Planning for tidal current turbine technology: A case study of the Gulf of St. Lawrence

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A B S T R A C T

The combustion of fossil fuels for purposes of energy production has accelerated the rate at which the planet is warming, thereby causing adverse effects on natural ecosystems across the globe. The consequences of climate change arising from the use of conventional fuels such as coal, oil, and gas demands a shift towards the use of sustainable, emissions-free renewable energy technologies. When planning for the implementation of new energy systems, several factors must be examined in order to determine the viability of a system to meet energy demands in a sustainable and efficient manner. This paper provides an overview of tidal current turbines (TCTs), examining how they function to produce electricity, the possible environmental impacts surrounding large-scale implementation, associated economic factors, and public acceptability. A case study of the Gulf of St. Lawrence is presented as an implementation site, demonstrating the potential for TCTs to assist in phasing out the use of fossil fuels for electricity generation on the Newfoundland island interconnected electricity system. A multi-criteria decision making matrix is presented to discern the benefits of TCTs compared to fossil fuels for the purpose of electricity generation. The paper concludes by examining the potential future of TCTs in the world.

1. Introduction

Current global energy demand is supplied primarily by environmentally detrimental fuel sources such as petroleum, natural gas, and coal, and non-renewable nuclear energy, collectively accounting for 87% of world's energy production, while renewable energy sources such as solar, wind, geothermal, and biomass only account for 13% (World Energy Council, 2013). However, as global atmospheric temperatures rise due to the greenhouse effect perpetuated by the excessive burning of fossil fuels, an increase in focus of policy makers has been placed on the development and implementation of clean renewable energy technologies to meet the energy demands of communities across the globe in a sustainable, emissions free manner (O'Rourke, Boyle, & Reynolds, 2010b).

The progressive implementation of plans, policies, and programs throughout the past two decades that support the deployment of renewable energy systems can be seen through a vast spectrum of scale including international treaties such as the Kyoto Protocol (1997), national adoption targets such as the UK's National Renewable Energy Action Plan, provincial incentives such as the Ontario Feed in Tariff (FIT) Program, and regional and municipal declarations to become 100% renewable as is the case for Oxford County, Ontario, and Vancouver, British Columbia respectively.

According to Kleinpeter (1995), there are six primary renewable energy sources which technologies can draw upon: solar, wind, biomass, geothermal, hydropower, and ocean energy. While technologies such as solar photovoltaic (PV) and onshore wind turbines have been thoroughly researched, tested, implemented, and analyzed due to the maturity of their technological development, the assessment of technologies deriving energy from the ocean such as tidal current turbines (TCTs) has been relatively neglected. In theory, harnessing less than 0.1% of the possible power of the oceans waves, thermal capacity, and tidal ranges and currents has the capability to meet 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). However, due to the infancy status of ocean power technologies, large-scale implementation has yet to be realized.

When planning for an energy system, planners must take into account several dynamic factors surrounding the implementation a particular technology. This paper will provide an overview of tidal current turbine technology; how it operates to produce electricity, an examination of the site specific conditions required to optimize energy output; and a review of its current implementation status. The paper will then provide an assessment of perceived environmental impacts, economic factors surrounding its implementation, and public acceptability of the technology. A case study of the Gulf of St. Lawrence will be presented as a possible site for implementation of TCT technology to provide electricity for the island of Newfoundland. An assessment of how communities in Newfoundland currently meet their energy needs will be reviewed. Drawing upon a literature review, a multi-criteria decision making matrix will then be formulated, presented, and analyzed in order to discern the benefits of implementing TCTs in the Gulf of St. Lawrence over the use of fossil fuels to provide electricity to the island of Newfoundland. Finally, the results of the matrix will be assessed and a discussion of the future potential of TCT technology will be theorized.

2. Overview of TCT technology

2.1. Production of electricity

TCTs are an attractive source of renewable energy due to the predictable conditions under which they function to produce electricity. TCT structures, very similar to the functional design parameters of wind turbines (O'Rourke, Boyle, & Reynolds, 2009), consist of a configuration of typically three blades, either mounted on a horizontal or vertical axis to a hub (together called a rotor), and connected to a gearbox, which is connected to a generator. The technology is placed on the ocean floor through various different engineering options (which will be discussed later), and extracts kinetic energy dissipated by tidal movements to turn the blades, rotate the rotor, and turn the generator via a gearbox, converting the speed of the rotor shaft to the anticipated output speed of the generator shaft.

Tidal current movements result from the gravitational and centrifugal forces perpetuated by the relationship of physics between the earth, sun, and moon (Clark, 2007). This gravitational and centrifugal process produces tidal flows both towards the coast, known as the flood current, and receding from the coast, known as the ebb current. This process occurs exactly every 24 hours, 50 minutes, and 28 seconds. Since TCT rotors have been engineered to revolve in both flow and ebb tide directions, the technology can operate to produce electricity under exact predictable conditions, making them advantageous with regards to the consistency of projected energy generation in comparison to other renewable energy technologies such as wind and solar, whose predictability is hindered by inconsistent weather patterns (Pelc & Fujita, 2002). The electrical energy produced by the turbines can then be transmitted via underwater cables to the shore where it then can be connected to the applicable electrical grid (Li & Florig 2006).

2.2. Optimal conditions for application

2.2.1. Environmental conditions

An in depth literature review of site conditions for the optimal application of TCTs reveal that locations able to support the implementation of the technology are fairly site-specific. Fraenkel (2006), amongst many others, suggest that, in order to be economically and structurally feasible, TCTs must be located in areas where mean spring peak tidal currents are faster than 4-5 knots, or 2-2.5 m/s (meters per seconds). These optimal locations for harnessing tidal power can be found at sites where narrow straights are exhibited between substantial landmasses or are adjacent to headlands such as capes and peninsulas (O'Rourke et al., 2010b).

While site specific, Hammons (1993) estimates that harnessing the total global potential of tidal energy from costal areas can produce 500-1000 TWh/yr (terawatt hours per year) of electricity. In Canada alone, Triton Consultants Ltd., in cooperation with the Canadian Hydraulic Centre and Natural Resources Canada, undertook a preliminary tidal resource inventory based on Canadian Sailing Directions, Nautical Charts and Tide Books, Tide and tidal current constituent data, and Numerical Tidal modeling data, and identified 191 potential sites for the extraction of tidal current energy, averaging 221MW (megawatts) of electricity generation per site, and collectively producing and estimated 42,240MW (Tarbotton & Larson, 2006). However, it is noteworthy to consider that these figures of the full potential for the utilization of tidal current energy does not reflect dynamics concerning environmental impacts, technological development, climatic and ecological factors (climate change and vast ice sheets), power grid accessibility, hydrogen economy developments, the effect of energy extraction on existing flow conditions, and economic factors.

2.2.2. Technological layout optimization

The optimal layout of a TCT farm must take into account geometric measures that may potentially manipulate the wakes (an area of flow immediately behind an object, caused by the flow of surrounding fluid on either side of the object) produced by TCTs to increase energy production, as well as avoid structural damage to technologies via placement of a TCT too close to the downstream wakes resulting from TCTs upstream (Myers, Bahaj, Retzler, Ricci, & Dhedin, 2010).

In an engineering research and development (R&D) study conducted to determine the optimum layout configuration of an array of TCTS, Myers and Bahaj (2012) constructed, tested, and analyzed a downscaled model of tidal current turbines (using specially designed discs to represent turbines) at the University of Southampton, England. Their research sought to maximize the energy production efficiency of TCTs while simultaneously upholding the structural integrity of the technology. The results demonstrate an optimal layout configuration of 1.5D (D = disc diameters) of lateral separation between two turbines in a front row, which enhances their combined wakes to provide and additional power of 22% to a third turbine placed directly between the wakes 3D downstream, as seen in Figure 1.

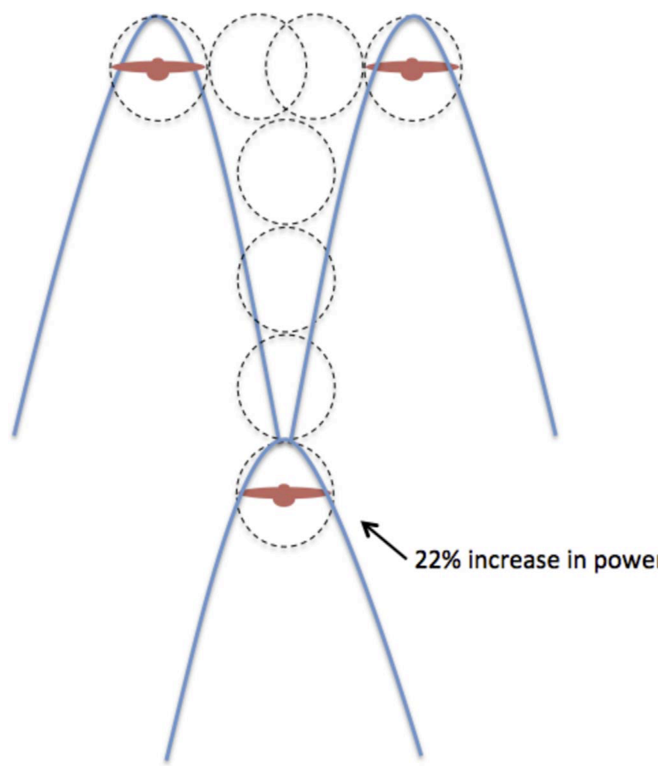

Figure 1: Concept drawing based on Meyers & Bahaj's layout optimization study

However, the article does not explore the effects of a wake of one TCT on the two laterally spaced TCTs in order to account for daily changes in tidal flows from flood tides to ebb tides. This means that, if placed in a grouping of four, in order to achieve this additional 22% increase in power output of a single TCT located downstream of the wakes of two TCTs throughout the entire tidal movement cycle, another single TCT must be placed in the same 3D distance in the opposite direction of the two

TCTs. Although, without further testing it is impossible to know for certain how this configuration of TCTs will alter the potential optimal output presented in the report, given that the single TCT located at the front of the configuration may increase the turbulence of tidal flow, thereby possibly adding an additional 11% increase in output to the two TCTs behind it respectively, and may also increase or decrease the original 22% on the single back TCT through the potential increase or reduction of wake velocity. Furthermore, flood and ebb tides produce different velocities from one another depending on the site of implementation (Tarbotton & Larson, 2006).

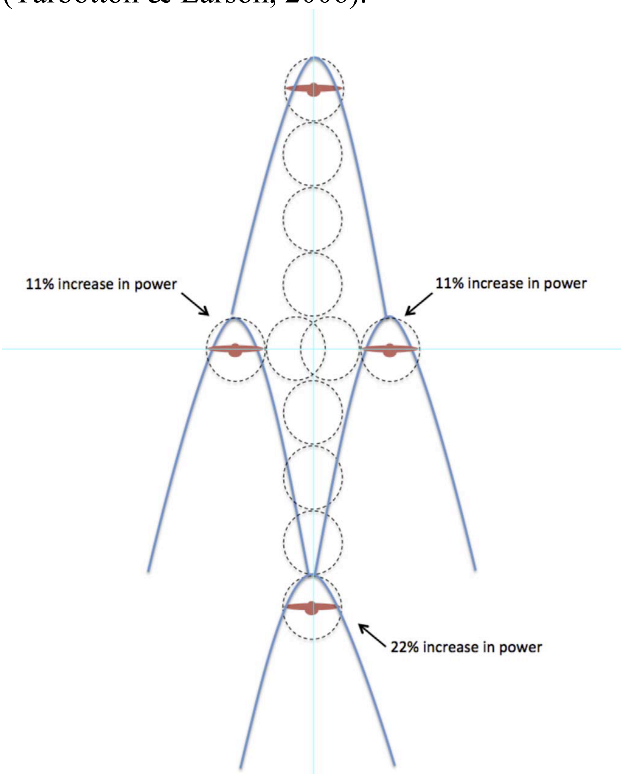

Figure 2: Concept drawing of a theoretical ideal layout optimization scenario expanding upon the Meyers & Bahaj's model

In theory, an ideal layout configuration scenario could provide 11% increased energy output to the two lateral TCTs, and an 22% increase to the single back TCT, thereby increasing energy output to 33% per configuration of four TCTs, as seen in figure 2. Regardless, the physics of tidal flow can be manipulated to enhance energy output of TCTs through a strategic layout configuration, but more research is needed through both downscaled model testing as well as full-scale site implementation.

When choosing an installation site for TCTs, it is imperative that the implementation does not occur in areas that conflict with other commercial and industrial uses of the sea, such as fishing and transportation. However, Fraenkel (2006) suggests that this is not a considerable variable since the optimal environmental conditions in which TCT technologies are to be applied in order to maximize their energy output occur in waters where usually high velocities are present, and therefore tend to be avoided as navigation routes for ships due to safety precautions.

Regarding the optimization of TCTs from a design and engineering perspective, current technological development in practice would suggest that a horizontal axis turbine system, as opposed to a vertical, helical, or open axis turbine, is the most practical and efficient technological 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 are designed around a horizontal axis turbine system.

2.3. Current status of technology

TCTs are one of the most recent renewable energy technologies to be designed and developed (Fraenkel, 2006), and therefore, currently remain in the planning and consenting stage (Myers, Keogh, & Bahaj, 2011). Due to the infancy status of TCT technology, there are currently no large-scale implementation sites feeding into a regional electrical grid. Rather, current efforts are focused on enhancing the engineering parameters of the technology in order to make it economically feasible and structurally sound for considerable long-term implementation (Dal Ferro, 2006). Much of the data available on recent advances in technological development and analysis of optimal application conditions is a product of testing downscaled models, as discussed above (see section 2.2.2.). However, the European Marine Energy Centre (EMEC), situated in Orkney, Scotland, became operational in 2005 and is the first full-scale prototype test centre for TCT technologies (O'Rourke et al., 2010b). EMEC allows developers of TCT technologies to use the test facility to implement technological designs under real life oceanic conditions. Following the inauguration of EMEC, numerous other test facilities have been launched across Europe, including sites in France and Wales (Myers et al., 2011).

Perhaps the most in depth analysis of the operation of a TCT is the SeaFlow Project (Fraenkel, 2006). Considered to be the world's first full-sized tidal current turbine, SeaFlow, a 300 kW system developed by Marine Current Turbines Ltd. (MCT), was installed in 2003 off the coast of the village of Lynmouth, Devon, England. The turbine was implemented 1.1km off the coast in a depth of 25 m, has a single 11m diameter rotor, and is currently not grid connected. The project cost in total £3.5 million and has yielded a vast amount of comprehensive data concerning commercial implementation procedures ranging from construction to operation to maintenance.

Figure 3: The SeaFlow tidal stream generator prototype with rotor raised" by Fundy/CC BY-SA 3.0

While projects such as Seaflow help contextualize the design, engineering, electricity generation, and lifecycle elements of TCTs, there remains a lack of concrete data on environmental, economic, and social factors surrounding the large-scale implementation of TCT technology relative to other forms of renewable energy, such as solar PV, as well as conventional fuel sources. Further research must be carried out to assess the sustainability of such technology. However, the development and implementation of TCTs is moving in a promising direction, as several countries have already undertaken, or are currently in the processing of developing, national assessments of the potential of harnessing tidal current energy within their coastal regions, and the implications surrounding their implementation (O'Rourke et al., 2010b). Such nations include Canada, France, Portugal, the UK, and the USA.

3. Environmental impacts

A literature review suggests that TCTs are considered to be one of the most environmentally friendly renewable energy technologies (Pelc & Fujita, 2002). Due to the immaturity of technological implementation, concrete data on the interactions of TCTs with the biophysical environment have yet to be determined in large-scale practical application scenarios. However, possible interactions have been theorized and data from small-scale installations has been analyzed. In the subsections below, concerns regarding the interactions of TCTs with benthic habitats, marine wildlife, and the possibility of pollution will be examined and challenged.

3.1. Effects on benthic habitats

There has been speculation that TCTs can alter benthic habitats through the displacement of sediment and the changing of water flows and wave structures (Neill, Litt, Couch, & Davies, 2009). The placement of large structures on the seabed floor will produce a turbulent wake effect that has the potential to disrupt natural patterns of water flow and possibly displace sediment, which in tern may reduce the growth of seagrass beds (Craig, Wyllie-Echeverria, Carrington, & Shafer, 2008). Conversely, the deposition of organic matter resulting from the wake effect could possibly increase benthic invertebrate populations, although, it has been theorized that fish may be attracted to large underwater structures and thus predation by fish may reduce the population of benthic communities (Langlois, Anderson, & Babcock, 2005).

However, the effect of sediment disposition resulting from the turbulent wakes produced by TCTs is thought to be minimal when taking into consideration that optimal environmental conditions for the installation of TCTs occurs in areas where exceptional tidal current flow already causes natural disturbance to benthic topography, particularly sediment displacement (Frid, Andonegi, Depestele, Judd, Rihan, Rogers, & Kenchington, 2012). Furthermore, an analysis of small-scale TCT prototype projects reveals that any environmental impacts are quickly and completely reversible upon decommissioning (Fraenkel, 2006). Nevertheless, it is important that cumulative effects on sediment disposition caused by the implementation of large-scale TCT farms be considered. In this case, the optimal layout configuration of three turbines proposed by Meyers and Bahaj (2012), and further expanded upon in this paper to account for the placement of a fourth turbine to take advantage of the directional change in tidal movements (see section 2.2.2.), can be used to maximize energy output, while such strategic groupings in a large-scale farm should be confined to four, with identical configurations separated far enough to minimize cumulative environmental impacts.

Even if sediment displacement was to occur and thus alter and deplete benthic communities via predation by fish attracted to the TCTs, as theorized by Langlois et al (2005), a study undertaken by Anon (2008) for the Roosevelt Island tidal energy project on the East River in New York demonstrated that only a miniscule number of fish were seen around the TCTs, ranging from 16-1400 per day. Furthermore, regarding the presence of TCTs possibility modifying wave heights by decreasing tidal amplitude, such impacts have been measured and concluded to be insignificant (Frid et al., 2012)

3.2. Effects on wildlife

3.2.1. Interactions with turbines

Due to the highly turbulent ecosystem conditions where tidal velocity reaches speeds able to accommodate TCTs, there are not many marine species found in these host areas (O'Rourke et al., 2010b). Nonetheless, it is important to examine whether the rotation of turbine blades will have an impact on mortality of marine wildlife, notably fish, marine mammals, and costal avian populations. Turbine velocities are expected to revolve at a speed of 25-50 rpm (rotations per minute) (Pelc & Fujita, 2002). At this speed, fish mortality is expected to be relatively insignificant as fish generally move at a speed much quicker than this and therefore have plenty of time to avoid contact. Furthermore, as alluded to above (see section 3.1.), theories of turbines attracting large fish populations (Langlois et al., 2005) were examined to be minor in practice (Anon, 2008), and therefore greatly downscale the possibility of mortality induced collisions with turbines.

Figure 4: Common Murre colony" by USFWS - Pacific Region/CC BY 2.0

Regarding the possibility of large marine mammals colliding with turbines, a literature review conducted by the US Department of Energy (2009) suggests that this scenario is extremely unlikely as marine mammals are generally agile enough to easily avoid turbine structures. This point is further emphasized by Fraenkel (2006) by comparing the slow rotation speed and ocean depths at which TCTs operate in comparison to the high rotation speed and close proximity to the ocean surface in which ship propellers operate.

The same theme of minimal impact is projected with diving sea birds (Anon, 2008). While some diving seabirds are to be taken into special consideration due to their ability to dive between 45-65m deep, such as auks, guillemots, and shags (Thaxter, Wanless, Daunt, Harris, Benvenuti, Watanuki, Gremillet, & Hamer, 2010), the agility of such animals in comparison to the slow rotation speeds of turbine blades suggests that mortality rates would be very low (Frid et al., 2012).

Although negative implications resulting from collision of marine wildlife with TCTs is projected to be extremely low, it is still imperative to plan TCT farms in a manner that mitigates the potential for such impacts. Large-scale TCT farms should ideally be sited for implementation in areas that provide optimal energy output, but avoid major marine species migration channels so that reproduction and recruitment processes are left unaffected (Pelc & Fujita, 2002; Fraenkel, 2006).

3.2.2. Noise implications

The installation of TCTs is very similar to the constructional dynamics involved in the implementation of offshore wind turbines with regards to anchoring the foundation of such structures to the ocean floor (Tougaard, Carstensen, Damsgaard Henriksen, & Teilmann, 2003). A study of the installation of offshore wind farms in Denmark demonstrated that, during the process of pile driving when anchoring the base of the wind turbines to the sea floor, marine wildlife exhibited minimal foraging behavior and a reduction of echolocation activity. Such effects were detected as far as 15 km from the construction site, although, they disseminated upon completion of installation (Carstensen, Henriksen, & Teilmann, 2006).

The installation of TCTs have the capacity to avoid such negative noise threshold implications. O'Rourke et al. (2010b) analyzed 14 different tidal current turbine prototypes and presented three different available support structures that can be used to install such technologies, one of which is referred to as a gravity structure, which utilizes large masses of concrete and steel at the base of the turbine to secure it in place. This installation design negates the necessity of pile driving and therefore avoids the negative noise implications associated with the installation of offshore wind turbines discussed above.

The operational noise produced from TCTs does not exceed threshold levels to the extent of which would adversely affect benthic communities (O'Rourke et al., 2010b). However, it is necessary to take into consideration the cumulative effects of operational noise that may result from a large-scale TCT farm. While more research is needed, the cumulative impacts of large-scale operational noise may be avoided via the optimal layout configuration introduced in section 2.2.2., and expanded upon in section 3.1., where groupings of four TCTs strategically configured to maximize energy output be separated far enough from identical groupings in order to minimize cumulative environmental impacts.

3.2.3. Electromagnetic implications

Electricity produced from TCTs will need to be transported and connected to the grid via underwater cables that emit electromagnetic fields (EMFs). This system of electricity transportation is identical to that of offshore wind turbines, which have been thoroughly studied, and reveal that EMF interactions with marine wildlife demonstrate no negative long-term impacts (Bochert, & Zettler, 2004; Hui, 1994).

3.3. Possibility of pollution

TCTs are a clean renewable energy technology proposed to replace fossil fuels and mitigate climate change, as they produce electricity without emitting greenhouse gases into the atmosphere. However, there have been concerns regarding the possibility of the technology to release pollutants such as lubricating oil and antifouling paints into the ocean (Fraenkel, 2006). This impact is regarded to be minor as the amount of lubricating oil required is miniscule and well contained, and antifouling paints used for the technology are proposed to be of the most environmentally friendly kind, present in much lesser amounts in comparison to ships, and may not even be required at all.

4. Economic factors

Due to the infancy status of TCT technology, there is currently an uncertainty of the concrete construction, installation, operation, maintenance, and decommissioning costs. A survey undertaken by Eaton and Harmony (2003) suggests that the uncertainty of economic factors is the grandest hindrance to the realization of large-scale implementation of TCT farms. O'Rourke et al. (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 process of implementation.

Capital costs for TCTs are relatively unknown and dependant on the individual developer company and the quantity purchased. However, an understanding of the economics of TCTs can be achieved by theorizing configuration parameters, and the operation and maintenance of such technologies. The strategic configuration of turbines discussed earlier (see section 2.2.2.) demonstrated through groupings of four turbines boosts the economic productivity of technologies to enhance energy output. However, the wide lateral spacing of these individual group of four TCTs in a large-scale farm required to reduce cumulative environmental impacts (see section 3.1.) has a negative impact on economic efficiency as electricity transmission lines will be separated at a greater distance, thereby exposing more cable and subsequently increasing maintenance costs (Li & Florig, 2006). This factor is compounded by the fact that geographic locations that possess the optimal environmental conditions to host TCTs are often located in energy dense costal areas where grid access is limited, thereby possibly requiring alterations to the grid network and further proliferating installation, operation, and maintenance costs (O'Rourke et al., 2010b). Essentially, planners and decision makers must assess the costs and benefits of optimal TCT farm configurations and determine whether economic efficiency should trump environmental sustainability or visa versa.

Developers of TCTs in Canada and the UK have proposed operational life-spans between 20-30 years, while research on TCTs at pre-commercial testing facilities have demonstrated that TCTs can operate without failure for five year periods (Li & Florig, 2006). This projected hardiness of lifecycle operation will reduce overall costs as routine maintenance (such as vibration and seal checks) is estimated to occur only once per year. However, economic factors surrounding maintenance must account for the premiums of transporting crews to the offshore site, the extraction of the TCT from the ocean floor to the vessel, and the number of TCTs being serviced. Furthermore, due to the turbulent tidal conditions required to power TCTs, maintenance can only be completed during slack tides (the transition of direction of tidal flow where no energy can be harnessed) in order to reduce technological damage and hazardous working conditions (O'Rourke et al., 2010b). Slack tides only occur for a few minutes, making maintenance procedures very time specific, requiring skilled laborers to execute maintenance procedures with considerable precision. Due to maintenance procedures requiring the extraction of the TCT from the ocean floor to a large vessel above, it is important to note that no power is being produced during this time (Li & Florig, 2006).

When examining the energy return on energy invested (ERoEI), TCTs are superior to the majority of energy technologies (Fraenkel, 2006). With an operational lifespan of 20-30 years, compounded by a projected energy return of six months, TCTs can provide an energy payback approximately 40 times greater than the energy invested to install and operate it over its lifespan. This analysis suggests that the ERoEI of this technology should be highlighted and presented as a key economic factor to policy makers for the years to come.

When taking into consideration all of the economic factors presented above, a literature review reveals that current economics suggest that the implementation of large-scale TCT farms, while feasible, is not yet ideal for the international market (O'Rourke et al., 2010b). However, as further R&D is undertaken, economies of scale can be realized and TCTs can be a competitive technology. 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).

5. Public acceptability

Public acceptance of an energy technology, particularly new technologies such as renewables, plays a crucial role in the eventual adoption of potential energy systems (Sala & Castellani, 2011). This reoccurring theme can be witnessed with respect to multiple different renewable energy systems in a variety of installation sites among different communities around the world; whether it be as severe as the rejection of a biomass plant in Cricklade, North Wiltshire, England due to public perceptions of increased smog produced from the plant leading to unfavorable road conditions (Upreti & van der Horst, 2004), or as simple as residents of Salina, Italy preferring the adoption of a small wind turbine energy system over a combined wind and PV system primary due to personal perceptions of aesthetic appeal (Cavallaro, & Ciraolo, 2005).

Since TCTs have yet to realize full-scale implementation status, comprehensive data concerning the public perception of the application of such technology is virtually unavailable. However, it is feasible to examine the potential public acceptability of TCTs by comparing noted public concerns for other energy technologies and assessing whether they are applicable to the implementation of TCT farms.

In Evans, Strezov, and Evans' (2009) article entitled *Assessment of Sustainability Indicators for Renewable Energy Technologies*, the authors undertook an extensive literature review to formulate a simple magnitude matrix to assess and compare the qualitative social impacts perceived by local communities with regards to the application of solar, wind, hydropower, and geothermal energy, and attributed a magnitude measurement of major or minor to each impact. Beyond criteria pertaining to perceived environmental implications (which were previously discussed and challenged above, see section 3) the assessment criteria they used included visual obstruction, unwanted odor, and noise pollution. TCTs are located beneath the surface of massive water bodies, and therefore do not cause significant reason for concern regarding visual, odor, or noise pollution, and thus can be categorized as minor.

6. The Gulf of St. Lawrence

Figure 5: Golfe Saint-Laurent en" by Benoit Rochon/CC BY-SA 3.0

The Gulf of St. Lawrence is a semi-enclosed basin of the Northwest Atlantic Ocean located within Canadian waters, bounded by Labrador and Quebec to the north, Newfoundland to the east, Nova Scotia to the south, and New Brunswick and Quebec to the west, and has a surface area of over 240,000km2 (Department of Fisheries and Oceans, 2012). A preliminary tidal resource inventory of Canadian coastal waters undertaken by Triton Consultants Ltd. (see section 2.2.1.) identified 191 potential sites that posses the ideal conditions required to host tidal current energy technologies (Tarbotton & Larson, 2006). This inventory identified three sites within in the Gulf of St. Lawrence that ranked in the top 50 largest potential tidal current power sites in Canada based on their capacity of mean potential power (MPP) generation measured in MW. Each of these sites are located off the coast of Newfoundland, and are as follows:

- Strait of Belle Island, ranked 12, having a MPP production of 373 MW
- Pointe Armour, ranked 44, having a MPP production of 48 MW
- Forteau, ranked 44, having a MPP production of 48 MW

The production and distribution of electricity on the island of Newfoundland is provided by two utilities, Newfoundland Power (NP) and Newfoundland and Labrador Hydro (Hydro) (Newfoundland and Labrador Department of Natural Resources, 2015). In 2008, Hydro supplied approximately 80% of its electricity from clean hydropower produced from its nine hydroelectric plants, with the remainder coming from one oil-fired plant, four gas turbines, and 25 diesel plants. Hydro provides NP with 92% of its electricity requirements, while NP's 23 small hydroelectric generating plants supply the remaining 8% of electricity produced and distributed throughout the interconnected island system. As of June 2009, NP and Hydro serviced approximately 240,000 customers on the Newfoundland Island interconnected system at a net generating capacity of 1,966MW.

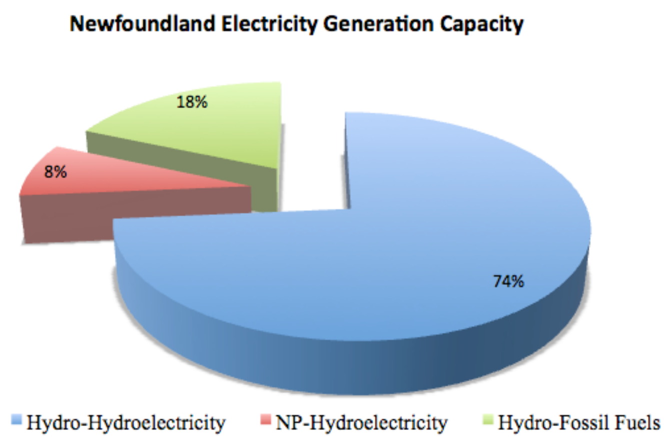

Figure 6: A breakdown of electricity sources in the Newfoundland interconnected electricity system

A statistical analysis of the data presented above demonstrates that 81.6% (73.6% from Hydro and 8% from NP), or 1,604.256MW (1446.976MW from Hydro and 157.28MW from NP) of electricity generation on the interconnected island system of Newfoundland is derived from hydroelectricity, while 18.4%, or 361.744MW of electricity generation is derived from fossil fuels. Given that the combined MPP of the Strait of Belle Island, Pointe Armour, and Forteau is 469MW, it is theoretically feasible that TCTs could phase out the use of fossil fuels for electricity generation on the island of Newfoundland as the net generation capacity of the three tidal current power sites is greater than the current net generation capacity of oil, gas, and diesel (361.744 MW).

Figure 7: SeaGen tidal power plant, Strangford, County Down, Northern Ireland, 2011 (blades raised for maintenance)" by Ardfern/ CC BY-SA 3.0

However, as O'Rourke, Boyle, and Reynolds (2010a) have noted in their resource assessment of Ireland, there are several factors that hinder the ability of TCTs to harness the theoretical MPP. One such factor that can be applied to the assessment of the Gulf of St. Lawrence is the amount of energy that can be extracted from the movement of the tides without conflicting with other marine spatial uses such as shipping, fishing, recreation, tourism, and protected areas. O'Rourke, Boyle, and Reynolds calculated this to be 25% of the available tidal resource, which, in the case of the Gulf of St. Lawrence, the revised MPP would become 117.25MW. Another factor to consider is the amount of output energy a TCT can produce after mechanical losses resulting from the conversion of kinetic tidal energy to electricity. Testing of MCT's twin rotor 1.2MW TCT SeaGen in the Strangford Narrows off of the coast of Northern Ireland demonstrated an overall systems efficiency of 42.5%, therefore, producing 510kW of output energy (Fraenkel, 2010). In comparison, fossil fuels such as gas have been measured on average to have a conversion efficiency of approximately 49% (Evans et al., 2009), which, when applied to Newfoundland's fossil fuel electricity supply rated at 361.744 MW, it can be calculated that the output efficiency would be 177.255MW.

Using the methodology presented above, it can be calculated that a maximum of 98 TCTs could be deployed in the Gulf of St. Lawrence, providing 49.98MW of output energy, eliminating approximately 28% of Newfoundland's fossil fuel based electricity supply. If Myers and Bahaj's (2012) optimal layout configuration is applied (see section 2.2.2.), whereby an additional 22% of power is available to 50% of TCTs within an array, then, assuming even distribution, the mean output efficiency of each TCT would increase from 510kW to 566.1kW. Therefore, the 98 deployed TCTs would produce an aggregate output of 55.578MW, eliminating approximately 31% of Newfoundland's fossil fuel based electricity supply. Finally, using a third scenario presented in this paper which expands upon Myers and Bahaj's model (see section 2.2.2.), where a grouping of four strategically placed TCTs increases the power available to the quad array by 33%, assuming even distribution, it can be calculated that the mean output efficiency of each TCT would increase from 510kW to 678.3kW. Therefore, the 98 deployed TCTs would produce an aggregate output of 66.473MW, eliminating approximately 38% of Newfoundland's fossil fuel based electricity supply.

Table 1: TCT deployment scenarios

	TCTs Deployed	Individual Output	Aggregate Output	Fossil Fuel Generation Capacity Replaced
Scenario 1	98	510kW	49.98MW	28%
Scenario 2	98	566.1kW	55.578MW	31%
Scenario 3	98	678.3kW	66.473MW	38%

7. Multi criteria decision making matrix

When planning and designing the implementation of a proposed energy technology or system, an important question that planners, consultants, and developers need to address and present to politicians, decision makers, and the public is why should the specific energy technology or system being proposed be implemented? What are the benefits of this energy production? What are the consequences? If the new form of energy generation were proposed to replace a different energy source, why would this new energy source be an improvement on the former source? Multi-criteria methodologies are commonly used as a tool to organize and present a wide range of data dealing with many different factors encompassed by a variety of disciplines in a simple comparable form in order to help decision makers model strong energy policies (Kahraman & Kaya, 2010).

Below, a multi-criteria decision making methodology in the form of a simple magnitude matrix will be presented to discern the pros and cons of implementing TCTs in comparison to fossil fuels for the production of electricity. The criteria assessed includes availability of energy source, site specificity for implementation, land use requirements, technological maturity, potential impacts on ecosystems, pollution, economic stability, public acceptability, efficiency of energy conversion, and water consumption. Drawing upon a literature review, each criterion will be afforded a ranking of 0-3, with 0 denoting no applicable concern, 1 denoting a minor concern, 2 denoting an intermediate concern, and 3 denoting a major concern. The rational behind the rankings afforded to each technology for each set of criteria will then be explained. Each set of criteria will be assumed to have equal importance relative to one another, and the energy technology that demonstrates the lower total value will be considered to be the more sustainable energy source.

Table 2: Multi-criteria decision making magnitude matrix comparing tidal current turbines to fossil fuels

Criteria	Energy Source	
	TCTs	Fossil Fuels
Availability of energy source	1	2
Site specificity	2	2
Land use requirements	0	2
Technological maturity	3	1
Impacts on natural ecology	1	3
Pollution	0	3
Economic stability	3	1
Public acceptability	1	2
Efficiency of energy conversion	2	1
Water consumption	0	3
Totals	13	20

7.1. Availability of energy source

TCTs draw upon the natural gravitational and centrifugal forces perpetuated by the relationship between the earth, sun, and moon to produce energy (Clark, 2007). As a result, the availability of tidal current energy is constant, predictable, and not limited. However, as with any renewable energy, intermittency of supply is a factor as a result of the absence of kinetic energy available during slack tides, thereby receiving a ranking of 1. While there are still vast reserves of fossil fuels, they are a non-renewable resource that can and may eventually be depleted (World Energy Council, 2013), thereby receiving a rank of 2.

7.2. Site specificity

The conditions required to host TCTs are site specific, however, such sites can be found in a large number of coastal communities across the globe and have a theoretical global capacity of electricity generation between 500-1000 TWh/yr (Hammons, 1993). While this generation capacity is substantial, site specificity of TCTs is still more limited than solar PV, which can be mounted on rooftops in cities across the globe (Evans et al., 2009), thereby receiving a ranking of 2, as site conditions can be more optimal. Fossil fuels, while also found across the globe, are limited to regions where resources are available and can be reasonably extracted, thereby receiving a ranking of 2.

7.3. Land use requirements

TCTs are an attractive source of renewable energy generation as they do not conflict with other terrestrial land uses, such as biomass energy which must compete for land use requirements with agricultural food production lands (Reilly & Paltsev, 2009), thereby receiving a ranking of 0. Fossil fuels require the use of land for terrestrial production and refining plants, although the size of the site may vary due to the scale of the operation, thereby receiving a ranking of 2.

7.4. Technological maturity

Due to the infancy stage of development and implementation in which TCT technology currently lies, large-scale installation of TCT farms has yet to be realized (Myers et al., 2011) and consequently the technology is considered to be relatively immature, thereby receiving a ranking of 3. Fossil fuels have accounted for the primary fuel source for energy production since the industrial revolution (IPCC, 2014), which has resulted in the technological advancement of fossil fuel technologies, thereby receiving a ranking of 1.

7.5. Impacts on natural ecology

TCTs have been theorized to be one of the most environmentally friendly renewable energy technologies with regards to impacts on natural ecology, particularly the benthic habitats in which they are situated (Pelc & Fujita, 2002). Effects on sediment disposition are considered to me miniscule and easily reversible upon decommissioning (Fraenkel, 2006), while negative effects resulting from wildlife interactions with turbine blades, installation and operation noise levels, and electromagnetic fields produced from electricity transmission lines are all considered to be minor (Pelc & Fujita, 2002), thereby receiving a ranking of 1. The increase of carbon in the atmosphere resulting from the combustion of fossil fuels for energy production has altered the Earth's natural planetary functions and has thus destroyed ecosystems across the planet, while land use demands for the extraction of fossil fuels from the ground typically results in permanent degradation of the natural ecosystem from which the resource was extracted (Vitousek, 1994), thereby resulting in a ranking of 3.

7.6. Pollution

TCTs draw energy from the velocity of tidal movements and are consequently carbon neutral, thereby receiving a ranking of 0. The burning of fossil fuels for energy is the primary reason for accelerated global climate change (IPCC, 2014), as natural gas, oil, and coal emit on average 205, 255, and 340 kg of CO2/MWh of energy production respectively (Barra, 2000), thereby receiving a ranking of 3.

7.7. Economic stability

As discussed in section 4., due to the infancy status of TCT technology, there is currently an uncertainty of the concrete construction, installation, operation, maintenance, and decommissioning costs, thereby receiving a ranking of 3. Fossil fuels have been a primary contributor to global energy production and consumption since the industrial revolution (IPCC, 2014), and consequently the economics of fossil fuels are very well understood, although the insecurity of supply is an ever looming threat, thereby receiving a ranking of 1.

7.8. Public acceptability

TCTs are not subject to the many public concerns surrounding visual obstruction, unwanted odor, and noise pollution that other renewable energy technologies such as solar, biomass, and wind are since they are typically fully submerged under water and consequently out of sight and out of mind, thereby receiving a ranking of 1. While fossil fuels have created an enormous amount of jobs since the industrial revolution, global concerns surrounding the combustion of fossil fuels perpetuating global climate change has become an increasing concern amongst the scientific community as well as the general public (IPCC, 2014), thereby receiving a ranking of 2.

7.9. Efficiency of energy conversion

As discussed in section 6., the SeaGen turbine developed by MCT demonstrated an overall systems efficiency of 42.5% (Fraenkel, 2010), which is higher than most renewable energy technologies such as solar, wind, biomass, and geothermal, (Evans et al., 2009), thereby receiving a ranking of 2. However, fossil fuels such as gas have an average energy conversion rate of 49%, which is slightly higher than that of TCTs, thereby receiving a ranking of 1.

7.10. Water consumption

Water consumption, defined as a loss of water from circulation of an ecosystem that may have an adverse impact on that ecosystem, as well as interconnected ecosystems, is not applicable to TCTs as no water is drawn out of a given system, thereby receiving a ranking of 0. Fossil fuels such as gas have a water consumption of 78kg/kWh of electricity produced, a figure which is higher than renewable energy technologies such as PV, wind, and hydro (Inhaber, 2004), thereby receiving a ranking of 3.

7.11. Results

The totals tallied from the multi-criteria decision making methodology produced a total score of 13 for TCTs and a total score 22 for fossil fuels. These numbers indicate that TCTs are a more sustainable and overall beneficial technology for purposes of electricity generation when compared to fossil fuels if all the criteria measured is attributed equal weight.

8. Future of tidal current turbines

There is an overwhelming scientific consensus that emissions produced from the burning of fossil fuels for energy have heated the Earth's atmosphere to levels that are altering natural planetary functions at an unprecedented rate (IPCC, 2014). While fossil fuel derived electricity production to date has had an adverse enough impact to perpetuate global climate change, there are still approximately 2 billion people in the world who lack access to electricity (Flavin & O'Meara, 1997). Taking these factors into consideration, and further compounding them by projections of rapid population growth and an increase in living standards (Pelc, & Fujita, 2002), it is clear that an increase in the production and distribution of electricity be met in a sustainable emissions free manner.

When planning for the implementation of an energy system, planners must take into consideration various factors surrounding the implementation of an energy technology, including location, layout configuration, potential site-specific environmental impacts, installation, operation, maintenance, decommissioning, and return on investment costs, land use requirements, and social acceptance. A literature review suggests that TCTs are one of the most environmentally friendly renewable energy technologies and are exempt from various public pushback factors in comparison to other technologies due to the fact that they are generally out of sight and out of mind (Fraenkel, 2006).

However, TCTs are currently at a disadvantage due to relatively unknown and estimated unfavorable associated costs, although offshore renewable energy technologies as a whole are becoming increasingly economic, especially when taking into consideration externalized costs not accounted for in current market prices, such as the ability for emissions free technologies to uphold ecological capital (Frid et al., 2012). It took wind energy approximately two decades to technologically mature to the point where they became competitive with conventional fuels sources (Herzog, 1999). While TCTs are considered to be 15 years behind wind energy technologies, modern advances in science and engineering suggest that TCTs may develop at a faster rate than that of wind energy (O'Rourke, 2010b).

In order to realize large-scale implementation of TCT technology, or any form of clean renewable energy production, proper incentivizing and command and control policies are essential, including financial tax incentives, feed-in tariffs, carbon taxes, and mandatory renewable energy targets (O'Rourke et al., 2010b). While the accumulation of such policies have been put into practice over the last two decades, the implementation of national legislation in countries across the globe is vital in order to ensure that such policy initiatives are strictly adhered to.

Conditions suitable for the implementation of TCTs, while site specific, can be found across the globe. Nations that can benefit from this predictable, emissions free, and environmentally friendly renewable energy technology include, but are not limited to, Canada, USA, UK, France, Italy, Argentina, Russia, Australia, and China (O'Rourke et al., 2010b). Total worldwide potential of tidal energy is predicted to range between 500-1000 TWh/yr (Hammons, 1993). It is imperative that further R&D is conducted in order to better understand the dynamics surrounding the implementation of TCTs in order for the technology to realize its potential in the near future.

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