UNIVERSITY OF CALGARY

Utilizing Wave Power as Green Energy for Remote BC Communities

by

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Abstract

The west coast of Canada has an abundance of potential wave energy. Currently there are many off-grid communities that do not take advantage of this renewable energy source and instead rely on diesel generators to fulfil their electricity needs. This study examines the viability of integration of wave energy converters into off-grid communities to lessen the reliance on fossil fuels for electricity. Implementation of a singular wave energy converter in the Tlatlasikwala community of Bull Harbour was estimated to yield 31.6 megawatt hours of electricity a year or around 13.3% of the yearly demand. Analysis of the economic viability through calculating payback periods using the average cost of wave energy converters and the fuel savings from renewable energy generation over a 20-year project life noted a requirement of funding by grants to recover costs. Included is a review of the current and proposed environmental concerns regarding wave energy converters.

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Thanks to the Tlatlasikwala First Nation for sharing their information with me, allowing for this research to occur.

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List of Abbreviations

BC	British Columbia
BCBN	BC Bioenergy Network
EIA	Environmental Impact Assessment
GHG	Greenhouse Gases
km	Kilometer
kW	Kilowatts
kWh	Kilowatt hours
MWh	Megawatt hours
NRCan	Natural Resources Canada
O&M	Operation and Maintenance
WEC	Wave Energy Converter

Chapter 1. Introduction

1.1 Research Purpose

The purpose of this research project is to get a better understanding of the potential for wave energy converters (WEC) to replace energy currently supplied by diesel generators, their economic potential, and environmental impact for Bull Harbour, a small off-grid indigenous community on British Columbia's (BC) west coast.

1.1.1 Research Question

"Can wave power electricity generation be used in Bull Harbour, British Colombia as a viable replacement for diesel generators?"

1.1.2 Importance of research question

More than 90% of BC's electricity comes from renewables sources, primarily hydro (BC Hydro, 2018). However, not all residents of BC have access to this clean energy grid, and many off-grid communities use diesel generators to satisfy their electricity needs (Government of Canada, 2011). Some of these communities have been looking for possible alternatives such as wind, hydro, and solar (Government of Canada, 2011; Tlatlasikwala Nation, 2018). Added to this list of energy sources should be ocean wave power, as the west coast of Canada has been identified to have some of the greatest potential for wave energy in the world (Khan, Kalair, Abas, & Haider, 2017).

I propose a system whereby WECs are tied into the existing diesel run system in order to lessen the carbon footprint of coastal off-grid BC settlements. This will help to answer whether WECs are capable of generating sufficient energy in a cost effective and environmentally conscientious manner to act as a viable option for replacement of diesel systems in remote off-grid settlements in British Colombia.

Currently, studies have looked into the viability of using wave power in Haida Gwaii (Boronowski, 2009), and the Ucluelet area on Vancouver Island (St. Germain, 2005). However, both of these studies look into the use of wave power tied into existing grids of 1,500 customers or more. This leaves the question of how smaller grids can take advantage of wave power.

On Hope Island off the north end of Vancouver Island is the Tlatlasikwala First Nation community of Bull Harbour (see Figure 1). The self reported population is 65 (Tlatlasikwala Nation, 2018) and they have an electricity demand of 27 kilowatts currently being met by a team of two diesel generators (Barth, personal communication, Jan 8, 2018) leading to a yearly consumption of 236.5 Megawatt hours (MWh). This community has been selected due to their small energy requirements, coastal location, and interest in having such a study performed.

Figure 1. Location of Bull Harbour

Adapted from (Google Maps, 2018)

The purpose of this study, as described by the research question, is to assess the potential and possible impacts of implementing a WEC project for Bull Harbour.

1.3 Three Dimensions of Study

This study focuses on three aspects of a WEC project: energy, economics, and the environment.

1.3.1 Energy

After comparing and contrasting some WEC designs to determine what would be a best fit for Bull Harbour, an analysis on electricity production was conducted to create an energy hindcast. Wave data was used from the wave buoy C46204 - West Sea Otter north west of Bull Harbour and the calculated power matrix from SeaBased WEC. This hindcast was then compared to the energy needs of Bull Harbour to analyze how much fuel savings the WECs led to. Results are presented in Chapter 5

1.3.2 Economics

Determining if the project saves the Tlatlasikwala First Nation money or not is a huge factor in the viability of a WEC project. Using information on the capital costs, operation and maintenance (O&M) costs, energy production hindcast, and the costs of diesel fuel for the community an analysis was performed to calculate the payback period. The impact of accessing the possible grants available for the project was also considered. Results are discussed in Chapter 6.

1.3.3 Environment

Wave energy is still a fairly new technology and the environmental impacts are not fully understood (Leeney, Greaves, Conley, & O'Hagan, 2014). With the variation of size and design, different models of WECs, as well as the nature of the project area location will give rise to different environmental challenges. I have discussed some of the possible impacts that should be considered if a WEC project is to be developed. Additionally, in the case of Bull Harbour, greenhouse gas (GHG) emissions from burning diesel will be avoided by energy created by the WEC. I have calculated the GHG emissions reduction that would arise from a WEC installation in Bull Harbour for one year. Results are presented in Chapter 7.

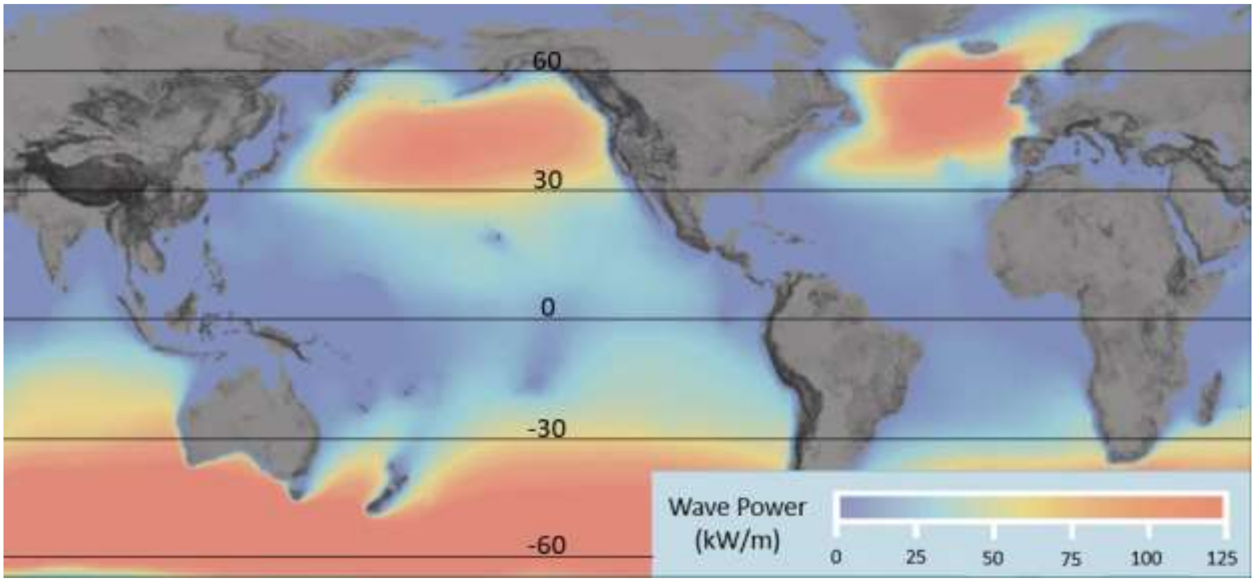
Chapter 2. Background

2.1 Wave energy and Canada’s potential

Canada’s Pan-Canadian Framework on Clean Growth and Climate Change discusses many strategies for Canada to meet their emissions reduction goals. Among those goals are increasing the amount of renewable electricity generated and reducing the reliance on diesel fuel by remote communities (Government of Canada, 2016). Most of the renewable energy in Canada has come from hydro, wind, biomass, and solar, with the majority coming from hydro (Natural Resources Canada, 2018b). With the emphasis on more conventional renewable energy, this has left the ocean’s energy largely unexploited.

Canada has taken steps towards harnessing the energy of the oceans starting with the tidal power projects of the east coast (Clark, 2015). However, Canada’s Maritimes are not the only places with abundant potential energy, estimates of the total possible wave energy off of the length of Canada’s west coast average roughly 37 Gigawatts, keeping in mind this figure does not account for the fact that it would be impossible to convert all of the wave energy to electricity (Canadian Copper and Brass Development Association, 2018). Wave energy has a higher energy density (Watts/meter^2) than wind or solar power, meaning more energy can potentially be taken in smaller scale projects (Mollison, 1986; Robertson, Bailey, & Buckham, 2017). As can be seen in Figure 2, there are areas with higher wave energy. Wave energy is greatest between 40 and 60 degrees of latitude (Khan, Kalair, Abas, & Haider, 2017). Wave power peaks in the winter months, which is beneficial for a climate like Canada where electricity demand also peaks in the winter (Robertson, Bailey, & Buckham, 2017). This is a particularly helpful trait because energy production rises naturally with energy demand, which would help smooth out energy demand changes for electricity from conventional fossil fuel sources.

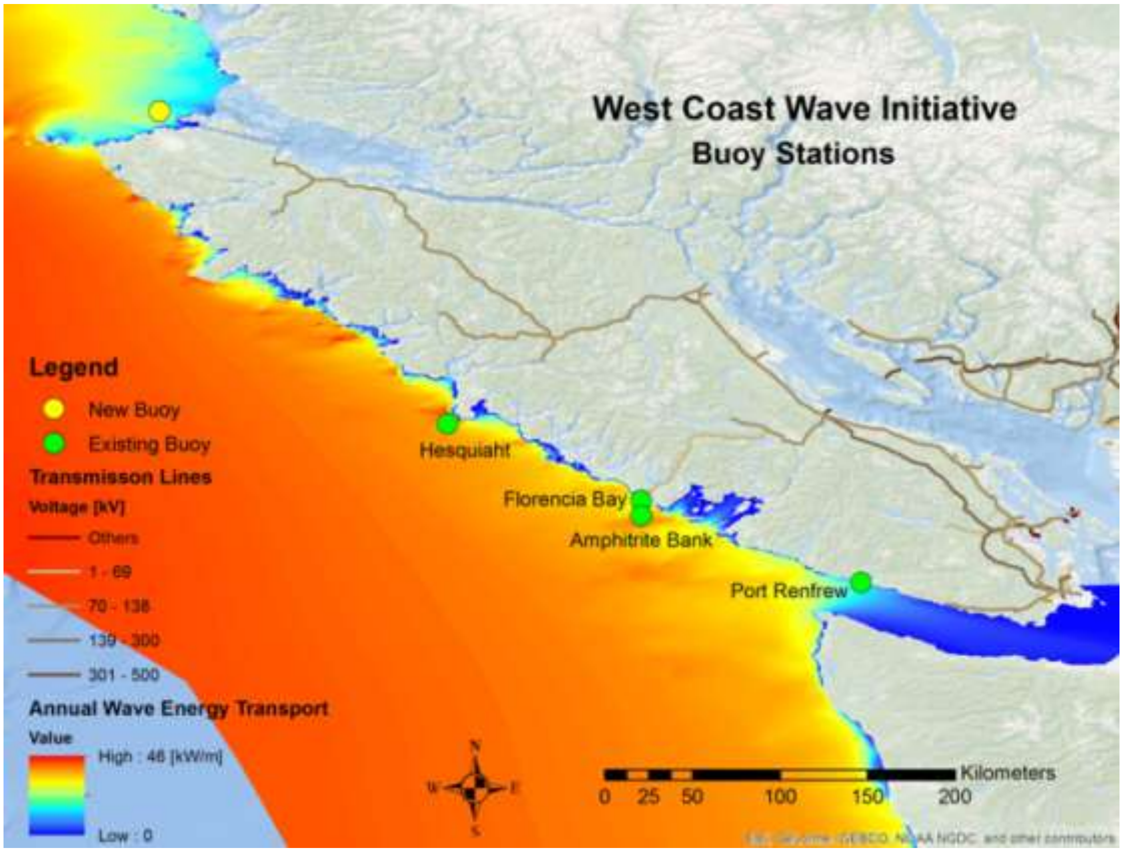
Figure 2. Global wave energy resource



Adapted from (Ocean Energy Systems, 2018)

The west coast of Vancouver Island has been a focus for assessing the available wave power of Canada by the West Coast Wave Initiative (2016). They have been launching wave buoys around the island as can be seen in Figure 3, and are currently working on getting another wave buoy very close to Hope Island (Robertson, personal communication, June 19, 2018), which once deployed, should be able to generate excellent data for further investigation into the feasibility of wave power for Bull Harbour and Queen Charlotte Sound.

Figure 3. Map of calculated annual wave energy around Vancouver Island and wave buoy locations



(West Coast Wave Initiative, 2016)

2.2 Wave characteristics and behaviour

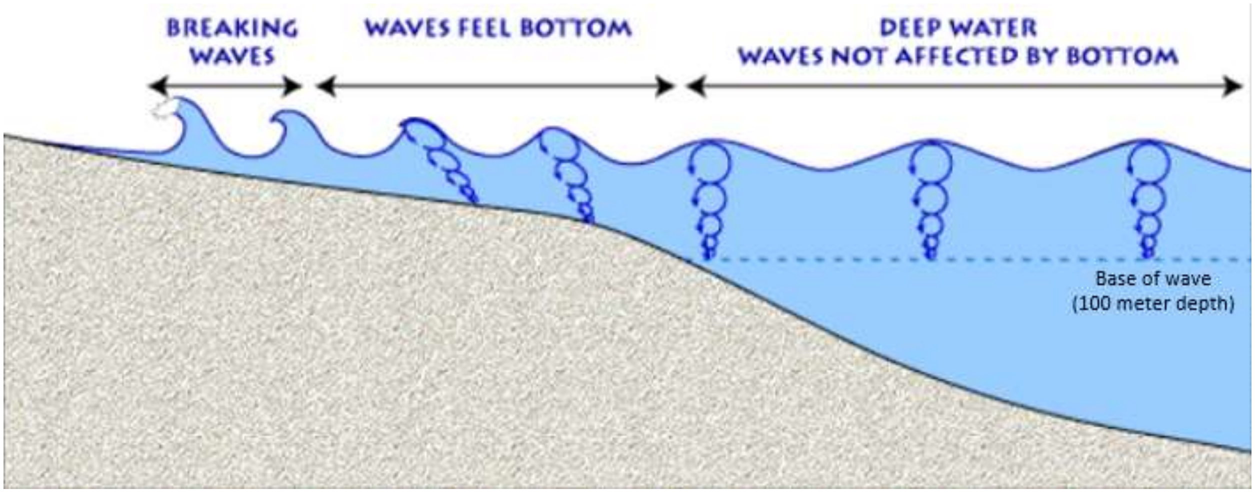
The power of a wave can be calculated through the equation:

$$P = \frac{\rho g^2 T H^2 L}{32\pi}$$

Where P is power expressed in Watts, ρ is the density of water, g is the acceleration of gravity, T is the wave period, and H is the wave height, and L is the length along the crest of the wave (Thorpe, 1999). Power in this instance, is the transfer of energy as water moves through a vertical plane parallel to the wave crest, the energy is seen as kinetic and potential energy as the water moves with and against gravity over the cycle of a wave (Thorpe, 1999). From this equation it is apparent that the two variables determining wave power in a specific area are the height and period of waves, with the height being a greater influence. It is of great import that we understand how these two characteristics change as waves travel so any WECs can be optimally placed.

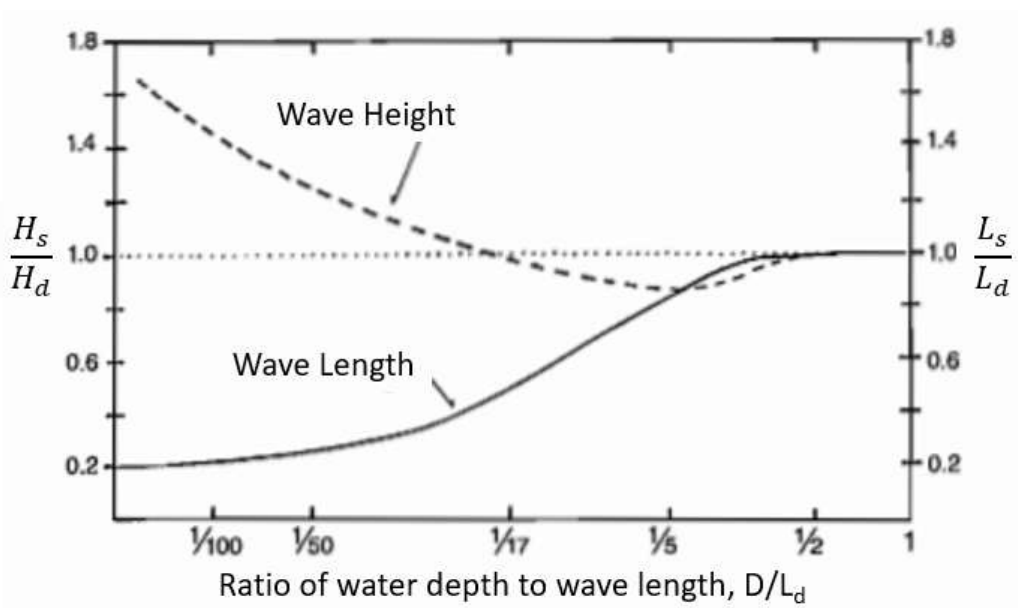
Major changes occur when waves move from deep water to shallow water. Since wave depth is half of the wave length, waves begin to be affected by the sea floor as they move into shallow water. The base of the wave is therefore used to delineate shallow water and is often regarded to be about 100 meters in depth (Jarocki, 2010) this can be seen in Figure 4. This interaction, known as shoaling, causes the wave to: slow down relative to the depth, (Thomson, 1981) increase the wave height, decrease wave length, while keeping a constant wave period (Jarocki, 2010). Wave height decreases slightly at depths of one half the wave length but increases rapidly at a depth of one seventeenth the wave length (Figure 5), until the wave becomes unstable and breaks, dissipating the energy (Jarocki, 2010). It is, therefore, advantageous to either select a location in shallower waters where the wave height is increased but before the area in which waves normally break to optimize energy availability or in deep enough water to avoid having peak wave height being diminished by shoaling, resulting in sub optimal energy outputs.

Figure 4. Wave depth and sea floor interaction



Adapted from (U.S. Geological Survey, 2017)

Figure 5. Change in wave height and length with change of depth



Adapted from (Jarocki, 2010). H_s is the shallow depth wave height, H_d is the deep depth wave height. L_s is shallow water wave length, L_d is deep water wave length, D is depth.

2.3 WEC types

The European Marine Energy Center (2018) has identified nine categories of WEC (eight of which are displayed in Figure 6):

A. Attenuators, which lay parallel to wave direction and absorb energy as the waves cause joints in the design to flex. The power-take-off is located within the arms on either side of the joint. Attenuators are generally deployed at a depth of 50 to 70 meters (Pelamis Wave Power, 2018).
B. Point absorbers, which use a tethered floating structure that heaves and surges (moves vertically and laterally) in the waves. This set up allows the device to absorb waves coming from any direction. Motion is used either by a power-take-off located on the sea floor or within the floating structure. Point absorbers are generally deployed in water between 20 and 100 meters in depth, however there are floating designs that can operate at deep open ocean conditions (Babarit, et al., 2012; Royer, 2015).
C. Oscillating wave surge converters, in which at least one large panel is oriented perpendicular to the wave direction. The panel is mounted on a pivoting joint and is pushed back and forth by wave surge, this action is converted to electricity by the power-take-off in the base of the structure. When affixed to the ocean floor, oscillating wave surge converters must be located relatively close to shore in depths of around 13 meters, but there are floating designs that can operate in deep open ocean conditions (Babarit, et al., 2012).
D. Oscillating water columns, which are hollow structures that are partially submerged with an opening to the ocean located below the surface of the water. There is an opening to the air with a turbine located in the structure. As the waves cause the water column within the structure to rise and fall, air is forced through the turbine which generates electricity. Designs such as this are located at or very close to shore, there are

floating designs that can be deployed in deep open ocean conditions (Babarit, et al., 2012; European Marine Energy Centre, 2018).

E. Overtopper/terminators, which have a ramp oriented perpendicular to the wave direction. As waves hit the ramp, water spills into a storage reservoir that has a drainage through a low-head turbine back into the ocean, the turbine generates electricity. Overtopper/terminators can be fixed to the shoreline or floating in depths of 20 meters or more (IRENA, 2014; Wave Dragon, 2018).

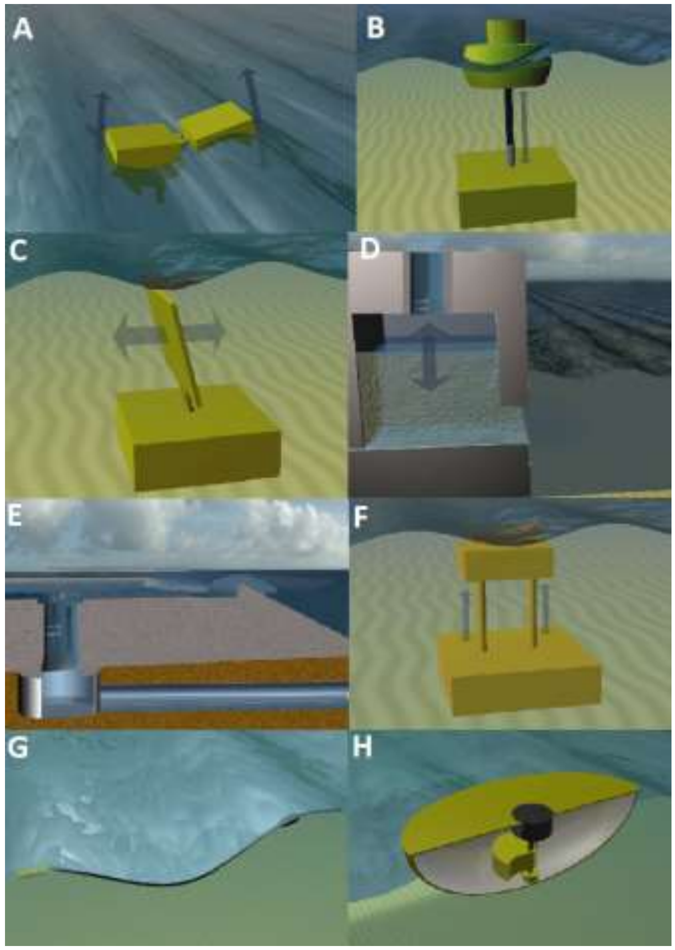
F. Submerged pressure differential devices, which are mounted on the ocean floor. As waves roll over them, the sea level rises and falls above the device which induces a pressure differential in the device. Pressure pumps within the device pump fluid through a power-take-off, generating electricity. These devices use a depth of at least 25 meters (AWS, 2018).

G. Bulge wave devices, which are rubber tubes oriented parallel with the wave direction and floating just below the surface. They are open at either end allowing water to enter them, as waves pass over the tube, pressure variations are created throughout the tube making bulges. As the bulges travel down the tube, it absorbs more energy and grows which forces the water out the end of it where a low-head turbine is located to generate electricity. Devices can be installed at depths between 40 and 100 meters (Clark E. , 2008).

H. Rotating mass devices, which heave and sway in the waves. Within them is a weight that rotates as the device sways in the waves, the circular motion is used to generate electricity. These devices are anchored at a depth of around 50 meters (Wello, 2018).

I. Other, which is just a category to cover designs that differ from the more established technologies above.

Figure 6. WEC technology designs



Adapted from (Aqua-RET, 2012)

2.4 Prediction of energy

A huge benefit wave energy has over wind and solar energy is that it is more predictable (Robertson, Bailey, & Buckham, 2017). In a study by Reikard, Robertson, and Bidlot (2015) errors of predicting energy from waves six hours away ranged 11-13%, where as wind and solar had an error rate of 77% and 93% respectively. Wave energy comes from two sources, swells and local conditions (Zheng, Sun, Guan, & Shao, 2015). In order to successfully predict total wave energy, one must be able to accurately predict both elements.

A storm or windy conditions in the ocean will create swells that propagate through the ocean. When a significant storm occurs somewhere in the same water basin one can predictably calculate the swells from a known event and when they will arrive (Reikard, Robertson, & Bidlot, 2015). For the area around Vancouver Island, the swell accounts for 50-80% of the wave energy (Zheng, Sun, Guan, & Shao, 2015). The other portion of the wave energy is from the local wind conditions which have seasonal changes in strength, allowing for seasonal average wave energy prediction (Zheng, Sun, Guan, & Shao, 2015). Combining predictions of these elements can lead to predictions of the total wave energy in a localised area. Alternatively, the total wave energy of a site can be predicted using empirical or physical models. Empirical modeling utilizes recent observations of a singular wave variable and looks for patterns or trends to estimate what that variable may look like in the near future. Physical models such as SWAN or WAVEWATCH III utilize complex algorithms and meteorological data from a larger area to calculate interactions between factors and predict wave characteristics over long periods of time (Reikard G. , Robertson, Buckham, Bidlot, & Hiles, 2015). Empirical modelling techniques are more accurate for predicting energy from zero to six-hour time intervals, while physics models are better for time intervals past six hours (Reikard G. , Robertson, Buckham, Bidlot, & Hiles, 2015). Having predictable power helps make it cheaper for integration into a grid as less reserve power is required and ramping events are detected earlier (Robertson, Bailey, & Buckham, 2017).

Chapter 3. Literature Review

3.1 Viability of WEC Technology

Monds (2014) studied three designs of WEC technology and their theoretical performance at three locations in Canada. The first technology included was the WaveDragon, which is an overtopping technology whereby waves move up a ramp to generate low pressure hydro power. The second was the AquaBuOY, which is a free-floating point absorber, which rides the waves and uses the up and down motion to power a piston that creates pressure to spin a turbine. The last was the Pelamis attenuator, which is a series of tubes connected by hinges, and as the tubes go over the waves, the hinges move and convert that energy into electricity. Two of the sites examined were off the east coast of Canada at Hibernia and St. Johns, while the third site was by Tofino and Ucluelet. The performance criteria included their capacity factor, rated power, capital cost, O&M cost, cost of electricity, maturity of technology and survivability. The study weighted cost of electricity, maturity, and rated power the most heavily. The WaveDragon led in rated power with 7,000 kW, a factor that doesn't change between sites, compared to the 250 kW of the AquaBuOY or 750 kW Pelamis. Maturity was led by the Pelamis which was the only product with commercial projects. The cost of electricity did vary from site to site and was led by the AquaBuOY in all three sites due to its much lower capital costs. For all sites, Monds found the overall performance from best to worst to be WaveDragon, AquaBuOY, and Pelamis.

Robertson et al. (2016) used wave height and period as well as wind measurements from wave buoy information as inputs into the Simulation Waves Nearshore model to determine the promising sites for 50MW wave farms. The addition of wind measurements accounts for the local conditions that could generate additional waves, accounting for the other portion of wave energy. Criteria involved for choosing sites included proximity to shore; with 15 km from shore being the cut off due to the high costs of laying sea floor electric cables; as well as existing grid infrastructure. Robertson et al. noted wave energy is much higher in winter than in the summer due to the smaller wave sizes in the summer.

When determining how much wave energy is in a certain area, two methods are used: hindcasts, and models. Hindcasts are created using historical data, which is compiled and used as an assumption that, going forward, similar amounts of energy will be available. One of the issues with hindcasts is that occasionally there is data missing, Reikard, Robertson, Buckham, Bidlot, & Hiles (2015) found that physics model simulations are the best way to find missing values when weather buoys have extended data gaps due to equipment failures, and shorter gaps are better resolved with time series predictions. The benefit of developing and using a model is that continued use can allow for prediction of power generation during the project's operation, which can help with integration into the grid (Boronowski, 2009). Since WECs "max out" at certain wave strengths, they have a much smoother energy profile, making electricity output easier to predict than wave energy flux (Reikard G. , Robertson, Buckham, Bidlot, & Hiles, 2015). When using a model to predict power output, it is important to consider the time interval being considered. Empirical modelling is more accurate at predicting power output of WECs at shorter time periods whereas physics models are more accurate at long time periods (Reikard G. , Robertson, Buckham, Bidlot, & Hiles, 2015). This means that when predicting the energy output of deep water WECs up to three hours in advance, or up to six hours for shallow water WECs, time series data should be used. For longer time periods, physics models are more accurate predicting tools. As previously discussed, this predictive power is more accurate for WECs than for solar or wind generators, giving them an advantage for integration into grids.

3.2 Environmental Impacts

The west coast of Canada is rich in biodiversity (MacDuffee, 2011). As such there are many different animals that may interact differently with a WEC. Grey and humpback whales as well as orcas are known to live in the waters around Hope Island and Queen Charlotte Sound (COSEWIC, 2003; 2008; Fisheries and Oceans Canada, 2010). Better understanding of how these species will interact with WECs is needed to mitigate impacts to populations as well as damage to WEC devices (Boehlert, McMurray, & Tortorici, 2008).

Langton, Davies, and Scott (2011) sought to explore the impact tidal and wave energy devices may have on seabird populations through direct collisions, avoidance behaviours, and changes in or loss of habitat. Langton, Davies, and Scott note first that information on collisions is lacking, however show that the depth of many different wave and tidal technologies overlaps with the foraging range of diving bird species and so may have an effect. A consideration for the use of a submerged WEC versus one on that sits on the surface, especially one with moving parts. However, higher levels of lighting on floating surface structures of WECs could cause greater collision incidences with nocturnal foraging seabirds (Boehlert, McMurray, & Tortorici, 2008). Langton, Davies, and Scott (2011) also noted that many seabirds tend to prefer to go around developments than over them, which can have a physiological cost of forcing longer trips for foraging and migration. This should be a concern when introducing development to a green field site. And lastly, human developments tend to act as artificial reefs which cause aggregation of prey species as they try to hide from predators (Langhamer, Haikonen, &

Sundberg, 2010). This can bring about changes to the structure of the local ecosystem, as increased fish populations could increase predation pressure on benthic organisms (Frid, et al., 2012). It is unclear whether the impact will be positive or negative on foraging seabirds (Langton, Davies, & Scott, 2011). The increased aggregation could lead to greater numbers of prey species in the area which could help bird populations (provided they do not actively avoid the areas where fish are aggregating), or the development could cause unpleasant stimuli which drives prey species away. This would cause bird species to have to travel further to find food, which would have physiological implications where the energy balance and time-activity budgets of bird species would change. The size of the wave park will affect the extent of the impacts, i.e. whether it is a singular device or an array of dozens of WECs.

Observations during operation of wildlife in and around wave parks indicate little to no impact from underwater noise, however noise during installation and decommissioning are still a concern (Langhamer, Haikonen, & Sundberg, 2010). Noise levels can vary, as can the effects on wildlife, from no observable effect to severe psychological, behavioural, or physiological effects that can sometimes be permanent (Sarić & Radonja, 2014).

Current studies on the environmental impacts of WECs have only been conducted on small scale projects and therefore must be scaled up to be predictive on the impacts of commercial scale projects, there is a need for focused studies to be run in concert with development of large scale WEC parks in order to prove or disprove theories on impacts (Frid, et al., 2012; Greaves, et al., 2016).

Chapter 4. Methodology

This research examines the energy, economic, and environmental benefits and impacts of a WEC project for the Tlatlasikwala First Nation community of Bull Harbour. The system selection is based on discussion with a community representative to assess the energy needs of Bull Harbour. Once the WEC model was selected, an estimation of the energy available was calculated using data from a nearby weather buoy and the WEC design specifications. Once the electricity generation was calculated, this information along with estimations of fuel usage and cost were used to determine the yearly savings. These annual savings and additional information related to the costs of developing, building, and maintaining a WEC project were used to determine a payback period. Finally, fuel savings were used to calculate the avoided GHG emissions and a literature review, including existing Environmental Impact Assessments (EIA) was completed to compile possible environmental effects relevant to the proposed site.

4.1 Electricity production

Bull Harbour has a demand of 27 kW using an estimated 236.5 MWh a year; and this energy need is satisfied by a system of two diesel generators (not necessarily running at the same time). Additionally, there is not current infrastructure to store or sell excess energy (Barth, personal communication, Jan 8, 2018). Conversation with the community representative also revealed that there was a preference for looking at a previously tested and commercially viable technology (Barth, personal communication, Jan 8, 2018). A search through academic literature and company websites for WEC's with a power rating of less than 27kW, having at least one commercial project and some information on the required depths was conducted. Findings comparing various WEC technologies can be seen in Table 1. The SeaBased WEC was chosen based upon four criteria. Firstly, it's smaller capacity of 15 kW per unit (Rusu, 2014) fits better with the needs with the community. Secondly, the SeaBased system has relatively high efficiency for a WEC, with its actual power production, when compared to the maximum power production possible, being competitive, as can be seen in Table 1 (Diaconu & Rusu, 2013). Next was the ability to scale easily if required (SeaBased, 2018) was beneficial, and lastly the SeaBased system is a proven commercial technology with operating wave farms in Sweden and Ghana (SeaBased, 2018) thus meeting a critical requirement for the community.

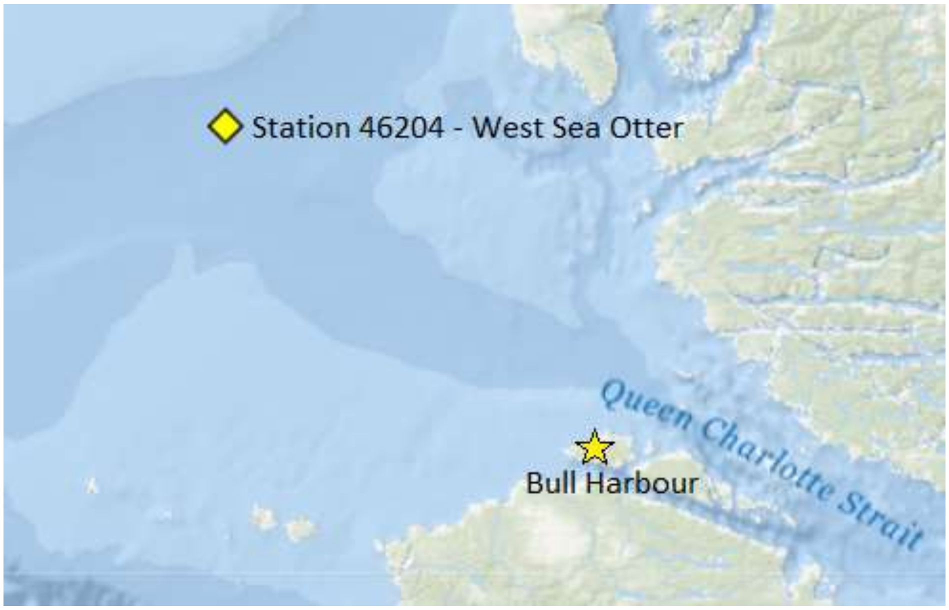
Table 1. Review of WEC technologies

Technology	Nationality	Power Rating (kW)	Commercial Projects	Efficiency (%)	Deployment Depth (m)
Archimedes Wave Swing	Scotland	25	No	2.42	40-100
Pelamis	Scotland	750	Yes	7.98	50-70
Aqua Buoy	Scotland & Ireland	250	No	6.37	>50
SeaBased	Sweden	15	Yes	10.52	16-100
Wave Dragon	Denmark	7000	No	5.6	30-50
Langlee	Norway	1665	Yes	3.98	Deep
Oceantec	Spain	500	No	19.21	30-50
Ocean Energy Buoy	Ireland	2800	No	3.36	Deep
Pontoon Power Converter	Norway	3620	No	4.54	Deep
CETO 5	Australia	240	Yes	Not available	20-50

Information on Archimedes Wave swing from (AWS, 2018), Pelamis from (Pelamis Wave Power, 2018), Aqua Buoy from (Boronowski, 2009), Seabased from (Chatzigiannakou, Dolguntseva, & Leijon, 2017; SeaBased, 2018), Wave Dragon from (Wave Dragon, 2008), Langlee from (REF, 2017), Oceantec from (Oceantec, 2017), OE Buoy from (Ocean Energy, 2017), Pontoon Power converter from (Pontoon Power, 2012), CETO 5 from (Carnegie, 2018), Efficiencies from (Diaconu & Rusu, 2013), Information on deployment depths and power ratings from (Rusu, 2014)

In order to calculate the amount of power that could be generated using the SeaBased System, an estimate of the available wave energy was required. Information regarding the significant wave height and average wave period was taken from the C46204 - West Sea Otter wave buoy in water of 222 meters of depth, located 77 kilometers (km) northwest of Bull Harbour as seen in Figure 6. Bathymetric maps of C46204 – West Sea Otter and Hope Island can be seen in Appendix A. Data was taken for the 2016 year as it was more complete than the 2017 data set, while remaining recent. The buoy takes hourly measurements of wave, water, and meteorological conditions and has a record going back to 1989 (Fisheries and Oceans Canada, 2018). Of particular importance for this research is the significant wave height; which is defined as the average of the highest third of waves measured tough to crest for that hour (National Weather Service, 2018a); and the average peak wave period; which is the average time between the most energetic waves (National Weather Service, 2018b). For the purposes of this study, we will assume WEC is located north of Hope Island in water 80 to 100 meters deep, this is to avoid the sheltering effects of the island and islands to the west (Figure 7) as well as friction losses from shallow waters to the west (Figure 15) the effects of which can be seen in Figure 3, and negative shoaling effects (Figure 5). It will also allow energy production results to be indicative for other remote settlements around Queen Charlotte Sound. These data were then used in combination with a product specific power matrix. A power matrix is a model output from the design specifications of the WEC that states the average energy output of the WEC during different combinations of wave periods and heights. The Significant Wave Height and Average Peak Wave Period are used to find the average power output for that hour within the power matrix. From this the average monthly power output of the device was determined, as was the estimated the yearly power output by a SeaBased WEC. The results are discussed in Chapter 5.

Figure 7. Location of weather buoy



Adapted from (National Data Buoy Center, 2018)

4.2 Economics

Comparing the average electricity output of a diesel generator per unit fuel to the electricity production calculated from the previous step results in the determination of the fuel savings for Bull Harbour. For this the price the Government of British Columbia has agreed to supply bulk diesel to coastal communities of $0.37/litre (Government of Canada, 2011) and the electricity output for the average generator of 1 MWh per 269.1 litres of diesel (Diesel Service & Supply, 2017) was assumed to calculate the savings generated by the WEC.

The capital and operational expenditures for the project were taken from a study by Ocean Energy Systems (2015) who had done a survey of the different WEC technologies to discern the average capital and operational expenditures per kW capacity. Using their range of costs, high, mid and low-cost scenarios were developed and the revenue of a project lasting 20 years was determined.

Additionally, the possibilities for financial assistance with a WEC project for Bull Harbour was assessed, and then ran the Low-cost scenario against different levels of funding that cover capital costs for the project to determine payback periods.

4.3 Environmental considerations

Using the fuel savings information, the approximate avoided direct GHG emissions per year was calculated. In addition, an examination of existing EIAs and academic literature was conducted to understand what kinds of environmental impacts different WECs have. These were compiled into a chart for easy comprehension and reference. Short and long-term noise pollution, shading effects, and electromagnetic effects on wildlife and the environment were considered.

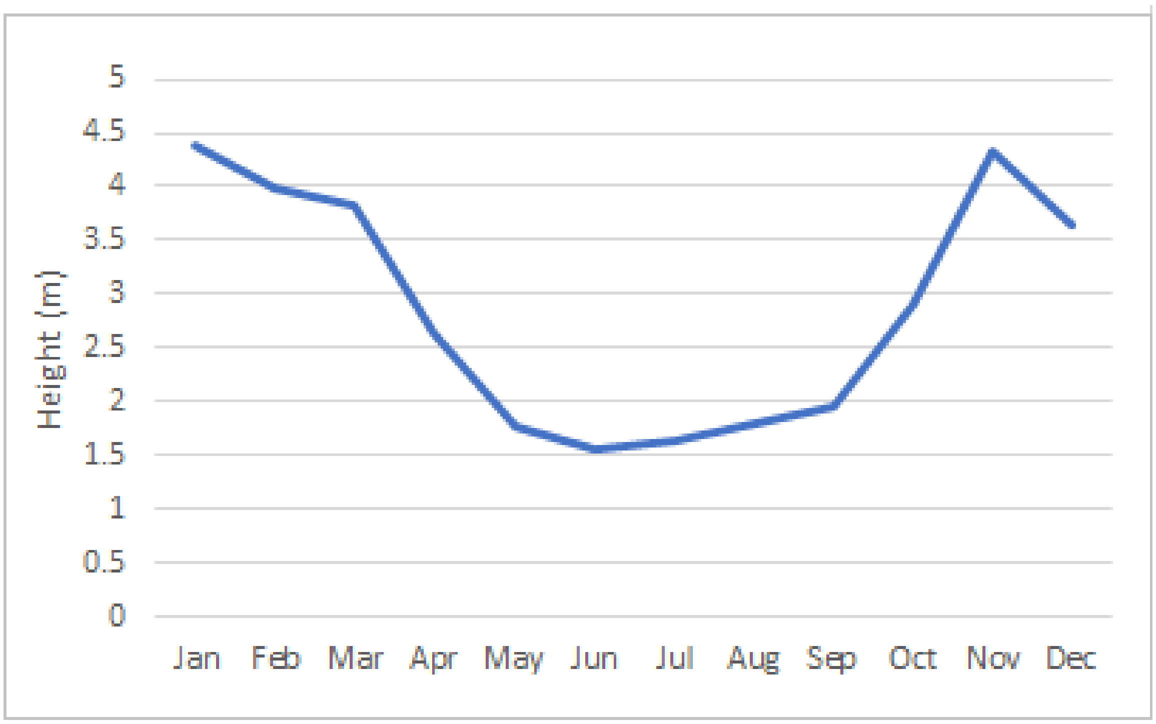
Chapter 5. Energy Hindcast

In order to successfully estimate the WEC's electricity generation, information on height and period of the waves was synthesised with technical specifications from the WEC.

5.1 Energy from the waves

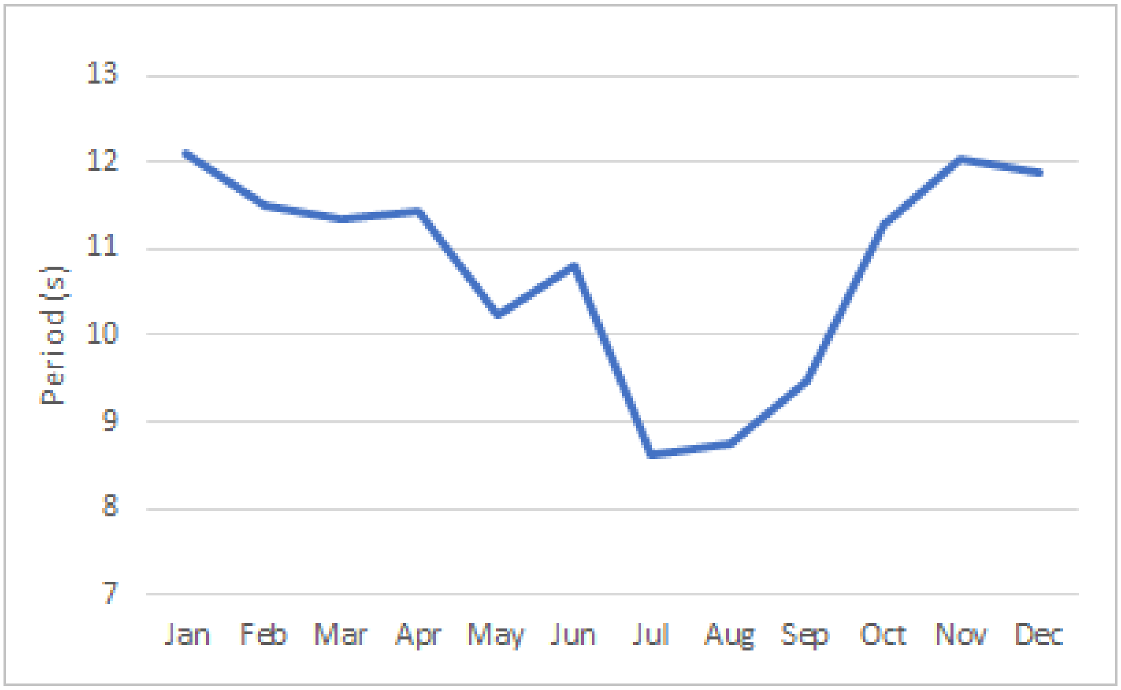
The first step required downloading the wave information from Fisheries and Oceans Canada (2018). Data from the year 2016 used, as it was the most recent year with a more complete data set. From Figure 8 and 9 we can see that potential wave energy seems to be more plentiful in the winter months than the summer as characterized by the larger Significant Wave size and longer wave periods. Also taken from the buoy data was the average wave period, which follows a similar pattern as Significant Wave size increases so does the average wave period as seen in Figure 9.

Figure 8. Monthly average wave height recorded for 2016



(Fischer, 2018)

Figure 9. Monthly average wave period recorded for 2016



(Fischer, 2018)

5.2 SeaBased WEC design and energy potential

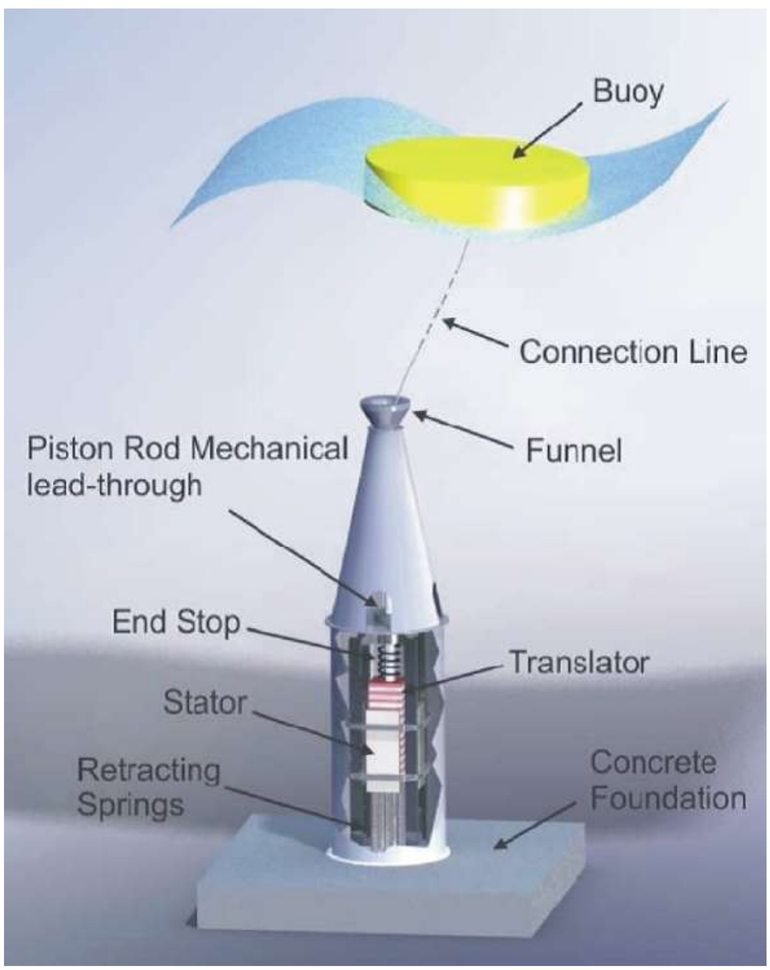
5.2.1 The Company

SeaBased is a wave energy developer out of Sweden with experience planning, building installing, and connecting wave energy (SeaBased, 2018). Founded in 2001, SeaBased has grown to have projects in Sweden, Finland, Ghana, and recently announcing a project in the Canary Islands (Ingram, 2018; SeaBased, 2018).

5.2.2 SeaBased Design

The SeaBased WEC is a point absorber or bottom referenced heaving buoy design (Babarit, et al., 2012). The design has a machine stand attached to a concrete foundation that keeps it anchored to the sea floor. A buoy at the surface is connected to a wire that attaches to a linear generator inside the machine stand, as can be seen in Figure 10. As the waves cause the buoy to heave and surge, the translator is moved within the device, generating electricity (Vattenfall, 2009). The electricity flows to an underwater switchgear that converts the current to one suitable for the grid, that then flows through cable along the sea floor to shore where it connects to the local grid (SeaBased, 2018). The simplicity of the design helps to cut down on O&M costs and make installation easier (SeaBased, 2018). The switch gear can be connected to multiple SeaBased WECs, so costs of developing a larger wave park are cut down and the installation is still a simple plug-and-play if a wave park wants to expand after initial development (SeaBased, 2018).

Figure 10. SeaBased design

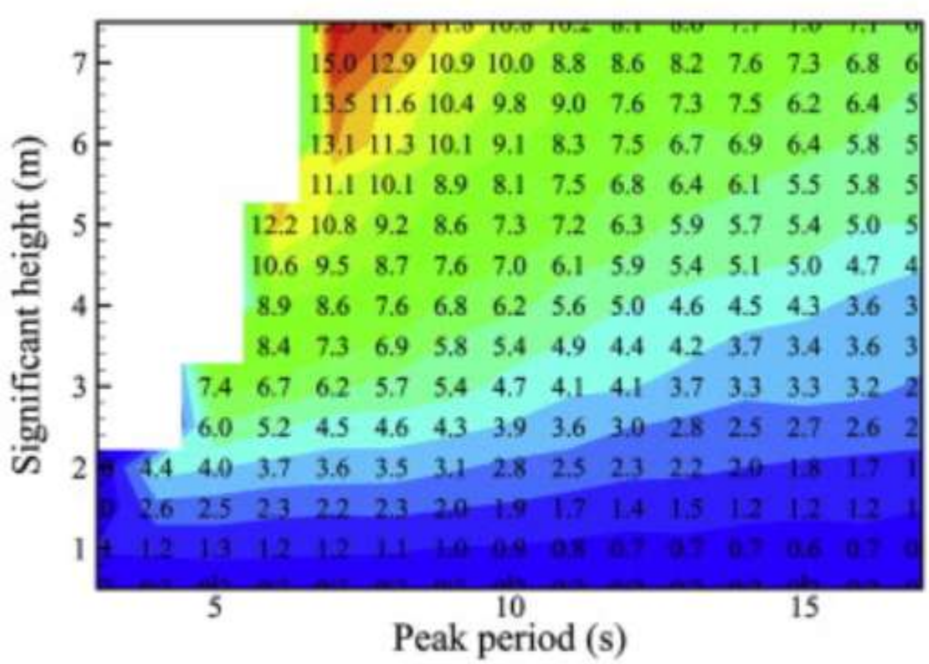


(Chatzigiannakou, Dolguntseva, & Leijon, 2014)

5.2.3 SeaBased electricity generation

A single SeaBased WEC is rated as having a 15 kW capacity, however the actual electricity generation is influenced by a number of factors. Babarit et al. (2012) found that the Seabased WEC electrical output was subject to uncertainty from optimization of the length of the wire (avoiding having slack or submerging the WEC), and energy losses from viscous dampening and the where kinetic energy is converted to electrical energy, also known as the power take off. Additionally, high tides could reduce power absorption by 30%, but low tide could increase it by 8%. The power matrix showing the average power generation at various sea states and factoring in tide changes (in a similar latitude of 46.7°N verses 50.9°N at Hope Island), dampening loss and optimal wire length for the SeaBased WEC is shown in Figure 11. A full summary sheet for an approximation the SeaBased WEC is available in Appendix B.

Figure 11. Seabased power matrix with average power output (kW) for combinations of Significant Wave Height and Peak periods

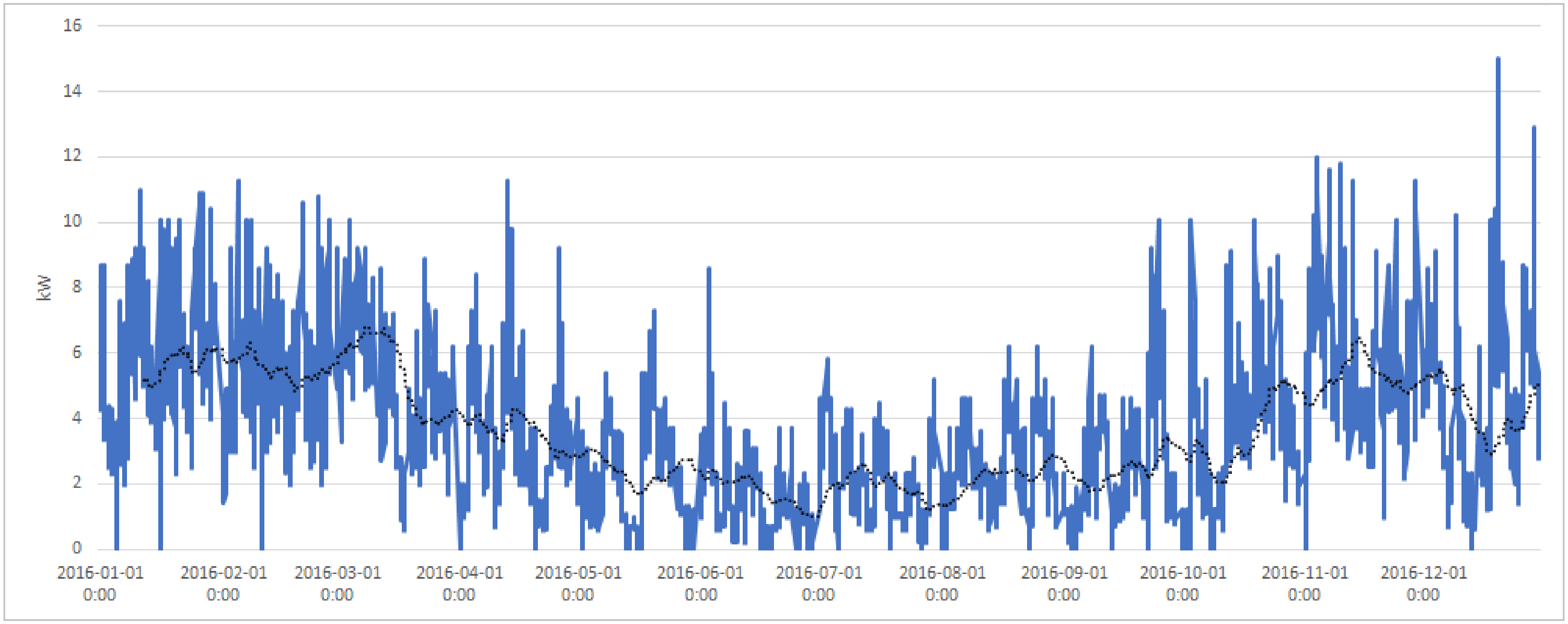


(Babarit, et al., 2012)

5.3 Electricity Output

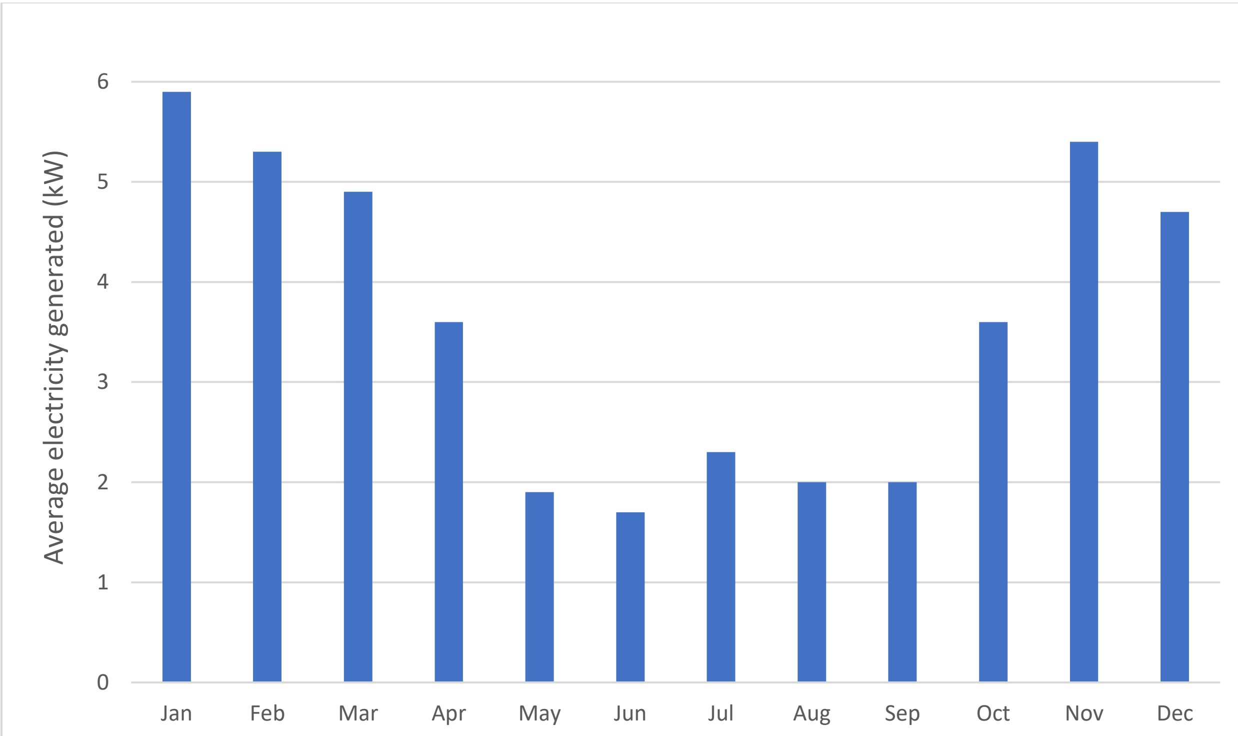
Using the power matrix and hourly reports of Significant Wave Height and Significant Wave Period, an hourly report for how much electricity the SeaBased WEC could generate was constructed. To account for shadow effects by Hope Island and Vancouver Island, the wind direction was assumed to be the dominant wave direction. When wind was directed Northwest or North (between 303-360°), the wave height was assumed to be half the recorded wave height from C46204 - West Sea Otter. Figure 12 shows the electricity hindcast for 2016 which was used as a typical year with a moving average of around 10 days used to help illustrate the average energy production throughout the year. Figure 13 illustrates the monthly average for electricity generation.

Figure 12. Calculated electricity generation by SeaBased design for Bull Harbour, 2016



(Fischer, 2018)

Figure 13. Calculated average electricity generated per month in 2016



(Fischer, 2018)

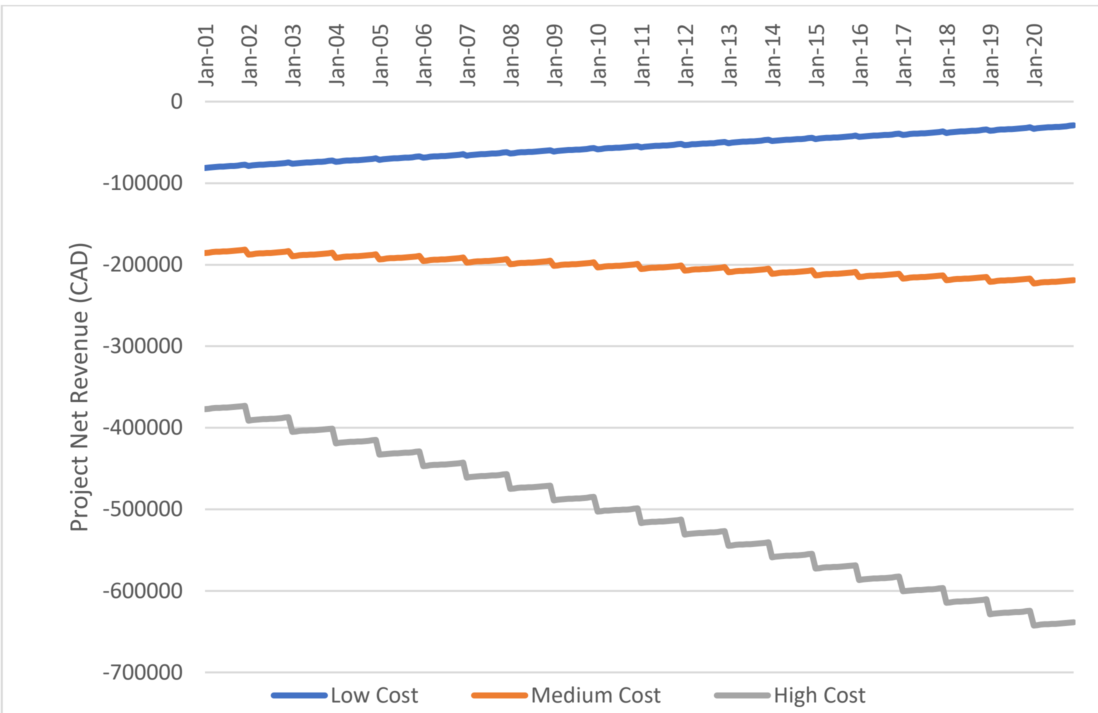
The estimated total generated electricity for one year is 31.6 MWh per year, which is around 13.3% of Bull Harbour's yearly electricity consumption. This is from a single WEC, so assuming the results would be the same for an additional device, just over a quarter of the electricity demand for a year could be met with using only two WECs.

Chapter 6. Economic Analysis

6.1 Revenue Analysis

The project economics are examined through a basic payback analysis. The purchase, installation, and O&M costs of a WEC project are offset by the savings on diesel fuel costs in this analysis. For the purchase and O&M costs, three different scenarios are considered: low, medium and high cost. The estimates in pricing come from a report by the Ocean Energy Systems (2015), the capital and O&M costs can be found in Appendix C. The minimum, and average, and maximum values were used to create the low medium and high cost scenarios. For the capital costs values of $4,000, 9,000, and 18,000 U.S. per kW were used as the low, medium and high cost scenarios respectively, making the cost of a single 15 kW WEC approximately $79,800, 179,550, and 359,100 Canadian (assuming an exchange ratio of $1.33 Canadian per $1.00 U.S.). The O&M costs were $150, 450, and 1,250 U.S. per kW per year which made the cost per 15 kW device $2,250, 6,750, 18,750 Canadian per year for the low medium and high cost scenarios, respectively. The breakdown of capital and operational expenses is not available, as such it is assumed that costs from malfunctions and maintenance are included in the O&M value, however it should be noted that having to bring in technicians from outside the community rather than train locals will add to costs. For a better idea of the distribution of Capital and O&M costs, included in Appendix D is the breakdown of the total cost of energy into its major categories. The value of diesel fuel is from a source stating bulk diesel fuel was being sold to coastal communities at $0.37/litre (Government of Canada, 2011). The community of Bull Harbour has two diesel generators (Barth, personal communication, 2018) and a survey from the Government of Canada (2011) puts their capacity at 70 kW. For the purpose of this study one 40 kW generator running at ¾ power, 24 hours a day was used to calculate fuel consumption. This came to approximately 12.1 litres of diesel fuel an hour (Diesel Service & Supply, 2017), or 106,374 litres of diesel a year costing around $39,358.47. The cost savings from reduced diesel expenditures are used to offset the project costs for the WEC. For this analysis this was assumed to be a "revenue". The assumed project life was 20 years, which is the estimated technical life of the SeaBased WEC (Dahlsten, 2009).

Figure 14. Calculated project revenue without additional funding for different cost scenarios



(Fischer, 2018)

As can be seen in Figure 14, payback period for both the medium and high cost scenarios does not exist as they continue to cost more than the offsetting diesel savings due to high O&M costs. Even our most optimistic scenario falls short by $18,500 in a 20-year period on a full cost basis. However, if some project costs can be alleviated using grants for development of a renewable energy project, then a WEC project could be implemented to help the project break even or become profitable for the community.

6.2 Sources of Funding

WEC technology is a younger sector than other renewable energy technologies, and as such is lagging behind in cost reductions (SI Ocean, 2013). Due to this and the size of the community, it is advisable to find additional funding to help finance the project and make it more profitable. There are a number of grants available for energy projects in Canada, including for rural and indigenous community initiatives. The following highlights some of the grants possibly available to a WEC project for Bull Harbour.

6.2.1 Promoting Clean Energy for Remote Communities (Natural Resources Canada)

This grant is specifically aimed at reducing diesel fuel usage by rural and remote communities for heat and power and is available for six years starting in 2018 (Government of Canada, 2018a). The grant can be used for deployment of renewable energy technology to reduce the usage of diesel fuel, Natural Resources Canada (NRCan) states that wave energy projects are eligible under the "Innovative demonstrations to reduce diesel use" program stream (Government of Canada, 2018a). Requirements include having a population of less than 1000 to be considered rural, or not having connections to the natural gas or electric grid to be considered remote (Government of Canada, 2018a). Referencing NRCan's atlas of remote communities, Tlatlasikwala is listed which means that the community is eligible (Natural Resources Canada, 2017). There is no minimum payment amount however there is eligibility of up to 100% of project costs to be covered by the grant (Natural Resources Canada, 2018). There is also no cap on how many submissions may be sent, so this could also be used to fund similar energy or efficiency projects in the community (Government of Canada, 2018a). Due to the wide range of possibilities in funding amounts this has been excluded from the analysis, but it does pose a significant area for funding.

6.2.2 Capital Projects (BC Bioenergy Network)

BC Bioenergy Network (BCBN) is an industry led non-profit that provides loans, grants, and equity investments for technologies that will have an impact on reducing GHG emissions in BC (BCBN, 2018). An example of projects they would invest in is "Assisted First Nations groups to develop solutions for replacing diesel and propane systems with reliable and renewable energy systems in remote BC communities", and with a possible investment of 10-30% of total project costs (BCBN, 2018). However, BCBN does require that the technology be from BC or have been deployed successfully outside BC and not yet within the province. This should not be an issue as SeaBased has successful projects in Sweden and Ghana (SeaBased, 2018), but does mean that if more WEC technologies develop in BC that BCBN should be revisited.

6.2.3 EcoAction Community Funding Program (Government of Canada)

The Government of Canada created this fund for projects that affect water cleanliness, or adaption or mitigation strategies for climate change (Government of Canada, 2018b). Due to the purpose of this project being to help reduce diesel usage and therefore avoid emissions, it can be argued that developing a green energy project in this case is a form of climate change mitigation. The grant is available to "Aboriginal organizations" and is between $14,000-100,000 (Government of Canada, 2018b). Applications are accepted once a year and require the applicants to develop reporting on the project concerning activity and finances (Government of

Canada, 2018b). This could act as an opportunity to create work for Tlatlasikwala band members as someone would have to compile and file these reports.

6.2.4 First Nations Clean Energy Business Fund (Government of BC)

Developed after the Clean Energy Act of 2010, the First Nations Clean Energy Business Fund was created to increase aboriginal participation in the renewable energy sector by supplying capacity funding, equity grants, and revenue sharing between indigenous communities and the BC government (Government of BC, 2015). The fund is available to First Nations bands and First Nations governing bodies. The fund could be used in different ways, for example, the application for capacity funding, which tops out at $50,000, but can be used to help with the feasibility studies, or financial analysis of renewable projects (Government of BC, 2015). It can also be used for training purposes, which could adequately prepare Bull Harbour citizens to deal with the installation, O&M, and decommissioning of the project, ensuring jobs for the entire length of the project and lowering costs as transient workers would not be required.

Equity grants and revenue sharing could be used if the project was not directly owned by the Tlatlasikwala. An equity grant may be up to $500,000 to be used to gain some share of the project, or revenue sharing between the province and the band on the rental of water and land used by the project where the band would receive 37.5% of the revenue from rentals (Government of BC, 2015).

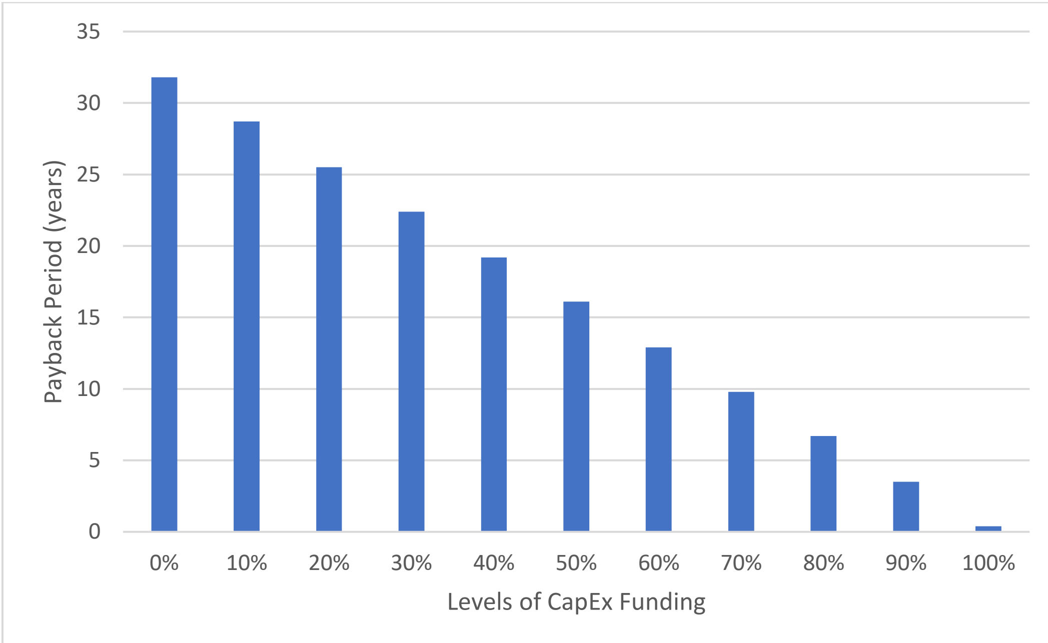
6.2.5 Selling emissions offsets to the province of BC

Despite BC having a carbon tax system, there is an opportunity to enter into an agreement with the provincial government to sell emissions offsets (Province of British Columbia, 2018). Projects that reduce diesel usage for remote communities are eligible to have their carbon offsets purchased, with 100,000 tonnes of carbon dioxide equivalent a year being the maximum the province will purchase from a single project at a maximum price of $8.50 a tonne. However, the province has worded the agreement in such a way that less than $8.50 a tonne can be offered and not all the offsets may be purchased. Due to this uncertainty, selling offsets has been omitted from my analysis.

6.3 Payback period with funding

From section 6.2, we see that funding can run anywhere between 0 to 100% funding. For simplicity, only funding affecting capital costs were considered and only the low-cost scenario was used in the analysis for payback periods. Figure 15 shows the results, and as can be seen, the project would require 36% of capital costs covered by grants in order to break even with a 20-year project life span.

Figure 15. Calculated Payback periods for low cost scenario with different levels of funding



(Fischer, 2018)

6.3 Indirect economic benefits

It is important to consider also the benefits to the province of British Colombia. As the government is currently supplying diesel at a subsidized cost of $0.37 per litre (Government of Canada, 2011), and the cost of wholesale diesel in Victoria has recently climbed to $0.945 per litre (Natural Resources Canada, 2018a). Savings from reducing fuel usage by Tlatlasikwasa results in a savings by the provincial government as well, and with the prediction of future fuel prices continuing to rise, the savings will increase with time (Trading Economics, 2018).

Chapter 7. Environmental Impacts

It is important to not lose sight of the impacts of even green technologies on the environment. The development of a WEC project has pros in the form of reducing carbon emissions, however it also has negative impacts on the local environment and the organisms inhabiting it. Not all impacts are as visible, so elements like electro magnetic fields, shading, piledriving foundations or moorings, and possible noise pollution effects of these devices should be considered when developing a WEC project. This section discusses the possible impacts from WECs as well as the specific impacts of the implementation of a singular SeaBased WEC.

7.1 GHG emission reduction

Burning diesel fuel creates 2.66 kg of carbon dioxide per liter (Natural Resources Canada, 2016). As calculated in Chapter 6, the incorporation of one SeaBased WEC would avoid burning 106,374 litres of diesel per year. This equates to 34.4 tonnes of avoided carbon dioxide per year to a total of 688 tonnes over the lifespan of the project.

7.2 Environmental effects

The exact effects on the environment depend on the type of WEC involved as different designs and the number of devices used. The effects can range from impacts on the physical environment, marine flora and fauna, as well as sociocultural impacts (AET, 2018).

7.2.1 Physical effects

Beginning with the base of the SeaBased WEC, which has a concrete ballast to keep it anchored, the placement will have a negative impact to the surface immediately beneath the WEC that will persist until the WEC is removed. The presence of the WEC will change the hydrodynamics around the site and possibly around the area (Hammar, et al., 2017). This can lead to a change in sedimentary deposition and beach shaping over the lifetime of the project (AET, 2018). However, a study on the effects of a 30 MW wave farm demonstrated an impact of no more than one to two centimeters loss of wave height at the shore and a negligible change to the period of waves (Millar, Smith, & Reeve, 2007). From this, it is safe to assume that implementing a system significantly smaller in capacity will have even less of an impact. With the size of the impact being negligible, concerns over changes in sediment deposition leading to changes in coastal and sea floor shape should be minimal.

There is also concern of mechanical seabed disturbance during the deployment and removal of the WEC (Hammar, et al., 2017; Oceanica, 2015). During the cable installation, anchoring of the barge required to ferry the WEC to and from the site, and the placement of the WEC, water quality may be impacted by increased turbidity (Oceanica, 2015). These impacts are localised and temporary as the turbidity should subside without constant disturbance. Turbidity from mooring or anchoring can be significant where piling or dredging for line burying (Oceanica, 2015). The Seabased WEC design does not require piling as it is weighted with a concrete pad, lessening the impact during installation (Chatzigiannakou, Dolguntseva, & Leijon, 2017). As for cable placement, the sea floor north of Hope Island has sand, gravel and pebbles close to shore with pebbles, shell, gravel, stone and sand in the deeper waters as can be seen in Figure 16 (GPS Nautical Charts, 2018). As such it would be up to the final design choice of the project whether the power line is simply laid across the top or buried under the substrate, and this choice would determine the extent of the disturbance.

Figure 16. Bathymetric map of Pacific Ocean North of Hope Island with description of substrate

Adapted from (GPS Nautical Charts, 2018)

7.2.2 Biological effects

Effects of WECs on flora and fauna are a mix of positive and negative (AET, 2018). Of particular concern by the majority of WEC projects is the effects on benthic communities (Leeney, Greaves, Conley, & O'Hagan, 2014). A study of benthic macrofauna in the Lysekil research park in Sweden where WEC are tested had mixed results where the fauna within the park was more diverse than control sites outside the park some years, and no difference in other years (Langhamer O. , 2010). Depending on the size, the electric cable could pose as a barrier to smaller benthic creatures (AET, 2018). The Seabased WEC design calls for a 12 kV subsea cable (SeaBased, 2018), which can have a diameter of around 80 to 120 millimeters

(ABB, 2010). Impacting smaller benthic wildlife can be avoided by burying the cable, at the cost of temporarily displacing the animals living within the substrate.

WECs can act as artificial reefs, and as such increased number of fish and fish species can be found around wave parks (Langhamer, Wilhelmsson, & Engstrom, 2009). The aggregation of prey species also brings an increased aggregation of predators (Dempster, 2005). As molluscs and other biomass grow and accumulate on the base and buoy of a WEC, this can increase the turbulence of the water around the WEC (Kundu & Cohen, 2004). This turbulence can increase the deposition of organic and mineral materials around the WEC (Langhamer, Haikonen, & Sundberg, 2010). This increased sedimentation could create eutrophic conditions for benthic communities (Guiral, Gourbault, & Helleouet, 1995). The lack of multiple WECs will minimize the turbulence effect, although the artificial reef effect will likely still be created.

Seabirds may accumulate around the WEC due to the increased prey concentration as well as the design having a buoy to rest upon (Langhamer, Haikonen, & Sundberg, 2010). The extent of the impact on migratory birds would depend on the number and spacing of the WECs (Gill, 2005), so the deployment of a singular WEC is likely to have a minimal effect. There is also a risk of collisions by diving birds, but as there are no rotating blades, the risk is more in striking mooring lines (Langton, Davies, & Scott, 2011)

It is doubtful that whales would be able to see mooring lines and cables underwater which could result in a strike or entanglement causing injury or death (AET, 2018; Boehlert, McMurray, & Tortorici, 2008). As well, a significant number of WECs could act as a barrier to migration paths and force paths to less favorable areas which may influence the success rates of predation (Boehlert, McMurray, & Tortorici, 2008). For a small number or singular WEC, the impact on migration will likely be minimal. As for impacts with mooring lines, there is only one suspended cable in the SeaBased design and it will be taut, minimizing the risk of entanglement (Boehlert, McMurray, & Tortorici, 2008). To reduce the damage done by strikes with the line, a larger diameter cable creates more of a blunt trauma than the lacerations of a smaller gauge cable (Boehlert, McMurray, & Tortorici, 2008), so determining a balance between design and impact mitigation should be a discussion.

There is a risk of generating noise pollution from the installation and operation of WECs (Boehlert, McMurray, & Tortorici, 2008; Frid, et al., 2012; Hammar, et al., 2017; Langhamer, Haikonen, & Sundberg, 2010). Severe to moderate impacts can occur from piling or drilling when installing WECs (Frid, et al., 2012; Sarić & Radonja, 2014). This could lead to a change of behaviour in avoidance or attraction, depending on the species (Boehlert, McMurray, & Tortorici, 2008). Noise from operation of the WEC is not likely to be ecologically significant, however a large number of WECs could lead to masking communication and echolocation of creatures nearby (Frid, et al., 2012). The noise levels during the development and retirement of a singular WEC for Bull Harbour is likely to have the greatest noise effects. During operation, the fact there is only one should reduce noise, however if cable noise is still a concern, a larger cable will produce a lower frequency noise and can help reduce noise pollution (Boehlert, McMurray, & Tortorici, 2008).

Shading effects by WEC will likely be minimal. Firstly, since the SeaBased WEC is only about three meters across (Rusu & Onea, 2018), it will cast a small shadow in comparison to other structures like docks. Secondly, because the proposed depth of deployment is at 80 to 100 meters of depth, any shading effect are minimized. Kelp forests are generally in waters of 2 to 30 meters in depth, (National Marine Sanctuaries, 2018) and therefore will not be impacted by shading. The photosynthetic activity at water depths where the WEC will be located is likely carried out by phytoplankton being carried by the currents (EarthSky, 2015), and therefore shading on this population will be very temporary.

The effects of electromagnetic fields from underwater cables on fauna is still not fully understood (Langhamer, Haikonen, & Sundberg, 2010). It is known that some species, like salmon, use electromagnetic fields for navigation (Gill, Bartlett, & Thomsen, 2012). On a positive note, a study on the long-term exposure to electromagnetic fields on benthic species showed no affect on survival or reproduction (Bochert & Zettler, 2004). If a WEC project is created, it could be an opportunity to observe the effects on pacific fauna.

7.2.3 Sociocultural effects

It is important to consider that the environment encompasses human activities as well, not to mention that changes to human activities will have additional impacts to the environment. Included in those effects are the creation of a no-take zone (Langhamer, Haikonen, & Sundberg, 2010). This is an area surrounding the WEC where use of nets would not be allowed due to risk of entanglement and damage to the WEC. This can lead to an increase of fish size, population, and species variation regardless of the size of the no-take zone (Halpern, 2003).

The WEC could also affect boating or shipping paths. However, due to the Navigation Protection Act (1985) it is unlikely that a WEC would be allowed to be placed in an established ferry or shipping lane. Boating safety is an important and so lighting would have to be attached to the top of the buoy to prevent ship strikes. The WEC buoy could also function as a marker to help with navigation as long as it was included on the maps being used by the boaters. Changing the direction of boats will move the location of the noise pollution, which may have negative impacts to wildlife, depending on the extent of the noise.

Recreational activities like diving could be improved as the WEC acting as an artificial reef would mean there is likely to be fish and benthic species to see (AET, 2018). However, similar to how boating could be impacted, sailing would also have safety issues that need to be avoided and possible navigational use (AET, 2018). If the diving boon is significant enough, it will increase boating traffic to the site which will create more noise pollution. It could also increase awareness of the ecology of the area which would make more of a demand to protect the environment.

Chapter 8. Conclusion

Wave power represents a huge opportunity for the energy sector of Canada's coasts. With the multitude of WEC designs and wave park projects coming online, more information will become available. This information will help develop and streamline the industry and lower costs. While there are currently opportunities for wave projects along British Columbia's coast, for small remote communities, the financial costs of implementing a small-scale wave energy project are high and have a lot of uncertainty. If a wave energy project was to progress further, exact information regarding costs and available funding would be needed. The environmental impacts of WECs are mixture of positive and negative, however the overall impact seems positive, especially when weighed against the production, refining, transport, and use of fossil fuels.

This study will hopefully help the inform Tlatlasikwala people and other remote coastal communities of the opportunities and shortcomings of wave power in its current state. It can also work as a reference point for decision makers when considering the some of the impacts wave energy could have.

8.1 Limitations

Limitations to this research lie within the data that was available. Without dominant wave direction, the actual shadow effects due to Hope Island and other land masses could not be properly calculated. This also limited the understanding of how waves would act closer to the shore of Hope Island, limiting the possibility of assessing a near shore project.

The exact costs of the Seabased WEC and associated project costs were not available and as such, secondary data in the form of industry averages were used to calculate the economic section. This led to more general results, and therefore a less accurate picture of what this wave project could represent from a financial perspective.

8.2 Possible future research

Possible future research could involve modeling a system that takes advantage of the winter peaking of wave power with the summer peaking of solar to create a synergistic renewable energy mix with a smoother energy profile. Additionally, looking into the real costs of diesel electricity for Canada through a lifecycle analysis from production, transportation, and use at remote communities to get a wholistic view of the environmental and financial cost of satisfying energy needs through diesel would help better understand the true cost of offset.

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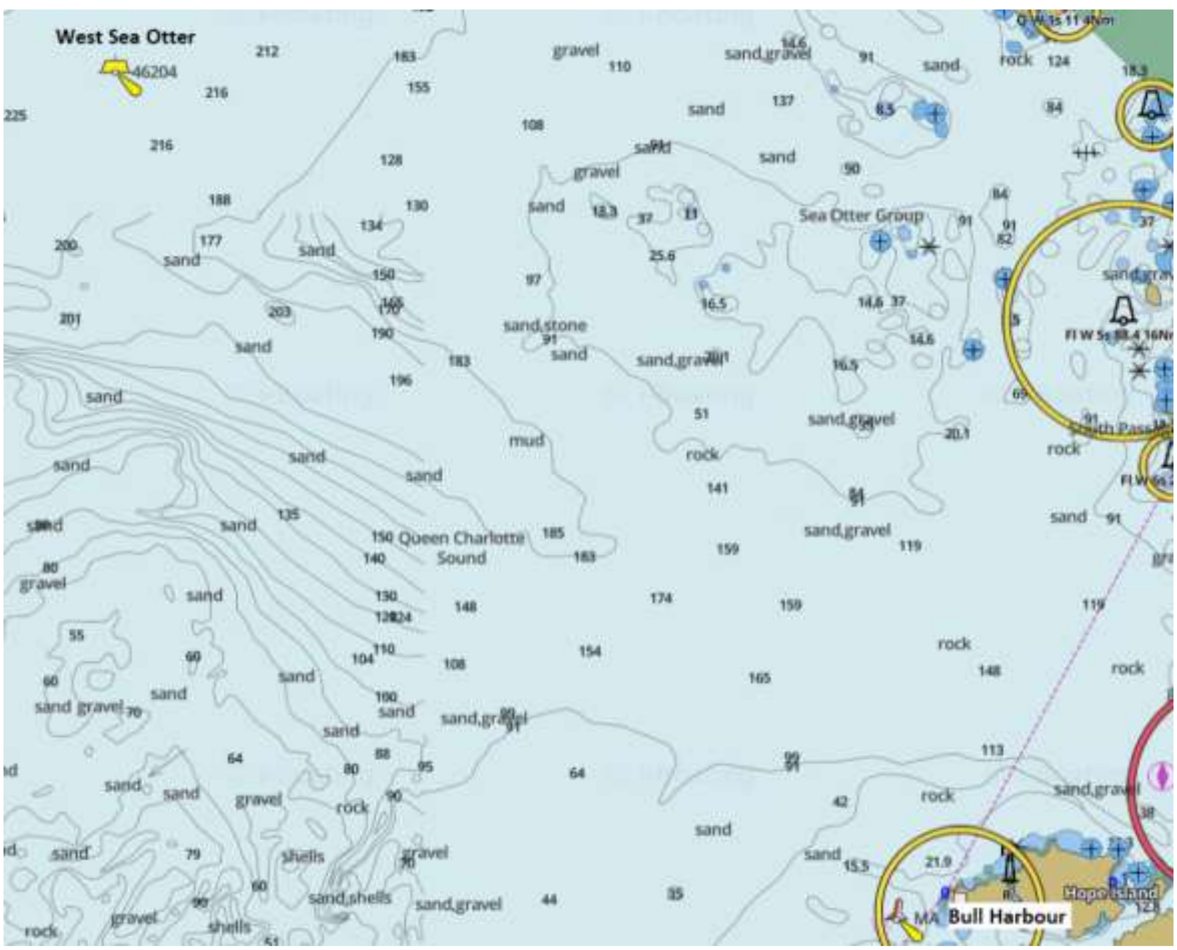
Appendix A. Bathymetric maps of Pacific Ocean around Hope Island

Important to understanding how the wave conditions may differ from C46204 to the shallow waters surrounding Hope Island is how the water depth changes. Information regarding the depths around the island are also necessary for selecting an appropriate depth and distance for WEC deployment. Finally, information on the type of sea bottom must be incorporated to give an idea for what types of benthic communities could be present and the type of disturbance that may occur during installation.

Figure 17. Bathymetric map of Pacific Ocean North and West Hope Island and C46204 West Sea Otter wave buoy



Adapted from (GPS Nautical Charts, 2018)

Appendix B. Summary for SeaBased-like WEC

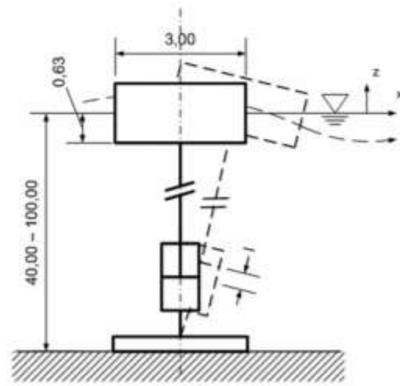
Summary sheet for the a WEC design based off of the SeaBased WEC design including design and how it works, power matrix, weight, and performance at five sites in Europe. The properties are similar but not exact.

Figure 18. Summary sheet of a bottom-referenced heaving buoy WEC

1. Small bottom-referenced heaving buoy (Bref-HB)

Working principle

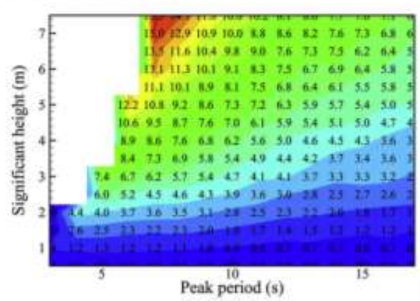
The device consists of an axi-symmetric buoy with ellipsoidal cross section floating on the ocean surface. Through a wire it is connected to a machinery unit standing at the sea bottom. The machinery consists of a linear generator placed inside a steel hull mounted on a concrete ballast structure. Under wave action, the buoy moves in surge and heave, resulting in a wire pull that drives the generator.



Main dimensions and parameters

Property	Value	Unit
Diameter	3.0	m
Draft	0.63	m
Displacement	2.83	m^3
Mass of the buoy	1000	kg
Stroke length	1.8	m
PTO model	Linear	
Char. surface area	42	m^2
Characteristic mass	31	Mg
Water depth	40 to 100	m

Power matrix



Estimates of performance measures

Site	SEMREV	EMEC	Yeu	Lisbon	Belmullet
Annual mean absorbed power (kW)	1.6	2.8	3.3	3.5	5.0
Capture width ratio (%)	3.6	4.2	4.1	3.1	2.1
Absorbed energy per characteristic mass (kWh/kg)	0.46	0.78	0.92	1.0	1.4
Absorbed energy per surface area (MWh/m^2)	0.34	0.57	0.68	0.73	1.0
Absorbed energy per RMS of PTO force (kWh/N)	1.5	2.1	2.3	2.2	2.6

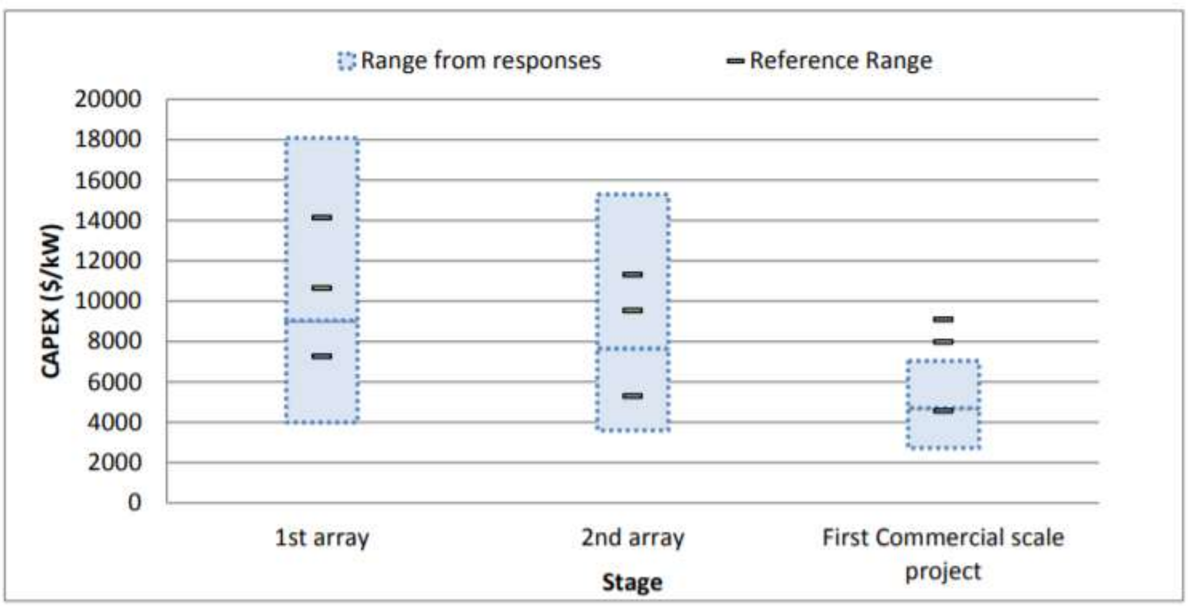
Capture width ratio is here defined as the ratio of capture width and the diameter of the buoy. The uncertainty on the annual mean absorbed power is estimated to be in the range of [-20,+20 %].

(Babarit, et al., 2012)

Appendix C. Estimates for Capital and O&M Costs

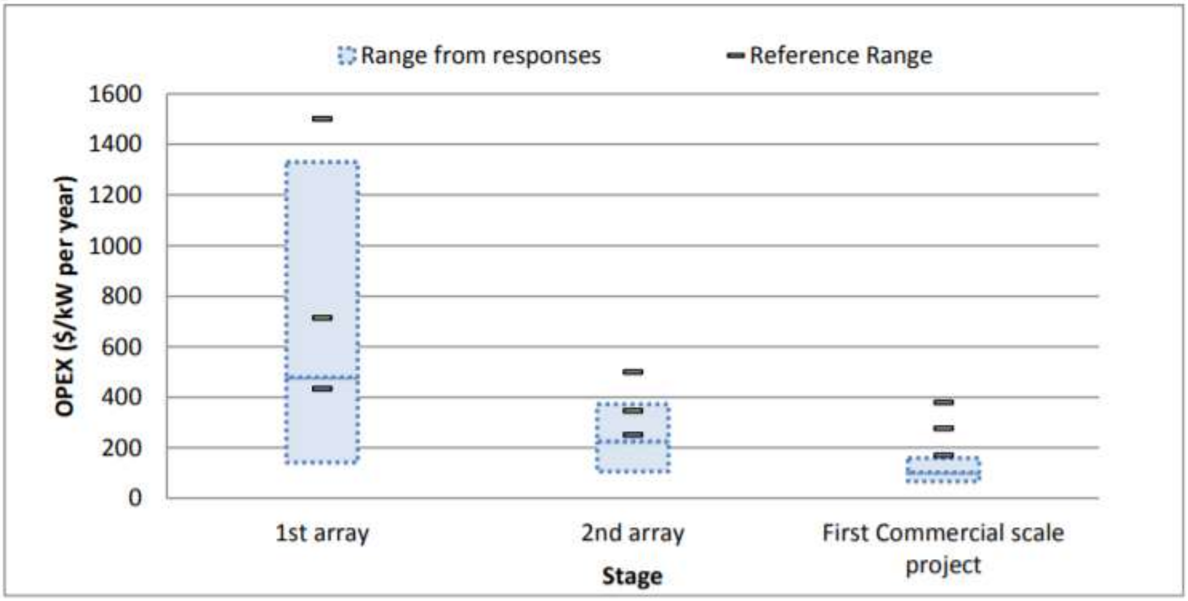
Capital and operational expenditure estimates for WEC projects. The boxes representing, maximum, minimum and average values from interviews with various stakeholders and the bars represent values from international reports as cited by Ocean Energy Systems (2015). In this graphic, array refers to a project, where by either a single device or a number of devices are deployed at once. First array refers to a first test deployment of a WEC, the second array refers to the second test project, and commercial scale is the first project aimed at financial return without capital or public-sector support. Uncertainties such as the remoteness of the location, the current lack of wave projects in Canada, and the small scale of the project led to the use of the first array numbers as they are more conservative.

Figure 19. Industry average capital expenditures per kilowatt for WECs at different development stages



(Ocean Energy Systems, 2015)

Figure 20. Industry average operational expenditures per kilowatt per year at different development stages

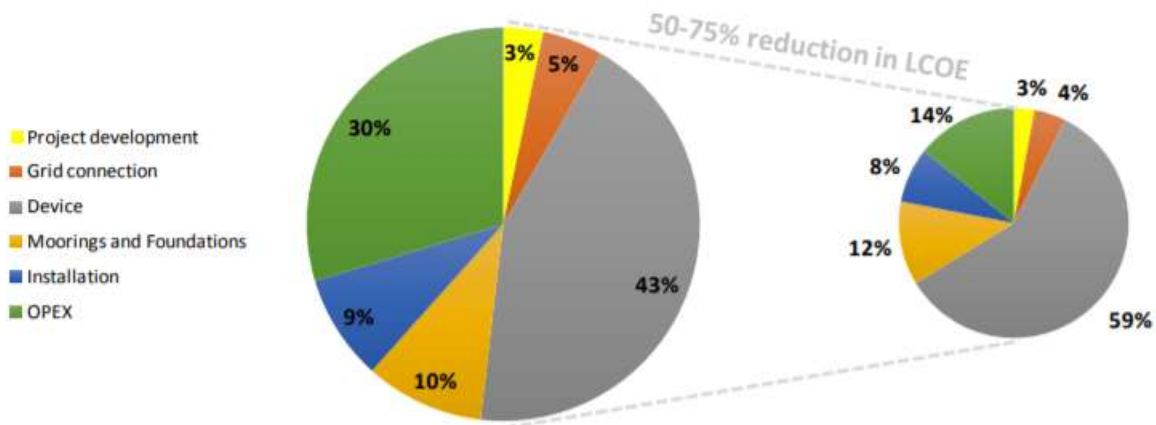


(Ocean Energy Systems, 2015)

Appendix D. Breakdown of cost contributions to levelized cost of energy for WEC

Levelized cost of energy is the total cost over the lifespan of the project, divided by the total energy produced. As such planning, acquisition, instillation, and operational costs are all included and given as percentages of the total cost. The included graphic contains the major contributing costs to a wave energy with current state on the left and goal for how the costs should be allotted in a commercial project on the right.

Figure 21. Cost contributors to levelized cost of energy for WEC projects



(Ocean Energy Systems, 2015)