Assessment and Mitigation of Environmental Impacts from the Bay of Fundy Tidal Energy Development, Atlantic Canada

by
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Executive Summary

Tidal energy has the potential to substantially advance future sustainable development. Tidal energy is a renewable energy resource that helps meet the continuously increasing global energy demand, while producing very little greenhouse gas emissions in comparison to other traditional energy sources (fossil fuels, coal, oil , etc.). In-stream tidal turbines placed under the ocean surface extract energy from the rise and fall of the tides. Tidal energy has attracted considerable attention, particularly in areas where tidal ranges are particularly high. The Bay of Fundy, Nova Scotia has the world's highest tidal range, making it an ideal location to develop tidal energy projects. Several tidal energy development projects are authorized for development at the Bay of Fundy.

Although there are many positive attributes of tidal energy, the tidal energy extraction has the potential to adversely affect the local environment and disturb natural ecosystems, including coastal habitat destruction, wildlife habitat fragmentation, and marine animal injury. The negative effects of marine energy extraction have been identified; however there is less consideration of implementation of the multiple tidal energy extraction projects on the Bay of Fundy environment in current study. A review of scientific literature concerning tidal energy extraction was conducted to assess potential negative impacts of Bay of Fundy tidal power development on the environment.

The report provides a comprehensive review on the potential environmental impacts of tidal energy extraction at the Bay of Fundy while considering further climate change and sea level rise, and provides a recommendation framework to mitigate these adverse effects. The Bay of Fundy tidal energy extraction process will lead to coastal habitat destruction and long-term suspended sediment concentration reduction. The construction and operation of turbine devices will generate noise, light and thermal pollution, release toxic chemicals to surrounding water and cause magnetic field distortion. Also, the combined influences of past, present and future tidal energy extraction and Earth's natural processes will result in more serious environmental harms; and the interaction among greater will potentially lead to greater interruption on the local environment and intensify injury and mortality of coastal animals and seabirds.

This report also provides a recommendation framework relevant to the Bay of Fundy tidal energy extraction, mainly including energy appliances enhancement, monitoring machinery establishment and regulatory agencies creation. Optimizing the blade shape, avoiding application of Cu-contains coating and applying seabird-friendly lights to mitigate the negative impacts. Building up rescue stations, establishing fully functional protected areas, and conducting soil remediation to restore the disturbed ecosystem.

Keywords: Tidal Energy, Renewable Energy, Environmental Impacts, Tidal Turbine, Bay of Fundy, Climate Change, Recommendations Framework

1. Introduction

With intensifying climate change, rapidly growing populations, increasing energy insecurity and declining provisions of conventional energy resources, renewable energy development has aroused widespread interest and has been vigorously promoted. Renewable energy is an attractive and environmentally sound technology which matches the current trends of environmental policies and energy-related legislation globally, and contributes to meet continuously increasing energy requirements while minimizing environmental burden.

Tidal energy is a greenhouse gas emission free energy resource, which helps to alleviate climate change by offsetting GHG emissions generated from fossil fuel combustion. Approximately 1 kg of CO_2 would be offset for each kilowatt hour (kWh) of power produced by applying tidal energy compared to diesel (Andries, 2020). The estimated global tidal potential is approximately 120 GW to 400 GW (Blandino, 2014). By the upward trend of renewables and optimal status of tidal potential, development of tidal energy is an increasingly favourable alternative to conventional energy sources (such as fossil fuels, coal, oil, etc.). In many regions including Swansea Bay (UK), Pentland Firth (Scotland) and Lake Sihwa (South Korea) (Power Technology, 2014).

Tidal power generators harness energy from the rise and fall of the ocean, which is driven by the gravitational attraction and centrifugal forces of the moon and sun. The orbital features of the Earth–Moon system makes tidal energy a highly predictable energy source, which guarantees steady electricity generation (Webb, 1982). The kinetic energy harnessed from water movement and tidal currents is converted into mechanical energy which rotates the blades of the tidal turbine. A generator connected to the turbines converts the mechanical energy into electrical energy. Tidal energy has a higher energy efficiency than wind energy because coastal water density is 800 times denser than air, which means more energy output can be generated per unit of energy input (Bhatia, 2014). Its predictability and high energy efficiency makes tidal energy a more attractive energy resource compared to other renewables like solar or wind energy.

Tidal energy developments in Bay of Fundy, Nova Scotia have attracted attention back 100 years (Government of Canada, 2017). The first tidal energy projects in the Bay of Fundy were developed in 1910, and since the 20th century, interest and support for these projects have increased substantially (Acadia University, 2010). Approximately 2,500 MW electrical power could be exploited in the Bay of Fundy, which has great potential to advance sustainable development and a green economy, while supporting local residents by satisfying nearly one quarter of Nova Scotia's electricity demand (Province of Nova Scotia, n.d.). The social-economic profits and benefits on the global environment of the Bay of Fundy tidal energy extraction have been well demonstrated; however the impact on the local environment has not yet been fully determined.

In 2021, there are three tidal energy projects in the Bay of Fundy, including Fundy Tidal Energy Demonstration Project, Big Moon Canada Corporation (BMP) and Pempa'q In-stream Tidal Energy Project. The Fundy Tidal Energy Demonstration Project was completed in Minas Basin in 2009 but was abandoned in 2018; and the other two projects are currently within a demonstration phase, which is not at the commercial stage, so environmental impact assessments are not yet done for these two projects. However, it is important to consider the potential impacts of the three projects on the local environment, because the operation of an individual project may not lead to harmful impacts, but the combined effect may exceed the safety threshold, like noise. Tidal energy developments have the potential to cause disturbances to local ecosystems and lead to irreversible environmental damages. There is a lack of systematic review on the environmental impacts of tidal turbines and marine devices operation targets to the Bay of Fundy, considering the past, current and potential marine energy extraction projects. However, it is essential that an assessment of the potential impacts of the designed tidal energy project is conducted, with emphasis on local environmental ecosystems to avoid and minimize harm and destruction.

1.1 Objectives

The objective of this paper is to provide a synthesis analysis of the adverse environmental impacts associated with the Bay of Fundy tidal power exploitation to further assist energy developers in mitigating environmental harms caused by energy extraction, and protecting ocean resources. Specifically, this paper will:

1. Assess the potential impacts of tidal energy development on aquatic and terrestrial ecosystems.
2. Provide recommendations for prevention methods, mitigation approaches, and restoration strategies for any potential negative impacts.

1.2 Significance

Understanding the potential impacts of the tidal energy development on the environment will help minimize the environmental harm and disturbances when designing tidal energy extraction instructions and during the construction process. The recommendations provided by this paper will aid in the development of protection and mitigation methods to prevent potential environmental risks of the tidal turbine installation and alleviate the adverse environmental influences. Moreover, this report will help guide future tidal energy development projects to be conducted in an environmentally friendly manner without major environmental destruction.

2. Methods

2.1 Literature Review

A systematic literature review was conducted to identify and assess the potential environmental impacts of the Bay of Fundy tidal energy development.

The categories of data used for this study are: 1) the Bay of Fundy climatic and geographic details; 2) the Bay of Fundy tidal energy development projects; 3) the influences of tidal energy development on aquatic ecosystem; 4) the influences of tidal energy development on terrestrial ecosystem; 5) the particular case study about environmental impacts on the Bay of Fundy tidal energy; 6) policy, legislation and soil license associated with tidal energy development; and 7) the protection methods, mitigation measures and restoration approaches related to tidal energy development.

The individual, cumulative, and synergistic effects of the Fundy Demonstration Project, Big Moon, and Pempa'q projects were examined in this paper (Figure 1). The aquatic and terrestrial impacts of tidal energy developments including the pre-construction, construction, operation and abandonment were identified and analyzed. The existing environment, temporal-spatial variability and system dynamics were taken into account when assessing the potential environmental influences. Furthermore, the synergistic effect and cumulative impacts of local environmental ecosystems were reviewed (Figure 1).

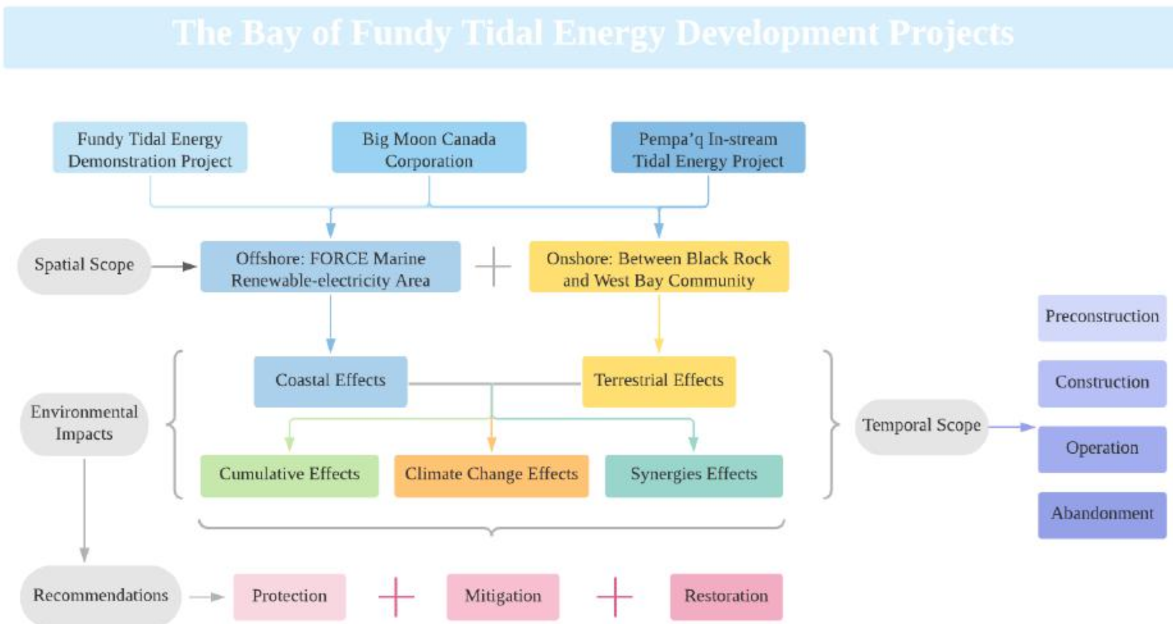

Figure 1. Methods framework showing the scope, temporal scale, and central components of this study.

The research, assessments and literature reviews used for analyzing the environmental effects of tidal energy development were mainly from three sources: 1) primary literature; 2) grey literature; and 3) online descriptions.

1) Peer-reviewed journals, reports, articles and scientific literature were searched using UBC Library, Google Scholar and Science Direct with keywords, such as “tidal energy + aquatic” or “Bay of Fundy + tidal energy + environment”.

2) Grey literature: government reports, policy statements and issues papers associated with the categories of data were searched through the search box of Nova Scotia Canada and Laws.justice.gc.ca.

3) Online descriptions: videos and blogs related to the data categories were searched using Google and Youtube (keywords: tidal energy; tidal turbine & mechanism)

The information resource, authority, publisher, relevance and timeliness were considered to evaluate the credibility and availability of the searched information. Various and diverse information was searched for each category of data from different resources to avoid bias and maximally ensure the objectivity of this study, like information collected for each environmental impact will be from research articles, scholarly publications, case studies, news and book chapters (BYU, 2021).

2.2 Assumption and Limitations

The limitations of this project are:

1) This study is literature-review based. Although this study emphasizes synthesis of information about the impacts of tidal energy extraction on the local environment, it should be noted that identification of environmental adverse impacts involves field data or parameters - no data were measured in the Bay of Fundy specifically targeted to this study. The experiments and model predictions from different sources relevant to this study are conducted in an early time period and/or different location/countries which may lead to inaccuracy. Studies included in this paper were conducted in various marine ecosystems across the world; although there is a lack of studies from the Bay of Fundy, the results of the studies used in this paper can be applied to the Bay of Fundy because the analysis including worldwide marine energy extraction cases, the detailed research for each environmental effect and the associated quantitative recording. Despite best efforts to extrapolate results to Bay of Fundy, differences between the study regions and the Bay of Fundy could result in some variability.

2) The assumptions of cumulative impacts and synthesis effects are estimated based on individual effects from various studies and research, the predictions of cumulative and synthesis effects may have human errors. In this report, the cumulative effects analyzed the potential environmental impacts of three tidal energy projects together; and the synthesis effects demonstrated the potential environmental consequences of the combination of individual effects.

3) It is also significant to note that ecosystems are interconnected, and the interactions between coastal and terrestrial environments are complex and hard to predict (Witt et al., 2012). The response of the ecosystem to such artificial perturbations is still underdetermined in current research (Witt et al., 2012).

4) Notably, the predicted impacts of climate change on the Bay of Fundy tidal energy development is based on climate prediction models. The climate models uncertainties will lead to the error of the estimated environment effects.

3. Background on Energy Projects in the Bay of Fundy

The Bay of Fundy is located between the Maritime Canadian provinces of Nova Scotia and New Brunswick, and is within the world's highest tides ecozone (Figure 2) where tides can reach up to 16 m. The flow rate of water in and out for each tide cycle is approximately 160 billion tons (Cornett, 2013).

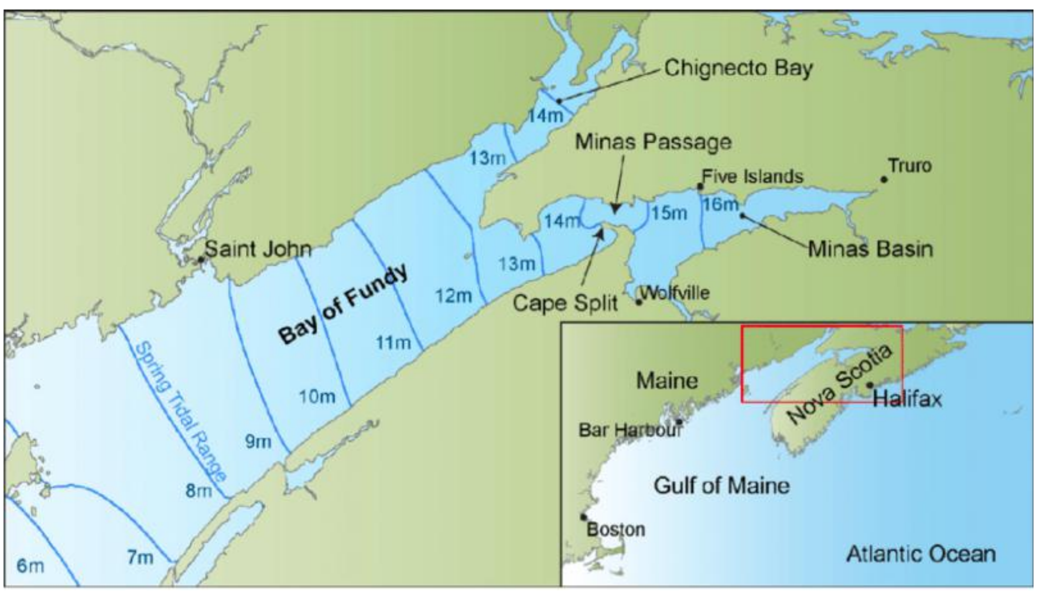

Figure 2. Spring tide range of the Bay of Fundy (from Cornett, 2013).

3.1 Coastal Environment

The Bay of Fundy is a linear embayment with a length of 155 km located in the northeastern corner of the Gulf of Maine which connects the Minas Channel and the Minas Basin (Fader, 2009). Minas Passage has the best position to harness energy from the tides, being only 5 km wide and 14 km long in northwest-southeast flow direction. It lies in the sub-basin of the Fundy Basin, which is the entrance to Minas Basin and connects to Minas Channel (Percy, 2001; FORCE, 2018; Figure 2). The Bay of Fundy is a semi-enclosed coastal region - the mixture of intense saline water fluctuations and minor freshwater intervention. The mean annual water temperature is approximately 5.6°C which is suitable for marine species to live (Collections Canada, 2018). The vertical temperature in the Minas Passage is isothermal due to the high speed current flow which ranges from 3 to 6 m/s. The salinity level of water in Minas Passage is approximately 30 ppm (Dadswell, 2004).

The Bay of Fundy is a cetacean hotspot and is famous for various marine mammals, especially whales, like Fin Whales, Humpback Whales, Minke Whales, and Northern Right Whales (Bay of Fundy, 2020). The common oceanic bird species in the Bay of Fundy are petrels, fulmars, shearwaters, Atlantic puffins, crested terns and herring gulls (AECOM Canada Ltd). Moreover, Minas Basin is important incubation area for various species of fish and lobsters; and the Minas Passage is an important path for various diadromous species including Atlantic salmon (*Salmo salar*), Atlantic halibut (*Hippoglossus hippoglossus*) and Atlantic sturgeon (*Acipenser oxyrhynchus*) migrate through the inner Bay of Fundy and Minas Basin (Stokesbury et al. 2016; Dadswell, 2004). It is important to note that Atlantic salmon is identified as an endangered species by IUCN; species such as American eel (*Anguilla rostrata*) and Atlantic Whitefish (*Coregonus huntsmani*) colonized within the turbine deployment area are also species at risk, which are sensitive to external disturbance (IUCN, n.d.; Species at Risk, n.d.; Dadswell, 2004).

3.2 Terrestrial Environment

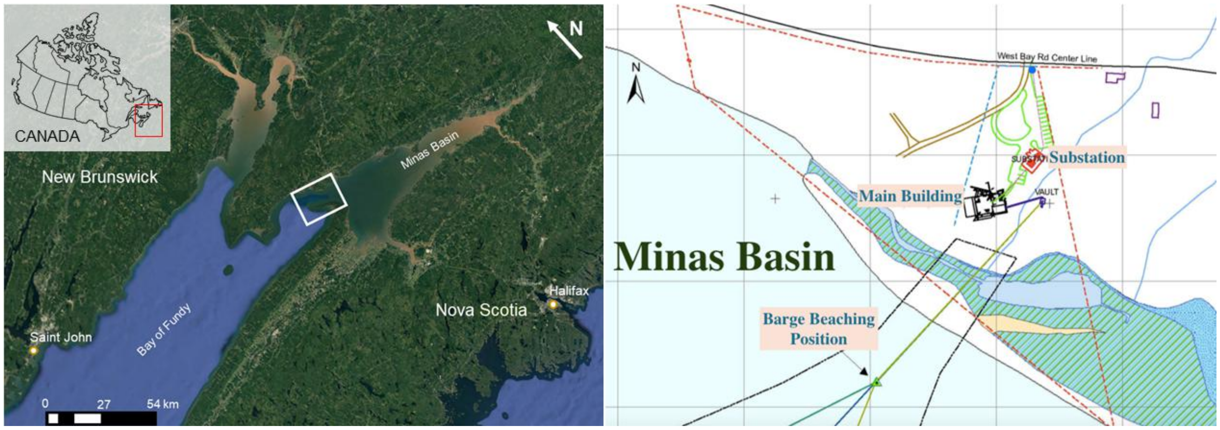

Figure 3. The onshore facility deployment location of the Fundy Demonstration in the Minas Passage in the Bay of Fundy shown in whitered square (AECOM Canada Ltd, 2009).

The adjacent terrestrial zones along Minas Basin are Central Lowlands and Cumberland Marshes (the green-shadow zone shown in the diagram) (Figure 3) (Neily et al., 2003). The climate along the coastline is moderate and humid, with a 1270 mm mean annual precipitation and a 6°C average annual temperature (Fundy National Park, n.d.). The Fundy Tidal Energy Demonstration Project (OpenHydro project) Environmental Assessment was conducted FORCE (Fundy Ocean Research Centre for Energy) in 2009. The Environmental Assessment indicates that the soil types at and adjacent to development areas mainly consisted of the basalt, sandstone, calcrete limestone, conglomerate, mudstone, silty till and clay. Soil texture ranges from medium to coarse textured with well to moderate soil water drainage to fine-textured soil with moderate to poor drainage (AECOM Canada Ltd, 2009).

The Environmental Assessment also indicates that the local terrestrial environment of the onshore facility deployment location (Figure 3) does not to support endangered plant species growth, and is not important wildlife habitat (determined based on Species at Risk Act; the deployed zones are mostly identified as former abandoned cultivation land), and no protected wetland are involved in the study area (AECOM Canada Ltd, 2009).

The dominant tree species in softwood forest are white spruce (*Picea glauca*), red spruce (*Picea rubens*), yellow birch (*Betula alleghaniensis*) and maple (*Acer sp.*). Moreover, the onshore deployment zone consists of an intertidal zone. Intertidal barachois pond and/or salt marsh is the dominant intertidal zone within the Minas Basin in the Bay of Fundy (AECOM Canada Ltd, 2009). Within the development area, *Spartina patens* is the commonly found marsh species in the saltmarsh; and Irises (*Iris* sp.), bulrushes and downy alder are the dominant freshwater wetland vegetation (AECOM Canada Ltd, 2009). Although the deployment location is considered as unimportant wildlife habitat, animals like American Peregrine Falcon (*Falco peregrinus anatum*) and Monarch Butterfly (*Danaus plexippus*) which are considered as vulnerable species in the federal Special Concern list were observed within the area (AECOM Canada Ltd, 2009).

3.3 Local Communities

Onshore facilities including observation centre and transformer substation are established between Black Rock and West Bay community, Cumberland County (Government of Canada, 2017, Nova Scotia Canada, 2017, Wall, 2021). There are no First Nations residents nor identified heritage resources around the deployment location (Minas Basin Pulp & Power Co. Ltd., 2007). Tourism contributes significantly to the economy of the Bay of Fundy. Whale-watching and recreational fishing are popular activities in the Bay of Fundy that attract a large number of tourists each summer (Crystal, 2020; Nova Scotia, 2018). According to the Bay of Fundy Tourism Partnership (2021), whale-watching tours can attract approximately 1 million nature tourists per year. Although local communities will undoubtedly be affected by the tidal energy projects, this paper focuses on impacts on the local environment.

3.4 Bay of Fundy tidal energy extraction projects

Three tidal energy development projects (hereafter referred to as the Bay of Fundy tidal energy projects) in the Bay of Fundy: The Fundy Tidal Energy Demonstration Project (hereafter referred to as the Fundy Demonstration), Big Moon Canada Corporation Tidal Project (hereafter referred to as BMP), and Pempa'q In-Stream Tidal Energy Project (hereafter referred to as Pempa'q). The Fundy Demonstration began in 2009, BMP in 2018 and Pempa'q in 2019 and are each at different phases of development (Figure 4).

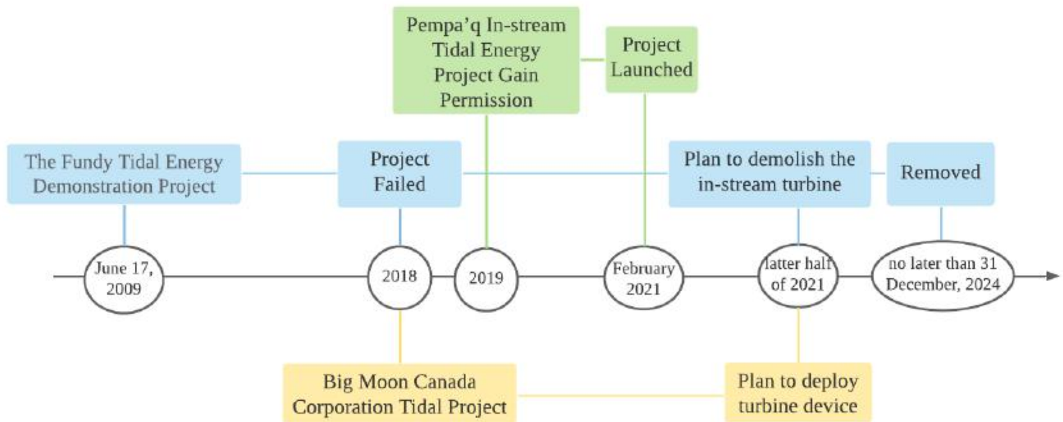

Figure 4. Timeline and condition of the Bay of Fundy tidal energy development projects. The Fundy Tidal Energy Demonstration Project (blue timeline), the Big Moon Project (yellow timeline), and the Pempa'q In-stream Tidal Energy Project (green timeline).

The time schedule of Bay of Fundy tidal energy projects is tight (Figure 4). The first tidal energy development project to be started was the Fundy Demonstration which was funded by the Cape Sharp Tidal Venture company and launched by the Fundy Ocean Research Centre for Energy (FORCE) on June 17, 2009 (Nova Scotia Canada, 2017). The turbine devices were placed on the ocean floor of Minas Passage. The Fundy Demonstration Project termination in 2018 due to Cape Sharp Tidal Venture company failing to take financial liability (AECOM Canada Ltd, 2009). BMP was authorized by the Nova Scotia government to fill the tidal energy development vacant berth in 2018 (Palmeter, 2020). As stated by FORCE, the custom-built floating turbine device is planned to be deployed at Minas Passage in late 2021 (Audi Canada, 2020). BMP Corporation will be responsible for demolishing the discarded Fundy Demonstration turbines (Energy and Mines, 2020). Pempa'q was initiated by the cooperation of the Sustainable Marine Energy (SME) and Minas Tidal LP in 2021 (Work Boat, 2021). The Pempa'q Project contributes to establishing the floating tidal energy array in the Minas Passage for the first time in the world (Work Boat, 2021).

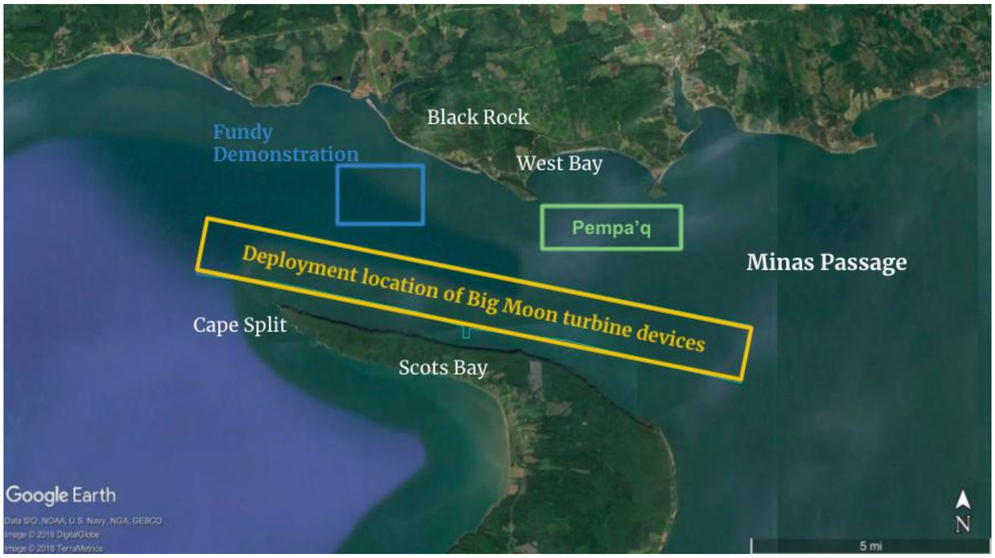

Figure 5. Deployment location of the turbine devices of Fundy Demonstration (shown in blue square), BMP (shown in yellow square) and Pempa'q (shown in green square).

The tidal turbine devices of the Bay of Fundy tidal energy projects will be placed within the FORCE Marine Renewable-electricity Area which is regulated by Marine Renewable-energy Act, 2015 under Schedule C (Appendix A). All the three projects were/will be installed within the Minas Passage (Figure 5). The deployment area of the Fundy Demonstration is near the Black Rock (AECOM Canada Ltd, 2009); for the BMP, the deployment location is along the north side of Scots Bay (Big Moon, n.d.); and the development area of the Pempa'q is near the Cape Sharp (Canadian Press, 2021).

The features and components of the turbine deceives and main installation processes of each project are described in Appendix B and the turbine appearance are shown in Appendix C. The onshore facilities of the Fundy Demonstration were located near Parrsboro County, and consists of six components including underground vault, transformer substation, electrical switchgear construction, underground cable receiver building, interpretive centre, parking lot. For BMP, there will be a land-based assembly area in the Blomidon Peninsula; and there will be a substation and observation centre for Pempa'q (Big Moon, n.d.; Wall, 2021). There is no clear information about the onshore facility for the other two projects. It is reasonable to assume that the onshore facilities for the BMP and Pempa'q are similar to the Fundy Demonstration.

3.5 Nova Scotia renewable energy development

The legal requirements set in the Nova Scotia Carbon and Greenhouse Gas Legislation declare 53% greenhouse gas emission reduction by 2030 compared to 2005 levels (Osler, 2021). The 2015 amended Electricity Act promotes renewable energy development (Energy and Mines, 2021). According to the newly released Government Amends Electricity Act (2020), 100% electricity would be generated from renewable energy by 2022 (Energy and Mines, 2020). The NS government implements the Green Choice program which declares all electricity will be generated by renewables by 2025 (Energy and Mines, 2021). The essential reason for facilitating tidal power development is it’s GHG free and forecastable nature. Operation of tidal turbines will generate zero greenhouse gas emission, which will help to achieve the provincial energy and electricity goals. And, the predictability of tides ensures the constant electricity supply. Notably, the Pempa'q project would contribute to generating 9 MW of electricity to the Nova Scotia grid which will supply enough electricity power to 3,000 Nova Scotian homes, and help to save approximately 17,000 tonnes of CO_2 (Work Boat, 2021, Weetch, 2021). Moreover, the implementation of BMP will produce 5 MW electricity, which will power 600 homes (Brucewark, 2018, Audi Canada, 2020).

4. Literature Review

4.1 Spatial and Temporal Scope of the Tidal Energy Projects

This literature review focuses on the environmental impacts of the construction, operation and abandonment phases, and does not consider the preconstruction process. Recovery time of the ecosystems discussed are also included within the temporal boundaries of the paper. Based on the 2009 Fundy Demonstration assessment, for the Fundy Demonstration, the benthic marine environment is likely to recover to baseline levels following the completion of the abandonment phase (AECOM Canada Ltd, 2009). However, there is lack of analysis on the environmental consequences of multiple marine renewable energy installation projects. It is reasonable to assume that recovery time will be longer due to the increasing perturbations. It may take many more years for water quality and coastal ecosystems to return to the baseline condition (AECOM Canada Ltd, 2009).

The spatial boundaries for this study consists of Minas Passage and the Minas Basin. All three tidal projects will be conducted with the FORCE Marine Renewable-electricity Area. According to the analysis of Environmental Effects of Tidal Energy Development (2010), the environmental effects of tidal turbine deployment is more likely to take place in local scale, therefore the spatial scope will mainly focus within Minas Passage and the Minas Basin.

4.2 Effects on Coastal Environment

4.2.1 Impacts on Water Sediment and Turbidity

The construction of subsea power cables of all three Bay of Fundy tidal energy projects, installation of pile foundation of the Marine Current turbine, and ring system of PLAT-I 6.40 are most likely to increase water turbidity, cause physical disturbance and result in sediment resuspension (Government of Canada, 2017; Wall, 2021; Taormina et al, 2018). The installation and abandonment phase of seabed-mounted turbine installation phase is more likely to cause extensive sediment transport, increase turbidity and current velocities, alter benthic sediment deposition and bottom substrates, and affect benthic habitats (Cada, 2009; Hargrave et al., 1983). The excessive turbidity will potentially cause light limitation and nutrient availability/absorption reduction, limiting growth and altering distribution of phytoplankton and benthic microalgae (Schallenberg & Burns, 2004; EPA, 2009; Hargrave et al., 1983). The increase in turbidity will affect the respiration rate and decrease phytoplankton production of benthic microalgae (Hargrave et al., 1983). Change in current velocities and sediment deposition and alteration of substrate composition and dynamics are likely to change oxygen concentration and alter phytoplankton respiration in the water column, which will potentially interfere with population and distribution of bottom-dwelling plants and animals, and cause animal behavioral alteration (Cada, 2009; Hargrave et al., 1983).

The installation of in-stream tidal turbines and floating turbines (BMP and Pempa'q) will potentially alter current velocities and limit sunlight penetration (EPA, 2009; Cada, 2009). The construction, operation and abandonment phase will directly or indirectly cause injuries and/or mortalities of marine animals and will potentially lead to mortality of sessile organisms (Cada, 2009). More specifically, based on the study of the effect of tidal energy extraction on tidal circulation in the Bay of Fundy (Hasegawa et al., 2011), there could be a 3 $m^2 s^{-1}$ to 10 $m^2 s^{-1}$ flow reduction due to tidal energy extraction. The decrease in tidal residual flow will potentially result in a water temperature increase (20% tidal residual flow reduction will cause a 0.3°C increase in water temperature) (Brown et al., 2016). Also, the change in residual circulation will lead to tidal straining (tidal straining indicates the disturbance on horizontal density gradients due to the vibration of tidal currents caused by vertical shear of tidal turbine), and further affect water stratification and alter longitudinal salinity gradients and salinity distribution (Bolanos et al., 2013; Yang & Zhao, 2017). The reduction in residual tidal flow is likely to increase the upstream salt fluxes (Becker et al., 2009).

Increases in water temperature will increase dissolved oxygen (10.92 mg/L oxygen at 4°C, 8.68 mg/L at 21°C), however, as salinity increases, dissolved oxygen decreases exponentially (Fondriest Environmental, 2013). The reduction of oxygen concentration will result in a decrease of phytoplankton respiration due to less available oxygen. Approximately 4-15 mg/L and 1-6 mg/L oxygen values are required to support the lives of benthic organisms (like crabs and oysters) and shallow water fish (Fondriest Environmental, 2013). Less dissolved oxygen (DO), will potentially lead to alteration of microorganism communities, affect marine species, zooplankton and phytoplankton activities, and interfere with macrofauna diversity and microbial functioning (Taormina et al., 2018; USGS, n.d.). Takarina et al. (2017) conducted a field experiment in Blanakan, West Java, and they found that when DO dropped from the mean value (7.63 ± 0.59 mg/L to 7.0 - 7.2 mg/L) , there was a significant reduction in phytoplankton population and zooplankton diversity. Therefore, the alteration of dissolved oxygen level will potentially lead to alteration of distribution of aquatic animal communities moving to adequate dissolved oxygen areas.

Alteration of sediment deposition will potentially alter marine species communities. Firstly, the installation and abandonment processes (like drilling and laying/removing submarine transmission cable) will create a sediment plume. The increase in concentrations of suspended sediment (SSC) will lead to restriction of sunlight and will limit photosynthetic activity due to sediments coating benthic macrophytes and periphyton (Fondriest Environmental, 2014; Cada, 2009). A study on the impact of underwater transmission cables on sediment deposition in the Strait of Georgia indicated that the installation and removal of 1.0 m x 1.0 m x 1.8 km (width x depth x length) cables can lead to suspended sediment amount greater than 1,000 mg/L (Jiang et al., 2008). The high SSC will potentially impede light penetration and clog gills of marine species (Fondriest Environmental, 2014). However, as the tidal turbines begin to operate, SSC will decrease (Ashall et al., 2016). According to a study from Coastal Engineering (Ashall et al., 2016), the implementation of a large-scale tidal energy project (200 m x 200 m OpenHydro farm) will lead to 5.6% to 37% decrease in SSC within the basin over a 43-year period from 1970s to 2013. The operation of multiple tidal energy extraction farms will potentially lead to a greater reduction in SSC. Reductions of SCC from baseline levels could impede submerged plant development from lack of nutrients carried with sediment, and lower sediment deposition will slow new habitat formation and therefore interference with coastal species breeding and lives (Fondriest Environmental, 2014).

4.2.2 Impacts on Electromagnetic Fields

The operation of submarine power cables will generate electromagnetic field (EMF) emissions and heat emissions. The magnetic fields produced by the electrical cables will potentially cause gradual alteration of reproduction or migration behavior of marine species (Cada, 2009). According to a field experiment of EMF on Elasmobranch conducted in the Northeast U.S. (Hutchison et al., 2020), a buried 300 kV DC (direct current) caused behavior alteration of American lobster and Little skate, like anomalous exploratory activity. The anomalous exploratory activity will result in consumption of extra energy, which will potentially decrease the fitness/survival of the environment and decrease reproduction success (Todd et al., 2015).

Moreover, a study by Westerberg & Lagenfelt (2008) in the Baltic Sea, found reduced swimming speed of European eels (*Anguilla anguilla*) when passing the energized cable zones and they had a 30 min delay in response of their migratory trajectories. Wyman et al. (2018) indicates that the installation of submarine cable (approximately 10% magnetic intensity distorted) will also affect migratory direction of Chinook salmon (*Oncorhynchus tshawytscha*). Although Chinook salmon and European eels are not found in the Atlantic Ocean, Atlantic salmon and

American eel may be impacted in the same manner. The study conducted by Granger et al. (2020) found that the magnetic field distortion will increase the occurrences of stranding of Gray whales (*Eschrichtius robustus)* citing the high levels of radio-frequency noise caused by EMF anomalies as the cause. The OpenHydro project established a 1.25 km x 200 m (length x width) 34.5 kV AC buried subsea cable corridor (AECOM Canada Ltd, 2009); there is no clear cable vault information for the other two projects. Rationally, the operation of multiple cable corridors will intensify temporal and spatial variation of EMF, and further impede coastal species.

4.2.3 Toxicity of Chemicals and Anti-Fouling Coatings

The chronic emission of toxic chemicals and heavy metals from antifouling coatings on marine devices would negatively affect water and sediment quality (Polagye, 2011). More specifically, the released chemicals and heavy metal will potentially result in sensory stimuli in the water column and negatively affect marine animal health and migrations (Taormina et al., 2018). Heavy metals, like copper and lead, contained in the cable's sheath are likely to dissolve in water and spread into the sediment, which will potentially threaten coastal organisms (Taormina et al., 2018). Based on the research from Bejarano et al. (2013), California State Lands Commission (2013) and Copping et al. (2015), the common chemicals released from marine energy devices are “aluminum, copper, and zinc, booster biocides such as diuron ($C_9H_{10}Cl_2N_2O$) and irgarol (Cybutryne, $C_{11}H_{19}N_5S$), hydrocarbons such as benzene, toluene, ethylbenzene and xylene (BTEX) and polycyclic aromatic hydrocarbon (PAH)” (Tornero & Hanke, 2016; p22). More specifically, cuprous oxide (Cu_2O) is the most common biocide ingredient in antifouling paints which is used to inhibit marine organisms colonization (Lagerström et al., 2020). Lagerström et al. (2020) concluded that most of the release rate of Cu contained antifouling paints considerably surpassed the critical release rate for the Atlantic ocean (10 µg $Cu/cm^2/day$). The increasing concentration of Cu and the chronic exposure to Cu will negatively affect coastal organisms, causing conditions such as sublethal gill impairment and immune system damage (Yanong, 2010).

The hazardous materials released from lubricants, paints and industrial cleaners used during construction, operation, etc. are likely to bioaccumulate in the food chain, and harm marine species, and even human consumers (Polagye et al., 2011). More specifically, the release of PAHs used in the electrical signals infrastructure for marine energy devices, will be absorbed through dermal absorption and gills, and bioaccumulate in coastal organisms (Honda & Suzuki, 2020). Honda and Suzuki (2020) found that the LC_{50} (the concentrations of the chemical that kills 50% of the test animals during the observation period) is approximately 114 µg/L in aquatic invertebrates; and the long-term exposure to PAHs will affect liver metabolism, early development and reproduction of marine organisms.

It is important to mention that there is a lack of quantitative measurement on the amount of toxic chemical emissions (such as PAHs and BTEX) from marine energy devices. Beside the chemicals released from operating turbines, the discarded turbines from 2018 (Fundy Demonstration Project) are more likely to have exposed surfaces and aggravate chemical release due to the lack of maintenance and surface erosion due to coastal water (Rasool & Stack, 2019). It is reasonable to infer that the concentrated tidal energy farms in the Bay of Fundy increase the likelihood of chemical release and increase the concentration in the local coastal environment, and therefore increase the risk of harm to coastal organisms.

Furthermore, it is worth noting that the turbine devices of the Fundy Demonstration have been discarded since 2018, the unoperated turbine would not be maintained, which would potentially lead to microorganism and biofouling organisms colonization on turbine surfaces (Heath et al., 2014). This could affect microbial communities and benthic substrate–microbe interactions (Stewart et al., 1996). More specifically, the artificial substrates have been shown to attract different bacterial groups (Donlan, 2001; Singh et al., 2006). Therefore, biofouling organisms (including plants, microorganisms, and small animals) colonized on the discarded turbine devices are more likely to be similar, and affect species abundances and diversity, and further affect bottom-up trophic cascade (Appendix D) (Heath et al., 2014). For example, according to the study conducted by Posacka (2017) on marine heterotrophic bacteria in fishery discards, most bacteria are affected by the variation of Cu level, however, *Pseudoalteromonas* spp. are unlikely to be impacted. Therefore, *Pseudoalteromonas* spp. are likely to colonize surrounding the turbine devices, which may potentially affect the bacterium community through microbial web. There is a lack of studies analyzing the impacts of discarded turbine devices on the environment, the potential environmental effects are estimated based on research about fishery discards.

4.2.4 Thermal Pollution

The transportation of electric energy through subsea power cables, especially the buried cables, will result in temperature rise at the surface of cables, which will emit thermal radiation to the surrounding area (Taormina et al., 2018). The heat emission from the buried cables will potentially warm the contacted sediment. The thermal dissipation from the subsea cables is likely to alter the physical and chemical properties of substratum. More specifically, the local temperature rise will decrease the oxygen concentration of surrounding water, and therefore alter redox interface depth (Taormina et al., 2018; Meißner et al., 2006).

Moreover, the change in water physical and chemical properties, specifically less dissolved oxygen (DO), will potentially lead to alteration of microorganism communities, affect marine species, zooplankton and phytoplankton activities, and interfere with macrofauna diversity and microbial functioning (Taormina et al., 2018; USGS, n.d.) by mechanisms previously discussed in Section 4.2.1. The estimation of thermal radiation to surrounding sediment and substratum is based on numerical modelling, and there is a lack of field measurement of the impact of heat dissipation from subsea cables on the ecological environment and benthic communities (Taormina et al., 2018). Although there is data absence, the implementation of multiple tidal energy farms will potentially increase the likelihood of local water temperature increase, and therefore threaten sensitive coastal species like pelagic fish and coral reefs (Petrik et al., 2020; Kennedy et al., 2002).

4.2.5 Noise Pollution

The installation, operation and abandonment of subsea cables and tidal turbines will generate noise. The noise generated by construction and operation of turbine devices is very likely to interfere with echolocation and marine mammals' communications (Taormina et al., 2018). A report investigating the noise level of a full-scale wave energy converter system in Pantelleria Island stated that noise generated during operation of underwater energy fixtures will potentially affect fish, crustaceans, marine mammals and pinnipeds within a 1,000 m radius (Buscaino et al., 2019). Moreover, based on the tidal turbine underwater noise research conducted by Risch et al (2020), the operation of a single 1.5 MW Atlantis AR1500 three-bladed turbine will generate approximately 50 to 1000 Hz noise, and a 40 dB increase in the third-octave band sound pressure. The ambient noise levels during the operation of the tidal turbine are increased by 5 dB, and the estimated maximum influenced radius is 2,300 m.

Marine mammals including whales and dolphins, seals and porpoises who communicate by emitting sound, and detect objectives (mates, prey, etc.) and identify territory by receiving echoes will be the victim of the noise generated by the devices (Richardson et al., 2013; Polagye et al., 2010). The fluctuation of amplitude and frequency bands (due to marine energy operation) will obscure signal-to-noise ratio emitted by marine mammals and therefore result in masking communication sounds, echolocation and predator and prey signals (Erbe, 2012). Whales, and other animals that use sound for navigation, will be at risk due to noise pollution (Bay Ferries Limited, 2018). The noise generated from the pile-driving and drilling activities during the installation of seabed-mounted tidal turbines will potentially result in hearing damage and even mortality of the surrounding marine lifes due to the high pressure levels (Taormina et al., 2018). Marine mammals rely on sound for navigation, reproduction and predation will be impeded by the noise-generating device (Bay Ferries Limited, 2018). More specifically, the noise emitted from device's operation will potentially decrease reproduction rate, increase animal's physiological stresses, decline foraging efficiency and alter distribution and communities of marine lifes (Cada, 2009; Taormina et al., 2018).

The thresholds of received levels of sound (RL) is different for each marine mammal species (Gomez et al., 2016). Southall et al. (2008), Miller et al. (2012) and Williams et al. (2014) concluded that change in sound pressure and frequency bands will lead to a lower RL, and the reduction in RL will alter or prevent reproductive calls, and therefore affect breeding behaviour and reproduction. Erbe (2012) also concluded that exposure to noise will affect hearing threshold of marine mammals, and lead to anomalous action such as fight-or-flight response and rapid surfacing, which increase the likelihood of decompression sickness.

Furthermore, offshore construction will potentially interfere with seabirds. The noise will negatively affect the reproduction rate of breeding behaviour of shorebirds. Seabirds may leave their breeding habitats due to the noise (Richardson et al., 2013). More specifically, the noise (140 dB individual clamor; or 125 dB multiple clamor; or 110 dB 72 hr continuous clamor) generated during the construction phase will potentially lead to harms of auditory receptors and stress responses including change in heart rate, hormone level alteration, lower immunity and reproductive success, etc. (Blickley & Patricelli, 2010). Although there is no quantitative recording about the noise level of the Bay of Fundy tidal energy projects, the tight schedule of demolishment and installation activities and the simultaneous operation of multiple turbines will potentially exacerbate the negative impacts of noise, especifically for the BMP and Pempa'q, besides turbine itself, operation of the barge and the trimaran ship hull will also generate noise.

4.2.6 Injuries and Mortalities of Marine Species

The spin of the rotor of the turbines will potentially lead to impingement, injury and even mortality of marine animals (Cada, 2009). Based on research by Wilson et al. (2007), the blade rotor is the main cause of marine vertebrate collision. Wilson et al. (2007) used a model to predict the likelihood of marine organisms colliding with tidal turbines near the Scottish coast, and found that the implementation of the "100 horizontal axis 8 m radius turbines" would result in 2% herring population and 3.6-10.7% of porpoise population face the collision risks. The strike force of the turbine blade is proportional to strike velocity thus, the outer periphery of the blade rotor will inflict the greatest harm to marine organisms (Cada, 2009; Buzzle, 2017). However, there is less data on what level of strike force will cause marine animal injury; and there are no current studies showing the evasive action of marine organisms (Wilson et al., 2007).

Beside the direct strike, water pressure changes are likely to cause injury and mortality of marine organisms. More specifically, water vapor bubbles will be formed as the pressure behind turbine blades drop below the vapor pressure of water due to the turbine blade rotating (Appendix E) (Cada, 2009), which is also called cavitation bubbles. Cavitation bubbles will transfer from the low water pressure zone to high pressure zone, which will crumble and result in shock waves. The point at which cavitation bubbles crumble will produce highest to tens of thousands of kilopascals of energy, and the strong bump will potentially impair nearby small marine organisms (Cada, 2009). More specifically, according to the study of computational fluid dynamics by Fawley Aquatic Research Laboratories, approximately 6.3% of fish injuries were caused by change in pressure flux (less than 1 MW power) around a tidal turbine (Turnpenny et al., 2000).

The floating tidal turbine (like Kinetic Keel and PLAT-I 6.40) and their mooring system of BMP and Pempa'q will increase the risk of entanglement, and therefore increase injury and mortality (Cada, 2009; Taormina et al., 2018; Appendix C-2-2 & Appendix C-3-2). Each square kilometer increase of the arrangement of dynamic cables and pelagic zone mooring lines will increase the risks of entanglement of large marine animals, because it is difficult for large marine animals like whales to pass the concentrated laid cables (Kropp, 2013; Michel et al., 2007). The installation of turbine devices will cause obstruction to marine organism migrations, which may potentially affect the population and distribution of marine animals (Cada, 2009; Taormina et al., 2018). Noakes et al (1988) concluded that the marine energy infrastructures including floating structures, transmission cables and mooring lines impede the long-distance migrations of anadromous fish and catadromous fish. The schedule for deployment, demolition and installation activities in late 2021 are likely to occur during the spawning season of Atlantic salmon (May to November), which will potentially disturb their seasonal mitigation to spawning habitat (Dadswell, 2010).

4.3 Effects on Adjacent Terrestrial Environment

4.3.1. Fauna

The construction of onshore facilities can also lead to adverse impacts on the terrestrial environments. Although there was an Environmental Assessment conducted by FORCE in 2009, there was a lack of investigation on the effects to migratory birds on the onland deployment site (AECOM Canada Ltd, 2009). Specifically, less consideration of migratory bird species may lead to underdetermination of harms and threats, and therefore increase the potential risks on migratory birds. The noise generated during onland facilities construction may potentially exceed the damage threshold values of seabird, and therefore lead to injury and interfere with migration activities (AECOM Canada Ltd, 2009; Polagye et al., 2010). Specifically, the noise generated during the pile driving process would result in a high acoustic pressure which can reach up to over 1000 Pa (Polagye et al., 2010). Based on a field study of noise effects on seabirds the average safe hearing thresholds for seabirds (such as Atlantic puffins, crested terns and herring gulls) are below 40 dB and 20 μPa (Mooney et al in 2020). The extreme high sound pressure would lead to hearing damage and even mortality of sea birds (Polagye et al., 2010; Blickley & Patricelli, 2010).

Also, the onshore artificial night lighting will potentially lead to seabirds light-induced grounding. Petrels and shearwaters are most affected by artificial night lights (Rodríguez et al., 2017). Bright artificial night lights will cause disorientation and temporary blindness, which is most likely to result in seabird attraction and mortality, specifically during the migratory season (Montevecchi, 2006). Based on a 17-year (1978 to 1994) investigation on light-induced seabird mortality, Ainley et al., 2001 found that a mean 1,432 (range 1,000-2,000) seabirds were light-attracted annually in the Kaua'i, Hawaiian Islands. A study on light-induced ground of Manx Shearwaters concluded that annually 1,646 birds were grounding in the west coast of the Scottish Highlands from 2009 to 2014 (Syposz et al., 2018).

Additionally, artificial night lighting can lead to alteration of seasonal reproduction and foraging habits of seabirds, especially shearwaters and petrels which are active at night (Montevecchi, 2006). Night lighting will also affect the physiology and circadian clocks of seabirds, and therefore threaten populations (Falcón et al., 2020). The interruption of circadian system will potentially affect hormonal balance and impede melatonin secretion, which would lead to the alteration of daily rhythms of birds (Renthlei & Trivedi, 2019). The perturbation on birds' circadian system will affect their orientation in time (Bell-Pedersen et al., 2005) and potentially cause developmental delays, anomalous courtship behaviour and breeding rate disorder, affecting reproduction and population of birds (Le Tallec, 2014).

4.3.2. Flora

The construction of onshore facilities is most likely to lead to direct destruction of local plants and freshwater marsh species, as well as indirect mortality due to soil compaction and sedimentation of watercourses (AECOM Canada Ltd, 2009). Pre-construction processes including construction of the transportation access route and construction material transportation will potentially lead to soil compaction (AECOM Canada Ltd, 2009). Although there is no field survey to show the level of soil compaction caused by construction activities in the Bay of Fundy, the study conducted by Shah et al. (2017) demonstrated the influences of soil compaction on soil health, specifically that compacted soil negatively affects plant growth. The water drainage ability of (the deployment zone) soils is moderate to poor (section 3.2); the compaction of soil will reduce soil water retention capacity and increase soil bulk density, which will potentially lead to waterlogging (Bay of Fundy receives about 1,270 mm of precipitation annually) and restrict root development (Colmer, 2003). The loss of habitat and reduction of edible resources will potentially lead to displacement of the sensitive animal species like American peregrine falcon and Monarch Butterfly. Like, Monarch butterfly consumes Milkweed (*Asclepias incarnata*) as main food resource; and the decrease of their edible material will affect abundance and distribution of these animals (Parker, 2007).

4.4 Cumulative Effects

Effects of tidal energy project construction on marine and terrestrial ecosystems will also be cumulative both in time and with the growing development of marine renewable energy installations (Witt et al., 2012).

Continuous construction will potentially change the abiotic and biotic structures of marine systems and even cause permanent alteration of morphology and/or topography of substrate

(Bouwman, n.d.). More specifically, the abandonment, installation and operation of tidal turbines will lead to reduction of suspended sediment concentration (SSC) and interfere with biological activity, such as spawn behavior and predator-prey avoidance, because insufficient substrates support organisms' activities (Mulligan, 2013; Kim, 2017). The continuous decrease in SSC, due to operation of multiple tidal energy farms, will potentially intensify nutrient deficiency and exacerbate insufficient habitat; and further lead to coastal organisms communities moving to nutrient-sufficient and substrates-sufficient regions, and therefore resulting in change in abundance of submerged vegetation and alteration of biological distribution (United States Environmental Protection Agency, 2021).

The decrease in current velocity and SSC reduction will exacerbate alteration of erosion patterns. Specifically, construction and abandonment activities are likely to increase bed sediment erosion and lead to the suspended sediment moving up in the water column. In terms of long-term sedimentation, the disturbance (from tidal projects) could aggravate bank erosion of upstream and downstream zones (Kim, 2017). Morris (2013) found that the long-term sediment loss due to operation of marine energy devices in La Rance and Annapolis Royal, Nova Scotia caused tidal range decrease and led to intertidal area reduction. The implementation of the tidal power station in Annapolis Royal (established in 1960s) caused a 6 m reduction (from 6.3 m to about 0.3 m) in tidal range; and approximately 35 ha intertidal areas in the lower basin were lost from 1954 to 1980 (Martec Ltd., 1987).

The noise generated by operation of individual device units may not surpass threshold levels of marine animals and will not lead to significant impacts; however, the cumulative noise production which is generated by multiple acoustic stressor units is most likely to obscure the echolocation sounds, and therefore adversely affect marine mammals (Cada, 2009). Additionally, the antifouling biocides released from turbine coating to the surrounding environment will be absorbed by marine primary consumers (such as fish, zooplankton and crustaceans) and accumulate into higher trophic levels (marine mammals, like dolphin and whale) by food web (Polagye et al., 2011). The increasing accumulation of toxic chemicals such as PAHs and BTEX will increase human health risks as consuming seafood. According to

Dhananjayan and Muralidharan (2012), the average PAHs intake is around 1.77 and 10.70 ng/kg body weight/day, and for seafish consumers, and the intake value of PAHs increases to 8.39-15.78 pg ng/kg body weight/day, which have been linked to increased cancer risk. However, there is no data clearly indicating how much PAHs will be released from marine energy devices; reasonably, PAHs release due to the multiple marine energy extraction projects will increase the health risk of marine organisms and humans.

4.5 Impacts of Climate Change on Tidal Energy Development

Climate change is predicted to intensify negative effects of tidal energy extraction projects. The Toulouse Unstructured Grid Ocean model is a numerical tidal model used to estimate the Bay of Fundy tidal water level under climate change. The model indicated that there will be a 0.5 m high water increase from 2000 to 2050, increasing to 1 m by 2100 (Greenberg et al., 2012). It is important to mention that the predictions from the numerical model only take into account the mean sea tide withouting considering meteorological forcing such as ocean surface swell, wind-induced storm surges and inverse barometer effects (Greenberg et al., 2012). Without considering meteorological factors, tidal peaks and flooding levels are likely to be underestimated (Greenberg et al., 2012).

Land-ice melt, sea water thermal expansion and isostatic adjustment will also contribute to sea level rise and tidal high water in the Bay of Fundy (Pelling & Mattias, 2013). Change in tidal high water and sea level will potentially result in inundation of new intertidal areas. The water level in the new inundated region will be relatively low, which will lead to a high tidal velocity (at the shallow water depth) and cause bed friction. This bed friction will dissipate a large amount of tidal energy, which will cause reduction of tidal power output (Pelling & Mattias, 2013; Ma, et al., 2019). A study on the influence of climate change on tidal dynamics in the Shelf Sea indicated continued climate change will lead to 6 m reduction of the mean spring tidal range (De Dominicis et al., 2018). The predicted decrease in tidal range and reduction in energy output mean more tidal turbine operations to generate the same amount of power as before, which will exacerbate environmental threats such as habitat loss and coastal bank erosion.

Climate change is also predicted to intensify the strength and frequency of extreme weather (Sattler, 2017). Storm surges will affect tidal range and therefore affect tidal resource extraction (Lewis et al., 2017). The Bay of Fundy is located within coasts of Atlantic Canada, which is significantly sensitive to storm surge impacts and sea level rise (Daigle, 2012). Tidal-range energy can decrease by 5% or increase up to 3% due to tidal levels fluctuations from storm surges (Lewis et al., 2017). Negative storm surges can cause both decreases and increases in tidal range, resulting in fluctuation of power output (Lewis et al., 2017). Storm surges that occur in the late fall to early spring, in the periods of high tides in the Bay of Fundy, are more likely to result in erosion of rotating equipment protection structures, destruction of coastal infrastructure, and damage and failure of turbine rotors (Daigle, 2012). Blade failure will further interfere with marine animal behavior and lead to injury/mortality of marine animals.

4.6 Synergistic Effects

4.6.1 Development of marine renewable energy installations & food web

Direct physical harms on migratory species including both marine and bird species, and disturbance to their habitat, like fragmentation and loss of edible material, will likely affect their population, and therefore influence trophic cascades (Witt et al., 2012). However, there is no current quantitative impacts of marine energy extraction on trophic cascades; based on the study from Annapolis Royal, it is rational to infer that the combined effects of continuous SSC reduction due to tidal energy extraction and intertidal zone decreases (habitat loss) will intensify deficiency of nutrients needed to support aquatic vegetation growth (phytoplankton), which will lower production. Consequently, there will be insufficient food resources for primary consumers such as coastal invertebrates and zooplankton. As food sources of primary consumers decrease, the population of primary consumers is likely to decrease, which will affect secondary consumers including fish and marine mammals (Kytinou et al., 2020). Combined with change in composition and abundance of microbial communities caused by the discarded turbine (section 4.2.6), SSC reduction may alter the food web through changes in bottom-up interactions, like a shift from “phytoplankton-dominated food web” to “bacterioplankton-based food web” (Trombetta et al., 2020; p1). The impacts and multi-stressors on population-level may lead to community-level changes, which will further lead to unexpected alterations on trophic interactions and food web (Witt et al., 2012).

4.6.2 Tidal turbine operation & climate change

The Bay of Fundy is experiencing impacts from changing climate. The operation of tidal turbines is likely to exacerbate sea level rise caused by intensifying thermal expansion and altering hydrodynamic patterns (O'Mahoney et al., 2020; Greenberg et al., 2012). According to the Fourth Assessment Report of Global Climate Projections (2007), thermal expansion contributes 70-75% of sea level rise.

A 3D ocean conceptual model used to estimate the relationship between stratification and the thermal expansion coefficient of Baltic Sea indicated a linear relationship between stratification and thermal expansion (Hordoir & Meier, 2012).Operation of tidal turbines can alter hydrodynamic processes and intensify thermal vertical stratification, further exacerbating local seawater warming (De Dominicis et al., 2017). More specifically, turbine operation can reduce vertical mixing and therefore increase water stratification, which will lead to anomaly patterns of sea surface temperature and sea bottom temperature (De Dominicis et al., 2017; Manasseh et al., 2017). A field study conducted by De Dominicis et al. (2017), analyzed the impacts of a large arraignment of marine energy devices in Pentland Firth, and showed that the operation of total 1.64 GW tidal turbines would lead to a 0.1-0.2°C increase in sea surface temperature during summer period (June to August). The heat radiation and emission released during turbine operation will potentially increase ocean local temperature, and exacerbate ocean thermal expansion (Taormina et al, 2018). Therefore, the combined effects of tidal energy development and climate change will aggravate sea level rise.

5. Recommendations

5.1. Protection methods to reduce negative environmental effects

5.1.1. Lighting

- Use seabird-friendly lights such as non-white lamps and proper spectral composition of lights to avoid light-induced collision or grounding (Rodríguez, 2017; Star Advertiser, 2017).
- Avoid the timing of construction/ decommission activities during the species migration or their reproductive period, therefore protect their population (Falcón, 2020; Rodríguez, 2017).

5.1.2 Noise

- Optimize the blade shape to reduce noise pollution caused by turbine operation (Polagye et al., 2011).
- Estimate the range of noise generated by piling activities and tidal turbine operation, and control noise generation within the appropriate safety threshold of underwater noise which will not cause significant harm to the Bay of Fundy marine species (Polagye et al., 2011).

5.1.3 Cavitation

- Considering the spanwise flow effects and blockage effect when designing the blade shape in order to mitigate the effects of cavitation (Wimshurst et al., 2018).
- Moreover, simulate the blade operation computations; assess the spanwise variation, dissolved air in water and time for fluid drop to vapour pressure in order to determine the likelihood of cavitation; and propose corrections to adjust the rotor plane in the face of cavitation (Wimshurst et al., 2018).

5.1.4 Habitat destruction

- Conduct sediment transport models to estimate sediment dynamic and benthic deposition, and fully assess the impacts of tidal energy extraction on local biodiversity (FORCE, 2012).
- Strictly control pollution and chemicals released from tidal energy exploitation, install turbine devices in photic zones, and/or regularly maintain turbine devices to avoid biofouling, and therefore reduce risks on resident fish species (Polagye et al., 2011).

5.1.5 (Migratory) animal injury/mortality

- Due to a lack of investigation on migratory birds, it is necessary to examine whether there are sensitive or endangered migratory bird species in the deployment location.
- Priorly assess the migratory season and avoid preconstruction and construction activities of the two new projects and the demolishment of the discarded devices during the migratory season (Polagye et al., 2011).

5.1.6 Climate change

- Implement storm surge prediction system and relevant climate change numerical modelling to anticipate how changing climate influences tidal range and energy output in Bay of Fundy (Lewis et al., 2017).
- Determine the impacts of climate change on animal mitigation patterns, and assess whether any alterations of population distribution in the Bay of Fundy to decide any change in the FORCE development location.
- Ensure the deployed turbine devices are designed with capacity to tolerate further climate change; and make sure the sea level rise and anomalous storm surges.

5.2. Mitigation measures for negative environmental effects

5.2.1. Lighting

- There are lighting requirements for safety reasons in the Nova Scotia Building Code Regulations, so it is impossible to completely eliminate the external illumination (Province of Nova Scotia, 2005).
- Only apply lighting when necessary at essential regions and avoid wasteful illumination to reduce interference of radiation emission of local animal communities (including both marine benthic communities, seabirds and terrestrial animals) and the reduce disturbance on their circadian clocks (Falcón, 2020).
- Decrease unnecessary light/radiation emissions through utilizing shield light fixtures, installing strobes lighting, using full cut-off lighting appliances and applying fixtures with longer light wavelengths (Rodríguez, 2017; Hawaii Department of Land and Natural Resources, 2020; Polagye et al., 2011)
- Prevent reflective surface or sky projection through adjusting lighting direction and directing

illumination fixtures downward to reduce bird visible emission (Rodríguez, 2017; Hawaii Department of Land and Natural Resources, 2020).

5.2.2 Noise

- In order to mitigate the noise generated from subsea base drilling and pile foundation construction, several noise reduction technologies can be implemented, like air bubble curtain, noise mitigation screen and hydro sound damper (Maglio, 2013).
- Moreover, noise monitoring technology is recommended to be applied such as acoustic monitoring protocol and visual monitoring protocol, which will help to better determine the noise level and detect the response of marine species to different noise levels (Maglio, 2013).

5.2.3 Hydrodynamic effects

- Apply a monitoring system to detect hydrodynamic changes. More specifically, conducting regular coastal water analysis with a particular focus on hydrodynamic change, and recording and updating new findings in the progress tracking system, which will also help determine environmental effects for further marine energy extraction projects.
- Furthermore, suitably reduce anchor sizes, reduce quantity of moorings and slack lines, and simplify support structures to minimize hydrodynamic effects (Polagye et al., 2011).

5.2.4 Habitat destruction

- In terms of cable installation, applying directional drilling approach to minimize the disturbance on benthic communities and mitigate sediment disruption (Polagye et al., 2011; AECOM Canada Ltd, 2009).
- Set up sediment monitoring systems to regularly detect the alteration of benthic contaminant levels and deposition dynamics in order to avoid significant destruction (Polagye et al., 2011).

5.2.5 (Migratory) animal injury/mortality

- Establish monitoring systems to detect the frequency and severity of the interaction between marine species (including mammals, fish and cetaceans) and tidal turbines (Polagye et al., 2011).
- Design shipping routes to alleviate the spread of danger that will threaten marine species

including oil spill or thermal emission during preconstruction phase (Earth Eclipse, 2021).

- Avoid application of Cu-contains coating and use vegetable based lubricants to reduce the impacts of chemical pollution.
- In terms of turbine device, enhance the visibility of rotors to fish, apply acoustic avoidance measure technology, set up shock absorbers on the edges of rotor blades to mitigate the collision of marine species (Polagye et al., 2011).
- Furthermore, screen the toxicity of applied biocides; try to avoid using antifouling biocides, and only apply when necessary to reduce threats on marine animals (Polagye et al., 2011).

5.3. Restoration approaches to alleviate negative environmental effects

5.3.1. Migratory animal injury

- Establish protected areas and rescue stations to treat and cure injured animals caused by turbine device operation or relevant energy extraction activities; and release them after (Jessen & Patton, 2008).

5.3.2 Habitat destruction

- Restore the destroyed ecosystems through planting artificial reefs and constructing fish aggregation devices, which provides for marine species (Inger et al., 2009).
- Remove any necessary roads after construction is completed, decompact soils and plant local vegetation species to create suitable living environments for wildlife.
- After demolishment of the Fundy Demonstration project, including the physical removal of turbines and substratum on seabed, leave a recovery time to allow the ecosystem to re-establishment. More specifically, the recovery time has a wide range depending on the disturbed environment, generally a 6-8 months recovery time is recommended (Newell et al., 1998). Conducting continuous monitoring to assess whether an excessive period of recovery is required.

5.4. Further Recommendations For Research Improvement

1. Conduct field experiments and measure relevant water and soil data such as SSC, current velocity, EMF, in the Bay of Fundy before and after implementation of tidal energy projects to obtain representative results for the region.

2. Further experiments at farm level in the Bay of Fundy can be conducted to investigate how the ecosystem interacts and responds to environment change, and help marine renewable energy managers better understand and determine to what extent these perturbations may have significantly adverse impacts on the environmental ecosystem.
3. Consider cumulative effects other than tidal energy development, like pit and quarry extraction near Bay of Fundy in order to identify the spatial and temporal bounding more accurately and better analyze the synthesis effects.
4. Take into account the potential severity, and consequence of natural events on Bay of Fundy tidal energy development (such as hurricanes, forest fires & electrical storms) to better assess the potential environmental impacts.
5. Last but not least, this study is focused on the environmental consequences of marine renewable energy development, and did not consider the social and economic effects of the Bay of Fundy tidal energy extraction; therefore, additional studies that consider socio-economic features should be conducted.

The framework summarized the individual, cumulative, and synergistic effects of the Fundy Demonstration Project, BMP, and Pempa'q including noise pollution, light pollution, etc.; and the overall recommendations (Figure 6).

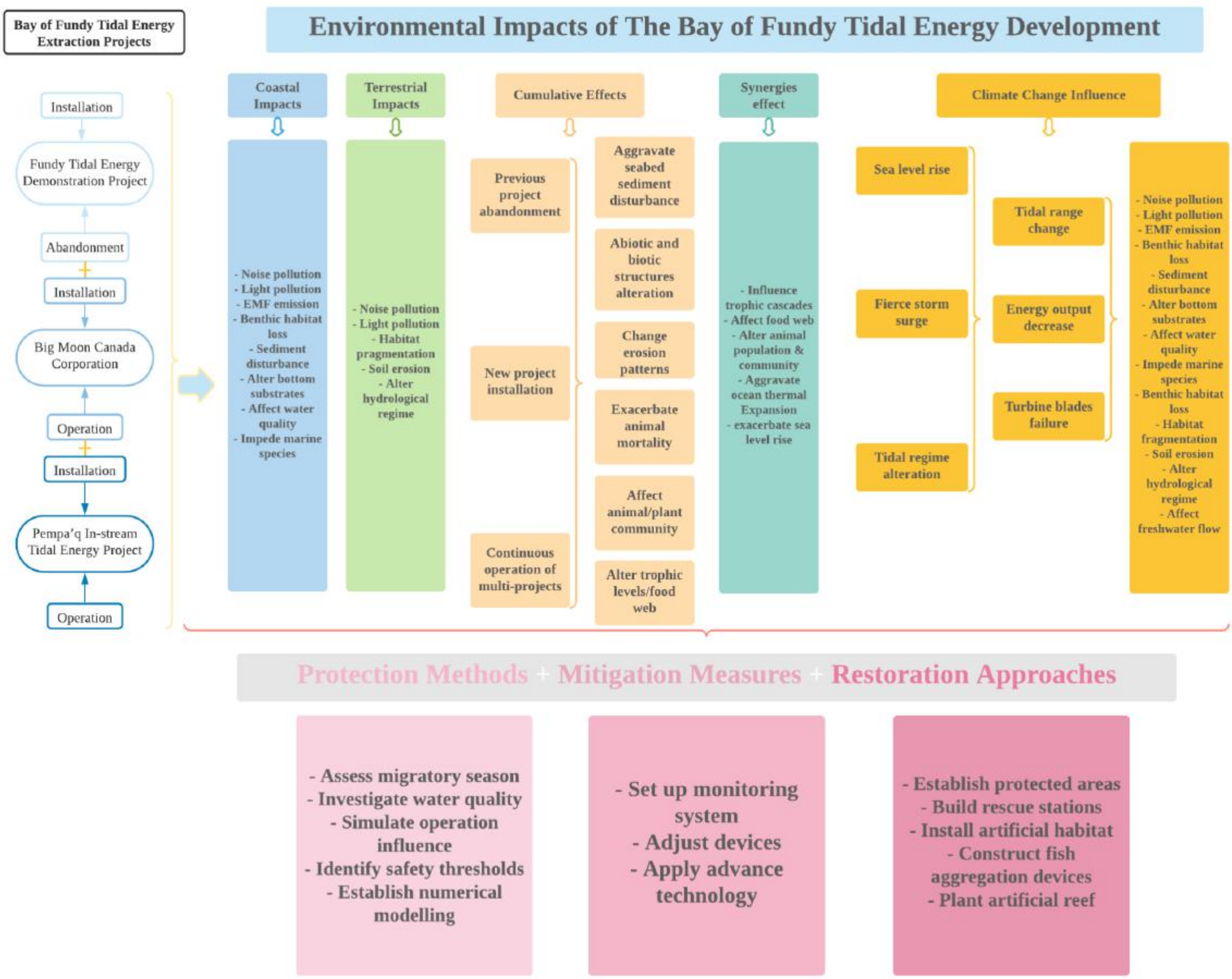

Figure 6. Framework and key environmental impacts of the Bay of Fundy Tidal Energy Development

6. Conclusions

The Bay of Fundy has the potential to satisfy Nova Scotia's energy requirement via development of tidal energy projects. Tidal energy extraction can lead to environmental disturbance, disrupt natural ecosystems, and threaten local animal populations and communities. Although some adverse environmental impacts are unavoidable for tidal energy exploitation such as habitat loss, noise and light pollution, these negative consequences and potential harms could be minimized through regulating activity practices and applying appropriate protection methods and mitigation measures including implementing advanced technology, conducting monitoring systems, and establishing rescue stations.

Tidal energy, which is environmentally friendly compared to traditional fossil fuel, can be developed in an environmentally conscientious manner by utilization of rigorous guidelines and full understanding of the potential risks.

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Appendix

Appendix A FORCE Marine Renewable-electricity Area

BEGINNING at a point located South 46° 08’ 37” East a distance of 572.525 metres from Nova Scotia coordinate monument number 15028;

THENCE North 61° 45’ 00” East a distance of 37 metres more or less to a point at ordinary high water mark as shown on the plan;

THENCE southeasterly along a portion of the shore of Minas Channel at ordinary high water mark a distance of 100 metres more or less to a point;

THENCE South 10° 30’ 46” West a distance of 46 metres more or less to a point located South 55° 34’ 00” East a distance of 134.544 metres from the point of beginning;

THENCE South 10° 30’ 46” West a distance of 309.867 metres to a point;

THENCE South 53° 38’ 38” West a distance of 699.837 metres to a point;

THENCE South 87° 26’ 14” West a distance of 724.802 metres to a point;

THENCE South 00° 00’ 00” West a distance of 100.721 metres to a point;

THENCE North 90° 00’ 00” West a distance of 1599.579 metres to a point;

THENCE North 00° 00’ 00” West a distance of 999.491 metres to a point;

THENCE South 90° 00’00” East a distance of 1599.579 metres to a point;

THENCE South 00° 00’ 00” West a distance of 87.741 metres to a point;

THENCE North 83° 52’ 39” East a distance of 440.788 metres to a point;

THENCE South 75° 55’1 1” East a distance of 598.049 metres to a point;

THENCE North 61° 45’ 00” East a distance of 243.960 metres to the PLACE OF BEGINNING.

Appendix A-1 Coordinate description of FORCE Marine Renewable-electricity Area - Parcel A (Marine Renewable-energy Act, 2015, p49).

THENCE North 50° 55’ 40” East a distance of 400.910 metres to a point;

THENCE North 77° 15’ 17” East a distance of 352.098 metres to a point;

THENCE South 76° 59’ 26” East a distance of 397.796 metres to a point;

THENCE South 53° 38’ 38” West a distance of 348.761 metres to a point;

THENCE South 87° 26’ 14” West a distance of 762.145 metres to the PLACE OF BEGINNING.

Appendix A-2 Coordinate description of FORCE Marine Renewable-electricity Area - Parcel B (Marine Renewable-energy Act, 2015, p49).

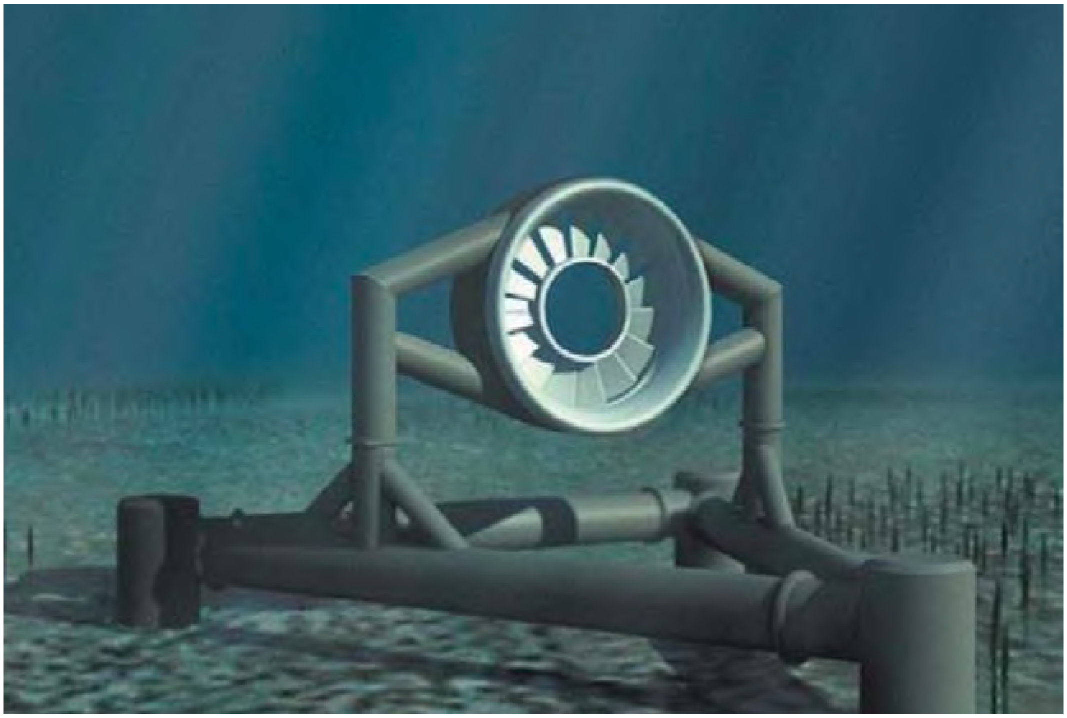
Appendix A-3 Location of the Fundy Ocean Resource Centre for Energy (FORCE) facility (Power Advisory LLC, 2019).

Appendix B Table of turbine placement for each tidal energy development project in the Bay of Fundy.

Project	Tidal Turbine Types	Turbine Features	Subsea Cable
Fundy Tidal Energy Demonstration Project (deployed data: 2009)	3 types of turbine devices are deployed: - OpenHydro **seabed-mounted** tidal turbines placed on the ocean floor of Minas Passage (Work Boat, 2021) - Clean Current placed on **seabed** (AECOM Canada Ltd, 2009; US Department of Energy, 2016). - Marine Current Turbine was with twin axial flow rotors placed on **ocean strata** through a quadrapod steel pin pile foundation (Fraenkel, 2011; Power Technology, 2014).	- OpenHydro: 1MW; 30 revolutions per minute; dissipating heat from turbine self through gravity base; require lubricants and dielectric insulating fluid when the turbine and grid are disconnected (AECOM Canada Ltd, 2009). - Clean Current: 2.2 MW; 5 m below the ocean surface; 10 to 18 revolutions per minute, and will generate buzzing noise when spinning; non-stick silicone based coating and marine anticorrosion epoxy coating is used to prevent biofouling for 5 years (AECOM Canada Ltd, 2009). - Marine Current Turbine: 1-1.2 MW; 12 revolutions per minute, and spin of the rator	Total three separate submarine electrical cables were connected to each turbine device to the onshore generator (AECOM Canada Ltd, 2009). The length of the cable corridor from turbine devices to onland vault was approximately 1.25km; and the occupied area is around 0.15 ha (AECOM Canada Ltd, 2009). Each cable was able to carry current up to 34.5 kV (AECOM Canada Ltd, 2009).

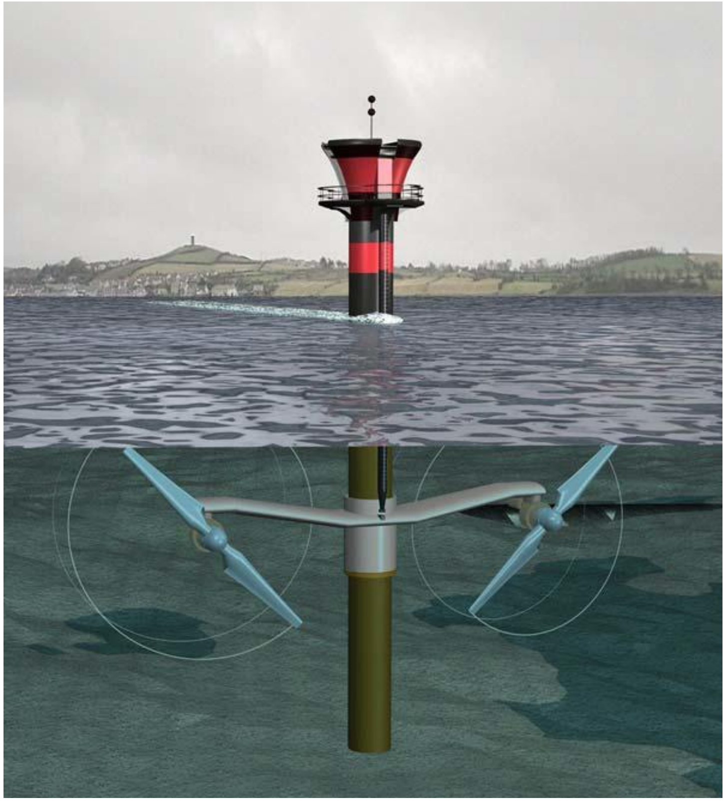
		will generate noise; steel pin pile foundations were drilled to the seabed (AECOM Canada Ltd, 2009).	
Big Moon Canada Corporation (plan to deploy in 2021)	Kinetic Keel **in-stream** tidal turbine (on land generator connected to deck barge by marine rope) (Gorman, 2016)	Kinetic Keel is rated to 1 MW; the proprietary barge and land-based generator are connected by a high-strength rope (Big Moon, n.d.; Gorman, 2016). A total of five turbines will be installed. Tides flow will cause the barge to move within the operation area. The barge operation diameter is 5 nautical miles from the land-based generator (Gorman, 2016). There will be submerged rope (3m below ocean surface) connecting the barge and Kinetic Keel.	Currently no distinct information about the submarine cable for BMP.
Pempa'q In-stream Tidal Energy Project (plan to deploy in 2021)	PLAT-I 6.40 trimaran designed **floating** in-stream turbine (Sustainable Marine Energy)	PLAT-I 6.40 is trimaran hull platform connected to six 70 kW instream turbines; and the platform is fixed through catenary mooring (Sustainable Marine, 2021). A total of three platforms will be installed.	Subsea electrical cables connect to the platform through a slip ring system (Sustainable Marine, 2021). Mooring lines move as the platform moves. 11 km subsea cable network

Appendix C Different tidal turbine models deployed in different projects



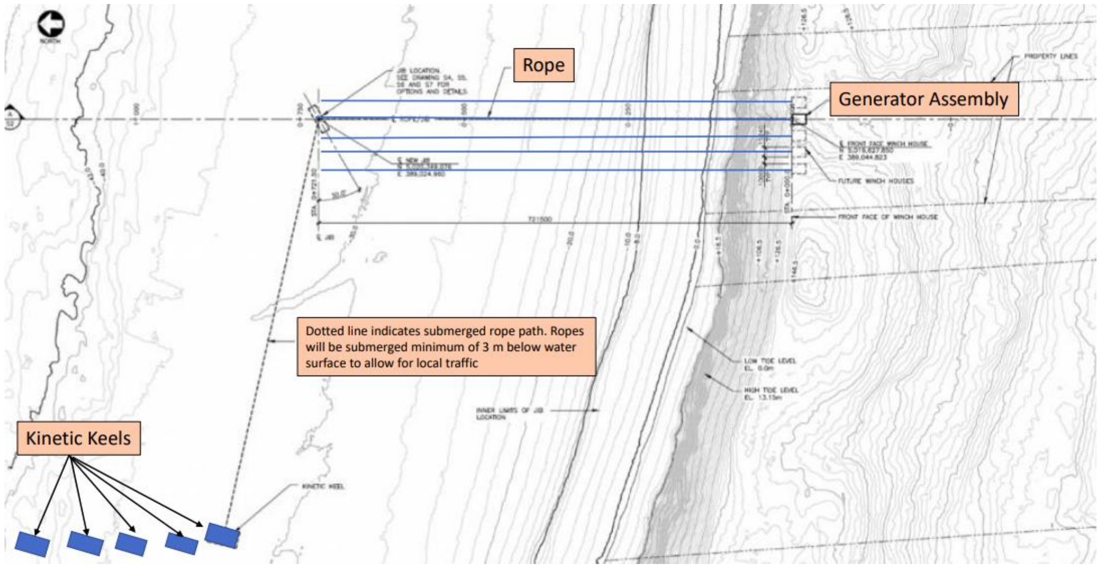
Appendix C-1-1 OpenHydro tidal turbine (Nguyen, 2019).

Appendix C-1-2 Clean Current tidal turbine (AECOM Canada Ltd, 2009).

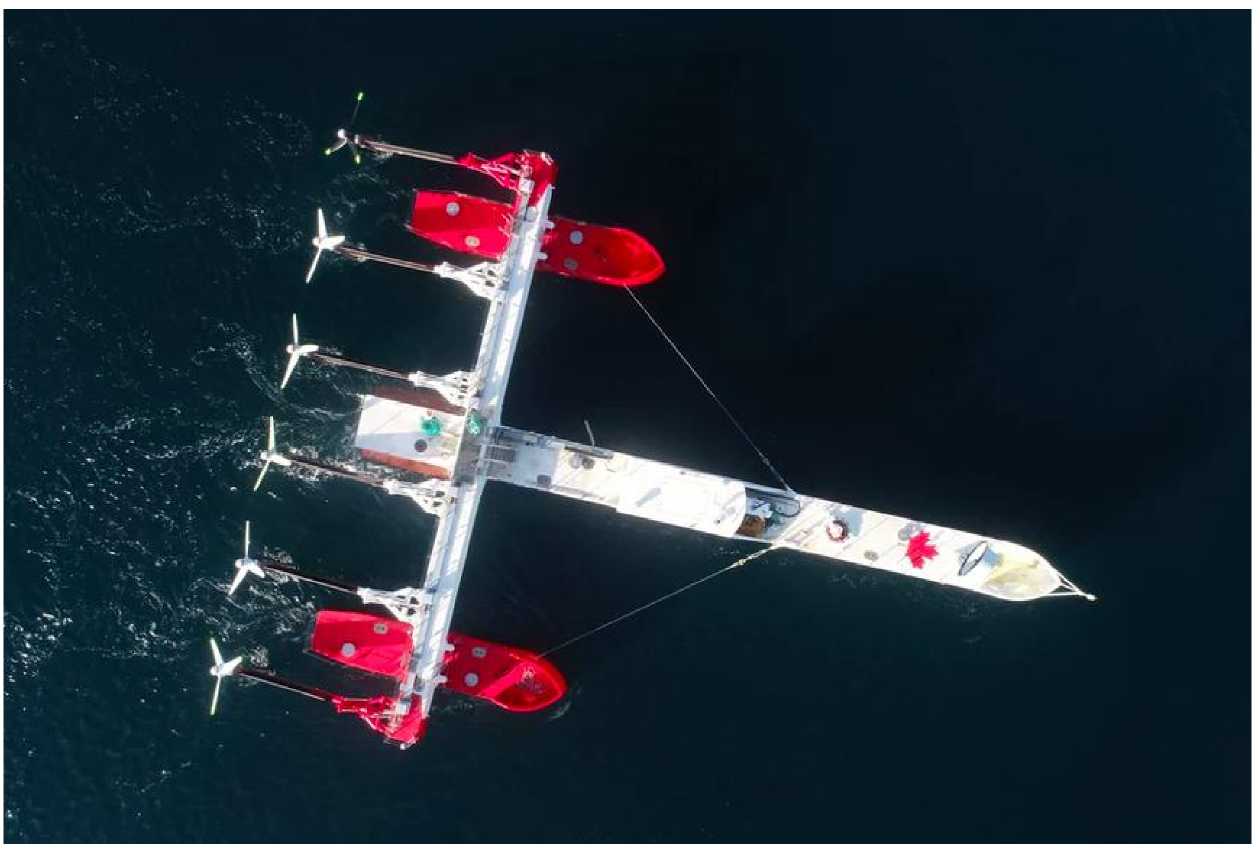


Appendix C-1-3 Marine Current tidal turbine (AECOM Canada Ltd, 2009).

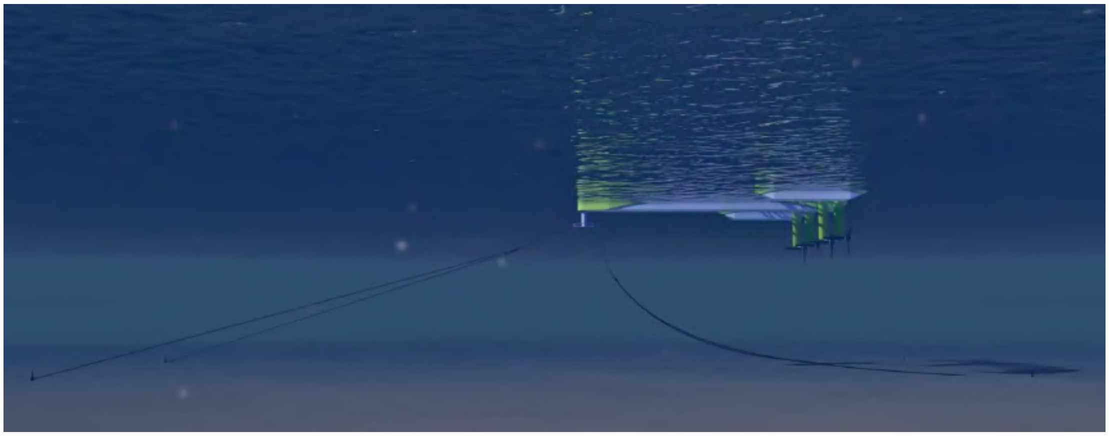
Appendix C-2-1 Kinetic Keel in-stream tidal turbine (BigMoon Power, 2021)



Appendix C-2-2 The diagram of the installation mode of Kinetic Keel in-stream tidal turbine (Big Moon, n.d.).



Appendix C-3-1 PLAT-I 6.40 floating tidal turbine (Sustainable Marine Energy, 2021).



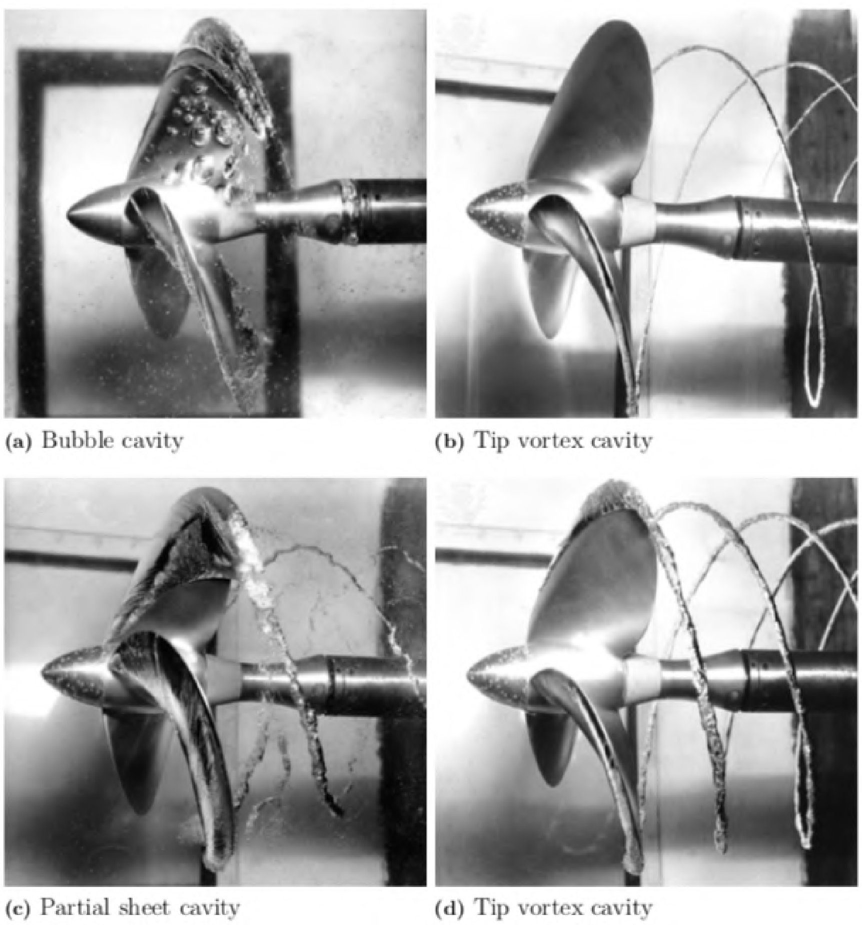
Appendix C-3-2 The diagram of the installation mode of PLAT-I 6.40 floating tidal turbine (Sustainable Marine Energy, 2021).

Appendix D Tidal Energy Turbine Fouling

Appendix D-1 The situation of microorganism colonization of a 521 days floating spherical buoy (NOAA, n.d.).

Appendix D-2 Six-month recording of fouling organisms on tidal turbines (Fletcher, 2007).

Appendix E Cavitation bubbles generated by different tidal turbine operation model (Gharraee et al., 2016, p13)



(a) Bubble cavity (b) Tip vortex cavity

(c) Partial sheet cavity (d) Tip vortex cavity