OCE 513: Ocean Renewable Energy
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Characterizing Tidal Stream Energy Resources in the San Juan Islands, Washington

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1. Introduction

1.1 <u>Objective</u>:

In the following report, the tidal stream energy resources residing in the Bellingham Channel of the San Juan Islands in Washington state, will be characterized in order to determine the feasibility of installing a small, tidal-stream device based, renewable energy plant at this location.

1.2 <u>Background</u>:

Tidal energy is currently one of the most favoured forms of marine renewable energy due to its dependence on astronomical tide generating forces. This inherently makes tidal energy more predictable, allowing for the creation of various tidal-stream devices and methods that can efficiently harvest renewable energy from the tidal forces.

The primary consideration when designing a potential renewable energy plant to harvest the power of tidal forces is location. In order for the plant to operate efficiently, the tidal stream energy resources available in the given location must be sufficient enough to meet the required specifications. This crucial first step of identifying the optimal location of the site will determine the overall success of the renewable energy plant. Once the location is chosen, an in depth tidal analysis must be complete in order to characterize the available tidal resources. The data acquired from this analysis will allow for the ideal tidal-stream device to be selected for installation. A Levelized Cost of Energy (LCOE) calculation can then be used to determine the hypothetical feasibility of the plant as a whole.

The following report utilizes this methodology stated above to design a hypothetical renewable energy plant residing in the Bellingham Channel of the San Juan Islands in Washington state that harvests energy from the available tidal stream resources. The rationale behind the selection of this location for the site will be provided along with a comprehensive analysis of the area's available tidal energy resources. A specific type of tidal-stream device would then be identified to harvest tidal energy from this location based factors discussed further throughout this report. Finally, an LCOE calculation was completed in order to determine the overall feasibility of this hypothetical plant.

2. Selection of Site Location

Selecting the location of this site is a pivotal first step that serves as the basis for the success of this hypothetical tidal dependent renewable energy plant. The available tidal stream energy resources at this location must be sufficient enough to allow for a selected tidal-stream device to efficiently harvest energy. Current tidal-stream device technology requires relatively high tidal power densities/velocities for productive operation, fundamentally limiting the locations where these devices could be installed. In order to identify the locations that exhibit high tidal power densities/velocities, a geographical tool called the Marine and Hydrokinetic (MHK) Atlas was used[10]. The MHK Atlas can geographically display a multitude of tidal energy resource related data for the waters of the United States.

It was important for the purpose of this report to select a site location that does not already have an operational renewable energy plant installed within the vicinity. With this in mind, the East coast of the United States was not considered due to the many already established renewable energy sites. The focus was shifted towards the West coast of the United States, specifically in the North West region of the country where there appeared to be a high concentration of annual tidal power density available. The San Juan Islands, located off the Northwest coast of Seattle in Washington state, were chosen as the main region of study for this site location due to the large amount of available tidal stream energy resources. This region is displayed in Figure 1 below.

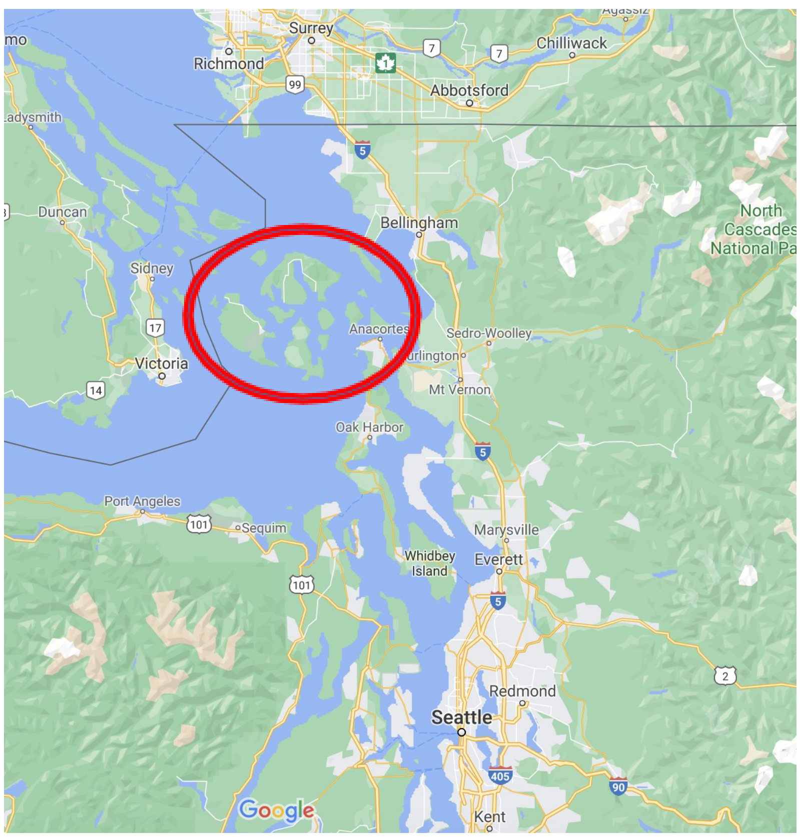

Figure 1: Site Location Region of Study

Figure 2 is an image from the MHK Atlas that depicts the annual tidal power density resource for the San Juan Islands. There are two major regions within these islands that exhibit power densities ranging from 900 W/m^2 - 1000 W/m^2: the Rosario Strait and the Bellingham Channel.

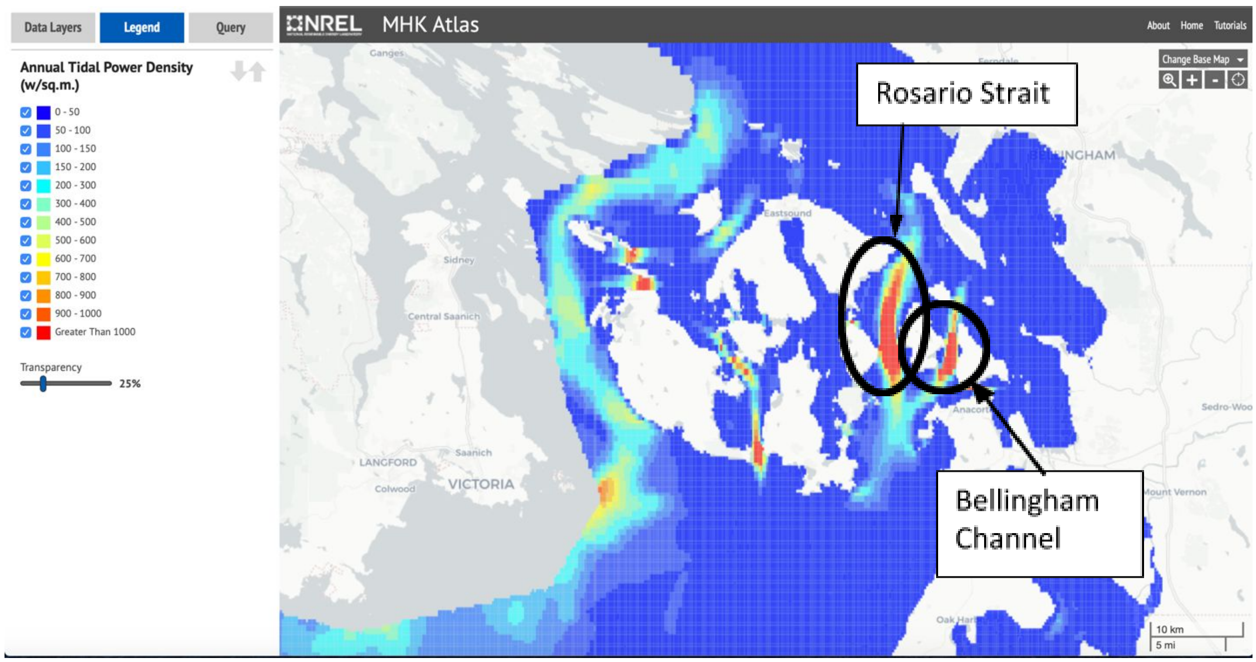

Figure 2: Annual Tidal Power Density in San Juan Islands[10]

With this in mind, the location for the site was narrowed down to these two main regions. Figure 3 and Figure 4 are charts from the National Oceanic and Atmospheric Administration (NOAA) that display the bathymetry of the Rosario Strait and Bellingham Strait respectively. These charts were used to gain a better understanding of the water depth and overall geographical structure of the two regions.

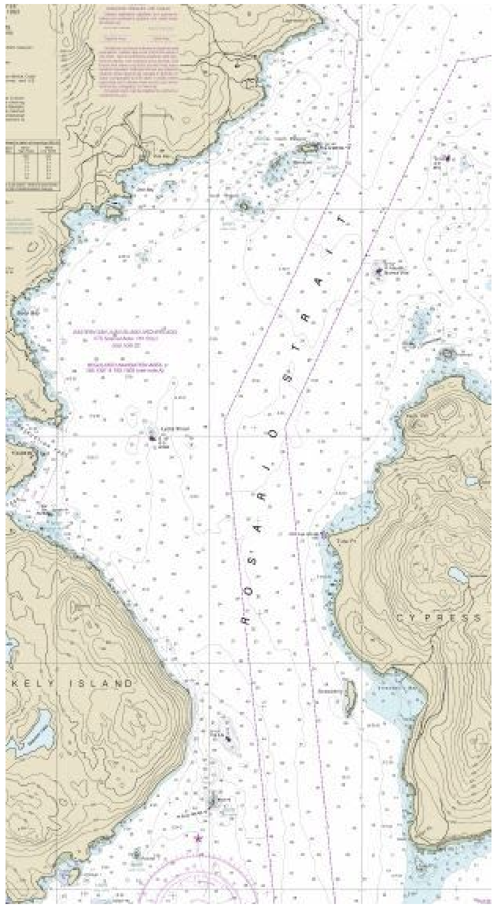

Figure 3: NOAA Chart 18340 (Soundings in Fathoms)

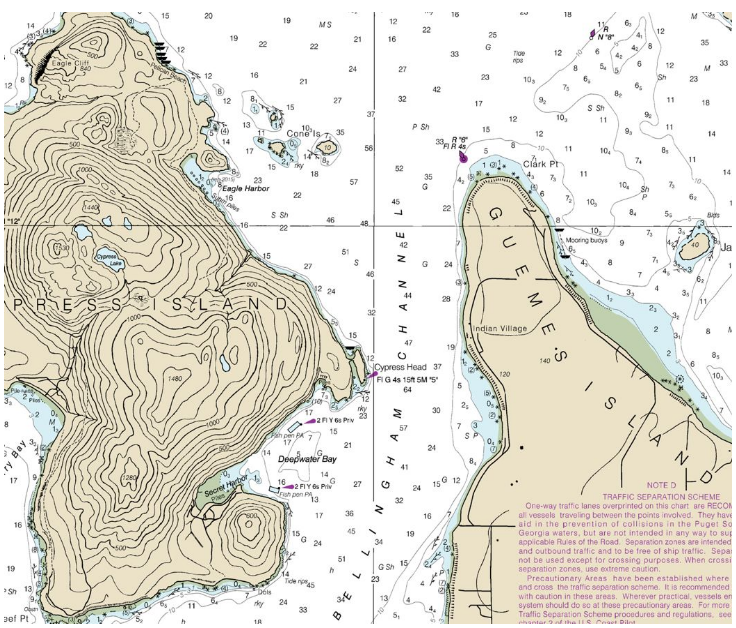

Figure 4: NOAA Chart 18424 (Soundings in Fathoms)

The bathymetry noted in Figure 3 for the Rosario Strait appears ideal as it has a more gently sloping bottom than that of the eastern Bellingham Channel, as displayed in Figure 4.

The annual tidal current velocities could also be displayed geographically using the MHK Atlas. Figure 5 depicts the annual tidal current velocities located within the waters of the Rosario Strait and Bellingham Channel. The peak annual tidal current velocity within these locations both range from 1.11 m/s to 1.40 m/s. These two locations also exhibit the highest tidal current velocities within the San Juan Islands region as displayed in Figure 6.

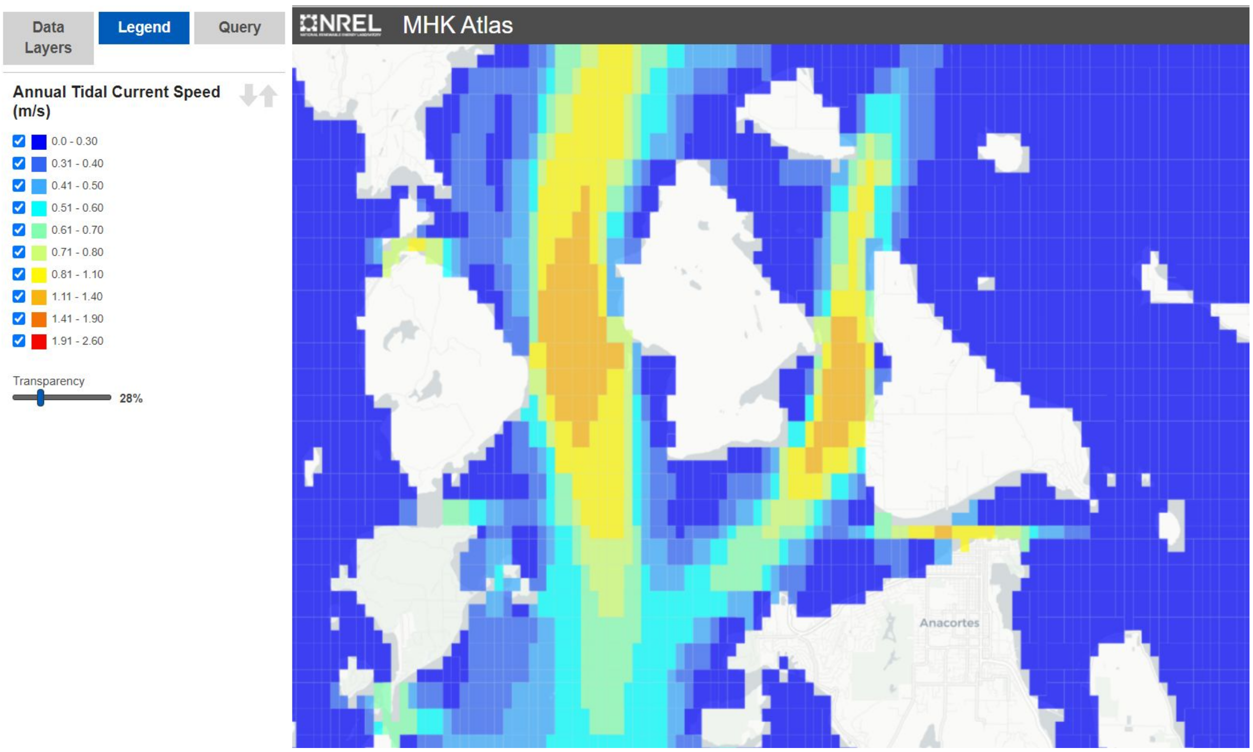

Figure 5: Annual Tidal Current Velocities in the Rosario Strait and Bellingham Channel[10]

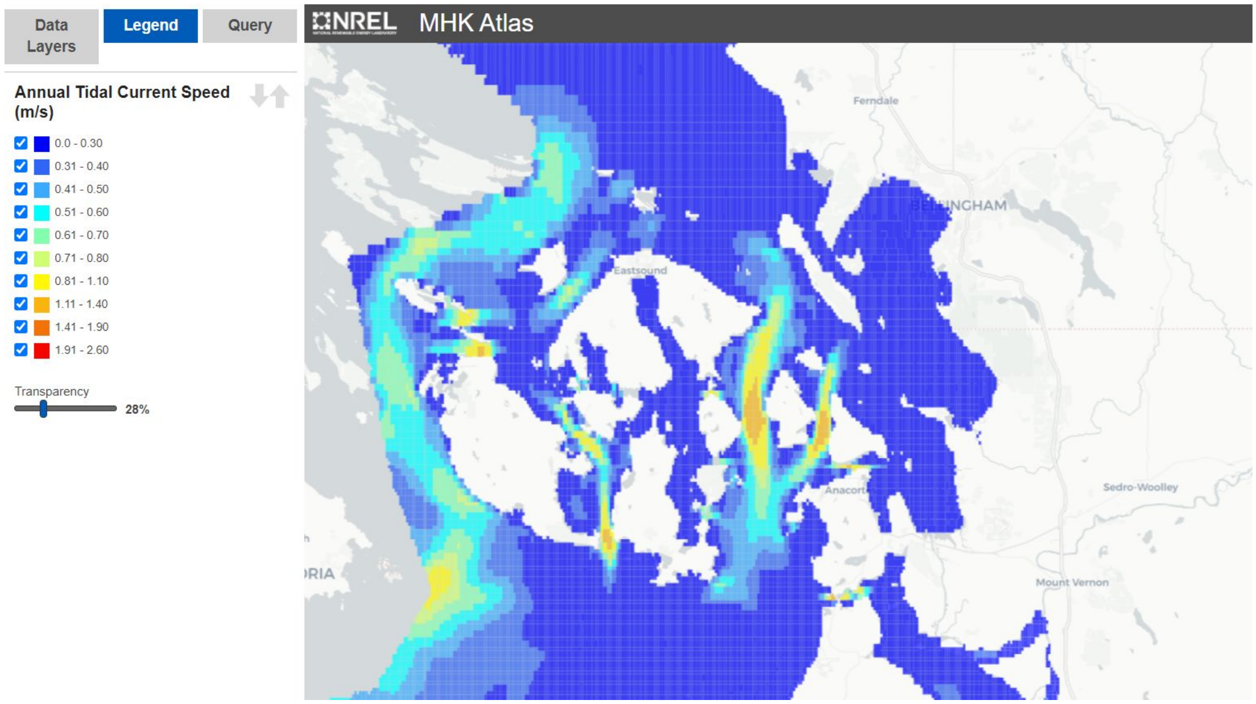

Figure 6: Annual Tidal Current Velocities in San Juan Islands[10]

The Rosario Strait appears to have a larger area of peak annual tidal current velocities than the Bellingham Channel. In conjunction with the more gently sloping bottom section of the Rosario Strait, it would appear that this region would be the ideal location for this hypothetical site. Despite this, the Bellingham Channel was selected as the primary location for this study, as the Rosario Strait is an established shipping traffic route that runs through the middle of the channel. This of course could be problematic for the installation and operation of several horizontal axis tidal stream turbines.

3. Methodology and Assumptions

3.1 Methodology:

Using the MHK Atlas Annual Tidal Current layer, the annual average tidal current in the Bellingham Channel will be determined, and compared with other sources of tidal velocity data if possible. There are two NOAA tidal stations located in the San Juan Islands, the Cherry Point tidal station 30 km to the north and the Friday Harbor station 25 km to the west. Since both of those are somewhat distant from the site location, they were not used in this analysis.

Once the tidal energy resources have been evaluated, a suitable tidal stream device will be chosen, as well as the quantity of these devices for this notional tidal energy plant. A power curve for the turbine will be necessary to determine power production, capacity factor, LCOE, and other characteristics. If the power curve is not publicly available, then a hypothetical power curve will be constructed and used for the remainder of the analysis. Once an LCOE is calculated, its sensitivity to Operations & Maintenance costs will be analyzed. The LCOE will also be compared to the average cost for electricity in Washington and a determination of feasibility will be made, along with suggestions for how LCOE could be reduced and therefore make this project more financially viable.

3.2 Assumptions:

For this study, it is assumed that tidal stream velocity does not vary significantly with depth; surface velocities are used in the calculations with the understanding that these would be maximum velocities, and that the tidal stream velocities at the depth of the turbines would be less than at the sea surface.

In order to calculate the Levelized Cost of Energy (LCOE) of the tidal array, a couple assumptions were made. The operation and maintenance (O&M) costs were assumed to be 25% of the annual costs of the tidal array. This was based on the O&M costs for a typical wind farm. The other assumption made was the interest rate used to calculate the CRF. The interest rate was assumed to be 3%. Both of these assumptions were derived from and used to perform the calculation of the LCOE of the Block Island Wind Farm for Assignment #1 in OCE 513.

4. Tidal Analysis

From Figure 5, the average annual tidal current in the Bellingham Channel ranges from 1.11 m/s to 1.40 m/s. A software application called AyeTides used primarily by recreational boaters was used as an additional source of tidal data for comparison with the MHK Atlas[2]. AyeTides has a reference station (see Appendix 1) in the Bellingham Channel just off the Cypress Head Light, at a depth of 9.4 m. However, it has some limitations; e.g, the maximum length of time that tidal current velocities could be compiled is one month, and water level plots for a maximum of five days could be shown at once.

November 2020 was chosen for analysis, and the water level and surface waters velocities are printed in a tabular format in Appendix 1. Sample output is shown in Figure 7 below.

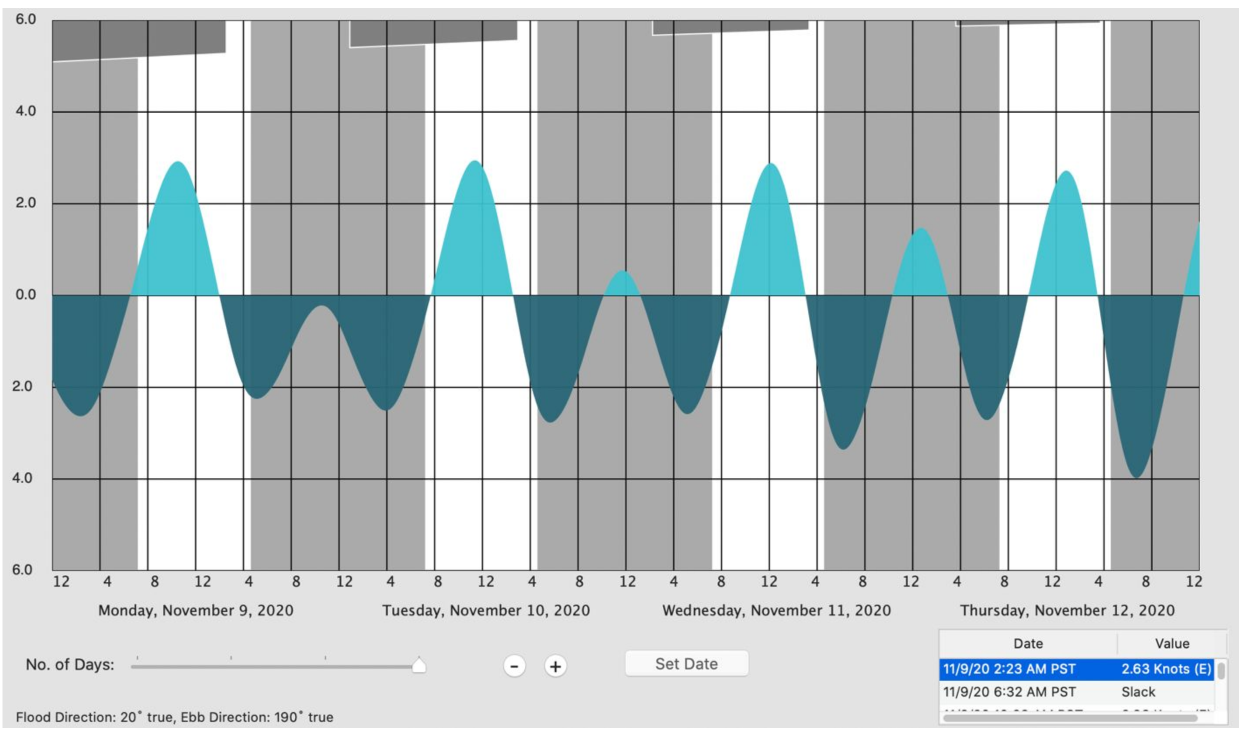

Figure 7: AyeTides output for 9 – 12 November (heights in feet)[2]

Of note, the Flood tidal current moves from south to north, and the Ebb tidal current from north to south. The box in the bottom-right corner of the screen provides the times of flood, ebb, slack water, etc., as well as the tidal current velocities during those periods. For example, for November 12, AyeTides tells us:

Thursday, November 12, 2020
12:40 AM PST 1.48 Knots (F)
2:56 AM PST Slack before ebb
6:11 AM PST 2.71 Knots (E)
9:40 AM PST Slack before flood
12:49 PM PST 2.72 Knots (F)
3:27 PM PST Slack before ebb
6:44 PM PST 3.98 Knots (E)
10:39 PM PST Slack before flood

F = flood
E = ebb

Since our turbine is bi-directional, the average velocity for flood tide and ebb tide were calculated for each day of November 2020, and then the flood and ebb tide daily average velocities were averaged over the month. The daily averages were calculated by using a weighted-average approach, as illustrated below for the Flood tide on November 12:

$$\frac{[(2.92\ hrs)(1.48\ knots)+(5.78\ hrs)(2.72\ knots)]}{(2.92\ hrs+5.78\ hrs)} = 2.3\ knots$$

The number of hours for each Flood tide was determined by finding the difference in time between occurrences of "Slack before Flood" and "Slack before Ebb", and the reverse for Ebb tides. The number of hours were rounded to the nearest whole hour, and many had to be "adjusted" so that the total number of hours for flood and ebb to add up to 24 hours in one day, because on some days the tides were diurnal and others semi-diurnal. For purposes of keeping our calculations manageable, we assume that the tidal velocity indicated is constant throughout the flood or ebb tide, as the case may be. In reality, the tidal currents would slow as slack water is approached and would accelerate in the opposite direction after slack water. Table 1 below depicts the daily recorded tidal stream velocities for the month of November.

Date	Tidal Current Direction	Speed (knots)	Hours	Speed (m/s)
1-Nov-20	Flood	2.0	10	1.0
	Ebb	3.1	14	1.6
2-Nov-20	Flood	2.2	11	1.1
	Ebb	3.0	13	1.5
3-Nov-20	Flood	2.3	10	1.2
	Ebb	2.9	14	1.5
4-Nov-20	Flood	2.7	8	1.4
	Ebb	2.7	16	1.4
5-Nov-20	Flood	2.9	8	1.5
	Ebb	0.9	16	0.4
6-Nov-20	Flood	2.9	8	1.5
	Ebb	1.7	16	0.9

7-Nov-20	Flood	2.8	8	1.4
	Ebb	1.6	14	0.8
8-Nov-20	Flood	2.9	8	1.5
	Ebb	1.7	14	0.9
9-Nov-20	Flood	2.9	7	1.5
	Ebb	1.7	17	0.9
10-Nov-20	Flood	2.4	9	1.2
	Ebb	2.6	15	1.3
11-Nov-20	Flood	2.9	8	1.5
	Ebb	3.0	16	1.5
12-Nov-20	Flood	2.3	9	1.2
	Ebb	3.4	15	1.7
13-Nov-20	Flood	2.4	10	1.2
	Ebb	3.7	14	1.9
14-Nov-20	Flood	2.7	10	1.4
	Ebb	4.0	14	2.1
15-Nov-20	Flood	3.1	11	1.6
	Ebb	4.1	13	2.1
16-Nov-20	Flood	3.4	11	1.7
	Ebb	4.0	13	2.1
17-Nov-20	Flood	3.6	10	1.9
	Ebb	3.8	14	2.0
18-Nov-20	Flood	4.4	9	2.3
	Ebb	3.4	15	1.7
19-Nov-20	Flood	4.3	8	2.2
	Ebb	1.2	16	0.6
20-Nov-20	Flood	3.9	8	2.0
	Ebb	2.1	16	1.1
21-Nov-20	Flood	3.6	8	1.9
	Ebb	2.3	16	1.2
22-Nov-20	Flood	3.2	8	1.6
	Ebb	2.3	16	1.2
23-Nov-20	Flood	2.3	9	1.2
	Ebb	2.5	15	1.3
24-Nov-20	Flood	2.4	8	1.2
	Ebb	2.5	16	1.3
25-Nov-20	Flood	1.7	9	0.9
	Ebb	2.6	15	1.3
26-Nov-20	Flood	1.6	10	0.8

	Ebb	2.7	14	1.4
27-Nov-20	Flood	1.7	10	0.9
	Ebb	2.9	14	1.5
28-Nov-20	Flood	1.9	10	1.0
	Ebb	3.0	14	1.5
29-Nov-20	Flood	2.2	10	1.1
	Ebb	3.2	14	1.6
30-Nov-20	Flood	2.5	10	1.3
	Ebb	3.2	14	1.6

Table 1: Daily Tidal Velocities, November 2020

The recorded daily tidal stream velocities fluctuated by a relatively large margin throughout the month of November. In order to simplify this data, the average flood and ebb tidal velocities were calculated. These average velocities are displayed in Table 2 below.

Flood Tide	**Ebb Tide**
Avg Speed (m/s)	Avg Speed (m/s)
1.41	1.40
Direction	Direction
020ºT	190ºT

Table 2: Average Tidal Velocities, November 2020

These results were somewhat surprising, as the calculated monthly average velocities for flood and ebb came out nearly identical. It is also important to note that these results were in very close agreement with the MHK Atlas average annual tidal current velocity numbers for this region of 1.11 m/s to 1.40 m/s.

5. Selection of Tidal-Stream Device

5.1 <u>Theory of Tidal Turbine Selection</u>:

The Nova M100 tidal turbine is an ideal horizontal axis tidal turbine to be installed in less energetic flow velocities. The turbine differs from normal by having a cut-in speed at 0.6 m/s and a tidal flow velocity of 2.0 m/s for the rated power output[12]. Typical tidal stream turbines have been rated to harness rated power with flow velocities above 2.0 m/s[6]. Higher flow velocities will allow for more energy production, but will increase the cost and complexities of a project. The recent technological advancements in horizontal axis tidal turbines by Nova Innovation and other organizations has tremendously widened the possibilities of potential locations for the installations of tidal turbines in less energetic flow velocity situations. This is ideal for the Bellingham Channel with an average annual flow velocity of 1.4 m/s, which makes the location potentially feasible for the installation of the Nova M100 tidal turbine. Inspiration of the selection of this tidal-stream device has been derived from the Bluemull Sound Tidal Array, as it is fully functional and supplying power to the grid.

Figure 8: Nova M100 Installation Preparation at Bluemull Sound Site[5]

Figure 9: Nova M100 Installation at Bluemull Sound Site[11]

5.2 <u>Nova M100 Tidal Turbine</u>:

The Nova M100 is Nova Innovation's 100 kilowatt horizontal axis tidal turbine with a conventional gear system. The Nova M100 is designed to harness and produce electricity in a safe and reliable manner for situations with less energetic flow velocities. The cut-in speed for the turbine starts at 0.6 m/s with a tidal speed of 2.0 m/s for the rated 100 kilowatt power. It has a life-span of 20 years with a rotor diameter of nine meters. The mounting of these turbines provides a simplified installation and maintenance process compared to other tidal-stream devices. The Nova M100 tidal turbine is seabed mounted using a simple rock-solid gravity based substructure. There is no requirement of drilling on the sea floor and this improves the ease of installation and installation costs. Due to this, there is minimal environmental impact to the surrounding environment and this tidal-stream turbine is hidden underwater from peoples' views above sea-level. The rotor consists of two nine-meter diameter blades, which also increases the ease of installation and decreases costs by allowing for low-cost vessels and vehicles to perform the shipment and deployment. The variable speed rotor provides the ability to convert the tidal flow energy in both directions without having to yaw the turbine or pitch the blades. This ability is the main difference to a typical wind turbine. The elimination of the need to yaw the turbine and pitch the blades allows for even further decrease in costs pertaining to the operation and maintenance (O&M), as these are the main cause of maintenance costs on wind turbines. This modular system is built with off-the-shelf components to allow mass production of the turbines, ease of manufacturability, and ease of global transportation[12]. Due to these attributes, the Nova M100 horizontal axis tidal turbine is a strong choice for the type of tidal-stream device to be installed in the Bellingham Channel. Design specifications for the M100 are shown in Table 3.

Nova M100 Design Specifications	
Rated Capacity	100 kW
Life-span	20 years
Rotor Diameter	9 meters
Rotor Speed	15-25 RPM
Cut-in Speed	0.6 m/s
Tidal Speed for Rated Power	2.0 m/s
Mouting Technique	Gravity Seabed Base

Table 3: Nova M100 Tidal Turbine Design Specifications

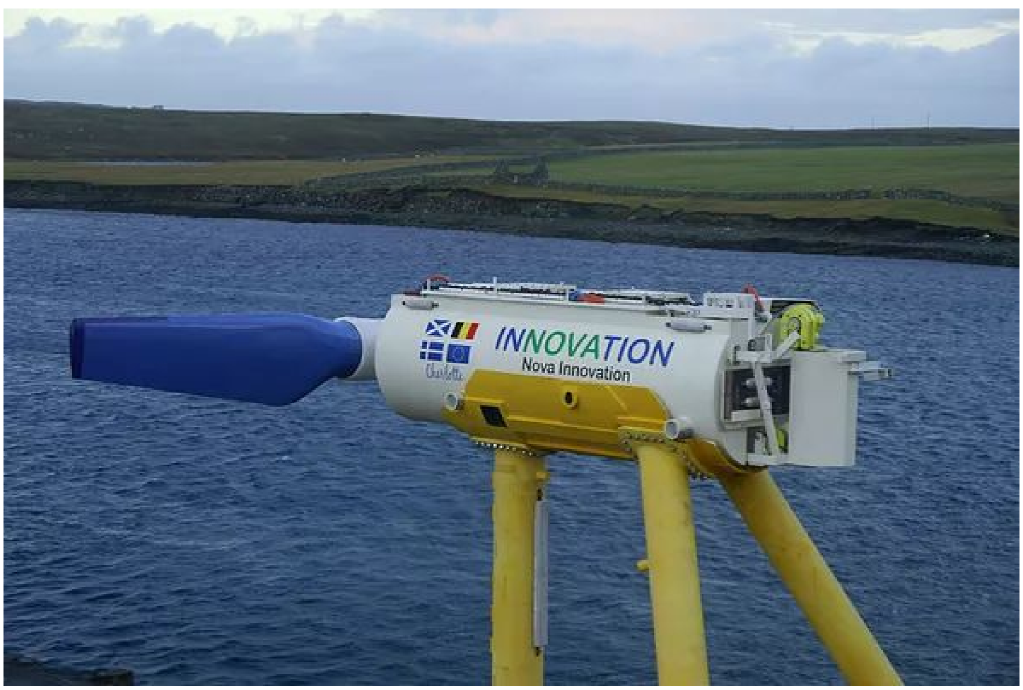

Figure 10: Nova M100 Horizontal Axis Tidal-Stream Turbine[12]

6. Bluemull Sound Tidal Array

The Bluemull Sound Tidal Array is the world's first tidal array to be fully functional and supplying electricity to the grid to power households. It is located right off the coast of the islands of Shetland in Scotland, as shown in Figure 11, and the array consists of three Nova M100 tidal turbines. The location of installation of the turbines has been strategically placed based on topography, surveying and experiments. The tidal turbines have been installed in relatively shallow waters of depths between 20 to 40 meters. The overall cost of the project is about €20.2 million with the EU Horizon 2020 Programme contributing €14.9 million[11]. Due to this project being the first functional tidal array, it has been and will be used as an experiment to collect critical data in order to improve the technology for the future. The layout of the turbines has been adjusted in order to understand the array interactions and study the optimisation of an operational tidal array[11]. Another important feature of this tidal array system is the Tesla powerpack battery that stores the energy during Shetland's slack tide. This is critical to ensure the supply of electricity is consistent to the grid. Due to a zero flow velocity during slack tide there is a reduction in the amount of energy available to be harnessed during this period[1]. Without a connection to the Tesla battery it would be impossible to supply a consistent flow of electricity to match the energy demand of the Shetland Islands.

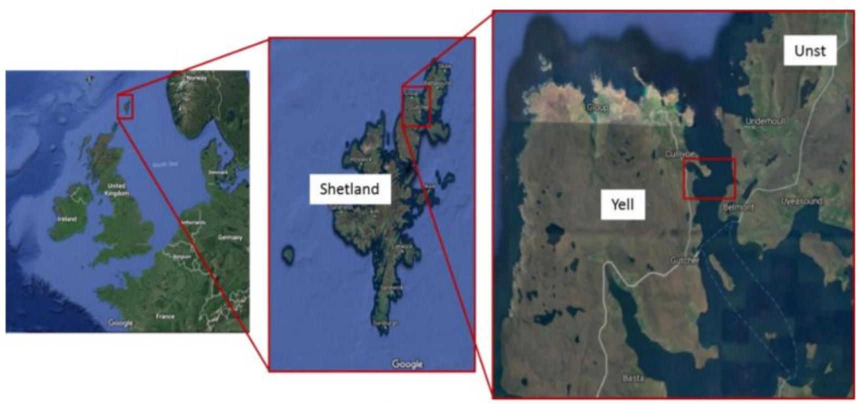

Figure 11: Location of Bluemull Sound[7]

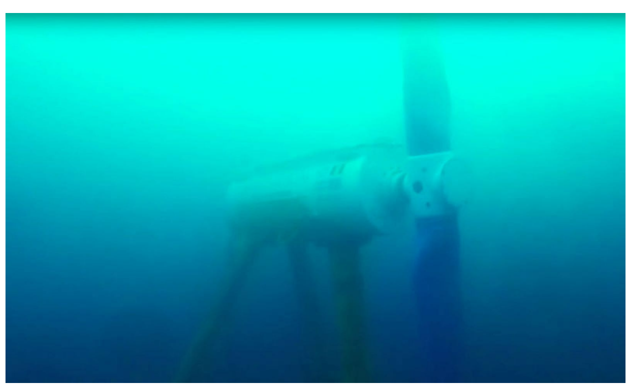

Figure 12: Nova M100 Installed at Bluemull Sound Site[1]

7. Hypothetical Site Layout

With the primary location of the site and specified tidal-stream device now established, the hypothetical site layout within the channel could now be constructed. Research obtained from the existing Bluemull Sound Tidal Array installation, the tidal and geographical data from the Bellingham Channel and specifications of the Nova M100 Tidal Turbine were all considered to substantiate the claims made in this section.

It is imperative that the exact location for this site falls within an area of the channel where the annual current velocity is at its peak. Figure 13 displays the location and distance of the transect that was created within the channel that represents the specific location for this site.

Figure 13: Transect Location/Distance (Google Earth)

This transect was created as the specific location of the site mainly due to the minimal variation in annual current velocity. Referring back to Figure 5, it is clear that the entirety of this transect spans an area within the channel where the annual current velocity is at a peak range of 1.11 m/s to 1.40 m/s. This is beneficial as it presents the choice of installing the tidal turbines at any point along this transect without losing the benefits of peak annual current velocity.

Using the NOAA bathymetry charts from Figures 3 and 4, a plot of the Bellingham Channel's depth along this transect was created. This chart is displayed below in Figure 14.

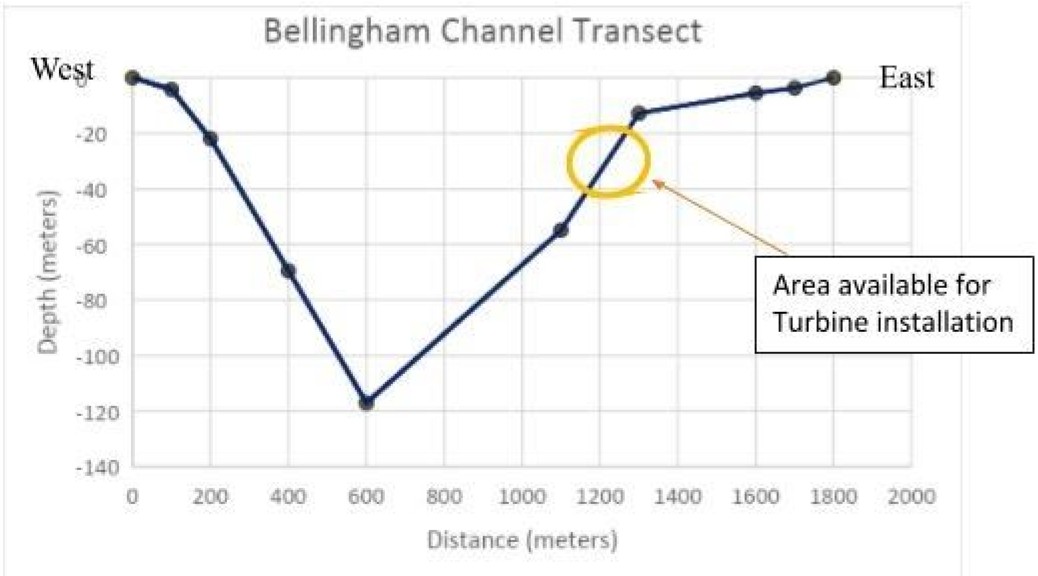

Figure 14: Transect Depth Plot

The maximum depth within the channel of approximately 120 m occurs in the middle section of the transect, closer to the Western side. Installing a tidal-stream device at the maximum depth would be problematic due to the increased cost and difficulties of installation and maintenance. As mentioned above, the benefit of the entirety of this transect spanning a region within the channel where the annual current velocity is at its peak is that the tidal turbines could be installed at any point along the transect without losing the benefits of peak annual current velocity. With this in mind, the deeper sections of the transect could be avoided and a shallower region could be considered for the installation.

The "Enabling Future Arrays in Tidal" (EnFAIT) report that focused on utilizing 3 to 6 Nova M100 Tidal Turbines in specific regions throughout Europe suggested that these turbines should be installed at least 20 m deep to avoid potential issues with shipping/boating traffic[7]. Taking a look at Figure 14, an approximately 75 m long section of the transect was circled. This section exhibits a depth range of 20 m to 40 m which would keep the tidal turbines away from shipping traffic while still residing in a relatively shallow region of the transect that would keep installation and maintenance costs to a minimum. Located roughly 500 m offshore, the site will still be in relatively close proximity to the Eastern shoreline of Guemes Island.

It was decided that a total of 3 Nova M100 Tidal Turbines would be installed within this selected location on the transect. The goal of this small renewable energy plant was to keep estimated initial costs to a minimum while also providing room for expansion of the site. If the 3 tidal turbine array is successful, there will still be room available along the transect for more turbines to be installed in the future once the cost of the technology decreases. Figure 15 below displays the proposed layout of the 3 Nova M100 Tidal Turbines. This image was originally from the

EnFAIT report which is why the turbines appear to be situated on the Western side of the channel. For this hypothetical tidal turbine array, the turbines will be situated on the Eastern side of the Bellingham Channel.

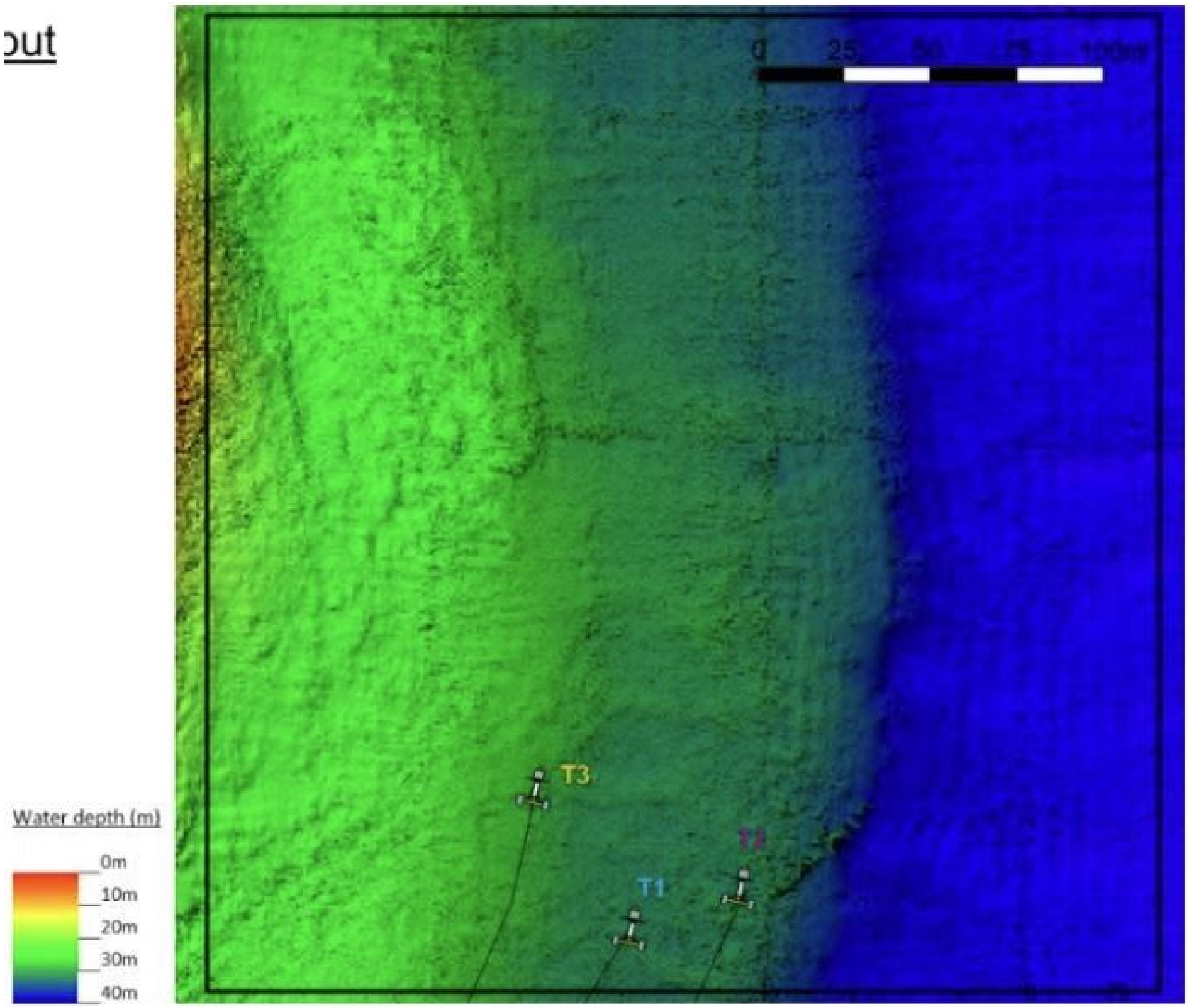

Figure 15: Proposed Layout of Tidal Turbine Array[7]

The three tidal turbines will be spaced equidistantly apart by roughly 25 m in order to avoid any potential losses due to turbulence/wake effects. This proposed layout will ensure maximum efficiency from the Nova M100 Tidal Turbines while also keeping installation and maintenance costs to a minimum.

8. Power Output Calculations

8.1 Initial Challenges:

In order to calculate power output numbers for the hypothetical tidal turbine array, it is crucial to understand the tidal current velocity data relative to the Bellingham Channel. Ideally, a substantial amount of hourly tidal current velocity data recorded over an extended period of time would be used for such calculations. Unfortunately, the nearest NOAA tidal station to the Bellingham Channel is approximately 30 km away, residing in an area of low tidal power density. Also, there were no NOAA stations within the entire region that logged hourly tidal current velocity data. This is one of the main challenges when analyzing a location that has not previously been considered for a renewable energy plant installation.

8.2 Construction of Power Curve:

Due to the issues stated above, the annual current velocity data acquired from the MHK Atlas in conjunction with the November 2020 data generated from the Tidal Analysis section would have to be the main sources of data for the following calculations. From Figure 5 and Figure 13, the tidal turbine array would be subject to an average annual current velocity range of 1.11 m/s to 1.40 m/s. These two values will be used to calculate the rated power output of a single Nova M100 Tidal Turbine at each specified velocity and then appropriately scaled to calculate the power output of an array of three Nova M100 Tidal Turbines. To complete this calculation, the power curve of the Nova M100 Turbine must be known. Figure 16 below displays the power curve of the Nova M100 Tidal Turbine.

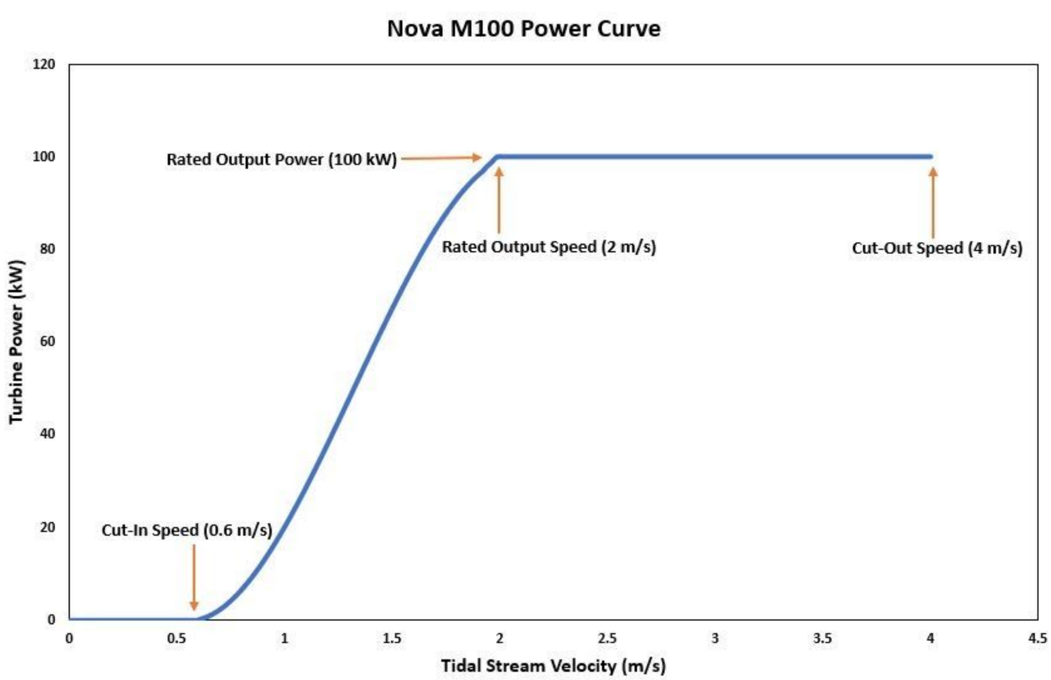

Figure 16: Nova M100 Tidal Turbine Power Curve

Ascribed to the relative recency and proprietary nature of renewable energy technology such as the Nova M100 Tidal Turbine, the exact power curve for this turbine is unknown. To combat this, the power curve above was constructed using a polynomial curve fit along with the known cut-in, cut-out and rated power speed values of the turbine[12]. It is important to note that the cut-out speed of this tidal turbine is 4 m/s. This velocity value is well above any of the tidal stream velocity values calculated in the Tidal Analysis section. A cut-out speed of 4 m/s ensures that the probability of the turbine ceasing to generate energy due to tidal current speeds exceeding the cut-out speed is negligible. With the power curve established, the power output of the turbine at the specified annual tidal stream velocity values could now be determined.

8.3 <u>Power Output Calculations</u>:

Given that the tidal stream velocity values taken from the MHK Atlas are annual averages, the energy generated by the tidal turbine(s) will also be calculated as annual values. This calculation was completed using the equation below[9].

$$E = P \times t$$

E (kWh) is the energy generated by the turbine over the specified time duration t (hours), and P (kW) is the power output of the turbine at the specific tidal stream velocity value in question. For this calculation, 8760 hours was used as the time duration variable due to the annual dependency. To determine the energy generated by the triple tidal turbine array, this value was simply multiplied by a factor of three. The maximum potential turbine energy available also must be calculated in order to determine the capacity factor of the array. The equation below was used to calculate the maximum potential turbine energy available.

$$E_{max} = P_{max} \times t$$

E_{max} (kWh) is the maximum potential turbine energy available over the specified time duration t (hours), and P_{max} (kW) is the maximum power output of the turbine which occurs between the rated power output speed of 2 m/s up to the cut-out speed of 4 m/s. Using the values of E and E_{max}, the capacity factor of the tidal turbine array can then be calculated. Below is the equation used for calculating the capacity factor of the site, where CF represents the capacity factor.

$$CF = \frac{E}{E_{max}}$$

The capacity factor is a key component for calculating the Levelized Cost of Energy in the following section. This value contributes heavily to the overall feasibility of the renewable energy plant. Table 4 below displays the final calculations described previously in this section.

Tidal Stream Velocity (m/s)	1.11	1.40
Power (kW)	30.72	58.65
Duration (h)	~8760	~8760
1x Turbine Energy (kWh)	269107.20	513774.00
3x Turbine Energy (kWh)	807321.60	1541322.00
Available 3x Turbine Energy (kWh)	2628000.00	2628000.00
Capacity Factor (%)	30.72	58.65

Table 4: Power Output Calculations

Both the lowest and highest tidal velocity current values within the range from the MHK Atlas were calculated to generate a "best" and "worst" case scenario. If the tidal turbine array is deemed to be sufficient based on the "worst" case scenario calculations, then surely the installation will be feasible throughout the given annual tidal current velocity range.

With a tidal current velocity of 1.11 m/s, the tidal turbine array was calculated to generate 807,321.60 kWh of energy annually. This leads to an overall capacity factor of 30.72%. With a tidal current velocity of 1.40 m/s, the tidal turbine array was calculated to generate 1,541,322.00 kWh of energy annually. This leads to an overall capacity factor of 58.65%.

It is important to consider that the average tidal current velocity values calculated for the month of November 2020 in the Tidal Analysis section are essentially identical to the "best" case scenario tidal current velocity of 1.40 m/s. Unfortunately due to time constraints, these values could not be calculated for each individual month of 2020. However, it is safe to assume that the tidal current velocities that the turbine array will be subject to at this site location will be closer to the "best" case scenario of 1.40 m/s annually.

9. Levelized Cost of Energy (LCOE)

9.1 <u>Approach and Calculation of LCOE</u>:

Currently, the LCOE data of the Bluemull Sound Tidal Array project is not available. This is due to the physical data needed to calculate the LCOE has not yet been obtained and analyzed from this tidal power station. The Bluemull Sound Tidal Array consisting of the three Nova M100s was mirrored as close as possible in order to calculate the LCOE for the presented hypothetical tidal array. Multiple factors or variables were used based on the Bluemull Sound Tidal Array like the overall cost of the project being €20.2 million or about $24.7 million (*P*) and the number of turbines used combining to a 300 kW rated power output (*Power*). Assumptions were made based on prior assignments to calculate the LCOE of a wind farm. The assumptions were the use of a 3% interest rate and an O&M cost of 25% of the annual cost of the project. The Capital Recovery Factor (*CRF*) was calculated using the 3% interest rate (*i*) and the 20 year life-span of the turbine (*n*) to obtain a value of 0.067 as seen in Appendix 2[9].

$$CRF = \frac{i \times (1+i)^{n}}{(1+i)^{n} - 1}$$

The capacity factor (*CF*) was determined using the power curve data that provided a rated power output of 30.72 kW for the lower range flow velocity value of 1.11 m/s and a rated power output of 58.65 kW for the higher range flow velocity value of 1.4 m/s. This gave a CF of 30.72% for the lower range flow velocity value and 58.65% for the higher range flow velocity value. The original approach in calculating the LCOE was to calculate the LCOE for the high and low range flow velocity values in order to determine if they were feasible values. The lower range flow velocity value was especially focused on because it is considered the “worst” case scenario. For an O&M at 25% of the annual costs a value of $308,707,76 was obtained. After all these values were determined, the LCOE for both scenarios was calculated as seen in Appendix 2[9].

$$LCOE = \frac{(CRF \times P) + O\&M}{(CF)(Power)(8760h)}$$

A LCOE value of 1.27 $/kWh was calculated for the higher range velocity of 1.40 m/s and a LCOE of 2.43 $/kWh for the lower range value of 1.11 m/s. Prior to presenting this report to Professor Hashemi and the class, it was thought that these LCOE values were very high, especially considering the low energy prices for the state of Washington. Professor Hashemi did advise that these LCOE values were actually viable costs per energy for the hypothetical tidal array. If it is not feasible to implement the hypothetical tidal array in Washington, it could most certainly be feasible at locations where energy prices are higher.

9.2 <u>Operation and Maintenance Cost Analysis</u>:

Further thought went into determining and calculating a lower LCOE of the hypothetical tidal array. Due to the nature of the Nova M100 design and the small scale array of only three turbines, it is reasonable to assume that the O&M value for the hypothetical site should be lower than the assumed 25% of annual costs. The typical O&M costs of a much larger scaled wind turbine farm is 25% of the plant's annual costs. Therefore, the O&M percentage of annual costs was manipulated in order to understand the decrease in the LCOE value. Table 5 below displays the percentage of annual cost used for the O&M value and the change in the LCOE. It is apparent that the LCOE will decrease in cost per energy when the O&M is decreased. These numbers did not decrease as much as expected, but definitely had an effect. It was worth understanding the impact of decreasing the O&M cost of this hypothetical tidal array, as this data has not been historically determined and studied.

O&M	LCOE 1.11 m/s Average Annual Velocity	LCOE 1.40 m/s Average Annual Velocity
5%	2.12 $/kWh	1.11 $/kWh
10%	2.20 $/kWh	1.15 $/kWh
15%	2.28 $/kWh	1.19 $/kWh
20%	2.36 $/kWh	1.23 $/kWh
25%	2.43 $/kWh	1.27 $/kWh

Table 5: O&M Costs With Corresponding LCOE Values

9.3 Comparison to BIWF LCOE

After Professor Hashemi confirmed the LCOE's of the hypothetical tidal array were viable values, a comparison of these values to another plant with LCOE data was sought out. The Block Island Wind Farm (BIWF) consists of five 6 MW wind turbines amounting to an overall rated power output of 30 MW or 30,000 kW. As stated prior to this section, the hypothetical site from this report consists of three turbines with an overall rated power output of 300 kW. The overall cost of the BIWF is $350 million compared to the $25 million for the hypothetical site, which is roughly 12 times the cost. The BIWF is a significantly larger project compared to the hypothetical site. Referring to Assignment #1 from OCE 513, the LCOE of the BIWF was determined to be about 0.287 $/kWh. The LCOE value of 1.27 $/kWh for the "best" case scenario velocity of 1.40 m/s is roughly 4.5 times larger than the BIWF LCOE, while the LCOE value of 2.43 $/kWh for the "worst" case scenario velocity of 1.11 m/s is roughly 8.5 times larger. This demonstrates that the LCOE values for this project actually scale quite favorably in comparison to the much larger BIWF operation. If the amount of tidal-stream turbines were increased, the overall cost of the project could be decreased. As a result, this could reduce the LCOE and potentially make the cost per energy feasible for Washington and even more feasible for a location with higher electricity rates like California, with a rate of about 0.183 $/kWh[15]. Comparing the hypothetical site's LCOEs to the BIWF LCOE further confirms the project's feasibility.

9.4 Other Considerations for LCOE Reduction:

There are other factors that could go into reducing the LCOE value for this hypothetical tidal array. Some of which could be the promotion of this technology by the government, state or various ocean renewable energy organizations. There could be an interest in expanding this technology for the future and for future energy demands. Similar to the Bluemull Sound Tidal Array project, there could be a want and need of creating a site to obtain experimental data. These situations could allow the LCOE to be higher than what would be potentially acceptable for economical purposes for an area. Therefore, this would subsidize the cost per energy and allow for a lower LCOE even if the overall cost of the project is still high.

10. Community Benefits

10.1 Overview:

The breadth of this hypothetical tidal turbine installation is quite small when compared with other existing renewable energy plants. As renewable energy technology is still relatively adolescent in terms of development and implementation, larger scale operations, such as the Block Island Wind Farm, benefit from heavily decreased price to performance ratios. These operations are capable of outputting enough energy to power large communities/industrial plants and receive substantial government funding to offset the initial costs of installation.

The proposed tidal turbine array described in this report is primarily aimed at providing a small amount of renewable energy to surrounding island communities that could benefit from this "off the grid" solution in the long term.

10.2 Washington State Residential Electricity Consumption:

Average residential electricity consumption in the state of Washington is 1,037 kWh/month, which ranks the state as the 18th highest consumer of electricity in the United States[15]. This value is 14.84% greater than the national average of 903 kWh/month. Despite this, the state of Washington still benefits from exhibiting the cheapest average residential electricity rate in the entire United States at 0.0853 $/kWh. This value is 28.2% less than the national average rate of 0.119 $/kWh.

On the surface, it might appear that installing this proposed renewable energy site would not be feasible as even the absolute best case LCOE value (O&M = 5%, 1.40 m/s annual tidal current velocity) is 1.11 $/kWh, well above the average rate of residential electricity in Washington state. However, there are a few other important factors to consider before coming to this conclusion.

10.3 Influential Factors:

The first and potentially most important factor to consider is the location of the communities that will be receiving energy from this plant. As this tidal turbine array will be located just off the West coast of Guemes Island, it would be logical to assume that this community would be on the receiving end of this renewable energy installation. Guemes Island has a population of 605 residents with 292 total households. With such a small population size in combination with the additional difficulties of providing grid energy to an island, it is safe to assume that the average cost of electricity is a fair amount higher on Guemes Island than the overall average electricity cost in the state of Washington. Installing this renewable energy site could reduce the island's dependency on grid energy, potentially reducing the cost of electricity.

Another key factor is that this proposed tidal turbine array was designed to allow the installation of additional tidal turbines in the future. As tidal turbine technology continues to advance, the prices for these turbines will begin to decrease. Installing an additional two to three turbines at a projected decrease in price will help drive the LCOE down to a more reasonable value. In the long term, this would be a substantial benefit for justifying the feasibility of the tidal array. Finally, potential government funding should also be considered as a realistic possibility for this project. The Bellingham Channel and neighboring Rosario Strait both exhibit strong tidal power densities that would appear to be ideal for the installation of future renewable energy sites. In order to investigate this theory, an experimental small renewable energy plant must first be installed and analyzed to prove whether or not these regions should continue to be evaluated for future, larger scale plants. There are clear benefits for the state of Washington to potentially fund a project such as this proposed site in the Bellingham Channel. If renewable energy is the future, then it would be a wise decision for the state of Washington to assess its own tidal resources by starting with a small scale operation such as this tidal turbine array.

10.4 Potential Number of Households Powered:

The following subsection will detail the process of estimating the total number of households on Guemes Island that could potentially be powered from this tidal turbine array. As stated above, there are a total of 292 households residing on Guemes Island. Using the value for average residential electricity consumption in the state of Washington (1,037 kWh/month[15]), a calculation can be completed to estimate the number of households on the island that could be powered solely from this proposed renewable energy site.

Following a similar procedure to what was detailed in the Power Output Calculation section of this report, a "worst" and "best" case scenario for the estimated number of households powered can be calculated. The only alteration to this procedure was the total amount of energy generated will now be calculated as a monthly value rather than annually to match up with the given average residential electricity consumption rate. Table 6 below displays the "worst" and "best" case estimations.

Tidal Stream Velocity (m/s)	1.11	1.40
Power (kW)	30.72	58.65
Duration (h)	~720	~720
3x Turbine Energy (kWh/month)	66355.20	126684.00
Average Residential Power Consumption (kWh/month)	1037.00	1037.00
Number of Houses Powered	63.99	122.16

Table 6: Number of Households Powered Estimation

For an annual tidal stream velocity of 1.11 m/s, it was estimated that approximately 64 households on Guemes Island could be powered from this tidal turbine array. That number represents roughly 22% of the total households on the island. For an annual tidal stream velocity of 1.40 m/s, it was estimated that approximately 122 households on Guemes Island could be powered from this tidal turbine array. That number represents roughly 42% of the total households on the island.

These numbers are not staggering when compared with much larger renewable energy operations, however the potential to power nearly half of the households on Guemes Island with such a small installation is an attractive proposition. If three more tidal turbines are added to the existing array once prices decrease in the future, this site could theoretically provide power for nearly all of the residents on Guemes Island.

11. Conclusion

A tidal-turbine array like the one currently in use in Scotland shows promise for utilization in the Bellingham Channel. This study has demonstrated that tidal stream power here is *technically* feasible. However, this study also highlights some economic shortcomings that would have to be addressed if this were to be a viable project. “Real world” costs that were not considered in the LCOE calculations would likely result in a significant increase in cost to the consumer, not to mention the time and money that would be consumed assessing environmental impacts and gaining community buy-in. That said, these additional costs could be offset by public and private funding, as well as other possibilities mentioned in Sections 9.4 and 10.3. As tidal energy technology evolves and costs come down, it can be expected to be deployed on a larger scale.

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Appendix 1: AyeTides Data

Flood Direction: 20° true, Ebb Direction: 190° true

Bellingham Channel, off Cypress Head Light, Rosario Strait, Washington Current

Sunday, November 1, 2020
1:34 AM PDT Slack before flood
3:47 AM PST 2.74 Knots (F)
6:55 AM PST Slack before ebb
9:34 AM PST 2.12 Knots (E)
1:03 PM PST Slack before flood
3:12 PM PST 1.08 Knots (F)
5:06 PM PST Slack before ebb
9:05 PM PST 3.95 Knots (E)

Monday, November 2, 2020
12:58 AM PST Slack before flood
4:19 AM PST 2.88 Knots (F)
7:43 AM PST Slack before ebb
10:18 AM PST 1.87 Knots (E)
1:45 PM PST Slack before flood
3:32 PM PST 0.73 Knots (F)
5:10 PM PST Slack before ebb
9:31 PM PST 4.01 Knots (E)

Tuesday, November 3, 2020
1:24 AM PST Slack before flood
4:55 AM PST 2.94 Knots (F)
8:33 AM PST Slack before ebb
11:06 AM PST 1.64 Knots (E)
2:37 PM PST Slack before flood
3:58 PM PST 0.38 Knots (F)
5:14 PM PST Slack before ebb
9:59 PM PST 3.98 Knots (E)

Wednesday, November 4, 2020
1:56 AM PST Slack before flood
5:37 AM PST 2.94 Knots (F)
9:29 AM PST Slack before ebb
12:00 PM PST 1.45 Knots (E)
4:07 PM PST Slack before flood
4:30 PM PST 0.03 Knots (F)
4:54 PM PST Slack before ebb
10:31 PM PST 3.86 Knots (E)

Thursday, November 5, 2020
2:34 AM PST Slack before flood
6:27 AM PST 2.91 Knots (F)
10:29 AM PST Slack before ebb
12:58 PM PST 1.33 Knots (E)
5:14 PM PST 0.32 Knots (E)
11:09 PM PST 3.65 Knots (E)

Friday, November 6, 2020
3:20 AM PST Slack before flood
7:25 AM PST 2.86 Knots (F)
11:29 AM PST Slack before ebb
2:06 PM PST 1.32 Knots (E)
6:12 PM PST 0.63 Knots (E)
11:57 PM PST 3.34 Knots (E)

Saturday, November 7, 2020
4:14 AM PST Slack before flood
8:29 AM PST 2.84 Knots (F)
12:27 PM PST Slack before ebb
3:22 PM PST 1.48 Knots (E)
7:30 PM PST 0.80 Knots (E)

Sunday, November 8, 2020
12:59 AM PST 2.97 Knots (E)
5:22 AM PST Slack before flood
9:33 AM PST 2.87 Knots (F)
1:17 PM PST Slack before ebb
4:26 PM PST 1.82 Knots (E)
9:04 PM PST 0.69 Knots (E)

Monday, November 9, 2020
2:23 AM PST 2.63 Knots (E)
6:32 AM PST Slack before flood
10:29 AM PST 2.93 Knots (F)
1:59 PM PST Slack before ebb
5:06 PM PST 2.25 Knots (E)
10:32 PM PST 0.21 Knots (E)

Tuesday, November 10, 2020
3:53 AM PST 2.51 Knots (E)
7:40 AM PST Slack before flood
11:21 AM PST 2.95 Knots (F)
2:33 PM PST Slack before ebb
5:40 PM PST 2.77 Knots (E)
10:09 PM PST Slack before flood
11:42 PM PST 0.55 Knots (F)

Wednesday, November 11, 2020
1:12 AM PST Slack before ebb
5:09 AM PST 2.58 Knots (E)
8:42 AM PST Slack before flood

12:07 PM PST 2.89 Knots (F)
3:01 PM PST Slack before ebb
6:12 PM PST 3.36 Knots (E)
10:17 PM PST Slack before flood

Thursday, November 12, 2020
12:40 AM PST 1.48 Knots (F)
2:56 AM PST Slack before ebb
6:11 AM PST 2.71 Knots (E)
9:40 AM PST Slack before flood
12:49 PM PST 2.72 Knots (F)
3:27 PM PST Slack before ebb
6:44 PM PST 3.98 Knots (E)
10:39 PM PST Slack before flood

Friday, November 13, 2020
1:32 AM PST 2.45 Knots (F)
4:12 AM PST Slack before ebb
7:09 AM PST 2.81 Knots (E)
10:36 AM PST Slack before flood
1:31 PM PST 2.44 Knots (F)
3:51 PM PST Slack before ebb
7:16 PM PST 4.57 Knots (E)
11:07 PM PST Slack before flood

Saturday, November 14, 2020
2:18 AM PST 3.35 Knots (F)
5:16 AM PST Slack before ebb
8:03 AM PST 2.83 Knots (E)
11:32 AM PST Slack before flood
2:09 PM PST 2.06 Knots (F)
4:15 PM PST Slack before ebb
7:50 PM PST 5.03 Knots (E)
11:39 PM PST Slack before flood

Sunday, November 15, 2020
3:02 AM PST 4.06 Knots (F)
6:18 AM PST Slack before ebb
8:57 AM PST 2.78 Knots (E)
12:30 PM PST Slack before flood
2:47 PM PST 1.59 Knots (F)
4:39 PM PST Slack before ebb
8:28 PM PST 5.29 Knots (E)

Monday, November 16, 2020
12:13 AM PST Slack before flood
3:48 AM PST 4.50 Knots (F)
7:16 AM PST Slack before ebb
9:53 AM PST 2.65 Knots (E)
1:34 PM PST Slack before flood
3:27 PM PST 1.06 Knots (F)
5:03 PM PST Slack before ebb
9:06 PM PST 5.30 Knots (E)

Tuesday, November 17, 2020
12:53 AM PST Slack before flood
4:36 AM PST 4.67 Knots (F)
8:14 AM PST Slack before ebb
10:51 AM PST 2.50 Knots (E)
2:48 PM PST Slack before flood
4:09 PM PST 0.51 Knots (F)
5:23 PM PST Slack before ebb
9:48 PM PST 5.05 Knots (E)

Wednesday, November 18, 2020
1:35 AM PST Slack before flood
5:28 AM PST 4.58 Knots (F)
9:14 AM PST Slack before ebb
11:53 AM PST 2.37 Knots (E)
4:50 PM PST Slack before flood
5:01 PM PST 0.01 Knots (F)
5:13 PM PST Slack before ebb
10:34 PM PST 4.59 Knots (E)

Thursday, November 19, 2020
2:21 AM PST Slack before flood
6:26 AM PST 4.31 Knots (F)
10:12 AM PST Slack before ebb
12:59 PM PST 2.29 Knots (E)
6:03 PM PST 0.38 Knots (E)
11:26 PM PST 3.98 Knots (E)

Friday, November 20, 2020
3:15 AM PST Slack before flood
7:26 AM PST 3.94 Knots (F)
11:10 AM PST Slack before ebb
2:07 PM PST 2.29 Knots (E)
7:17 PM PST 0.59 Knots (E)

Saturday, November 21, 2020
12:24 AM PST 3.32 Knots (E)
4:17 AM PST Slack before flood

8:30 AM PST 3.55 Knots (F)
12:06 PM PST Slack before ebb
3:23 PM PST 2.39 Knots (E)
8:39 PM PST 0.54 Knots (E)

Sunday, November 22, 2020
1:32 AM PST 2.68 Knots (E)
5:27 AM PST Slack before flood
9:32 AM PST 3.17 Knots (F)
12:56 PM PST Slack before ebb
4:25 PM PST 2.58 Knots (E)
10:01 PM PST 0.22 Knots (E)

Monday, November 23, 2020
2:50 AM PST 2.18 Knots (E)
6:39 AM PST Slack before flood
10:30 AM PST 2.81 Knots (F)
1:40 PM PST Slack before ebb
5:09 PM PST 2.79 Knots (E)
10:06 PM PST Slack before flood
11:13 PM PST 0.30 Knots (F)

Tuesday, November 24, 2020
12:25 AM PST Slack before ebb
4:14 AM PST 1.92 Knots (E)
7:49 AM PST Slack before flood
11:20 AM PST 2.44 Knots (F)
2:18 PM PST Slack before ebb
5:45 PM PST 3.01 Knots (E)
10:18 PM PST Slack before flood

Wednesday, November 25, 2020
12:15 AM PST 0.90 Knots (F)
2:21 AM PST Slack before ebb
5:26 AM PST 1.83 Knots (E)
8:53 AM PST Slack before flood
12:06 PM PST 2.05 Knots (F)
2:46 PM PST Slack before ebb
6:13 PM PST 3.24 Knots (E)
10:36 PM PST Slack before flood

Thursday, November 26, 2020
1:07 AM PST 1.52 Knots (F)
3:39 AM PST Slack before ebb
6:24 AM PST 1.80 Knots (E)
9:49 AM PST Slack before flood
12:42 PM PST 1.65 Knots (F)
3:06 PM PST Slack before ebb
6:39 PM PST 3.49 Knots (E)
10:54 PM PST Slack before flood

Friday, November 27, 2020
1:49 AM PST 2.10 Knots (F)
4:39 AM PST Slack before ebb
7:16 AM PST 1.77 Knots (E)
10:39 AM PST Slack before flood
1:14 PM PST 1.27 Knots (F)
3:18 PM PST Slack before ebb
7:03 PM PST 3.75 Knots (E)
11:14 PM PST Slack before flood

Saturday, November 28, 2020
2:25 AM PST 2.59 Knots (F)
5:31 AM PST Slack before ebb
8:00 AM PST 1.73 Knots (E)
11:27 AM PST Slack before flood
1:38 PM PST 0.93 Knots (F)
3:26 PM PST Slack before ebb
7:29 PM PST 4.00 Knots (E)
11:34 PM PST Slack before flood

Sunday, November 29, 2020
2:57 AM PST 3.00 Knots (F)
6:19 AM PST Slack before ebb
8:44 AM PST 1.69 Knots (E)
12:13 PM PST Slack before flood
2:02 PM PST 0.65 Knots (F)
3:34 PM PST Slack before ebb
7:55 PM PST 4.21 Knots (E)
11:56 PM PST Slack before flood

Monday, November 30, 2020
3:29 AM PST 3.30 Knots (F)
7:03 AM PST Slack before ebb
9:26 AM PST 1.64 Knots (E)
1:03 PM PST Slack before flood
2:26 PM PST 0.41 Knots (F)
3:42 PM PST Slack before ebb
8:23 PM PST 4.34 Knots (E)

Tuesday, December 1, 2020
12:22 AM PST Slack before flood

4:03 AM PST	3.50 Knots (F)
7:49 AM PST	Slack before ebb
10:12 AM PST	1.60 Knots (E)
2:03 PM PST	Slack before flood
2:56 PM PST	0.18 Knots (F)
3:46 PM PST	Slack before ebb
8:53 PM PST	4.38 Knots (E)

Station information for Bellingham Channel, off Cypress Head Light, Rosario Strait, Washington Current

This station is a reference station

the time zone is America/Los_Angeles (GMT-8:00)

The location is latitude 48.5585˚ , longitude -122.6618˚

Station ID: PUG1740

Station depth is 31 feet

Appendix 2: LCOE Calculations

LCOE of Hypothetical Tidal Array:

$$CRF = \frac{i * (1+i)^n}{(1+i)^n - 1}$$

$$i = 3\%$$

$$n = 20\ years$$

$$CRF = 0.067$$

$$LCOE\ of\ Lower\ Range\ Value\ (1.11\frac{m}{s}):$$

$$LCOE = \frac{(CRF * P) + O\&M}{(CF)(Power)(8760\ h)}$$

$$P = €20.2\ million = \$24{,}696{,}621.00\ million$$

$$CF = 30.72\%$$

$$Power = 300\ kW\ (3\ turbines)$$

$$O\&M = \$308{,}707.76\ (25\%\ of\ annual\ costs)$$

$$LCOE = 2.43\ \$/kWh$$

$$LCOE\ of\ Higher\ Range\ Value\ (1.40\frac{m}{s}):$$

$$LCOE = \frac{(CRF * P) + O\&M}{(CF)(Power)(8760\ h)}$$

$$P = €20.2\ million = \$24{,}696{,}621.00\ million$$

$$CF = 58.65\%$$

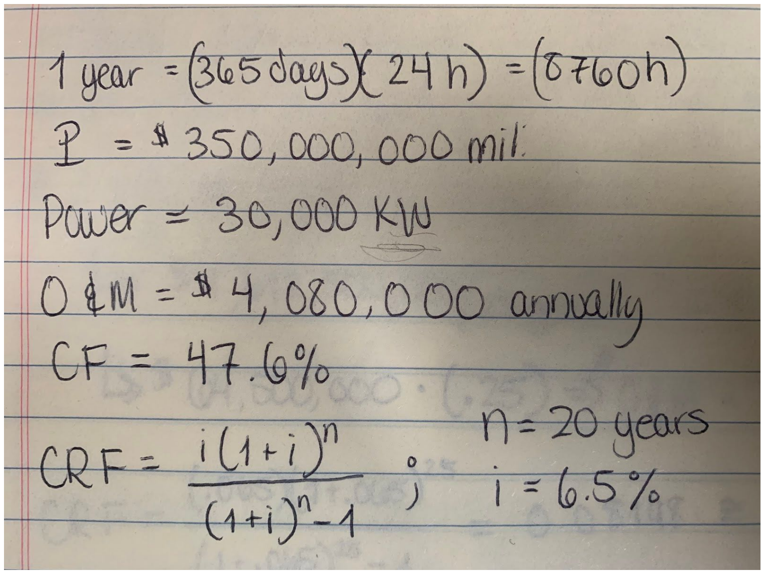
$$Power = 300\ kW\ (3\ turbines)$$

$$O\&M = \$308{,}707.76\ (25\%\ of\ annual\ costs)$$

$$LCOE = 1.27\ \$/kWh$$

LCOE of the BIWF:

Variables:



1 year = (365 days)(24 h) = (8760 h)

P = \$350,000,000 mil

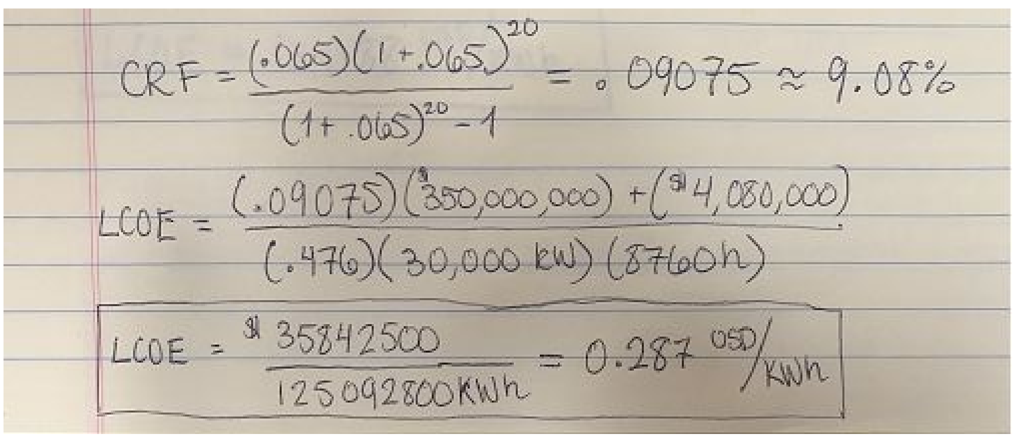
Power = 30,000 KW

O & M = \$4,080,000 annually

CF = 47.6%

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \; ; \quad n = 20 \text{ years}, \; i = 6.5\%$$

Calculation:



$$CRF = \frac{(.065)(1+.065)^{20}}{(1+.065)^{20}-1} = .09075 \approx 9.08\%$$

$$LCOE = \frac{(.09075)(\$350,000,000) + (\$4,080,000)}{(.476)(30,000 \text{ kW})(8760 \text{h})}$$

$$LCOE = \frac{\$35842500}{125092800 \text{ KWh}} = 0.287 \text{ USD/KWh}$$