European nations is subject to individual national legislation, (Norris, Cowan, Bristow, Magagna, & Giebhardt, 2014), each nation must abide by overarching EU driven biological conservation legislation. This legislation aims to create a EU-wide network of conservation areas restricted from development, referred to as Natura 2000 (European Commission, 2005), and formed by the Birds Directive (Council of the European Communities Directive, 1979), which provides a framework for the siting of Special Protection Areas (SPAs), and the Habitats Directive (Council of the European Communities Directive, 1992),which provides a framework for the siting of Special Areas of Conservation (SACs).

Taking the BPNS as an example, such EU marine biological conservation legislation has facilitated the requirement that offshore energy projects obtain development licenses and conduct preliminary environmental impact assessments (Douvere et al., 2007). Following the granting of a license, developments are subject to continuous monitoring programs and environmental impact surveys financed by the developer. At this point, if any unacceptable or undeclared environmentally detrimental impacts ensue, the license can immediately be suspended or withdrawn. This method of regulation follows the precautionary principle, signifying the inherent uncertainty of the dynamics of the marine environment, which in turn has hindered the ability of developers to obtain environmental consents and thus assisted in limiting the technological maturation and streamlined implementation of TCTs (Bryden & Couch, 2006). However, as alluded to in section 4., in order to promote a healthy planet while meeting society's modern lifestyle demands, it is essential that environmentally detrimental energy sources be substituted for environmentally benign energy sources. Therefore, strict environmental regulations on the deployment of ocean energy technologies such as TCTs are essential in order to achieve an ecologically sustainable energy transition. That said, a healthy balance must be achieved between safeguarding the environment without stifling technological innovation.

Much of the reason that TCT implementation has encountered strict environmental regulations and has thus yet to be streamlined within MSPs is not only a result of the unknown dynamics of the marine environment itself, but also a consequence of the lack of substantial concrete baseline data available on how TCTs interact with their surrounding environment, due to their infancy status. Although test centers such as EMEC and FORCE have undertaken extensive environmental monitoring studies, they have done so on an ad hoc basis, with no standardized consenting process in place between such organizations. Norris et al. (2014) suggest that European TCT test centers should adopt a coordinated approach towards environmental monitoring in order facilitate the dissemination of standardized information, thereby allowing the MSPs of different nations to draw upon similar regulatory approaches to streamline the licensing process, environmental monitoring approaches, and eventual implementation.

6.2. Zoning and ecosystem trade-offs

Regardless of ecosystem-based approaches to MSP and an ideal streamlined environmental consenting and permitting process, the sheer number of uses of marine space will require MSP practices to make ecosystem trade-offs when constructing a zoning map of a master plan. The trade-offs are needed to balance the range of societal demands of ecosystem services provided by the marine environment (Lester, McLeod, Tallis, Ruckelshaus, Halpern, Levin, Chavez, Pomeroy, McCay, Costello, Gaines, Mace, Barth, Fluharty, & Parrish, 2010). Some ecosystem services can be quantified, such as the annual fish catch within a particular site, how many people profited from the yield, the total resulting food provision, and the money made that was likely to be cycled back into the local economy, while other ecosystem services cannot, such as the aesthetic value of an unobstructed view of the ocean (Lester et al., 2013). Regardless of the ecosystem service in question, the complexity of both the marine environment and the economy suggests that most, if not all ecosystem services are intertwined with one another. Trade-offs will have to be made in order to accommodate TCTs and strategically zone them according to economic production theory in order to minimize the trade-offs made and maximize social, environmental, and economic gains. Two ways in which TCTs can be zoned according to this principle is by siting them in ecologically degraded areas, thereby creating a de facto no fishing zone and potentially affording refuge for particular marine species to rehabilitate their population (Lester et al., 2013), and by implementing TCT arrays of a particular size in a particular depth that permit sufficient clearance for ships, thereby negating the necessity to close off maritime transportation routes (Bryden & Couch, 2006).

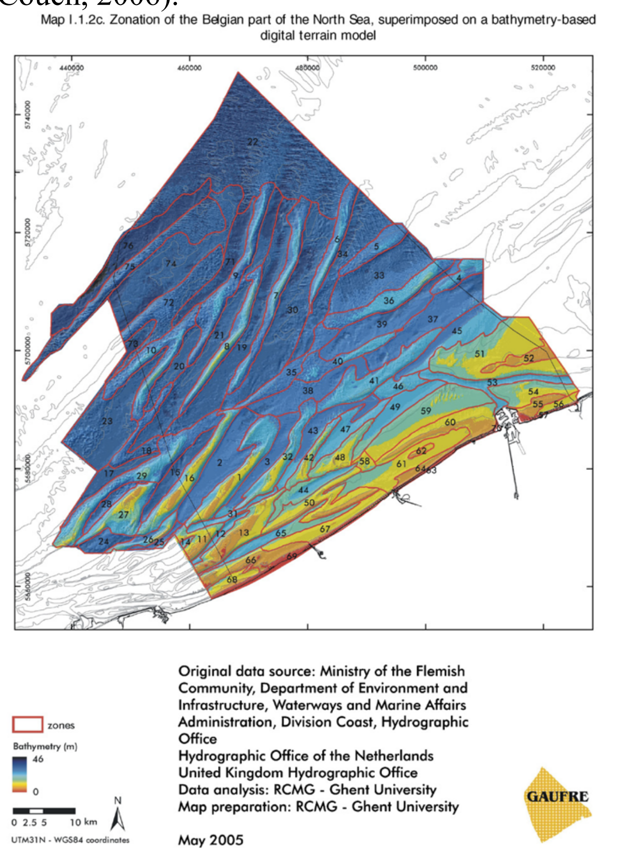

Figure 17: Zoning map of the BPNS (Douvere et al., 2007)

6.3. Integrated approach to MSP

Zoning strategies to minimize ecosystem trade-offs have begun to emerge in the construction of comprehensive MSPs of individual nations around the world. For bordering nations developing MSPs within the same sea, a more integrated regional approach to MSP that better reflects natural ecosystem boundaries and migratory paths of marine wildlife inhabiting the sea as opposed to political borders is required in order to properly site TCT arrays (Douvere & Ehler, 2009). For example, the EU Thematic Strategy for the Marine Environment has identified 11 ecoregions predicated on biogeographic, oceanographic, political, social, and management features, in which the Dutch, Belgian, and German MSPs share the same North Sea region (ICES, 2004). Thus far, there has been no international cooperation amongst these nations in developing an integrated MSP, nor any nations for that matter (Douvere & Ehler, 2009). However, if an integrated ecosystem approach to MSP were to be adopted, larger-scale ecosystem trade-offs can be distinguished and minimized, such as the avoidance of blocking mass maritime transportation routes, and like the SEA model discussed in section 4.4., cumulative environmental impacts can be identified more cohesively (Foley et al., 2010), thereby allowing for the identification of regional TCT suitability zones and subsequently streamlining their commercial implementation.

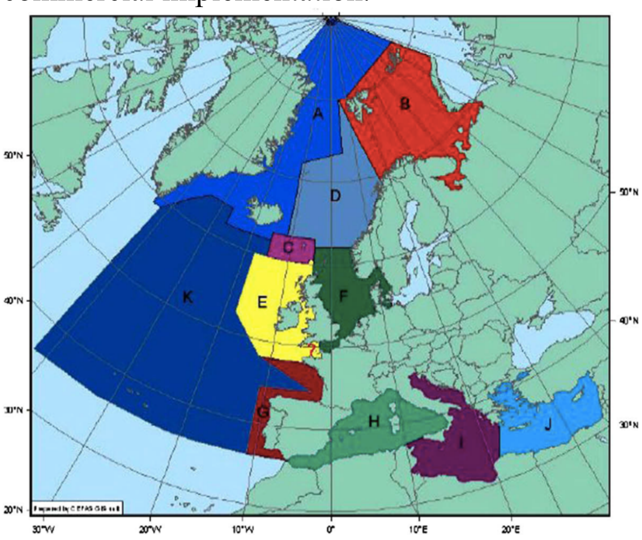

Figure 18: European Marine Ecoregions (Douvere & Ehler, 2009)

6.4. Public acceptability and participation in MSP

In proposing the implementation of a new renewable energy technology such as TCTs, public acceptability or opposition is central in determining the success or failure of a development (Bronfman, Jiménez, Arévalo, & Cifuentes, 2012). Due to the sheer population of modern society and the resulting complexity of systematic societal interdependence attributed to specialization in expertise, the concept of trust has become vital in order for urban and regional populations to operate on a daily basis. In the context of TCT implementation in MSPs, this concept of societal trust in regulatory authorities must be strong, as the lack of public support in a disruptive energy system will result in the failure of its adoption (Perlaviciute & Steg, 2014). Some examples include the rejection of a biomass plant in Cricklade, North Wiltshire, England, where the siting of the plant had taken place without public involvement and information about regarding the operational impacts of the plant was not disseminated, resulting in strong public dissent due to perceptions of increased smog produced from the plant leading to unfavorable road conditions, (Upreti & van der Horst, 2004). In the case of a wind farm development in the Rheinland-Pfalz region of Germany, failure to notify the public of the planning decision resulted in public dissent and lawsuits which delayed the planning process and increased costs to local planning authorities (Pendleton, Atiyah, & Moorthy, 2007).

Such cases strongly suggest that public engagement as early in the planning process as possible is essential in order to obtain public support and work towards the implementation of a renewable energy system. Bronfman et al. (2012) suggests that regulatory institutions seeking to obtain public trust and support in the adopting of a renewable energy technology undertake environmental impact assessments (EIAs) and create social and economic policies in a transparent and inclusive manner that integrates expert and local knowledge. Once this relationship of trust is solidified, the adoption of renewables faces three other hurdles which planners must address, namely economic, lifestyle, and communal place attachment (Perlaviciute & Steg, 2014).

Since TCTs are a relatively new renewable energy technology and deployment has yet to achieve commercial status, electricity price reductions facilitated by economies of scale have not yet been achieved, and therefore such high prices can act as a barrier for planners to pitch TCT implementation. However, Aldy, Kotchen, and Leiserowitz (2012) conducted a study that demonstrated that over 70% of American citizens partaking in a survey claimed that they would be willing to accept a costs increase in their energy bill between US$5–35 when provided with a future clean energy scenario of 80% renewables by 2035, although such willingness to pay increased prices was applicable more so to an energy alternative that relied solely on renewables for energy provision as opposed to a mix of renewables with natural gas and/or nuclear energy. The high capacity factors of TCTs, and nearly constant operational ratios that can easily accommodate energy storage or provide base load power via regional tidal peak velocity phase shifting where possible (see section 3.5.), suits this model of an increased willingness to pay higher prices for energy provision. This is because such provision is solely renewable based, thus overcoming the second hurdle of public acceptance related to changing lifestyle energy consumption patterns to match energy output timing characteristic of the intrinsic intermittent nature of most renewable energy technologies (Wolsink, 2012).

The third hurdle of public acceptance of renewable energy systems related to communal place attachment can be demonstrated through a community's willingness to support renewable energy implementation in general, but to a much lesser extent if siting within their specific community, thereby resulting in the NIMBYism phenomenon (Devine-Wright, 2009). A Norwegian case study demonstrated that community members who felt a communal place attachment to natural landscapes expressed strong opposition to the development of a hydroelectricity dam development due to the alteration of naturally functioning ecological systems intrinsic to the development and operation of a hydroelectricity plant (Vorkinn & Riese, 2001), while mass public uprising in opposition to the construction of five hydroelectric dams in the Chilean Patagonia was sparked during the HidroAyse´n project's EIA for similar reasons (Bronfman et al., 2012). However, such NIMBYism concerns over audio and visual pollution resulting from wind energy projects have generally shown less concern for offshore installations as opposed to onshore (Parkhill, Demski, Butler, Spence, & Pidgeon, 2013), possibly due to the reduction in associated communal place attachment. With respect to TCTs, as discussed in section 4., proper siting and scaling result in environmentally benign developments, whereby fully submerged devices further negate public dissent due to their non-existent audio and visual profile, thereby allowing planners to more readily grant consent (Fraenkel, 2002), while the surface piercing SeaGen TCT implemented in the Strangford Narrows off of the coast of Northern Ireland has precipitated an enhancement of communal place attachment effects via branding (Devine-Wright, 2011).

This being recognized, not all offshore renewable energy developments that bypass typical environmental, social, economic barriers will be subject to implementation if public participation in the MSP process is neglected. In 2010, the announcement of the potential development of an offshore wind farm off the shores of Machrihanish, Kintyre, a peninsula off the west coast of Scotland known for its fishing, shipping, and tourist industries, was met with considerable public dissent, which ultimately led to the withdrawal of the project (Alexander, Janssen, Arciniegas, O'Higgins, Eikelboom, & Wilding, 2012). The Mull of Kintyre has also been proposed as a TCT test site, with a seabed lease offered by Marine Scotland and the UK Crown Estate. In order to overcome public backlash towards the development of the potential TCT site, Alexander et al. (2012) held an interactive spatial decision support system workshop designed to engage public stakeholder representatives of local fishing, commercial shipping, recreational, and tourism industries in the early stages of the MSP process to determine the most suitable location with the least spatial conflicts affecting stakeholders of a TCT array. The workshop used six GIS maps and an interactive touch table to allow participants to allocate the spatial importance of their respected industries to 500m x 500m cells in the study area. The results of this workshop allowed the participants to identify a mutually suitable location for the allocation of the TCT array that had minimal to negligible conflict with each of their respective industries, as demonstrated in figures 19, 20, and 21.

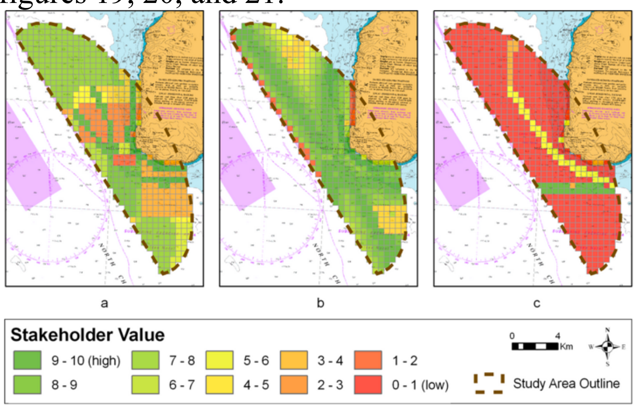

Figure 19: Mull of Kintyre TCT stakeholder value map (Alexander et al., 2012)

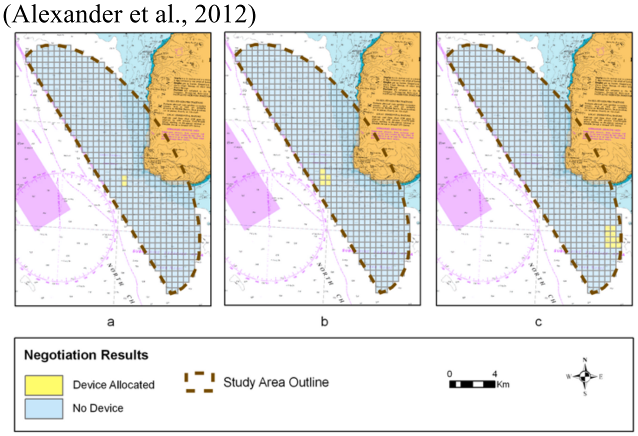

Figure 20: Mull of Kintyre TCT proposed negotiated areas

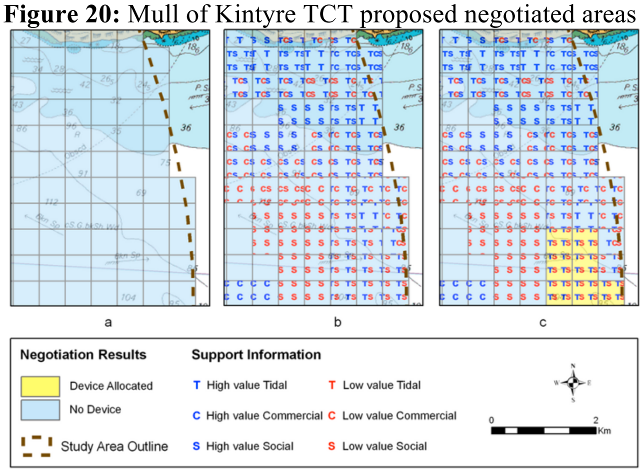

Figure 21: Mull of Kintyre TCT agreed allocation area

7. Optimal Design

Due to the early stages of R&D which TCT technologies currently reside, and the large amount of developers engineering a plethora of designs, no optimal design configuration for a TCT has yet been agreed upon, as was the case for wind turbines, where tri-bladed horizontal axis turbines were deemed more efficient than vertical axis Darrieus designs, and have therefore become the standard commercial model (O'Rourke, Boyle, & Reynolds, 2010). As demonstrated in Myers & Bahaj's (2005) TCT array configuration in Alderney Race that took into account local bathymetry and geology alluded to in section 3.4., an assemblage of various TCT sizes may be required in order to accommodate local site conditions. A similar concept was further explained in section 3.3. with respect to employing various TCT technological designs whose intrinsic engineered parameters function to optimize specific economic, bathymetric, and flow velocity conditions. Despite such dynamics, this section aims to draw upon the previous sections presented in this paper in order to theorize an optimal universal TCT design.

Out of the 14 different variations of TCT technologies presented in O'Rourke et al.'s (2010b) Tidal Energy Update 2009 article, only five of the technologies to date have been implemented into full-scale operation to produce electricity, all of which employ a horizontal axis rotor hub, suggesting that this is the most efficient rotor configuration. Moreover, vertical axis TCTs are costlier, as similarly rated devices are larger and therefore require more material, a factor further exacerbated by their inability to self start, requiring even more material (Fraenkel, 2002).

Figure 22: OpenHydro rimmed TCT rotor design (EMEC, 2016)

Much like vertical axis TCTs, venturi-type shrouds are more susceptible to cavitation, and the increased costs of constructing a shroud cancels out the costs saved through a smaller rotor design, while the shroud itself may enhance marine wildlife mortality via blade strike as there is less room for maneuverability around the rotor. At the moment, little is known about the operation of oscillating hydrofoil TCTs, so they will be excluded from analysis. While the horizontal axis rotor seems to be the most optimal design choice, the bladed configuration may be at a disadvantage to the rimmed TCT horizontal design, as there are less mechanical parts, making them more resilient and requiring less maintenance, therefore making them less costly (Ben Elghali, Benbouzid, & Charpentier, 2007). Furthermore, the open center design may reduce potential for blade strike induced mortality of marine species. It is improbable that the rimmed TCT design could be amalgamated with the tethered free motion kite design, which in any event has disadvantages of having a large associated spatial footprint and potential marine species collision risk (O'Driscoll, 2012).

In order to anchor the rimmed TCT to the seabed, a monopole structure provides an intermediate cost solution between gravity bases and floating buoys (Fraenkel, 2002). However, from an ecological standpoint, gravity structures do not require pile driving and therefore do not induce interruptions in the inhabitation of deployment sites during the installation process (Tougaard, 2003), thereby allowing for a larger window for installation timing to balance such operations with the presence of marine species in the site's vicinity (Fraenkel, 2010). Gravity structures are also fully submerged, thereby negating potential NIMBYism concerns surrounding aesthetic pollution that may be associated with visible surface penetrating buoy anchors (Parkhill et al., 2013), as well as concerns regarding seabird collisions with surface penetrating structures (Boehlert & Gill, 2010), although no such correlations have been witnessed from SeaGen testing (O'Driscoll, 2012). Although surface penetrating monopole structures that can raise the turbine above the ocean surface to allow easy access for maintenance, thereby reducing maintenance costs, the lower requirement for maintenance for rimmed TCTs could potentially counterbalance the increased maintenance costs of a fully submerged TCT (Ben Elghali, Benbouzid, & Charpentier, 2007).

While Fraenkel (2002) suggests that gravity based structures are only feasible in shallower waters, which, when located near the coastline, reduce installation, maintenance, and cable costs (Li & Florig, 2006), Bryden and Melville (2004) suggest that large gravity bases can be employed in greater water depths if there is considerable tidal current velocities and economies of scale are taken advantage of. Since deeper waters require higher installation, maintenance, and cable costs, once again, the reduction in maintenance requirement for rimmed TCTs lend themselves well to such implementation by balancing overall costs (Ben Elghali, Benbouzid, & Charpentier, 2007), while fully submerged devices in greater depths require less ecosystem trade-offs within a MSP as sufficient clearance negates the closure of commercial shipping routes above the TCT array (Lester et al., 2013). Since marine mammals are believed to be capable of avoiding TCTs via their natural agility (Fraenkel, 2006) and heightened echolocation (Akamatsu et al., 2005), underwater lights attached to TCTs with the intention of deterring marine mammals is unnecessary, simultaneously reducing concerns over such lights attracting seabird populations, although SeaGen operation has not demonstrated such a correlation (O'Driscoll, 2012).

Furthermore, to reduce cable costs via larger spatial footprints which also simultaneously increase ecosystem trade-offs, TCTs arrays should be configured using Myers and Bahaj's (2012) optimization layout model that maximizes output efficiency while maintaining the structural integrity of individual TCTs. Finally, while deploying a significant amount of TCTs in an array are necessary to achieve economies of scale that reduce economic limitations surrounding high capital costs, the implementation of TCT arrays at specific sites must be mindful not to take up a large enough portion of a given cross section that harnesses over 25% of the available kinetic energy flux, the upper limit of extraction deemed to be acceptable without significant impacts on natural hydrology (Bryden et al., 2007), as well as repercussions surrounding environmentally detrimental amounts of sediment disposition (Ahmadian, Falconer, & Bockelmann-Evans, 2012). To summarize, based on a trade-off analysis developed with regard to an extensive literature review, this paper suggests that an optimal individual TCT design is one of a rimmed horizontal axis hub secured to the seabed via a gravity base.

8. International implementation

8.1. Purpose and methodology

The primary purpose of the creation of TCTs and the promotion of their commercial deployment is to provide societies with GHG-free renewable electricity, in order to replace a carbon based economy. This section of this paper will assess an implementation model for three nations known to have considerable tidal current resources, notably Canada, China, and Norway (Hardisty, 2009). Although national and regional resource assessments calculating the potential power available in coastal waters of these nations have been undertaken, as this paper has discussed, there are several mechanical, environmental, ecological, social, economic, marine spatial, and various other logistical factors hindering the ability of TCTs to harness the total rated resource potential available in any given site. Therefore, the portion of O'Rourke, Boyle, and Reynolds' (2010a) accessible tidal current energy resource model developed for Ireland will be employed for Canada's east and west coasts, China's east coast, and Norway's west coast, where potential environmental impacts and applicable legislation, perceived health and safety concerns, regulatory planning matters, and marine spatial conflicts such as shipping navigation routes delimited the prior resource assessment by 25%. If this theory is downscaled and applied to each individual site assessed within regions of a nation, it fits perfectly with Bryden et al.'s (2007) theory of harnessing 25% of the kinetic energy flux for a given site as the upper limit of extraction without resulting in significant velocity reductions.

When calculating total system efficiency, however, O'Rourke, Boyle, and Reynolds' (2010a) technical resource assessment methodology measured against the gross theoretical power potential will not be used. Rather, system efficiency will be modeled after SeaGen operational results (Fraenkel, 2010), rated at 1.2MW, which demonstrated a 60% Cf (conservative estimate), with the developers aiming to achieve an operational ratio of 95% considering the necessity for routine and emergency maintenance. An optimal Cp of 59.3 will be injected into the equation, assuming advancements in engineering via technological maturation (Fraenkel, 2002). Array layout configurations will be manipulated to maximize power output of downstream TCTs by 22%, as per Myers and Bahaj's (2012) model. Taking all of these factors into account, the equation to discern the actual output power of a single turbine becomes:

$$1.2\text{MW} \times \text{Cp } 0.593 \times \text{Cf } 0.6 \times 0.95 \quad \text{(EQ1)}$$

This suggests that each TCT generates 405.6 kW of output energy. Such system efficiency estimates will allow for the measurement of how many TCTs will need to be implemented and in what configuration in order to quantify the upper limit of TCTs that examined sites in Canada, China, and Norway can accommodate. It will also provide a basis for calculating the amount of GHG emissions eliminated from current fossil fuel electricity generation regimes by substituting GHG producing plants with TCT arrays.

Total capital, installation, and grid connection costs for the deployment of TCT arrays can then be estimated using the 20MW TCT array currently underway in Hammerfest, Norway, estimated to reach $18,216,800 (see section 5.) (Charlier, 2003). This figure can be dissected to assume that every MW of installed capacity amounts to $910,840. The price of electricity generation will then be given by averaging the introduction of a feed-in tariff in Portugal's 2008 ocean energy figure of at 34 cents/kWh (Soerensen & Naef, 2008), with Esteban and Leary's (2012) estimated price decrease of 10 cents/kWh by 2021, thereby assuming a current 2016 price of 22 cents/kWh.

Finally, TCT implementation induced employment will be calculated using Esteban and Leary's (2012) estimate of 1 million jobs being created in the ocean energy sector (TCTs, tidal barrages, offshore wind turbines, OTECs, and WECs) by 2030 through providing 7% of the global annual electricity consumption, estimated at 2082.5TWh. If it is assumed that one third of installed ocean energy capacity is provided by TCTs, as their deployment is advocated over tidal barrages, OTECs, and WECs for a several reasons (Pelc & Fujita, 2002), then this figure becomes 333,333 jobs per 687.225TWh of generated electricity, assuming two thirds of which will work in the maintenance sector thereby potentially lasting the maximum projected 30-year lifespan of a TCT (Esteban & Leary, 2012).

Canada				
Canada's Maritime Region				
Site Name	**Gross MPP**	**Accessible and Sustainably Extractable Resource**	**Number of TCTs Deployable**	**Annual Electricity Output**
Bay of Fundy				
Nova Scotia				
Minas Basin	1.903GW	475.75MW	396	1.562TWh
Northwest Ledge	73MW	18.25MW	15	58.692GWh
The Hospital	50MW	12.5MW	10	38.544GWh
NS Totals	2.026GW	506.5MW	421	1.623TWh
New Brunswick				
Clarks Ground	216MW	54MW	45	176.953GWh
Devils Half Acre	95MW	23.75MW	19	76.212GWh
Old Snow	83MW	20.75MW	17	65.7GWh
Head Harbour Passage 1	74MW	18.5MW	15	58.692GWh
Gran Mahan Channel	50MW	12.5	10	38.544GWh
NB Totals	518MW	129.5	106	416.101GWh
BoF Totals	2.544GW	636MW	527	2.039TWh
Gulf of St. Lawrence				
Newfoundland				
Strait of Belle Isle	373MW	93.25MW	77	303.096GWh
Pointe Armour	48MW	12MW	10	38544GWh
Forteau	48MW	12MW	10	38544GWh
GoSt.L Totals	469MW	117.25MW	97	380.184GWh
CMR Totals	3.013GW	753.25MW	624	2.419TWh
British Columbia				
Vancouver Island Mainland				
Seymour Narrows	786MW	196.5MW	163	651.744GWh
North Boundary Passage	366MW	91.5MW	76	299.592GWh
Discovery Passage South	327MW	81.75MW	68	268.056GWh
Boundary Passage	265MW	66.25MW	55	218.124GWh
Current Passage 2	208MW	52MW	43	169.068GWh
Weyton Passage	200MW	50MW	41	161.184GWh
Current Passage 1	139MW	34.75MW	28	111.252GWh
Dent Rapids	139MW	34.75MW	28	111.252GWh

South Pender Island	101MW	25.25MW	21	93.732GWh
Yaculta Rapids	94MW	23.5MW	19	76.212GWh
Arran Rapids	89MW	22.25MW	18	71.832GWh
Secheldt Rapids 2	76MW	19MW	15	58.692GWh
Gillard Passage 1	52MW	13MW	10	38.544GWh
Scott Channel	51MW	12.75MW	10	38.544GWh
Active Pass	50MW	12.5MW	10	38.544GWh
Nahwitti Bar 1	45MW	11.25MW	9	35.04GWh
VIM Totals	2.988GW	747MW	614	2.33TWh
		Pacific Mainland North		
Nakwakto Rapids	164MW	41MW	34	134.028GWh
Otter Passage	61MW	15.25MW	12	46.428GWh
Beaver Passage	46MW	11.5MW	9	35.04GWh
PMN Totals	272MW	67.75MW	55	215.496GWh
BC Totals	3.26GW	814.75MW	669	2.545TWh
Canada Totals	**6.273GW**	**1.568GW**	**1,293**	**4.964TWh**

China				
Site Name	**Gross MPP**	**Accessible and Sustainably Extractable Resource**	**Number of TCTs Deployable**	**Annual Electricity Output**
Liaoning Province	1.131GW	282.75MW	235	972.684GWh
Shandong Province	1.178GW	294.5MW	245	966.228GWh
Estuary of Yangtze River	304.9MW	76.23MW	63	248.784GWh
Zhejiang Province	7.09GW	1.77GW	1477	5.825TWh
Fujian Province	1.281GW	320.25MW	266	1.489TWh
Taiwan Province	2.283GW	570.75MW	475	1.873TWh
Guangdong Province	376.6MW	94.15MW	78	307.476GWh
Hainan Province	282.4MW	70.6MW	58	229.512GWh
Totals	**13.927GW**	**3.479GW**	**2,897**	**11.912TWh**

Norway				
Site Name	**Gross MPP**	**Accessible and Sustainably Extractable Resource**	**Number of TCTs Deployable**	**Annual Electricity Output**

Sørsalten	5MW	1.25MW	1	3.553GWh
Nærøysundet	89MW	22.25MW	18	71.832GWh
Kr°akøya	158MW	39.5MW	32	126.144GWh
Bakkastraumen	10MW	2.5MW	2	7.106GWh
Toftsundet	24MW	6MW	5	19.272GWh
Visten, Ausa	16MW	4MW	3	11.388GWh
Brasøysundet	6MW	1.5MW	1	3.553GWh
Lamøysundet	9MW	2.25MW	1	3.553GWh
By Svenningen	11MW	2.75MW	2	7.108GWh
Nordfjorden	38MW	9.5MW	7	27.156GWh
Sjuløya	27MW	6.75MW	5	19.272GWh
Støtt strait	20MW	5MW	4	15.768GWh
Saltstraumen	205MW	51.25MW	42	165.564GWh
Graddstraumen	40MW	10MW	8	31.536GWh
By Hopen	36MW	9MW	7	27.156GWh
Area around Røst	1.580GW	395MW	329	1.297TWh
Kjellingsundet	16MW	4MW	3	11.388GWh
Around Værøy	355MW	88.75MW	73	288.204GWh
Buholmsflaget	284MW	71MW	59	233.016GWh
Moskenstraumen	4.798GW	1.200GW	1000	3.944TWh
Engsundet	36MW	9MW	7	27.156GWh
Nesstraumen	61MW	15.25MW	12	46.428GWh
Akterøya – Aslakøya	6MW	1.5MW	1	3.553GWh
Sundstraumen Fagernes	18MW	4.5MW	3	11.388GWh
Kaldv°agsstraumen	19MW	4.75MW	3	11.388GWh
Dyna – Følfoten	202MW	50.5MW	42	136.564GWh
Store Bremholmsundet	202MW	50.5MW	42	136.564GWh
Gimsøystraumen	60MW	15MW	12	46.428GWh
Sundklakkstraumen	13MW	3.25MW	2	7.108GWh
Øyhellsundet	8MW	2MW	1	3.553GWh
Kjerringvikstraumen	14MW	3.5MW	2	7.108GWh
Trangstraumen	19MW	4.75MW	3	11.388GWh
Vesterstraumen	10MW	2.5MW	2	7.108GWh
Kanstadfjorden	7MW	1.75MW	1	3.553GWh
Sandtorgstraumen	47MW	11.75MW	9	35.04GWh
Nordøygrunnen	19MW	4.75MW	3	11.388GWh

Salangverket	533MW	133.25MW	111	438GWh
N Nappstraumen	122MW	30.5MW	25	97.236GWh
Meistervik	5MW	1.25MW	1	3.553GWh
Rystraumen	384MW	96MW	80	315.36GWh
Storstraumen	32MW	8MW	6	23.652GWh
Sørsundet	5MW	1.25MW	1	3.553GWh
Kvalsundet Troms	308MW	77MW	64	253.164GWh
Store V°agsøysundet	316MW	79MW	65	256.668GWh
Litle v°agsøysundet	32MW	8MW	6	23.652GWh
Storstraumen	21MW	5.25MW	4	15.768GWh
Lyngøya	28MW	7MW	5	19.272GWh
Gjøssøysundet	10MW	2.5MW	2	7.108GWh
Vesterbotn	16MW	4MW	3	11.388GWh
Brynilen, Svartskjer	2.772GW	693MW	577	2.275TWh
Marholmen – Bergsfjorden	21MW	5.25MW	4	15.768GWh
Austertana	7MW	1.75MW	1	3.553GWh
Kartøysundet	1.493GW	373.25MW	311	1.227TWh
Kamøysundet – Lilla Kamøya	19MW	4.75MW	3	11.388GWh
Inlet to Straumsfjorden	25MW	6.25MW	5	19.272GWh
Around Latøyan	320MW	80MW	66	260.172GWh
Magerøysundet	348MW	87MW	72	283.824GWh
Grøtøysundet Troms	304MW	76MW	63	248.784GWh
Vesterbotn – Brennelvfjorden	11MW	2.75MW	2	7.108GWh
Trollsundet	506MW	126.5MW	105	414.348GWh
Totals	**16.099GW**	**4.025GW**	**3,329**	**13.054TWh**

8.2. Canada

Triton Consultants Ltd. undertook a Canadian national tidal current energy resource inventory in order to determine which sites within Canadian waters were most suitable to host TCTs (Tarbotton & Larson, 2006). In order to assign an accurate energy rating for each site, Triton Consultants Ltd. incorporated the fluctuations in tidal movements from flood to slack to ebb tides and back, as well as spring and neap tides within the lunar cycle, and calculated them into a measurement of mean potential power (MPP) in MW, with a total MPP of 42240MW. Out of the 191 sites suitable for TCT implementation, 34,890MW (82.6%) where located in Canada's arctic regions of Nunavut, the Northwest Territories, and the remote northern tip of Ungava Bay, Quebec. Although this resource potential is vast, an assessment of the implementation of TCTs in Canada's northernmost arctic regions will be excluded from this paper due to concerns regarding environmental impacts on artic climates, a lack of large-scale electricity demand due to the remote nature of residing communities, economic barriers concerning operations and maintenance in frozen climates, the sheer infrastructure requirements necessary to accommodate the distance of electricity transmission lines, and an absence of conveniently located electrical grids of significant capacity. Rather, the Canada tidal current resource assessment will focus on the eastern Maritime region and the west coast of British Columbia.

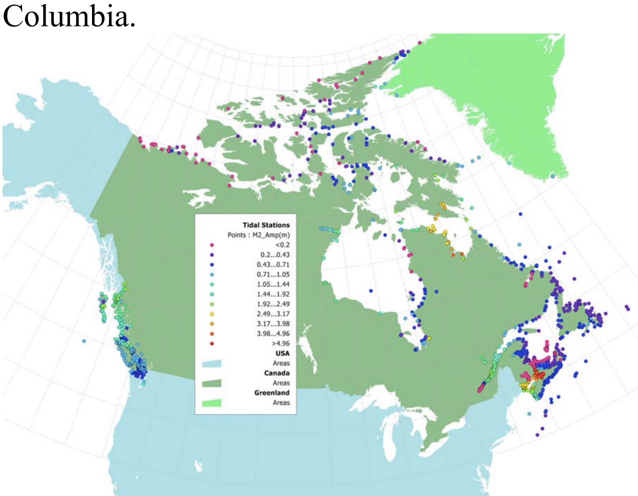

Figure 23: Tidal current resource map of Canada (Tarbotton & Larson, 2006)

8.2.1. Canada's Maritime Region

In assessing the top 50 largest tidal current energy sites in Canada, Triton Consultants Ltd. found that 11 of these sites where found in Canada's Maritime Region, totaling 3.013GW (7% of Canada's national resource). Eight of these sites are found within the Bay of Fundy, three in Nova Scotia and five in New Brunswick, totaling 2.544GW, while the remaining three sites are found within Newfoundland's coastal waters in the Gulf of St. Lawrence, totaling 469MW. In order to properly model the implementation of TCT arrays for the purposes given in section 8.1., and following the stated methodology, it is necessary that each identified tidal site be assessed individually.

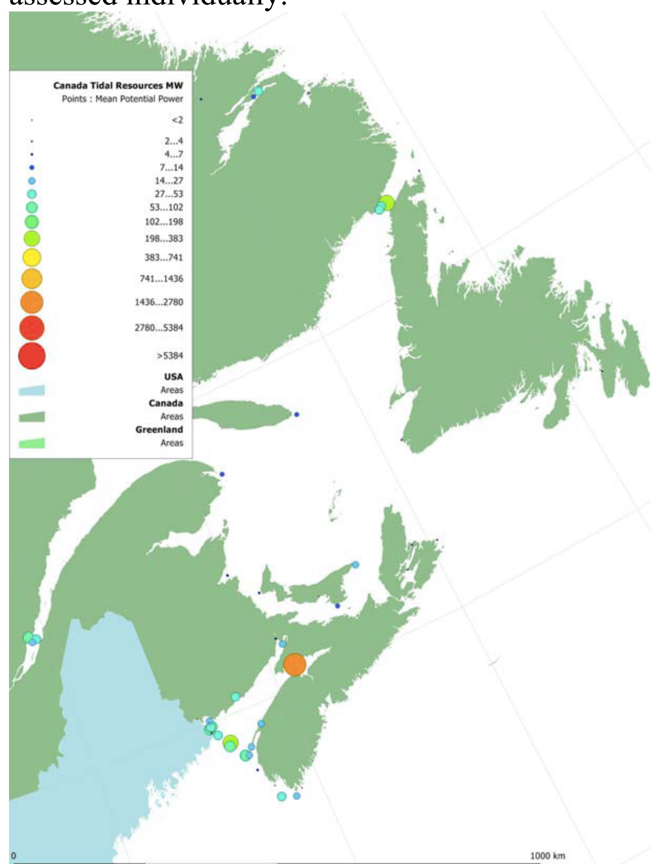

Figure 23: Canada's Maritime Region tidal current resource sites

8.2.1.1. Bay of Fundy

The Minas Basin site has the highest MPP of any site within Nova Scotia's Bay of Fundy coastal waters, with a rating of 1.903GW, and will be used as an example of how each site examined in this paper will be analyzed. Adopting O'Rourke, Boyle, and Reynolds' (2010a) accessible tidal current energy resource model of a 25% reduction in MPP, which works interchangeably with Bryden et al.'s (2007) upper limit of environmentally sustainable kinetic energy flux extraction theory, the Minas Basin site would be rated at 475.75MW, expressed as:

$$\text{MPP x } 0.25 \qquad \text{(EQ2)}$$

This would mean that 396 TCTs could be deployed at the site, as this paper employs SeaGen power ratings of 1.2MW per TCT (see section 8.1.), expressed as:

$$\text{EQ2/1.2} \qquad \text{(EQ3)}$$

In order to calculate the amount of output electricity produced annually from the number of acceptably deployable TCTs given by EQ3, EQ3 must be multiplied by the systems efficiency model demonstrated in EQ1 (405.6kW). The resulting total would then have to be multiplied by 8760, the total number of hours within a year (Tarbotton & Larson, 2006), to obtain the following figure:

$$\text{EQ3 x EQ1 x } 8760 \qquad \text{(EQ4)}$$

EQ4 suggests that Minas Passage can produce 1.407TWh/yr of output electricity. However, if Myers and Bahaj's (2012) array layout optimization model is employed to maximize the power available to downstream TCTs by 22%, taking into account the bidirectional flow of the tides, the final total annual electricity output of a TCT array can be expressed as follows:

$$\begin{gathered}\text{EQ3/2 x EQ1=X,}\\ \text{(X x 0.22) + X = Y,}\\ \text{(X + Y) x 8760}\end{gathered} \qquad \text{(EQ5)}$$

This suggests that 397 TCTs can produce 1.565TWh/yr if implemented at the Minas Basin site. EQ2, EQ3, and EQ5 can be used to assess the accessible/sustainably extractable tidal current resource, the upper limit of TCTs implemented, and the final annual electricity output of a TCT array respectively, for all other sites examined in this paper.

In summary, the calculations for the Minas Basin site are as follows:

- Gross MPP = 1.903GW
- Accessible and sustainably extractable resource = 475.75MW
- Number of TCTs deployable = 396
- Annual electricity output = 1.562TWh

The formulas presented in the Minas Basin example have been organized in the chart above for the rest of the sites examines throughout this paper.

Figure 24: Bay of Fundy (Bay of Fundy species information, 2016)

8.2.1.1.1. Nova Scotia

Out of the 2.026GW of MPP estimated around Nova Scotia's costal boundaries within the Bay of Fundy, 506.5MW are accessible following O'Rourke, Boyle, and Reynolds' (2010a) model for Ireland, accounting for potential environmental impacts and applicable legislation, perceived health and safety concerns, regulatory planning matters, and marine spatial conflicts, as well as Bryden et al.'s (2007) theory of extracting a maximum sustainable portion of a site's kinetic energy flux. Given these figures, 421 TCTs can be deployed, amounting to 505.2MW of installed capacity, costing $460,156,368 for purchase, installation, and grid connection (Charlier, 2003), creating 787 jobs (Esteban & Leary, 2012), 519 of which will span 30 years (Fraenkel, 2006), producing 1.623TWh/yr, and eliminating 811,500 tonnes of

CO2e (based on the IEA global average of kgCO2/kWh of electricity generation = 0.5; Brander, Sood, Wylie, Haughton, & Lovell, 2011).

8.2.1.1.2. New Brunswick

Out of the 518MW of MPP estimated around New Brunswick's costal boundaries within the Bay of Fundy, 129.5MW are accessible and sustainably extractable. Given these figures, 106 TCTs can be deployed, amounting to 127.2MW of installed capacity, costing $115,858,848, creating 202 jobs, 133 of which will span 30 years, producing 416.101GWh/yr, and eliminating 208,051 tonnes of CO2e.

8.2.1.2 Bay of Fundy totals

Out of the 2.544GW of MPP estimated within the Bay of Fundy, 636MW are accessible and sustainably extractable. Given these figures, 527 TCTs can be deployed, amounting to 632.4MW of installed capacity, costing $576,015,216, creating 989 jobs, 652 of which will span 30 years, producing 2.039TWh/yr, and eliminating 1,019,551 tonnes of CO2e.

8.2.1.1.3. Gulf of St. Lawrence

Out of the 469MW of MPP estimated within the Gulf of St. Lawrence, 117.25MW are accessible and sustainably extractable. Given these figures, 97 TCTs can be deployed, amounting to 116.4MW of installed capacity, costing $106,021,776, creating 184 jobs, 123 of which will span 30 years, producing 380.184GWh/yr, and eliminating 190,092 tonnes of CO2e.

8.2.2. Canada's Maritime Region totals

Out of the 3.013GW of MPP estimated within the Canada's Maritime Region, 753.25MW are accessible and sustainably extractable. Given these figures, 624 TCTs can be deployed, amounting to 748.8MW of installed capacity, costing $682,036,992, creating 1,173 jobs, 775 of which will span 30 years, producing 2.419TWh/yr, and eliminating 1,209,643 tonnes of CO2e.

Figure 25: Gulf of St. Lawrence (Department of Fisheries and Oceans, 2012)

8.2.3. Canada's west coast; British Columbia

In assessing the top 50 largest tidal current energy sites in Canada, Triton Consultants Ltd. found that 19 of these sites where found off the coast of British Columbia, totaling 3.717GW (9% of Canada's national resource). 16 of these sites are found within the Vancouver Island Mainland coastal region, totaling 3.446GW, and 3 within Pacific Mainland North coastal region, totaling 271MW.

8.2.3.1. Vancouver Island Mainland totals

Out of the 2.988GW of MPP estimated within the Vancouver Island Mainland coastal region, 747MW are accessible and sustainably extractable. Given these figures, 614 TCTs can be deployed, amounting to 736.8MW of installed capacity, costing $671,106,912, creating 1,130 jobs, 746 of which will span 30 years, producing 2.33TWh/yr, and eliminating 1,165,000 tonnes of CO2e.

8.2.3.2. Pacific Mainland North totals

Out of the 272MW of MPP estimated within British Columbia's Pacific Mainland North coastal region, 67.75MW are accessible and sustainably extractable. Given these figures, 55 TCTs can be deployed, amounting to 66MW of installed capacity, costing $60,115,440, creating 105 jobs, 69 of which will span 30 years, producing 215.496GWh/yr, and eliminating 107,748 tonnes of CO2e.

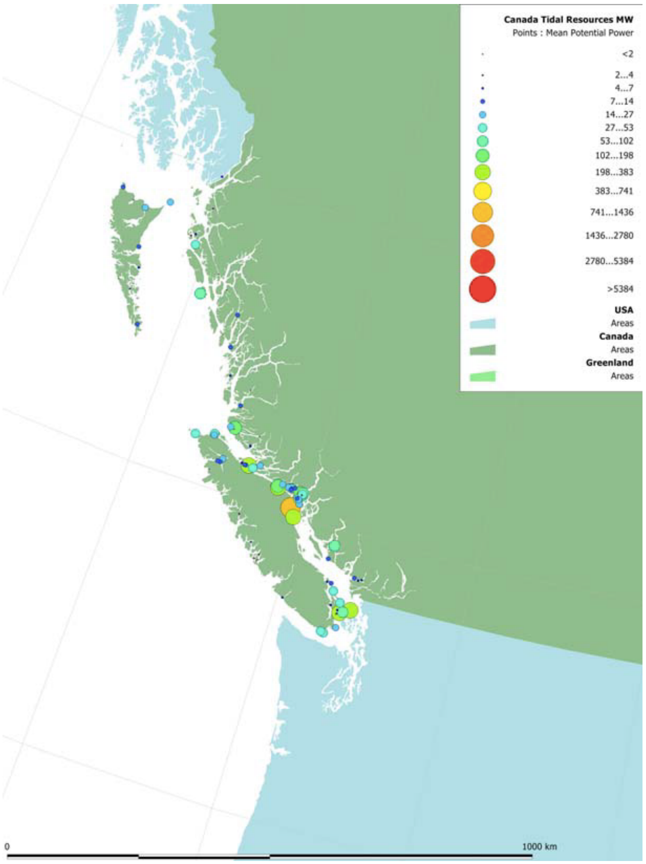

Figure 26: Canada's Pacific coast tidal current resource sites (Tarbotton & Larson, 2006)

8.2.4. British Columbia totals

Out of the 3.26GW of MPP estimated within British Columbia's coastal region, 814.75MW are accessible and sustainably extractable. Given these figures, 669 TCTs can be deployed, amounting to 802.8MW of installed capacity, costing $731,222,352, creating 2,235 jobs, 815 of which will span 30 years, producing 2.545TWh/yr, and eliminating 1,272,748 tonnes of CO2e.

8.2.5. Canada totals

Out of the 6.273GW of MPP estimated within the Canada's eastern and western coastal waters, 1.568GW are accessible and sustainably extractable. Given these figures, 1,293 TCTs can be deployed, amounting to 1.552GW of installed capacity, costing $1,413,259,344, creating 3,408 jobs, 1,590 of which will span 30 years, producing 4.964TWh/yr, and eliminating 2,482,000 tonnes of CO2e, approximately 3% of Canada's projected electricity sector GHG emissions for 2016 (Environment Canada, 2013).

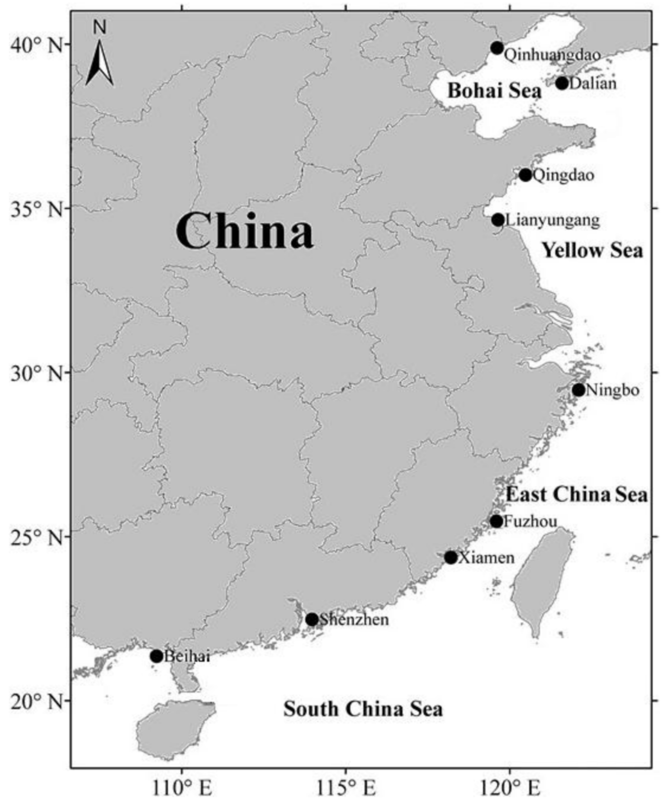

Figure 27: China's coastline (Yang, Zhao, Yan, & Wang, 2013)

8.3. China

Unlike Canada's tidal current energy atlas, which is divided into individual sites within coastal areas (Tarbotton & Larson, 2006), the tidal current resource estimates in China, provided by Chuankun and Wei (2009), can be categorized into 8 distinct regions, with MPP ratings of straits, estuaries, and channels aggregated into single geographical regions. Out of the 13.927GW of MPP estimated within the China's coastal waters, 3.479GW are accessible and sustainably extractable. Given these figures, 2,897 TCTs can be deployed, amounting to 3.476GW of installed capacity, costing $3,166,079,840, creating 5,777 jobs, 3,813 of which will span 30 years, producing 11.912TWh/yr, and eliminating 5,956,000 tonnes of CO2e.

8.4. Norway

Grabbe, Lalander, Lundin, and Leijon (2009) combined data from Blunden and Bahaj

(2007) and Rørvik–Lødingen & Andenes (2001) in order to organize 104 potential tidal current resource sites along the Weestern coast of Norway, presented from the most northerly site down to the southern tip. For the purposes of this paper's international implementation assessment of TCTs, Norwegian sites with a mean spring tidal current velocity of less than 2m/s have been omitted, as the current status of TCT technology is only considered economically viable when deployed in mean spring tidal velocities of 2m/s or greater (Fraenkel, 2010).

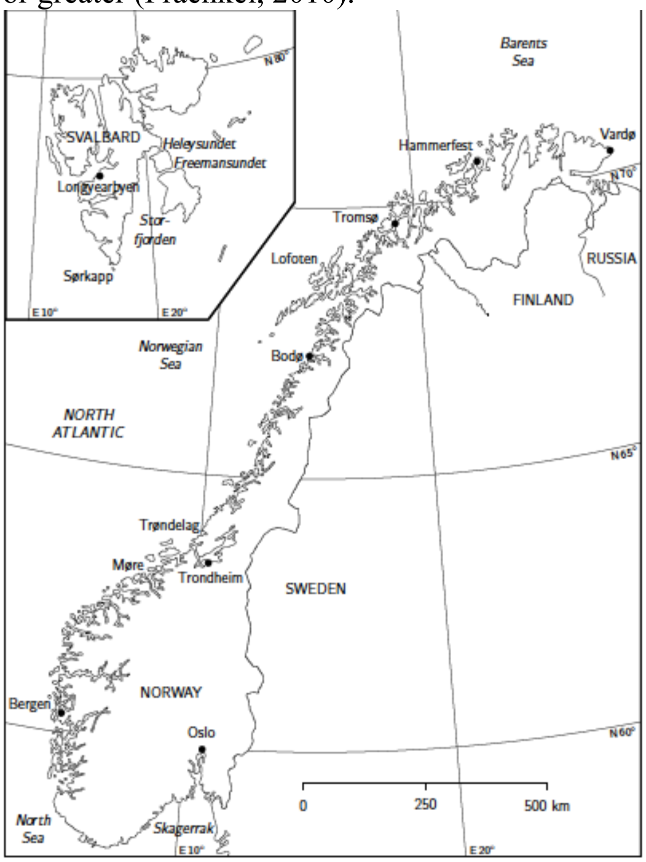

Figure 28: Norwegian coastline (Grabbe et al., 2009)

Furthermore, as the majority of Norwegian tidal sites are located in fjords, and are therefore isolated from adjoining bodies of water, sites that are rated less than 5MW of MPP are not feasible in order to accommodate TCTs, as barriers surrounding the acceptable and sustainably extractable resource of 25% hinder the accommodation of the 1.2MW SeaGen model measured for Canada and China. Therefore, sites that are rated less than 5MW thus have also been omitted from this paper's analysis. Therefore, 44 sites have been omitted, leaving 60 sites available for analysis. Finally, while sites rated between 5-14MW will be included in the assessment, they do not provide an opportunity to accommodate more than two TCTs, and therefore cannot take advantage of Myers and Bahaj's (2012) array layout optimization model. Thus, the annual electrical output will not include a 22% increase in power available to a downstream TCT.

Out of the 16.099GW of MPP estimated within the Norway's coastal waters, 4.025GW are accessible and sustainably extractable. Given these figures, 3,329 TCTs can be deployed, amounting to 3.995GW of installed capacity, costing $3,638,805,800, creating 6,331 jobs, 4,179 of which will span 30 years, producing 13.054TWh/yr, and eliminating 6,527,000 tonnes of CO2e.

8.5. Canada, China, and Norway totals

Out of the 36.299GW of MPP estimated within Canada, China, and Norway's combined coastal waters, 9.072GW are accessible and sustainably extractable. Given these figures, 7,519 TCTs can be deployed, amounting to 9.023GW of installed capacity, costing $8,218,144,984, creating 15,516 jobs, 9,582 of which will span 30 years, producing 29.93TWh/yr, sold at approximately 22 cents/kWh if deployed in 2016 (Esteban & Leary, 2012), and eliminating a total of 14,965,000 tonnes of CO2e. Under the current policy regime, the quantity of electricity generation provided from TCT implementation in Canada, China, and Norway alone, following the methodology provided in this paper, has the capacity to meet 0.1% of the projected global electricity demand for 2016 in a sustainable, predictable, resilient, and GHG emissions-free manner, while eliminating approximately 0.2% of estimated 2016 fossil fuel produced electricity GHG emissions (Cozzi, 2011). Although this percentage may seem insignificant, the tidal current resources assessed in this paper only represent 3.8% of the estimated extractable global tidal current resource (Esteban & Leary, 2012).

9. Future of TCTs

Due to similarities in the installation and scaling-up of technologies, Esteban and Leary (2012) suggest that the future adoption of ocean energy technologies such as TCTs have a great potential to follow development patterns of wind energy, a theory also shared by O'Rourke, Boyle, and Reynolds (2010b). Using Lemming, Morthorst, Clausen, and Hjuler Jensen's (2009) Wind Reference Model, Esteban and Leary (2012) proposed three future international implementation scenarios for ocean energy; a very optimistic scenario, where 309GWof installed capacity can be realized by 2050, providing 1,281TWh of electricity, 4.2% of global demand; an optimistic-realistic scenario, with 194GW of installed capacity providing 773TWh of electricity, 2.5% of global demand; and a pessimistic scenario, with 40GW of installed capacity providing 152TWh of electricity, 0.5% of global demand. Based on assumptions made in this paper that one-third of installed ocean energy capacity is provided by TCTs, an estimate cautiously advocated by (Pelc & Fujita, 2002) due to environmental, social, and economic advantages of TCTs over tidal barrages, WECs, and OTECs, it is plausible that the estimated extractable 788.4 TWh/yr of electricity that can be generated from TCTs (Esteban & Leary, 2012) will provide a great deal of future ocean energy implementation projections, considering nations such as Canada, China, and Norway, as well as Italy, Ireland, Brazil, USA, UK, Mexico, Australia, New Zealand, France, Greece, the Philippines, Taiwan, Papua New Guinea, and a plethora of other tidal current resource abundant countries (Charlier, 2003) harness the tidal current resource potential off of their coasts.

TCTs are advantageous in comparison to other renewable energy technologies due to their predictability, reliability, high capacity factors, favorable overall systems efficiency, ability to easily accommodate energy storage or provide base load power via matching tidal phase shifting, their non-existent terrestrial spatial footprint, relatively negligible visual and audio pollution, and projected benign environmental implications. However, like any renewable energy, high capital costs and electricity prices currently hinder the realization of large-scale adoption (Timmons, Harris, & Roach, 2014). This economic disadvantage in relation to fossil fuel energy is particularly concerning for TCTs due to their infancy status relative to other renewable energy technologies (Fraenkel, 2002). Therefore, long-term government financial incentives are essential in order to facilitate the commercial implementation of TCTs and speed up the renewable energy transition (Bryden & Couch, 2006), such as the Portuguese government's feed-in tariff for ocean renewables, which has seen considerable decreases in ocean energy prices per kWh of electricity generation (Esteban & Leary, 2012). Such fiscal incentives have increased the economic viability of ocean energy technologies such as TCTs in recent years, which, if continued, will help facilitate the implementation of economies of scale, therefore making TCTs cost competitive with fossil fuel technologies, as has been the case with wind energy (Herzog, 1999).

While many experts on TCTs have suggested that current unfavorable economic conditions of TCTs are the most significant hindrance to their commercial deployment, as this paper has thoroughly explored, another equally important factor that must be acknowledged is the lack of site specific baseline data on environmental interactions from which planners can draw when developing zoning, permitting, and consenting procedures (Fidler & Noble, 2012). However, once the TCT industry develops, and baseline data collection and presentation gathered from sources such as MCT, EMEC, and FORCE becomes standardized, regional SEAs can assist in the construction and implementation of integrated MSPs across nations sharing marine borders, thereby facilitating the streamlining of TCT deployment in allotted MSP zones.

The excessive combustion of fossil fuels for energy provision introduced during the Industrial Revolution of the late 18th century and proceeding to modern societies within the 21st century have significantly warmed the Earth's temperature at a rapid enough pace to alter natural planetary functions (NOAA, 2004). This has led many countries within the international scene to advocate for a reduction in GHG emissions, focusing on the large-scale adoption of renewable energy technologies as one of the primary drivers to obtain this objective (Union, 2009). While renewables such as solar, wind, and biomass have been thoroughly researched, developed, and deployed, the extraction of energy from tidal currents for purposes of electricity generation has received considerably less attention. However, due to the increasing international R&D expenditures allotted to TCTs (Johnstone, Haščič, & Popp, 2010), and the Scottish government's declaration to achieve commercial scale deployment this year in 2016 (Johnson, Kerr, & Side, 2012), a turning of the tides regarding the international implementation status of TCTs may be on the near horizon, solidifying their place in the society's impending renewable energy transition.

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