An Oscillating Water Column Wave Energy Converter for Small-Scale Disaster Relief

Marine Energy Collegiate Competition 2022

WEBB INSTITUTE

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Nomenclature

Abbreviations

- FERC – Federal Energy Regulatory Commission
- IEC – International Electrotechnical Commission
- LR – Lloyd's Register
- NHA – National Hydropower Association
- NREL – National Renewable Energy Laboratory
- NYSERDA - New York State Energy Research and Development Authority
- OWC – Oscillating water column
- PNNL – Pacific Northwest National Laboratory
- PTO – Power take-off
- RMB – Webb Institute's Robin Model Basin
- RO – Reverse osmosis
- ROLS-W – Remote Optical Laser Sensor
- TC – Technical Committee
- TRL – Technology Readiness Levels
- WEC – Wave energy converter
- WPW – Water Power Week

Variables

- P – Power
- R – Resistance
- V – Voltage

1 Executive Summary

The Webb Institute MECC team is a first-time competitor and is excited to partake in such an experience. The team is comprised of seven naval architecture and marine engineering undergraduate students, spanning from first- to fourth-year students. This report encompasses the research performed by the 2021-2022 team regarding the technical design, construction, and market analysis of an oscillating water column wave energy converter (OWC) for use in small-scale disaster relief for small, isolated communities.

The design of this system pulled from a large body of research that has studied the optimization of individual OWC components. The analysis of this design weighed not only the performance of the system, but also its feasibility of construction, affordability, and survival.

A model-scale OWC system was used to assess the performance of a simplified design. Tank-testing was performed to evaluate both shaft output rotation and electrical power. Testing yielded promising results, with coupled RPM values upwards of 1000 and output power values reaching 113 mW at the higher end of the testing matrix. While these results are encouraging for prototype testing, they become even more-so when considering the possibilities for use-cases at full-scale.

2 Business Plan

The proposed OWC design is simple to build, scalable, and cost effective. In light of the climate crisis and the urgent need for reliable, accessible, and renewable energy generating sources, the OWC concept is a promising alternative that can power remote or developing communities while providing breakwater capabilities. Meant to be situated by the shore, the fixed structure will be adequately positioned to take full advantage of the constant wave resource. The intended use and capability of the design concept will be explored in further detail in the following sections, with the ultimate goal of exploring the market feasibility of constructing and implementing an OWC. The feasibility of such a concept will be determined by the perceived marketability, ease of construction, public and market opinion, and market competitiveness.

2.1 Concept Overview

The original idea of the project was to develop a novel system for creating clean energy which would be feasible in terms of constructability and practicality. Upon further investigation of different systems, our team chose to design an OWC as it offers the benefits of multiple methods of integration and minimal moving parts. The OWC could be properly sized for the necessary power output, and it could be implemented either bottom standing, in a floating structure, or integrated in a breakwater. The only moving part of OWCs are the air-driven turbine which limits the amount of maintenance and potential issues which would arise from a more complex system.

The potential commercial application for the OWC was subsequently analyzed. The discussions with relevant stakeholders (shown in Section 2.2) revealed potential markets to deploy our OWCs. While the initial intention was to deliver power to communities as an alternative to traditional fossil fuel power plants, we learned that a potential market would be for disaster relief, especially for underdeveloped, isolated communities. The application of our OWCs for disaster relief has a multitude of benefits. It would provide clean power to maintain resiliency in small communities subject to natural disasters, and it would reduce the potential impact from the natural disasters.

From this assessment, we determined that the concept which could be offered is a series of OWCs integrated into a breakwater along a coastline. The power generated from the system would be used to either power water desalination equipment, medical equipment, or emergency light for disaster relief efforts. The integration of the system into a breakwater would provide the additional benefit of a protective structure, thus decreasing the destructive impact on a community. The system offers significant social value as it allows for a means of preventing and reducing the impact of natural disasters on small communities. The lives of those impacted would be upended to a lesser extent, and it offers a meaningful system to support financially by private companies and charities. There is the added environmental value of providing a stable means of clean power to these small communities and potentially providing power to areas without power currently.

2.2 Relevant Stakeholders

Stakeholder 1

Potential stakeholders for disaster relief efforts include governmental bodies. It is in the interest of governmental bodies to invest in reliable means of disaster relief to prevent the impact on a community. Due to the increasing number of natural disaster events as a result of global warming, the importance of maintaining the resiliency of a country and its infrastructure is becoming more important. Certain countries include budgets for disaster relief within infrastructure bills. For example, the United States recently committed $1.2 trillion to investing in climate change and maintain resiliency. While this is an extreme example of a financial commitment from a government, this shows that there are countries committed to financially support maintaining a country's resiliency.

Stakeholder 2

Foundations and charities committed to aiding countries act as potential stakeholders as well. Depending on the organization, the group either directly develops projects to provide aid or provide funding to other entrepreneurs or companies to invest in such efforts. One of the most charitable organizations, the Gates Foundation, is a prime example of this. The Gates Foundation allows for the submission of RFPs for grants to fund efforts to fight disease and inequity, and the foundation seeks out companies to invest in.

2.3 Discussions with Industry Professionals

To gain a better understanding of the nuances behind formulating a business plan and the current climate of wave energy innovation, industry professionals were consulted. Each of the following professionals provided unique insight into the contributing factors of a successful market plan, identifying feasibility and scalability, investor interest, and security as some of the most important elements.

Additionally, two team members participated in the annual National Hydropower Association's (NHA) WaterPower Week located in Washington D.C. to gather information, create connections, and become more informed on the current state of waterpower in the United States, especially in respect to marine energy generation. During their time in Washington, D.C. the team members attended panels and plenary sessions relevant to the Marine Energy Collegiate Competition. One of the main takeaways was an understanding of the regulatory and legislative hurdles facing the waterpower industry. Despite these setbacks, there are a number of various interest groups working to make waterpower an integral part of the renewable energy solution. Although hydro power was a major focus of the conference, it was also possible to gain understanding of similar challenges that marine energy will encounter.

Based on information from the conference, water power is on the rise, albeit at a much slower pace than wind or solar power. The increase of funding in water power over the last 15 years is evidence of that. Developers, customers, and government agents hope to increase this growth by funding water power at the same level as solar and wind power were funded; the exponential growth of the solar and wind industries is largely due to the government's aid in the early development of wind and solar, making those projects more financially feasible when market entrance would have been prohibitively costly.

Industry Professional 1

Name: Myron Spenser Boyd

Affiliation: Energy and Systems Engineer at L&S Energy Services

Discussion with Industry Professional: Spenser Boyd is a PhD candidate with a Master of Engineering in energy systems. He has worked on energy projects with NYSERDA, National Grid, and Eversource Energy which has helped save millions of kilowatts of energy in New York State. Spenser suggested that the Wells turbine can provide coastal resilience and suggested the team analyze a more niche market. Instead of focusing solely on scaling OWCs for major industrial applications, OWCs can be used for geographically isolated areas. The device may provide energy for sensors for communication towers, weather buoys, or subsea buoys off the coast. Secluded locations with lighthouses can utilize OWCs to work as both coastal protection for breakwater and coastal powering.

Industry Professional 2

Name: Gabrielle A. Piasio

Affiliation: Vice President, Sponsor Finance at Bank Prov

Discussion with Industry Professional: Gabrielle Piasio was one of the panelists at Water Power Week (WPW) 2022 speaking on Finding Financing for Development: Innovative Financing for Small Hydro and Marine Energy. Bank Prov was different from typical banks because it is a crypto-focused bank that was interested in funding small commercial wind, solar, hydro, and marine energy projects. Gabrielle stressed the importance of ensuring that water power projects could demonstrate that they are low risk investments. This meant having historical streamflow data indicating that waterflow in the given project region was reliable. To investors funding these construction projects, this meant having revenue guarantee, or having power suppliers committed to using the energy generated by the project at hand. Power suppliers looked at the economic feasibility of using the energy generated from these projects.

Industry Professional 3

Name: Jonathan Colby

Affiliation: Director of Technology Performance for Verdant Power

Discussion with Industry Professional: Jonathan Colby was a facilitator and a speaker for a panelist discussion on Marine Energy: Path to Commercialization during WPW 2022. Wind energy and solar energy are gaining significant attention in the United States, but do not provide a consistent reliable energy source like hydropower and marine energy. When the wind stops blowing on a calm day and the sun stops shining at night, hydropower and marine power is able to improve security of supply by generating electricity at times of peak demand. Jonathan agrees there is not only one renewable energy which will help us reach carbon neutrality by 2050, but a combination of all renewable energies. He also explains the trend for the turning points in wind and solar power: the International Electrotechnical Commission (IEC) standardization. Once IEC technical committees (TC) 82 was established for solar photovoltaic energy systems and IEC TC 88 was established for wind energy generation systems, the capacity of each energy system skyrocketed. Until hydropower and marine power have a similar quality management standard, advancements will struggle to match that of other renewable energy technologies.

Industry Professional 4

Name: Bradley Golden

Affiliation: President and Naval Architect, Golden Marine and Offshore

Discussion with Industry Professional: Bradley Golden has previously worked with Ocean Energy to build the OE Buoy, a floating offshore OWC, which utilizes a similar energy generation principle – pressured air rotates a bi-directional turbine. As an offshore unit, it was fitted with its own control and monitoring system to provide condition-based maintenance. Another common maintenance procedure considered is preventive maintenance. Preventive maintenance is the regular maintenance of equipment to keep them operating. However, condition-based maintenance is a better approach for remote units as they continuously assess the state of the system and signal when equipment is deteriorating. Bradley also spoke on some of the risks associated with delivering the prototype. No rules or regulations were developed for this type of structure at the time. Insurance was still being processed at the time it was being constructed. Collision risk was a major consideration when visibility of the offshore OWC from the perspective of a passing vessel. Bradley recommended looking into technology readiness levels (TRLs) as a method for estimating the maturity of this technology and reducing risks that arise.

2.4 Market Opportunity

2.4.1 Market Definition

Disaster relief offers a viable opportunity to implement OWCs, especially for isolated communities which are not connected to large power grids. The impacts of a natural disaster on a small community are felt for months to potentially years afterwards. Personal property and community infrastructure are destroyed as a result of large natural disasters. It is time, labor, and financially expensive to redevelop the lost property. Implementing an OWC would help decrease the time and labor necessary to recover from natural disasters.

Responses to natural disasters are broken down into various phases. The initial phase is a search and rescue operation to assess individuals missing and saving lives in imminent danger. The following step is the initial emergency relief. This consists of providing the affected community with temporary shelter, food, water, and medicine. Depending on the magnitude of the disaster and availability of resources, this phase can last for a short or rather long period. Once the community has infrastructure and systems in place to assure stable food and water supplies, the early recovery period is started. Temporary shelters are still utilized in this phase, but people begin to transition to their normal routines such as going to church and school in tents. The final phase is the medium to long term recovery. This is when permanent structures are built, and life returns to normal. Each of the recovery phases last for months to years depending on the availability of resources locally and external support.

The implementation of OWCs would reduce the time for a community to recover from a natural disaster. The power generated from an OWC could be used to power water desalination equipment or electricity for lights and cooking equipment. The permanent installation would provide security for the community as it would assure a constant supply of power. This would reduce or possibly eliminate the initial emergency relief phase, since a water and food supply would be maintained. The recovery phases would be reduced in length as well as it would eliminate the need to provide emergency power generation equipment from external resources. Communities would be able to recover in a short period and return to a sense of normalcy quickly. Thus, the disaster affected communities would receive both positive economic and societal benefits.

2.4.2 Competition

There are two main sources of competition for power generation in disaster relief situations. The most conventional method is the use of gasoline or diesel generators. Solar panels are the other main alternative. Both provide convenient, and nearly immediate, relief in emergency scenarios.

Fossil Fuel Generators: These generators can run off gasoline, diesel, propane, or natural gas. Until the commercialization of solar power, this was the most common power generation source for disaster relief. Given its status as the most conventional method, it is still a widely used solution. The continued use of these generators is not only harmful to the environment but presents continued operational costs since fuel stores need to be maintained for power generation. These operating costs are less of a concern when using either solar or marine power because the energy generating sources are freely available.

Solar Power: Solar power is becoming a more attractive option as solar panels become more commercially available. The installation of solar power is relatively straightforward and can supply nearly immediate power relief in disaster stricken areas. A set back to this method is the dependency on a solar source, which can be unreliable in certain places based on either the climate or landscape of the affected area.

In comparison, the installation of an OWC breakwater system would be more material and time intensive. However, this system provides additional shore-side protection and harm mitigation as well as a long term, constant energy supply. In locations that are at high risk for such natural disasters, especially hurricanes, monsoons, or typhoons, the breakwater system can be installed in anticipation. In cases where immediate power is needed, fossil fueled generators or solar panels can be used while an OWC breakwater system is constructed.

To further improve the viability of the intended project implementation, places need to be analyzed in relation to their need for a breakwater system. For example, while a breakwater OWC would be beneficial in areas of the Gulf Coast, which are susceptible to extreme hurricane weather, this might not be the case in places like Puerto Rico. As an island trying to maintain a thriving marine life and conserve coastal plant and animal species, Puerto Rico could face challenges when installing such a structure in sensitive locations. Additionally, Puerto Rico, like some other islands, depends on natural sediment migration to reduce coastal erosion effects; the disruption of normal sediment migration patterns would be felt more in Puerto Rico than in Mississippi. Selectively placing the OWC breakwaters would maximize the positive effects from implementing such a system, minimize the negative effects to the surrounding environments, and ultimately make this a more competitive option when applied appropriately. More environmental factors are discussed in Section 3.3.8.

2.5 Development and Operations

2.5.1 Deployment

This business plan focused on the use of the OWC for disaster relief. This requires fast response time at a relatively low expense to provide preliminary aid. It was also weighed in that having the OWC be made of strong, durable materials. The specific disaster relief that our design will provide is desalination for clean water, and enough power for a small ambulatory health care facility. Within the development of this design, the entirety of the desalination plant was included, and it was assumed that other organizations would be supplying the medical equipment that the OWC will power.

The analysis suggested that advantages lied within a smaller energy output, so we decided to target smaller communities that could be affected by larger disasters since these locations may not receive the same rapid response from relief organizations that the more populated coastal cities could receive. With this in mind, the OWC was scaled to provide clean drinking water for 100 people and provide electricity to an ambulatory facility that can treat 50 people.

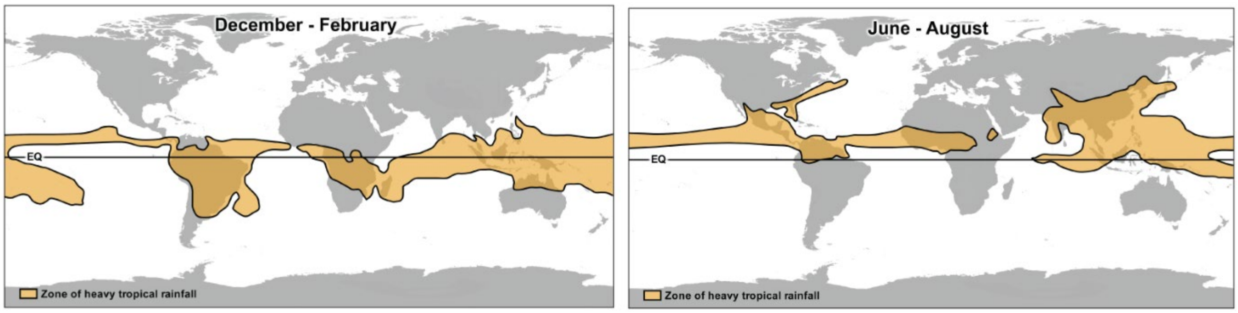

Figure 1. Zones of Heavy Rainfall
Source: UCAR

Figure 1 indicates that most of Southeast Asia and the Southern parts of Africa are subject to monsoons. Namely, Bangladesh is known for having its coastline villages destroyed and its populations displaced due to monsoons. Over 25 million people were displaced in Bangladesh as well as adjacent countries in South Asia in 2020 alone. [1]. Mozambique is another country commonly affected by monsoons as 70% of its population lives along rivers and coastline. The Mozambican Red Cross in 2012 among other organizations aided in the mass relocation of populations affected by monsoons on an annual basis. [2]. There are a number of countries in Southeast Asia and Africa which are in similar situations with natural disasters, and the majority of their populations are spread out across isolated rural villages. Therefore, there are several locations within Bangladesh and Mozambique among others that would be viable candidates for deployment.

2.5.2 Risk Management and Opportunities

Any project implementing a developing technology will inherently be a risky investment given the novelty of technologies at hand, limited empirical data, and lack of established rules and regulations behind the structures. At a commercial level, risks are related to securing funding, partnerships, and energy supply. Investors and electricity suppliers largely inform these risks. From an investor's perspective, as is validated through Gabrielle Piasio's experience, demonstrating dependable water supply is crucial. Since our device will be located by the shore, this means that a constant wave resource is guaranteed. Revenue guarantee is another risk that investors will consider, this means having power suppliers committed to using the energy generated by the project. In the case of disaster relief projects intended for isolated communities, power needs are a given. Additionally, governments and charitable organizations will have a vested interest in supporting energy implementation methods. In the case of total power loss, electricity suppliers do not present an additional risk because the affected communities' needs arise from their inability to access the general electricity grid.

To compensate for the lack of rules and regulations governing the construction and stability of the OWCs, we were advised to look at existing bodies of work. For Professor Bradley Golden's project, he referred to Lloyd's Register for the structural design process of the floating OWC. In the absence of regulatory bodies specifically addressing fixed OWCs, the governing maritime regulatory bodies of the project's residing country will be referenced.

2.5.3 Maintenance and Upkeep

OWC's moving components, unlike other marine energy devices, are not constantly subject to corrosive sea water. The air turbine being stored far from the waves allows for easy maintenance and greatly increases its life cycle.

The OWC we designed for disaster relief was built to last for a 30-year lifespan. It is made up of a solid concrete chamber that houses a steel Wells Turbine protected from corrosion. It is anticipated that these components will require little to no maintenance once installed. The main components that will need upkeep are the generator and the RO system. The sensitive cabling of the generator will require a total generator replacement every five years since it will be exposed to the same ocean spray as the turbine. The RO system can be placed in a slightly more protected space but will still require backwashing and occasional total replacement of the filters. For these reasons, an annual operating expense of $8,080 was applied based on previous research form NREL and the Pacific Northwest National Laboratory [3], and a new generator will be purchased every five years. Compared to diesel generator maintenance, there fewer small tasks that require frequent inspection such as all of the filters and oils, and less long-term maintenance such as valve calibrations and retuning's [4]. The simplicity of our design becomes advantageous here since it eliminates the need for any fine calibrations or tunings.

Since this system will not be under constant watch, a pressure drop alarm will be installed on the RO system, a voltage reader will sound an alarm if the generator ever drops below a given threshold, and a fire detection alarm will be installed by the generator to avoid the risk of electrical fires.

2.6 Financial and Benefits Analysis

The costs for this OWC design were determined by finding the costs of individual materials and parts, as well as the labor costs for manufacturing components unique to this design.

The dimensions and structural descriptions in Section 2.6.1 are not intended to be a description of the technical design, which is instead discussed in Section 3.3 of this report. Instead, these values function as a means to calculate costs of this design more accurately.

A summary of all CAPEX values calculated can be found below in Table 1.

Table 1. Final Cost Breakdown of Scaled OWC

Cement	$	34,163
Cement Labor	$	1,554
Blade Steel	$	1,331
Blade Labor	$	109,923
Fuselage Production	$	72,714
60 hp Generator	$	3,597
15 hp Motor	$	1,330
Pump	$	6,873
RO Filters	$	1,701
Total	**$**	**233,185**

2.6.1 Cost Estimate

To gain an accurate model for financial analysis, the dimensions and power output from the testing portion were utilized and scaled to obtain material and maintenance costs. The full-scale model is scaled to meet the operating loads for the system, which are defined later in Section 3.3.6.1. OWC chambers scale in an exponential manner in accordance with the Handbook of Ocean Wave Energy [5]. This handbook states that the scaling factor used for the volume of the design must be squared to account for compressibility effects that occur in the air chamber. This led to large gains in power output with smaller increases in size. The model dimensions and full-scale dimensions are located in Table 2 and Table 3 , respectively.

Table 2. Model Dimensions

Chamber Volume	1.68	ft^3
Blade Volume	0.00003	ft^3
No. of Blades	14	
Fuselage Diameter	0.02	ft

Table 3. Full-Scale Dimensions

Chamber Volume	1118	ft^3
Blade Volume	0.022	ft^3
No. of Blades	14	
Fuselage Diameter	4.2	ft

The chamber volume refers to the chamber where waves are captured to create the oscillating wave column. For ease of calculation, the chamber is calculated as a uniform, thick-walled cylinder to estimate material costs. The fuselage is the component that contains the turbine hub and blades. The volume of these two components were separated in the cost analysis since they require separate manufacturing processes.

2.6.1.1 Raw Material Costs

This provided a fast method of finding costs per unit volume or mass of the materials we need and adding them to our financial model. The first material considered is the cost of a cylindrical concrete chamber. As mentioned previously, the diameter of the chamber is 15.4 ft and is six feet tall. A wall thickness of 1.3 ft was calculated by extrapolating from common concrete pipe sizes [6]. This resulted in a total required volume of 342 ft^3, which cost a total of $34,200 at a rate of $100/$ft^3$ [7]. A labor rate of $4.55/$ft^3$ was used to create a total labor cost of $1554 for the concrete chamber production.

The turbine blades were made of 3040 stainless steel and each of the 14 blades had a volume of 0.02 ft^3 for a total volume of 0.3 ft^3. 3040 stainless steel has a cost per volume of $4,320/$ft^3$ which led to a total cost of $1,331. The machining cost of these blades was set for $5/hour at a feed rate of 0.01 ft^3/hr. This resulted in a labor cost of $360,951. The fuselage was made of a less expensive steel and used a method described for shipbuilding, which also involves moving steel into complex shapes [8]. This method uses the weight of steel, a build rate, and a labor rate, to calculate one number for the total production. For this analysis, a labor rate of $45/hr and a build rate of 30 ton/hr were applied to a total weight of steel of 177 tons to produce a final cost of $238,770. An additional 20% was added to the total steel cost to account for any shafting and structure required which resulted in a final value of $574,600 for both the fuselage and blades.

2.6.1.2 System Components

In addition to the raw materials used to manufacture our OWC, several components were sourced from distributors to complete the entire system. The first major component purchased was the generator. To accommodate the 40 kW design size of our OWC, a PTJ 60 horsepower 3-phase electric generator was selected at a cost of $3,597. As mentioned earlier, this generator was replaced every five years. The rest of the major components selected were for the desalination plant. The first, is the RO system itself. This system was designed for an output of 100 gal/day and cost $1,701. The pump and motor combination that was discussed previously cost a total of $8,203 leading to a total desalination cost of $9,904.

2.6.1.3 Final Costs

The CAPEX of the entire design including the OWC, and the desalination plant was $984,812. With an annual OPEX of $8,080 over a 30-year lifespan, the total cost of our design will be $1,245,200. With an energy rating of 40 kW, it is projected that our design will produce 350,400 kWh annually. Using these values in our LCOE equation with an assumed discount rate of 10%, we arrive at a final value of $0.29/kWh.

The LCOE's of the most remote states in the United States (Alaska and Hawaii) are $0.23/kWh and $0.33/kWh respectively [9]. Our OWC has an LCOE that is within this range which means we have a cost competitive option. This comparison is not exactly fair, however, considering that these costs are for entire states with much larger energy requirements than our design could provide.

3 Technical Design

The concept design of this OWC is made up of three main components: the power generating column, the height adjustment mechanism, and the energy storage bank. The column converts the vertical motions of waves into the unidirectional rotation of the turbine and generating usable electrical energy. The height adjustment mechanism allows for optimization of the converter's performance and protection of the unit. The energy storage bank uses a combination of battery and potential energy storage devices to store large amounts of usable energy in the event of a grid failure.

3.1 Design Objective

The overall objective of this design is to develop a midrange-scale, modular, and relatively affordable OWC for use in areas where power grids are vulnerable and natural disasters create highly variable and unpredictable energy demands. This device aims to provide power when conventional power sources have been disabled as well as subsidize the electric grid on a consistent basis making it useful as both a conventional power station and disaster protection measure. This device is intended to be rugged and self-sufficient generating enough power to tune itself and store energy with minimal unscheduled maintenance.

3.2 Guiding Principles

3.2.1 OWC Components

OWCs comprise of three main components: the chamber that houses the water column, the turbine, and the power take-off (PTO). The theoretical workings of the chamber and turbine will be described in the following sections. The system stages can be seen in Figure 2.

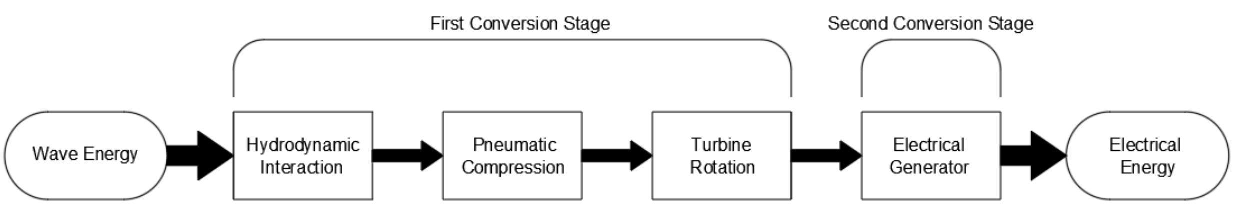

Figure 2. OWC Stages of Conversion
Adapted from Doyle and Aggidis

3.2.1.1 Chamber Theory

OWCs utilize rising and falling water columns to create pushing and suction forces in the air column of the chamber. When the water column rises in the chamber, air is pushed from the chamber through an opening in the chamber, which acts as the outlet. When the water column falls within the chamber, air is pulled into the chamber through that same opening, which now acts as an inlet. This rising and falling action can be seen in Figure 3.

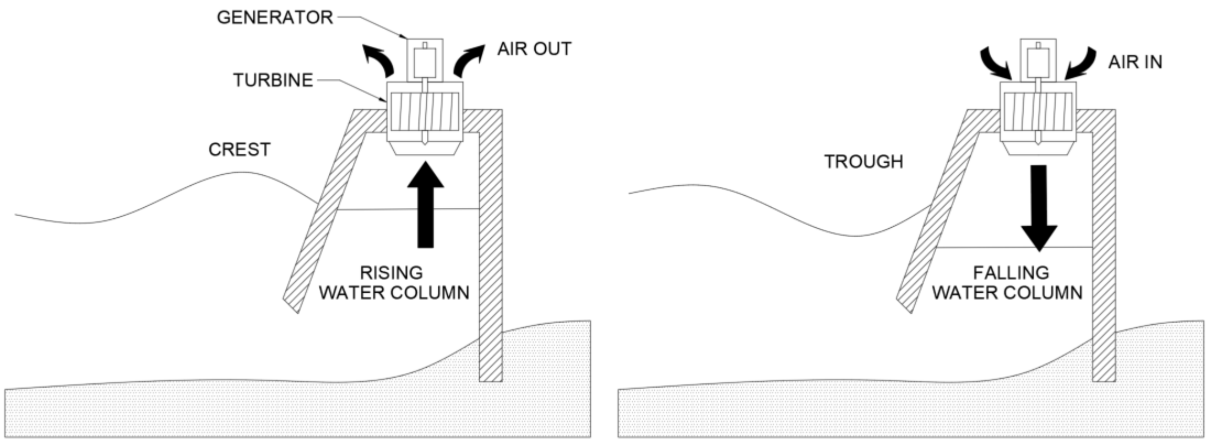

Figure 3. OWC/Rising/Falling Action
Adapted from Crespo *et al.*

3.2.1.2 Turbine Theory

As seen in Section 3.2.1.1, the air flows through the system in two directions. Typically referred to as a bidirectional airflow, the flow is perpendicular to the turbine blades. To accommodate for this bidirectional airflow, special considerations must be given to the turbine design to maintain unidirectional rotation of the turbine. This can be resolved with either a check valve on a standard turbine, or specifically designed stators and rotors. A check valve is an additional moving part and is therefore typically deemed an undesirable solution. There are two popular designs for bidirectional air turbines, the impulse turbine and the Wells turbine, respectively shown in Figure 4 and Figure 5. The impulse turbine consists of a typical rotor design and stators on either side of the rotor that redirect air into the rotor regardless of the direction of incoming air. The Wells turbine does not use stators to redirect air, but instead utilizes a symmetrical foil design for the rotor blades.

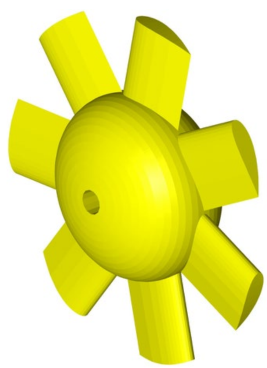

Figure 4. Wells Turbine
Adapted from Penalba & Ringwood

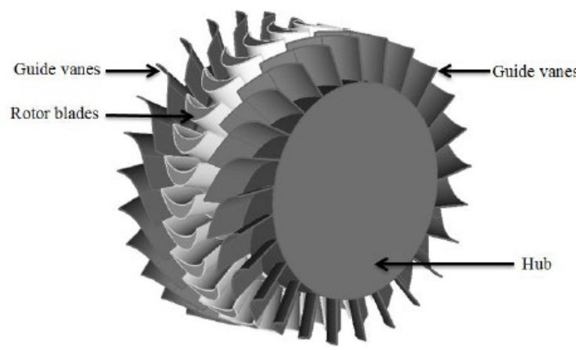

Figure 5. Impulse Turbine
Source: Karthikeyan, Samad, and Badhurshah

According to research compiled by Das et al., there are a number of key advantages and disadvantages to consider when selecting an OWC turbine. According to research compiled by Das et al., there are a number of key advantages and disadvantages to consider when selecting an OWC turbine. The Wells turbine has the benefit of being easy to manufacture and install and can attain a higher peak efficiency. However, the operation range of Wells turbines is narrow than an impulse turbine. By comparison, impulse turbines are more difficult to build, have a lower peak efficiency, but have wider operation ranges.

For the purposes of this research, a Wells turbine was used for its ease of creation and minimal moving parts. Figure 5 shows the position of the Wells turbine foils and hub relative to the incoming airflow.

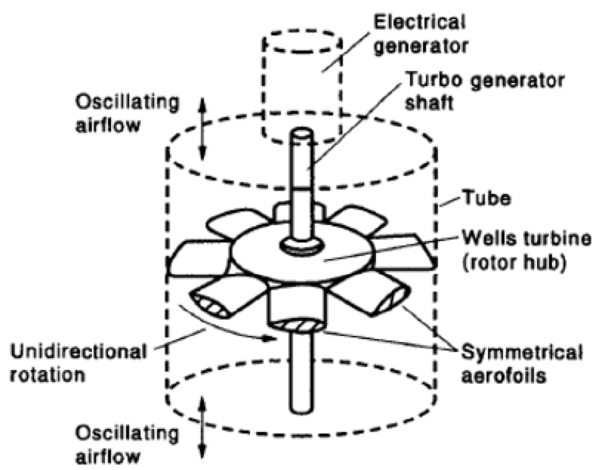

Figure 6. Wells Turbine OWC System
Adapted from S. Raghunathan

As seen in Figure 7, regardless of the direction of incoming air flow, the turbine rotates in a consistent direction.

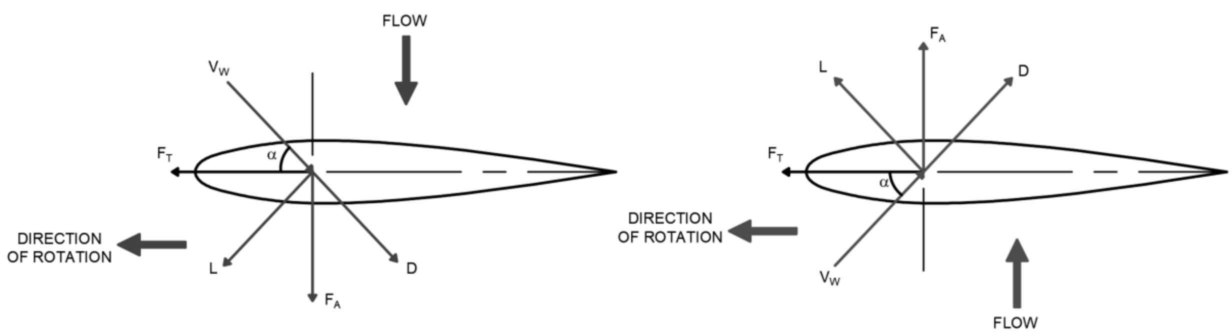

Figure 7. Foil Blade Force Diagram

3.3 System Design

3.3.1 Turbine Design

The turbines for this research were designed using 3D modelling in Rhino and followed guidelines summarized by Das et al. [10]. Table 4. Wells Turbine Parameters shows a summary of these guidelines, where solidity represents the blockage of the airflow by the turbine blades, hub-to-tip ratio is the ratio of diameters of the hub and tip, aspect ratio is the ratio of blade length (hub to tip) to chord length, and tip clearance is the measurement from the tip of the blades to the inner surface of the turbine housing.

Table 4. Wells Turbine Parameters

Parameter	Value
Solidity	> 0.5
Hub-to-tip ratio	0.6
Aspect ratio	0.5
Tip clearance	< 2% of c

There were four major design iterations that took place over the course of this project and can be seen in Figure 8. These iterations sought not only to increase the efficiency of the turbine, but also to create a design that could be easily implemented in the construction and design phases of this research. The first iteration, labeled "1," was found on an open-source 3D modeling website, Thingiverse, and featured a spherical hub and seven blades with low thickness-to-chord ratio. In the second iteration, labeled below as "2," the foil thickness-to-chord ratio was increased, the blades were flared out, as shown in Figure 9, to increase the solidity, and the hub was distorted into a long, conical shape. This conical hub allowed for an easier integration with the turbine shafting. The third iteration, labeled "3," maintained the hub and foil shapes, but incorporated a rest for a bearing to decrease rotational friction. Finally, iteration "4" integrated two stages of foils to increase the usage of airflow. The higher mass of this design also results in a higher rotational inertia, which is important for maintaining continuous rotation during operation. All stages of turbine design feature a bore through the center for shafting.

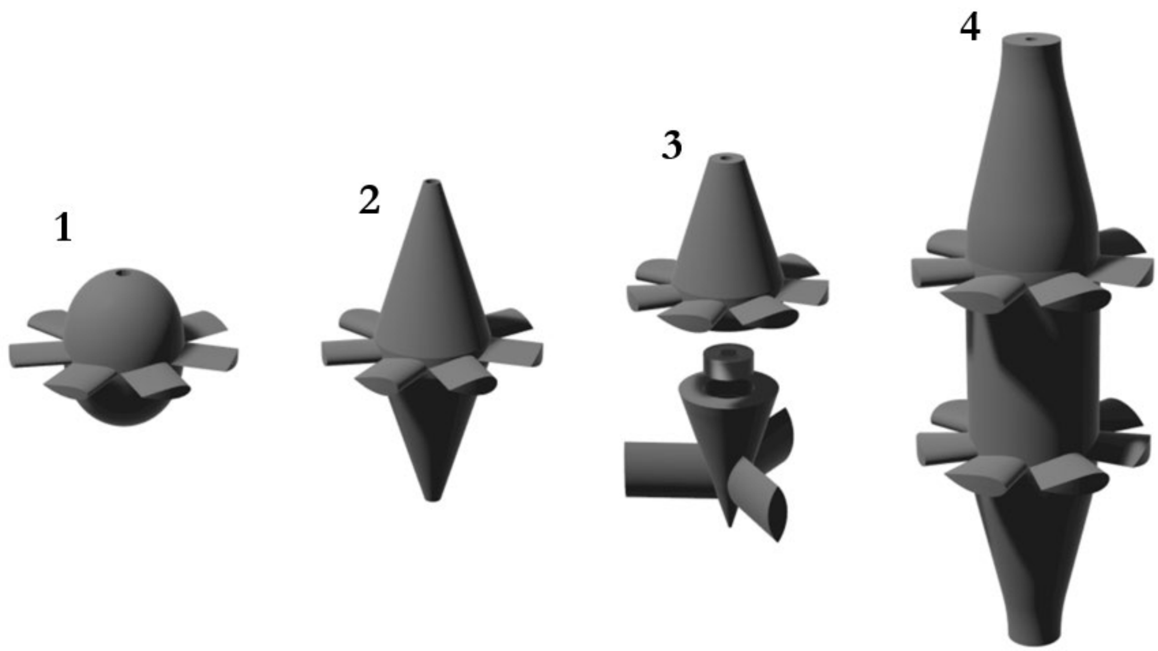

Figure 8. Turbine Design Iterations

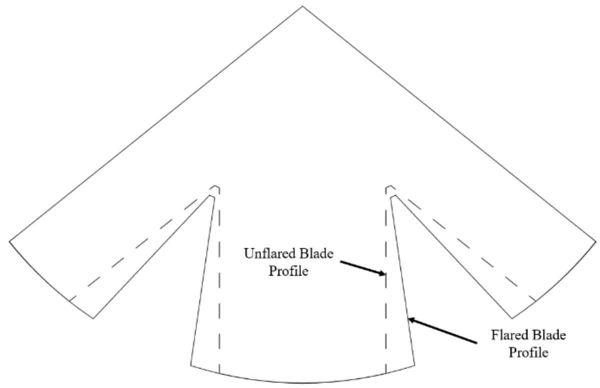

Figure 9. Flared Blades

3.3.2 Generator Mount Design

To integrate the generator shaft with the turbine shaft, a coupling and generator mount were developed to secure the generator directly in line with the turbine. This positions the generator and other sensitive equipment pertaining to energy conversion within the protective enclosure above the chamber and allows for effective waterproofing of the unit. This design also avoids powertrain losses in the most effective manner and allows for a flywheel to be incorporated into another already essential component of the system: the coupling.

3.3.3 Chamber Design

The chamber for this research was designed using 3D modelling in Rhino and followed guidelines summarized by Morris-Thomas et al. in their paper entitled "An Investigation Into the Hydrodynamic Efficiency of an Oscillating Water Column" [11]. The authors of this paper established a relationship between the front wall dimensions of OWC chambers and their efficiencies. To summarize their findings, the authors found that a front wall submersion-to-water depth ratio of 0.185 was optimal for achieving higher system efficiency over a wide range of wave frequencies.

Table 5 summarizes the approximate dimensions of the chamber, which were obtained from the scaled volume as described in 2.6.1 and approximate ratios of chamber dimensions as described in Section 4.2.2.

Table 5. Full-Scale Chamber Dimensions

Width	19 ft
Height	6 ft
Length	9 ft

The width refers to the dimension parallel to the water channel, the height refers to the height of the chamber above the water line, and the length refers to the dimension of the chamber perpendicular to the water channel.

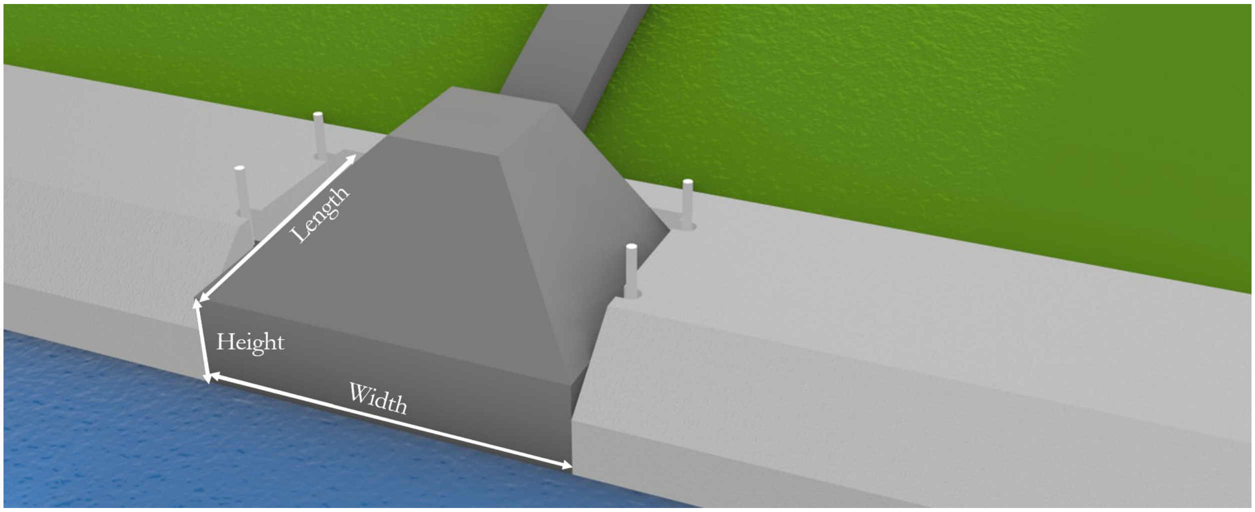

Figure 10. Chamber Dimensions

3.3.4 Production Materials

As mentioned earlier, since the intended operation of this design is for recently disaster-stricken areas, the entire OWC was designed out of rugged and durable materials. The entirety of the cylindrical chamber is designed to be constructed of reinforced concrete since that will be an ideal material for the endurance of its breakwater task [12]. The fuselage of the turbine is a simple shape that requires relatively low tolerances. For these reasons, the fuselage will be made from a rolled steel coated to be protected from ocean spray. The turbine blades are much more complex in their foil shape. In this OWC, they will be made of machined 3040 stainless steel due to its natural resistance to corrosion.

3.3.4.1 Height Adjustment Technology

As a solution to operating at a wider range of tidal and wave conditions, a height adjustment system was integrated into this system. The chamber rides on four machine screws, which are located on the four corners of the converter. Four motors running simultaneously provide consistent, level height adjustment. Power for these motors will come from the small onboard battery bank which can be discharged fully to accomplish the motion and recharged by the converter from its new location or from the larger battery bank.

The height adjustment mechanism functions on the rotary motion of a machine screw to guide a fixed collar along its length (see Figure 11). The machine screw is attached to a gearing reduction system allowing it to be run off a DC motor. A DC motor was selected for this function to limit losses in converting between AC and DC voltage in the battery, and because the power of these motors is relatively low by comparison to the desalination pump motor.

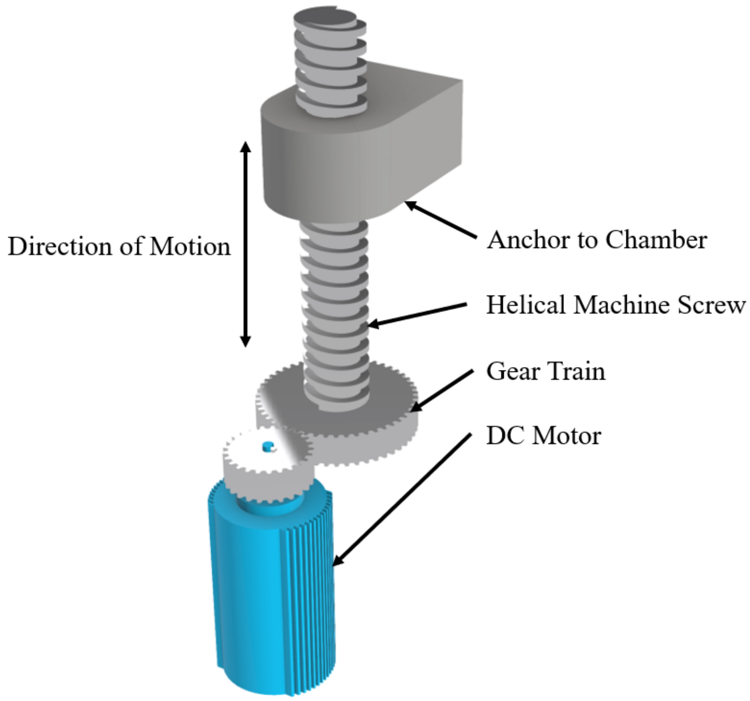

Figure 11. Height Adjustment Design

3.3.5 System End Uses

3.3.5.1 Desalination Plant

The desalination plant was designed to provide fresh drinking water for 100 people each day assuming each person should consume approximately one gallon of water [13]. This flow rate was then used to select the equipment used in the desalination plant. The first step was selecting a method of desalination. For this, we decided that reverse osmosis (RO) would be the ideal method. While it is not as efficient as directly connecting the OWC to the RO system [14], transferring OWC energy to electricity to operate the RO system is still more efficient than many other desalination methods. The first component of the desalination plant required is a pump. It was established that the pump would need to be durable to be submerged and drawing from contaminated, brackish water. The constant operating properties were defined from using specifications from a reverse osmosis system distributor [15]. This system required a flow rate of four gallons per hour at an operating pressure of 40 psi. Applying all these variables into a pump selection program provided by Crane Pumps resulted in the selection of the Barnes 4SE113 Non-Clog submergible pump. The program from crane also provided that the RO system required a 10 hp electric motor to drive it and a 15 hp motor was selected to add some margin for peak operation if needed. Once this was all selected, the same RO system distributor site was used to source a plant that will produce enough drinking water to our target community. The entirety of the desalination plant added a total of 10 kW to the required production of the OWC.

3.3.5.2 Ambulatory Health Care Facility

The ambulatory health care facility was treated as an electric load to be supplied by the OWC. This load was calculated by finding an occupant load factor, and then an electric consumption rate per square footage of the facility. The first occupant load factor was the Fire Protection Research Foundation [16]. This value was taken as 267 ft^2 per person being treated. This was then multiplied by an electric consumption rate supplied by researchers in Oslo, Norway of 61.2kBTU/ft^2 annually. This resulted in a total annual energy consumption of 236 MWh which added another 27 kW to the size of the OWC.

3.3.6 System Concept Design

Figure 12 shows a concept design of the system integration into the environment and the subsequent loads of the system.

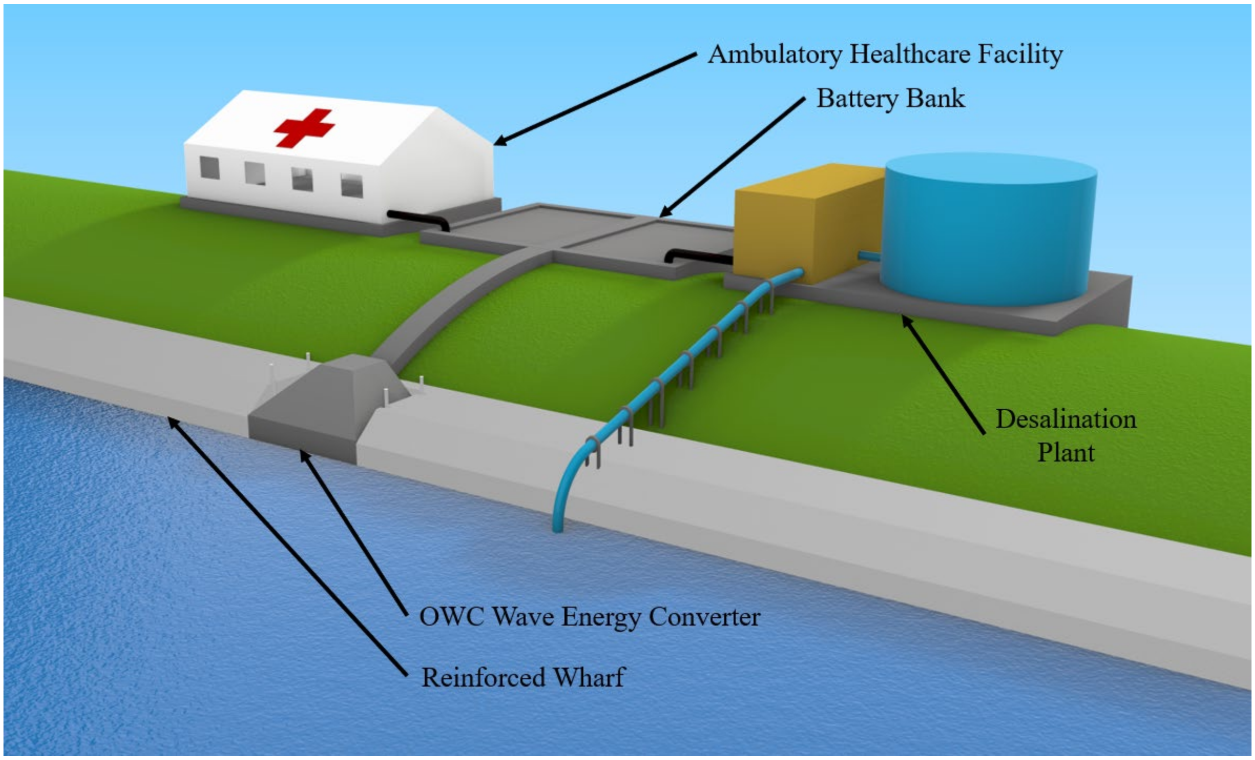

Figure 12. System Concept Design

As can be seen in the figure, the concrete chamber is integrated into the shoreside wharf, which acts as a breakwater. The connection between the wharf and chamber is where the height adjustment mechanism is located. The opening for the Wells turbine is located on the face opposite the water to shield the turbine and subsequent moving components from the harsh marine environment. This is set to reduce the operating expenses incurred from wear and damages to the moving components.

Power from the generator is fed to the battery banks on shore where they are protected from water. This battery bank has two separate electric loads drawing from it. The first leads to the ambulatory healthcare facility to operate necessary healthcare equipment, such as refrigeration, food preparation, and lighting. This facility can house 50 patients and is primarily for treating injuries received from natural disaster. This facility does not have the more sensitive equipment of a hospital that would draw even more power. The ambulatory healthcare facility will contain equipment and personal supplied by other relief agencies, so the specific information for that was not analyzed here.

The desalination plant contains a reverse osmosis system and a freshwater holding tank. Contaminated, brackish water is delivered to the RO system by an electric motor-driven pump. The electric motor in this case is the component of the desalination plant that draws from the battery bank. The pump simply feeds water through a multi-layered filtration system into the freshwater holding tank. The RO system is designed to allow for occasional backwashing to remove particulate build-up in the filters, and for temporary shutoff to replace the filtration units altogether.

The converter body is made up of two main sections: the chamber on the lower end, and the electronics containment above the chamber. The chamber is held in place by the height adjustment tie rods and is the setting for the actual water column's motion. The electronics containment includes the turbine which has an inlet in the "ceiling" of the chamber, the generator unit, and the onboard battery pack which provides power for startup and height adjustment. The turbine intake on the outside of the converter faces away from the ocean and into the cabling protection containment where it is unlikely to be damaged by water or other environmental factors. Figure 13 and Figure 14 show external and internal views of the OWC, respectively.

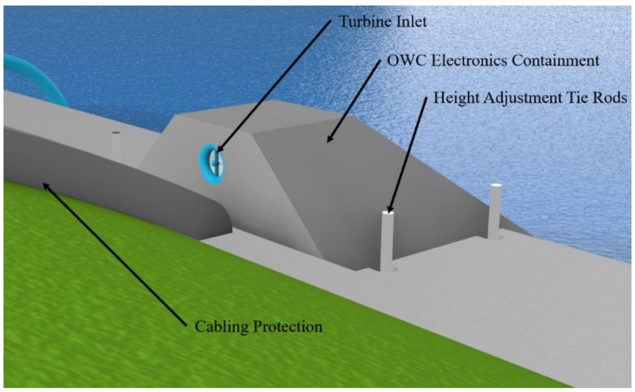

Figure 13. External System Components

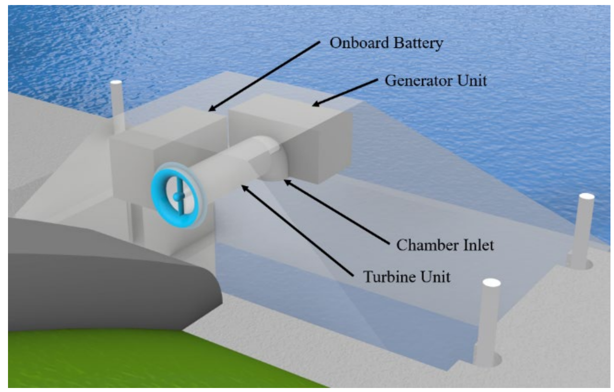

Figure 14. Internal System Components

3.3.6.1 System Electrical Loads

This design's electrical conversion mechanism is fairly simplistic, but due to the fact that it must often provide for multiple sources simultaneously, it has some noteworthy features. Electricity in this converter is taken from the generator and passes on to two separate battery banks: a large battery bank meant to retain enough power to supply disaster relief needs until normal wave conditions are restored, and a smaller onboard unit. The smaller battery bank provides the converter with its autonomy, providing power for the four height adjustment motors and startup capabilities for the turbine. Additionally, power runs from the large battery bank and/or generator through a transformer and AC converter to provide AC power to the desalination pump and healthcare facility. In downtime when the converter is not required, it can safely rest outside of the corrosive environment of the sea using its remaining charge to start up when necessary or when forecasts suggest it may be needed. This allows for easy routine maintenance to be performed on the device. Additionally, the large battery bank can be used to charge the onboard battery bank if it runs out creating redundancy in the device.

Figure 15 shows a schematic of the electrical loads associated with this system.

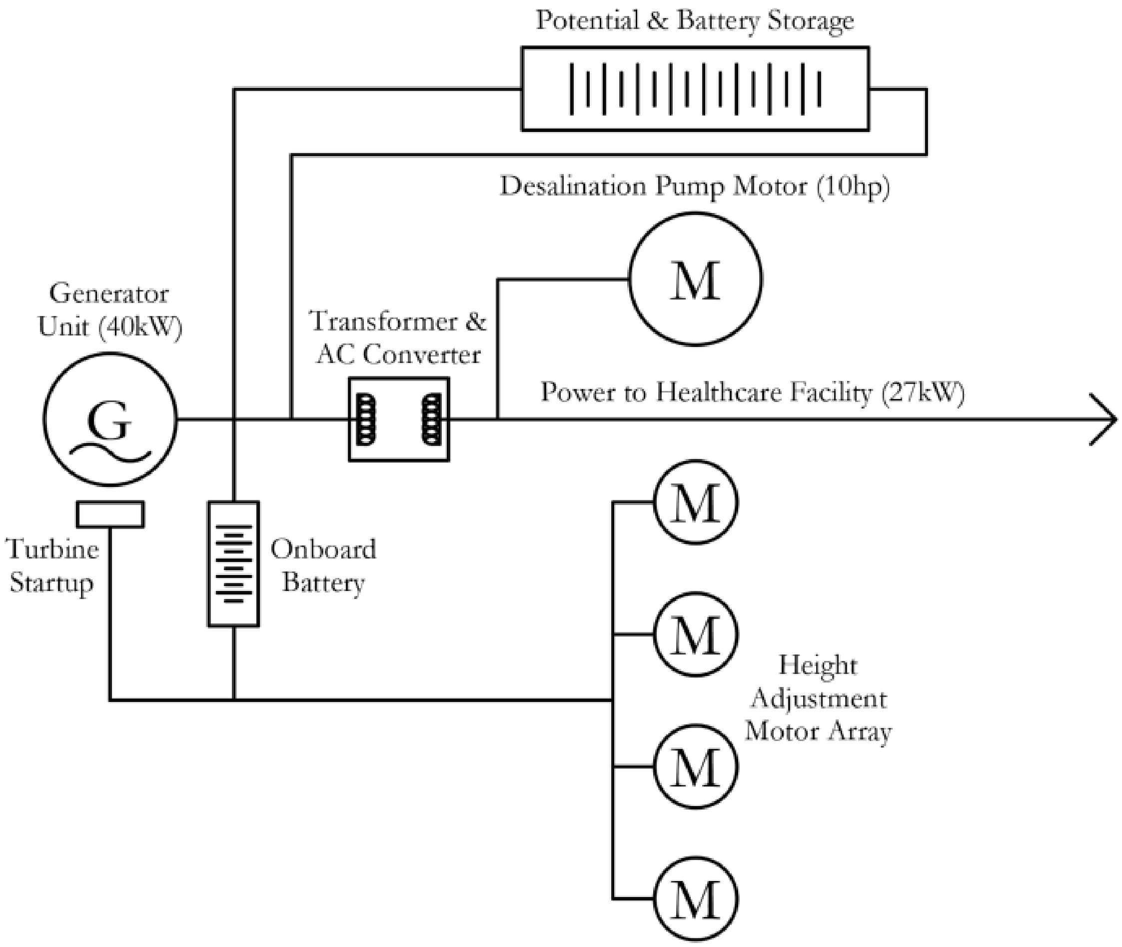

Figure 15. System Electrical Loads

3.3.7 Survivability

A major design consideration in the development of this OWC was its survivability in everyday operation as well as likely severe conditions. The coastal location of the unit is very beneficial to the survivability of this design; however. it has the potential of exposing the converter to severe storm surge conditions and wave forces. The OWC is built into a concrete wharf and the front wall is flush with the otherwise smooth concrete surface mitigating the effect of headquartering waves (waves which hit at an angle to the shore) on the alignment of the device. Additionally, in the case of a storm surge condition or an excessively high tide, the converter comes built with a height adjustment system which can raise the converter by several feet preventing possible damage in these rough conditions. This system is powered using an on-board battery bank allowing the converter to be raised in the event of a loss of grid power. This height adjustment mechanism can also be used to optimize the OWC's performance as tidal conditions change during regular operation. Additionally, the turbine inlet of the converter is positioned facing away from the shore, protecting the unit from being overwhelmed by oncoming waves. It is important to note that in the raised position the intake is also at a significant height from the ground making it safe from backwash or flooding.

3.3.8 Environmental and Sustainability Factors

The construction and long-term use of OWC-style wave energy converters along the coastline has the potential for great environmental benefits especially in areas where conventional fossil fuel power generating plants run largely unregulated from the environmental pollutant standpoint, however; some downsides of this technology should not be overlooked in the concept design stage of this device's development.

This device is actually a vast improvement from an environmental standpoint by comparison to other power generation methods. This device has no moving parts which could trap marine life at the intake of the turbine is out of the water on both ends; it generates no harmful electrical interference for the same reason. In addition, this device alters the existing landscape of the shoreline relatively little in some cases. However, OWC's do generate somewhat significant noise pollution, and a poorly chosen site for this device could disrupt important migration patterns and damage environments. To mitigate these issues, it is recommended that these devices be placed in smaller clusters as opposed to large banks, and in areas where natural tidepools or sandy beaches are not the dominant coastal feature. Tide pools, on top of not being particularly well suited for OWC's in low tide conditions, are also areas with an immense amount of biodiversity.

4 Build and Test

4.1 Objectives

The objectives of the construction and testing portion of this research were to create a model OWC using simple design principles and test that model for its power generating capacity. The model must not only be effective but must also be relatively easy to recreate and expand upon. A secondary objective of these phases of research were to promote continued research into OWCs at Webb Institute and other engineering institutions. Compared to the design described in Section 3.3, the model design is simplified, both in chamber shape and functionality. The model used in testing is stationary and the height does not articulate. The construction and testing of this simplified model serves as a sample configuration for one possible vertical position described in the technical design.

4.2 Build

4.2.1 Model Scaling

This model was created for use in the Robinson Model Basin (RMB), located on the Webb Institute campus. Instead of scaling the model down from the real-world technical design, the model was designed to fit within a channel located at the end of the RMB. Scaling to full-scale was performed as discussed in Section 2.6.1, using the results from the testing of this model to make final design decisions for the full-scale model.

4.2.2 Chamber Construction

The chamber of the model was designed to fit the dimensions of the RMB channel, whose location was chosen for its enclosed structure and reduced water depth, which allowed for a smaller-scale model to be constructed. Two construction iterations were completed for the chamber. Both chambers had an air chamber length of 36 inches, a height of seven inches above the waterline, and a width of 11.5 inches. The front wall of the chamber protruded three inches below the waterline in both cases.

The first iteration used quarter-inch plywood as the build material with a length of 2x4 as a bracing. Weights were placed on the top plate to better secure the chamber to the basin during preliminary testing. Duct tape was placed around the edge of the chamber to seal the chamber to the basin walls. A two-inch hole was bored into the top plate as an opening for the initial turbine housing setup. This initial construction was functional but could be improved upon both visually and practically.

For the second iteration, two acrylic sheets were used to construct the chamber of the device. While this is not reflective of a real-world setup, acrylic was used for its benefits in a testing setup. Half-inch acrylic sheets provided the necessary rigidity for the chamber while also allowing for visual inspection of the device. A length of 80/20 aluminum was used to connect the top plate and front wall of the chamber and provide rigidity. A bracket was bolted to the underside of the plates for additional strength. A four-inch hole was bored into the top plate as the opening for the turbine housing. Neoprene gasketing was placed around the boundaries between the top plate and tank walls as a sealant. This prevented air leakage from the chamber during testing procedures. A bracing ran vertically from the basin railing to the top plate to hold the chamber in place to ensure rigidity during testing. Figure 16 shows the initial, plywood chamber construction and Figure 17 shows the final, acrylic chamber construction.

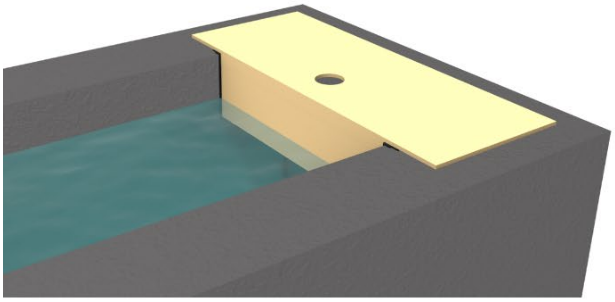

Figure 16. Initial Chamber Construction

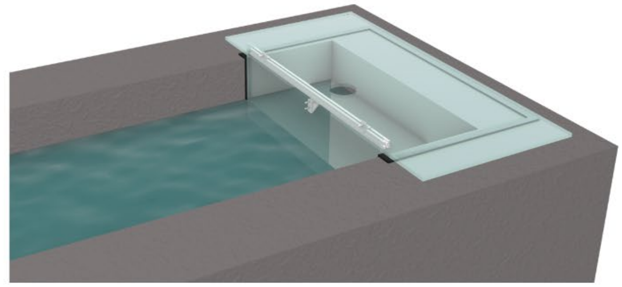

Figure 17. Final Chamber Construction

4.2.3 Turbine Construction

The turbines used in this project were printed on a Prusa i3 MK3S 3D printer using ABS and ASA filaments. The turbines were printed in halves and super-glued together. The shafting for the turbine was a three-millimeter metal rod with both ends press-fit into bearings to reduce rotational friction during operation.

4.2.4 Turbine Housing Construction

Two iterations were completed for the turbine housing construction, one with two-inch nominal PVC pipe and another with rigid acrylic tubing with an inner diameter of 70 millimeters.

For the first iteration, two-inch nominal PVC was chosen as the housing because of its wide availability. However, the roughness of the inner surface was relatively high and did not allow for high tolerances for tip clearance.

For the second iteration, 70-millimeter inner diameter extruded acrylic rigid tubing was used for the turbine housing. The roughness of this pipe was much lower than the PVC, allowing for higher tolerances to be achieved when obtaining the clearances between the turbine blades and the housing. The clear acrylic piping also allowed for visual inspection of the turbine during testing.

4.2.5 Generator Mount Construction

Both the mount for the generator above the turbine housing and the coupling of the turbine and generator shafts were 3D printed with the previously mentioned Prusa printer using ASA filament. Two generators were used in the testing procedure, a CrocSee hobby generator/motor, and a Keprovig hobby generator. The CrocSee generator had higher internal friction, making it difficult to obtain output torque during testing. The Keprovig generator had lower internal friction than the CrocSee model, allowing for easier start-up rotation during the testing procedure.

The generator mount consists of four threaded rods to hold the generator bracing in place above the end of the turbine housing, a bottom collar to fit around the turbine housing, and the coupling to integrate the turbine and generator shafts. Figure 18 shows the two generator mount designs with the initial rotation on the left and final iteration on the right.

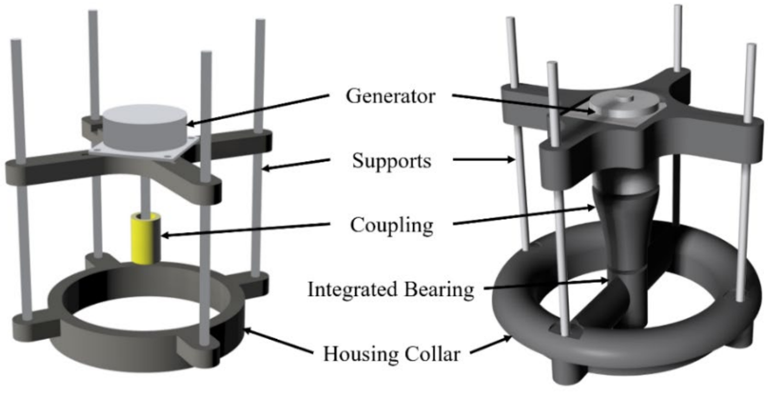

Figure 18. Generator Mounts

4.2.6 Full System Construction

Figure 19 shows an exploded view of the integration of the turbine, turbine housing, and generator. Figure 20 and Figure 21 show the turbine housing in the vertical position mounted on the chamber for both the initial and final construction iterations.

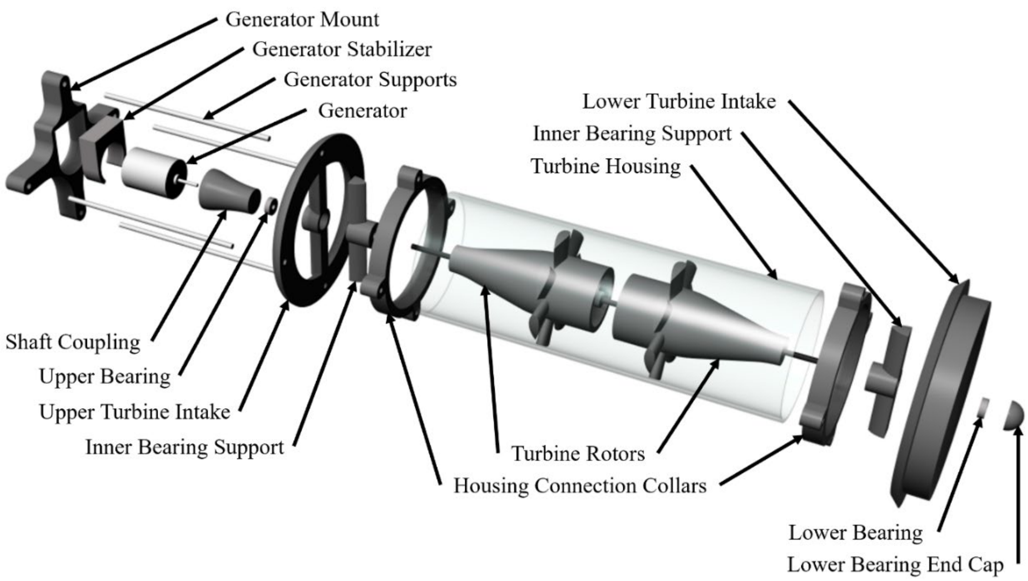

Figure 19. Turbine and Generator Exploded View

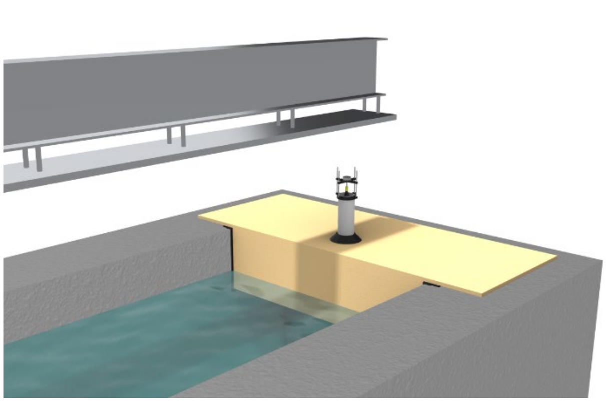

Figure 20. Initial System Integration

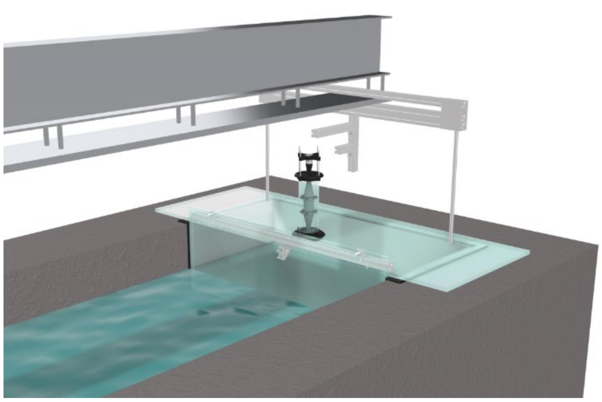

Figure 21. Final System Integration

4.3 Testing

4.3.1 Testing Equipment

A laser sensor and recording tachometer were used to measure and record the RPM of the turbine shaft during testing. A Monarch Instrument Remote Optical Laser Sensor (ROLS-W) and Monarch Instrument ACT-1B Series Panel Tachometer were chosen as the sensor and tachometer, respectively. Reflective tape was affixed to the turbine shaft and the sensor counted the number of times the tape passed by in a minute. A wavemaker was used to generate a variety of wave conditions. All testing was performed in the RMB, which has a length of 80 feet, a width of 10 feet, and a water depth of five feet. The model was secured into the finger channel at the end of the RMB, which has a length of four feet, a width of three feet, and a water depth of 18 inches. A National Instruments myDAQ board was used to measure the output voltage of the generator during testing.

4.3.2 Testing Setup

There were two main elements to the testing setup. The first element was using the ROLS-W and panel tachometer to measure the RPM of the turbine shaft while coupled to the generator. The ROLS-W was mounted adjacent to the turbine housing and directed at the shaft coupling. A small piece of reflective tape was placed on the coupling and the ROLS-W measured the number of times that the reflective tape passed the sensor per minute. The second element tested the output voltage of the turbine, whose shafting was coupled to the generator shafting. The myDAQ board was connected to the generator cables to get a voltage reading from the system. Figure 22 depicts the setup used to record both shaft RPM and output voltage.

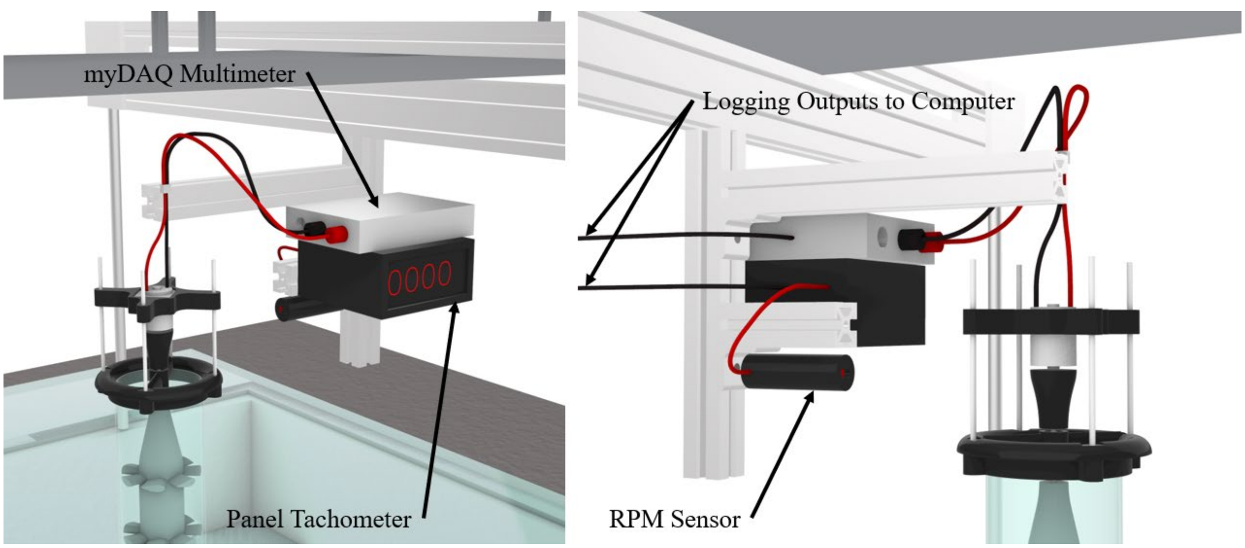

Figure 22. Data Recording Setup

4.3.3 Data Post-Processing

Figure 23 shows the circuit used to acquire both RPM and voltage readings. The myDAQ board has the ability to record a maximum voltage of 10 volts, which limited voltage readings at higher levels. To remedy this, a 100 ohm resistor was added to the circuit to reduce the readings taken by the myDAQ board.

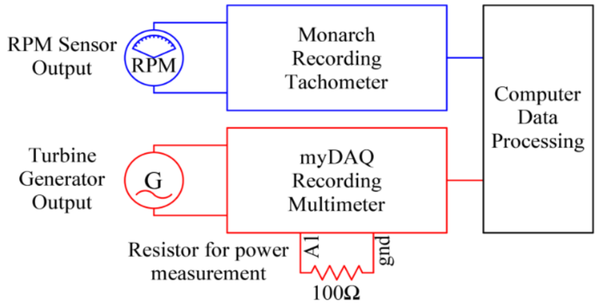

Figure 23. Data Acquisition Setup

4.3.3.1 RPM Readings

The panel tachometer has the ability to integrate into Microsoft Excel, which allows for real-time acquisition of RPM readings during testing runs. The tachometer records one reading each second, so the timestep of each of the data points was known. In post-processing, the number of RPM readings was converted to timesteps in order to plot the voltage readings over time.

4.3.3.2 Voltage Readings

The myDAQ board records voltage readings through a "Data Logger," which is included in the National Instruments student suite. These data points are recorded in an LSV file, which can be imported into Microsoft Excel for post-processing. Data points were recorded every thousandth of a second but were pared down to readings every second in Microsoft Excel. The recorded voltages, as well as the known resistor value of 100 ohms, were used to calculate the output power of the system using Ohm's Law and the definition of power dissipation for a resistor, $P = {V^2}/{R}$. The subsequent values of power output were used in the following plots for analysis.

4.3.4 Testing Matrix I (Wave Amplitude)

To test the effect of wave amplitude on the output RPM of the turbine shaft, a testing matrix of varying wave amplitudes was created. The model was tested at wave amplitudes of 0.010, 0.015, 0.020, 0.025, 0.030, and 0.035 meters. The upper and lower bounds of the testing matrix were determined by the capabilities of the wavemaker and chosen to ensure that water did not overflow from the basin.

Figure 24 shows the changes in RPM of the turbine shaft over time for each of the tested amplitudes. All data points in this plot are taken from runs with a wave frequency of 0.4 Hz. It can be seen from this plot that for each of the runs the output RPM follows similar trends, showing peaks approximately every ten seconds. It can also be seen that higher amplitudes generate higher output RPM with the upper end of the testing matrix producing the highest RPM.

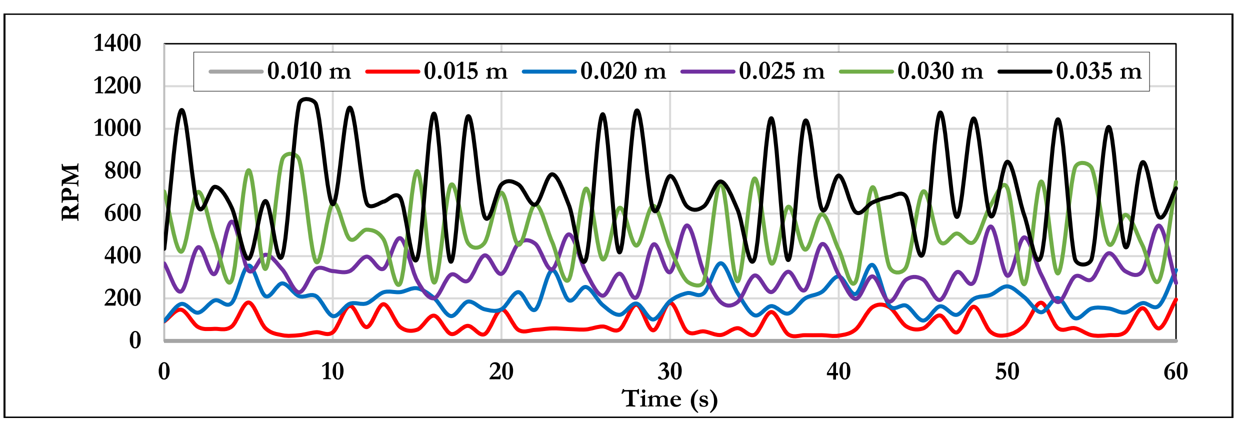

Figure 24. RPM Values for Each Tested Amplitude

Figure 25 shows a plot of the maximum and mean RPM values for each of the amplitude runs (all tested at a wave frequency of 0.7 Hz), which were extracted from the collected data. It can be seen from this plot that both mean and maximum RPM values increase at a relatively linear rate over the tested range of amplitudes. It is unclear from this plot whether this trend would change or taper at higher amplitude ranges. Figure 26 shows a sample run of RPM over time, which more clearly depicts the trends of RPM at a given amplitude and frequency.

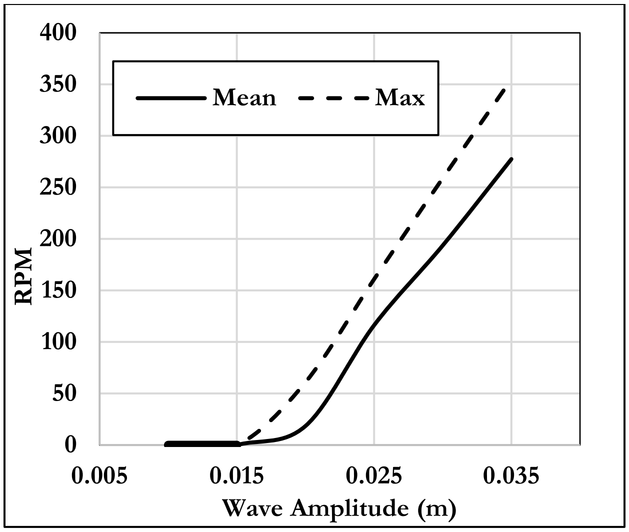

Figure 25. RPM vs. Wave Amplitude

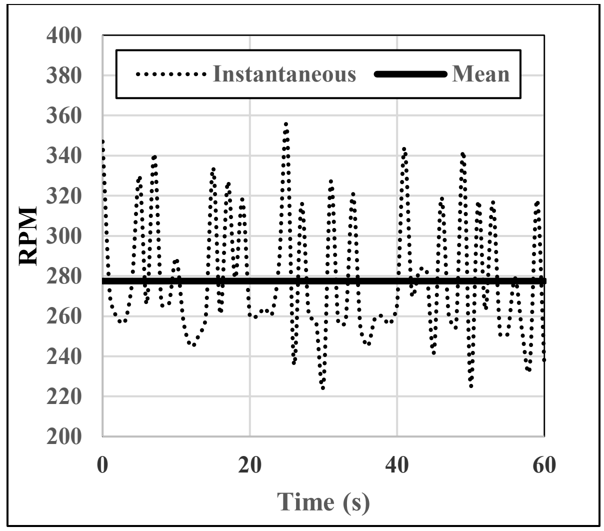

Figure 26. RPM over time, 0.035 m, 0.7 Hz

Figure 27 shows the changes in power for the system over time for each of the tested wave amplitudes. All data points on this plot were run at a wave frequency of 0.4 Hz. These power values were obtained from voltage data points as described in Section 4.3.3.2. It can be seen from this plot that for all of the amplitude runs, the output power values follow a similar trend with peaks approximately every five seconds. It also shows that for the tested range of amplitudes, the maximum amplitude of 0.035 meters produced the highest power output.

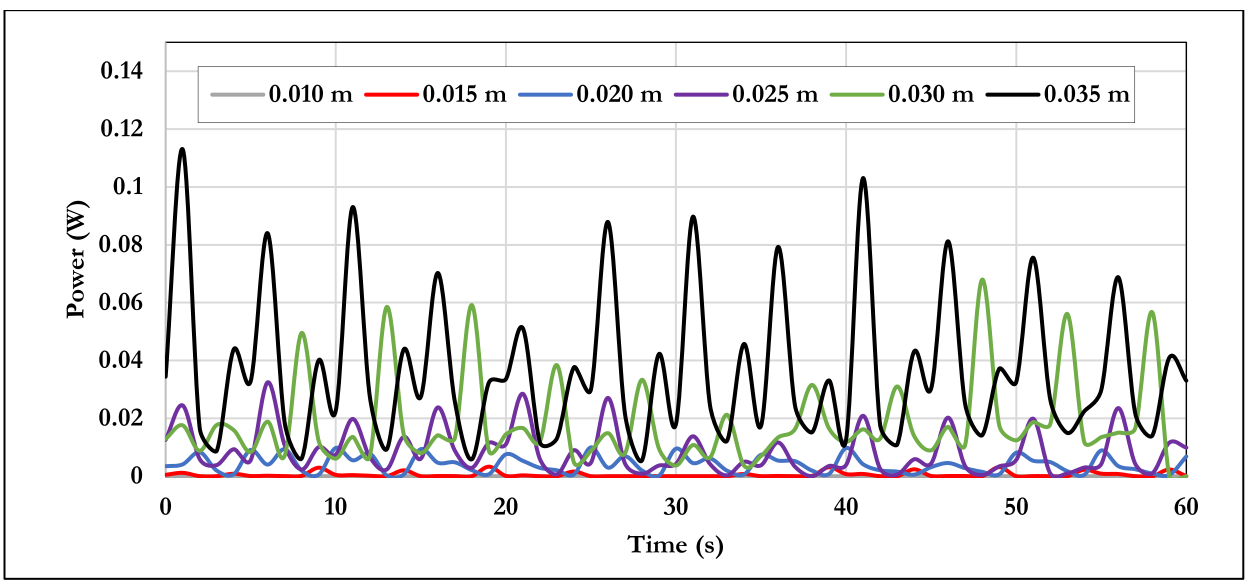

Figure 27. Output Power Values for Each Tested Amplitude

Figure 28 shows a plot of the mean and maximum output power values for each of the amplitude runs (all tested at wave frequency of 0.4 Hz). It can be seen from this plot that both the mean and maximum power output increase at a squared rate relative to the change in wave amplitude. This trend is expected considering that the obtained voltage values were squared when calculating power. Figure 26 shows a sample run of power over time, which more clearly depicts the trends of power output at a given amplitude and frequency.

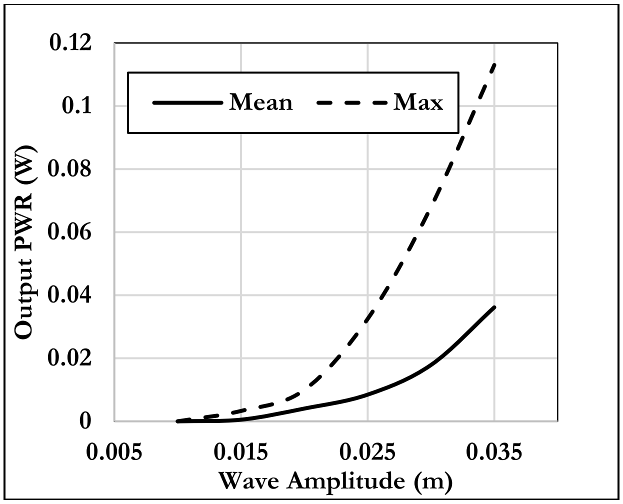

Figure 28. Output Power vs. Wave Amplitude

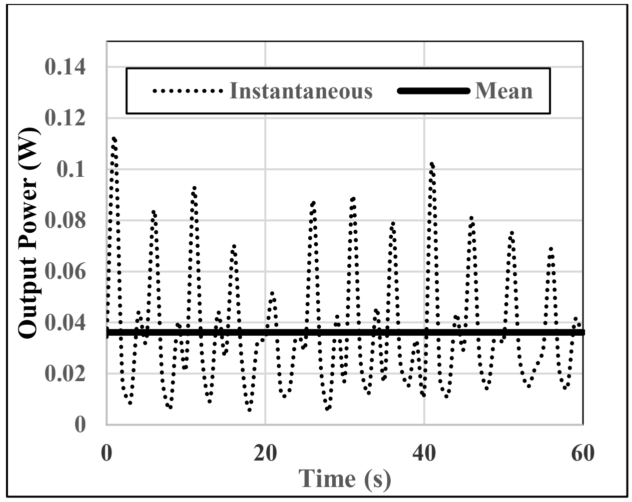

Figure 29. Power over time, 0.035 m, 0.4 Hz

4.3.5 Testing Matrix II (Wave Frequency/Period)

To establish a relationship between wave frequency and output RPM of the turbine shaft, a testing matrix of varying wave frequencies was created. The model was tested at wave frequencies of 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, and 1.0 Hz. The upper and lower bounds of the testing matrix were determined by the capabilities of the wavemaker and chosen to ensure that water did not overflow from the basin. The following plots use wave period, rather than wave frequencies, to convey the data in a more digestible manner. The conversions from frequency to period are located below in Table 6.

Table 6. Frequency to Period Conversion

Frequency (Hz)	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Period (s)	2.50	2.00	1.67	1.43	1.25	1.11	1.00

Figure 30 shows the changes in RPM of the turbine shaft over time for each of the tested wave periods. All data points in this plot are taken from runs with a wave amplitude of 0.025 meters. It can be seen from this plot that the highest tested period of 2.50 seconds produced the highest values of RPM.

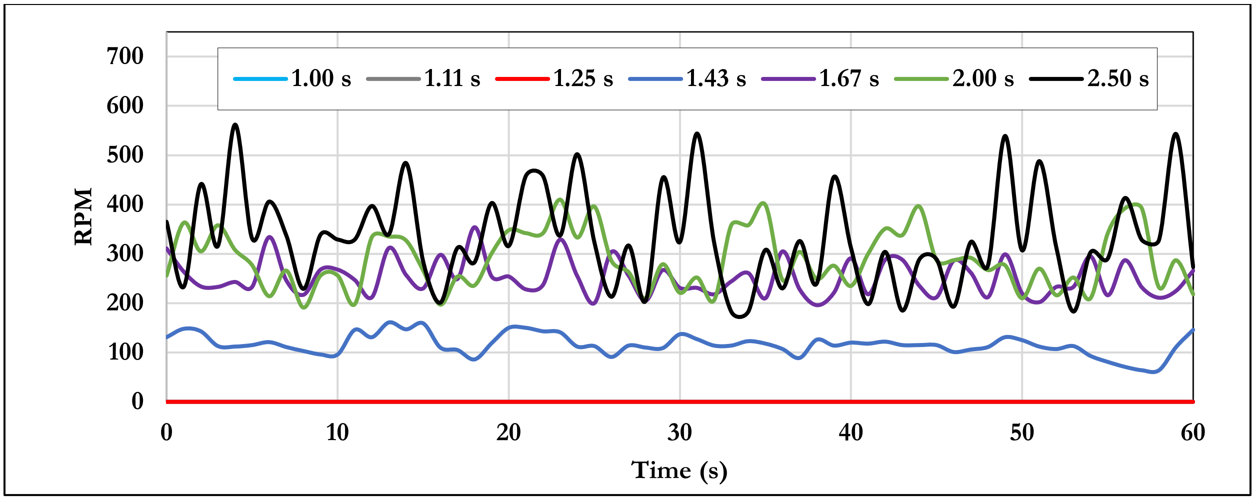

Figure 30. RPM Values for Each Tested Wave Period

Figure 31 shows a plot of the mean and maximum RPM values achieved for each wave frequency value (all data points collected at a wave amplitude of 0.020 meters). From this plot, it can be seen that there is a proportional relationship between wave period and output RPM. While the mean RPM values appear to taper at periods higher than 1.50 seconds, the maximum RPM appears to continuously increase over the tested range of wave periods. Figure 32 shows a sample plot of RPM over time for a given amplitude and frequency, which more clearly shows the trends present in a testing run.

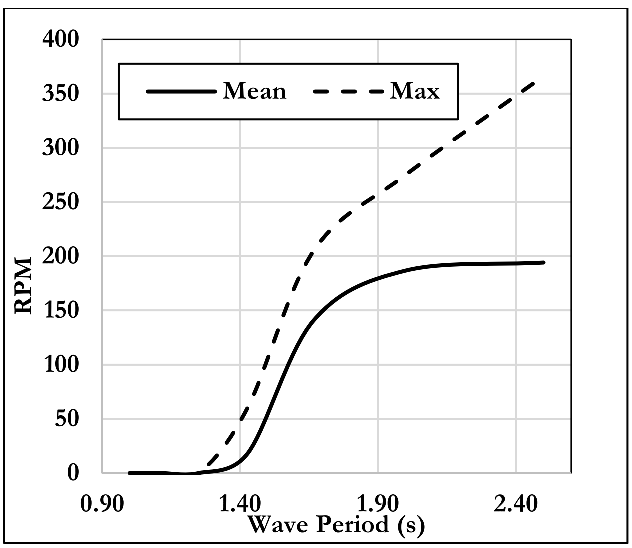

Figure 31. RPM vs. Time

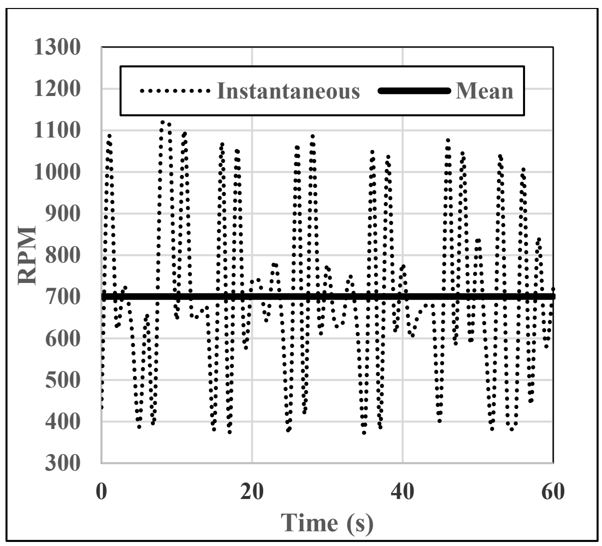

Figure 32. RPM over time, 0.035 m, 0.4 Hz

Figure 33 shows the changes in power for the system over time for each of the tested wave periods. All data points on this plot were run at a wave amplitude of 0.035 meters. These power values were obtained from voltage data points as described in Section 4.3.3.2. It can be seen from this plot that for all of the period runs, the output power values follow a similar trend with peaks approximately every five seconds. It also shows that for the tested range of period, the maximum period of 2.50 seconds produced the highest power output.

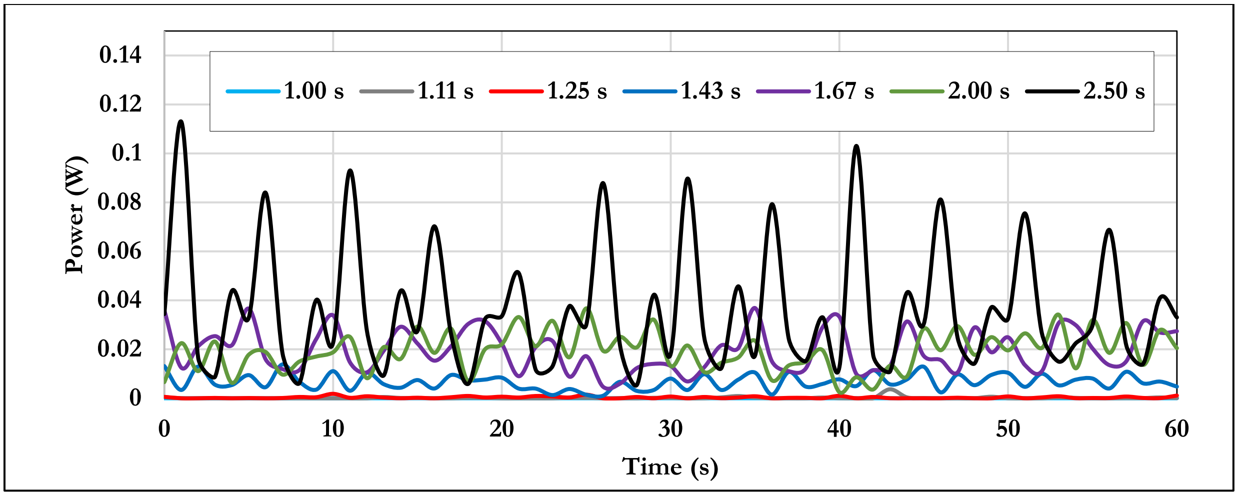

Figure 33. Output Power Values for Each Tested Wave Period

Figure 34 shows a plot of the mean and maximum output power values achieved for each wave frequency value (all data points collected at a wave amplitude of 0.035 meters). From this plot, it can be seen that generally there is a positive relationship between wave period and power output, with a major exception occurring at a wave period 2.00 seconds. While the mean power values appear to increase less rapidly at periods higher than 1.90 seconds, the maximum power output appears to continuously increase over the tested range of wave periods. Figure 35 shows a sample plot of power output over time for a given amplitude and frequency, which more clearly shows the trends present in a testing run.

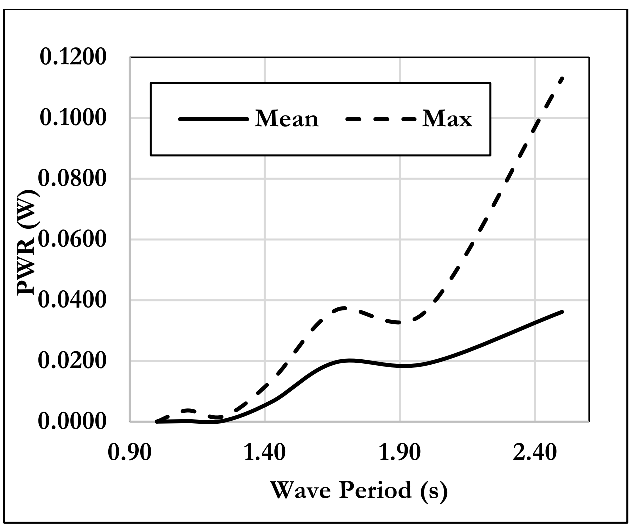

Figure 34. Output Power vs. Wave Period

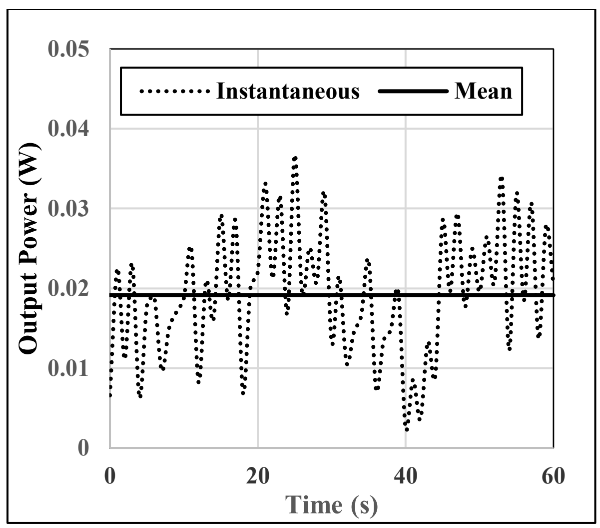

Figure 35. Max Voltage vs. Wave Frequency

4.4 Result Matrices

Figure 36 shows the mean and maximum RPM and output power values obtained for each wave amplitude and frequency tested. Higher values of RPM and output power are denoted by green and lower values are denoted with red. It can be seen that there are general positive trends in both RPM and output power as wave period and amplitude increase, as demonstrated by darker green values at the highest values of wave amplitude and period. It is also interesting to notice that at lower values of amplitude and frequency, both mean and maximum values of RPM and power are zero. This suggests that there are minimum wave properties required for system start-up. It appears that once this threshold is crossed, there is a consistent increase in performance over the tested range of amplitudes and frequencies.

Mean RPM						
	Amplitude (m)					
Period (s)	0.010	0.015	0.020	0.025	0.030	0.035
1.00	0	0	0	0	0	0
1.11	0	0	0	0	0	34
1.25	0	0	0	0	24	72
1.43	0	0	19	116	194	277
1.67	0	0	141	252	363	487
2.00	0	0	187	289	404	574
2.50	0	78	194	333	529	700

Max RPM						
	Amplitude (m)					
Period (s)	0.010	0.015	0.020	0.025	0.030	0.035
1.00	0	0	0	0	0	0
1.11	0	0	0	0	0	70
1.25	0	0	0	0	80	160
1.43	0	0	61	161	259	355
1.67	0	0	205	354	520	644
2.00	0	0	275	410	570	728
2.50	0	195	366	562	854	1115

Mean PWR (mW)						
	Amplitude (m)					
Period (s)	0.010	0.015	0.020	0.025	0.030	0.035
1.00	0.00	0.00	0.00	0.00	0.00	0.00
1.11	0.00	0.01	0.02	0.00	0.00	0.17
1.25	0.00	0.00	0.00	0.00	0.04	0.34
1.43	0.00	0.00	0.08	1.05	3.49	6.68
1.67	0.00	0.00	1.59	5.44	12.82	19.64
2.00	0.00	0.01	3.80	3.57	9.69	19.14
2.50	0.00	0.52	4.05	8.46	17.87	36.15

Max PWR (mW)						
	Amplitude (m)					
Period (s)	0.010	0.015	0.020	0.025	0.030	0.035
1.00	0.00	0.00	0.00	0.00	0.00	0.00
1.11	0.00	0.60	1.52	0.11	0.00	3.68
1.25	0.00	0.00	0.00	0.00	0.57	1.81
1.43	0.00	0.00	0.79	2.95	7.97	13.83
1.67	0.00	0.00	4.52	12.66	24.26	36.86
2.00	0.00	0.32	7.64	7.21	15.74	36.73
2.50	0.00	3.29	9.96	32.46	67.97	113.01

Figure 36. Result Matrices

4.5 Lessons Learned and Recommendations for Future Work

4.5.1 Lessons Learned

One of the most valuable lessons learned from the testing of this system is the importance of post-processing data and acquiring data in a way that is usable. The equipment used to obtain voltage and power data had not been previously used by the testing leads of the team. A better understanding of the outputs being recorded by the equipment, especially regarding timesteps, would have led to more seamless post-processing.

5 Conclusions

Through the construction and testing phases of this project, it was established that the construction and operation of a simple, small-use case OWC is feasible. The design and business plan proposed in this report have the ability to provide substantial benefits to remote communities.

The research outlined in this report provides a framework for potential use cases for OWCs as well as created a model to promote continued research into OWCs at Webb Institute. The documentation of the construction and testing procedures were intended to act as a source for interested students to begin their own research into OWCs or continue the research started with this project. The importance of widespread research on wave energy is recognized and the widening of access to construction resources was a major focus of this project.

5.1 Recommendations for Future Work

5.1.1 Business Plan Improvements and Additions

There is much work that could be done in terms of expanding the analysis of the feasibility and marketability of an OWC for disaster relief applications. The first recommendation is to perform a detailed parametric analysis of isolated communities around the globe. This analysis would identify critical factors required for a successful integration of this system into a community. These factors could then be used to determine real-world communities in which this system would provide the most inherent benefit. Some of these factors may include environmental and tidal properties, population size, and susceptibility to natural disasters.

Another recommendation would be to expand the cost estimate to a higher level of detail. This may include an in-depth analysis of the system's electrical loads, which could aid in better understanding CAPEX and OPEX of the total system.

5.1.2 Technical Improvements and Additions

With a preexisting testing platform of an OWC, there are a few recommendations that can be made for future work. These recommendations involve the improvement or use of the OWC to promote further research, or further business model analysis.

The bidirectional turbine used in this research was of a Wells design. Future work could be done to investigate the integration of an impulse turbine into this design. As mentioned in this thesis, impulse turbines have the potential to be more efficient across a wider range of flow conditions. While the build of a small-scale impulse turbine is more difficult than that of a small-scale Wells turbine, it may be beneficial to compare the efficiency of this OWC design with the implementation of an impulse turbine.

While this thesis creates a platform for stationary OWCs, there is a possibility for attempting to create a design in which the chamber of the OWC itself is tuned for resonance with a particular wave period. Given the importance of this device working over a wide range of conditions, it would be beneficial to understand the benefits of tuning the chamber design to maximize overall RPM output. Additionally, a testing rig that utilizes the proposed height adjustment features could be constructed. At an even higher level of design, it would be interesting to integrate a wave depth sensor and motors that automatically adjust the column height to better tune for the present wave depth conditions.

This research uses a one-chamber design, but future work may consider investigating a multi-chamber design and performing an analysis of the efficiency of the system given the number of chambers in the air column.

Acknowledgments

The Webb Institute MECC team would like to extend its thanks to those who made this research possible. Professors Richard Royce and Michael Martin were the primary advisors for this project, providing technical expertise and guidance throughout. Professors Edwin Wiggins and Richard Harris aided in the editing of this report. Spenser Boyd, a Webb alum, provided valuable insight into the world of blue energy and assisted in the development of the foundation of the business plan. Kevin Becker, a fellow Webb student, was kind enough to share his time and knowledge on 3D-printing with the team's design leads. Pat Doherty, Webb Institute's lab technician, assisted with the model testing setup and data acquisition. Finally, the team would like to thank the National Renewable Energy Laboratory for hosting the Marine Energy Collegiate Competition and providing the funding resources necessary for this research.

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