Swellular - Wave Powered Emergency Communications Device

POWERING
the BLUE ECONOMY™
Marine Energy
Collegiate
Competition
U.S. DEPARTMENT OF ENERGY

SWELLULAR
UNH 2023

TECH 797 – Ocean Undergraduate Research
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Terminology

- AC – Alternating Current
- BOEM – Bureau of Ocean Energy Management
- CAGR – Compound Annual Growth Rate
- CED – Cumulative energy demand
- DC – Direct Current
- DOE – Department of Energy
- DOD – Department of Defense
- FERC – Federal Energy Regulatory Commission
- FEMA – Federal Emergency Management Agency
- GDP – Gross domestic product
- IFRC – International Federation of the Red Cross
- LCA – Life cycle analysis
- MECC – Marine Energy Collegiate Competition
- MRE –Marine Renewable Energy
- NOAA – National Oceanographic and Atmospheric Association
- NREL – National Renewable Energy Laboratory
- NSF – National Science Foundation
- PTO – Power take-off
- PVC – Polyvinyl chloride
- RAO – Response amplitude operator
- RIB – Rigid inflatable boats
- SAM – System for award management
- SMIR – Small business innovation research
- SWEC – "Swellular" wave energy converter
- SAM – System for award management
- UNH – University of New Hampshire
- WEC – Wave energy converter
- WEC-sim – Wave energy converter simulator

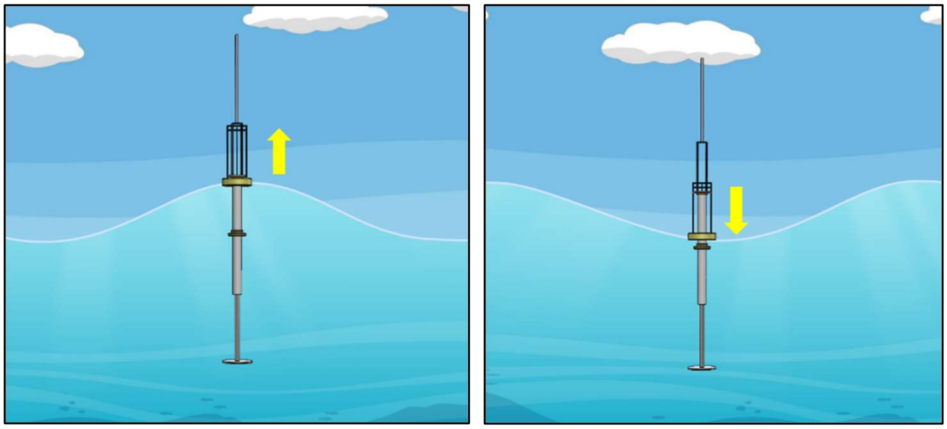
1. Executive Summary

The 2023 Marine Energy Collegiate Competition focuses on challenging university students to develop novel and unique solutions to harness marine energy to power the Blue Economy. The goal for these students is to find marine energy solutions to aid in a variety of applications, including power at sea and resiliency in coastal communities. The team from the University of New Hampshire (UNH) has developed a product that re-establishes communication for first responders following a natural disaster in a coastal community. With many failed companies and designs in the wave energy converter (WEC) field, the UNH team focused on a design that eliminated the two major failure points – underwater cabling and long-term deployments. Therefore, UNH developed a self-sustaining product that uses wave energy to locally power a radio communication system. The WEC can be rapidly deployed offshore of impacted communities and retrieved once the communication systems are restored in the region.

The UNH team named their company "Swellular", and Swellular's Wave Energy Converter (SWEC) is a two-body point absorber WEC that uses ocean waves to mobilize a direct drive linear generator that produces electricity. The electricity is stored in rechargeable batteries within the device, which consistently powers an attached radio repeater antenna. The product was designed to operate well in typical waves in the Caribbean, which is a region regularly impacted by hurricanes. There are wave conditions in other regions globally, allowing for a larger market as well. The UNH team's business plan is focused on supplying communities and disaster response teams with an inexpensive and simple product, focusing on communities with reduced funding and available infrastructure. The device can provide increased infrastructure for larger communities by deploying multiple units together, at the expense of increasing upfront costs. From design calculations and small-scale wave tank testing, the product will work and reach the desired power output needed to operate a communication antenna. This is explained in greater detail in the remainder of the business plan.

2. Concept Overview

The goal of this project is to design an affordable, reliable, and effective system which provides communication infrastructure to coastal communities. When a natural disaster strikes an island or coastal community, power lines and communication networks are often interrupted or destroyed entirely. This provides the need for temporary communication infrastructure to be deployed to accommodate the existing, or increased demand. To help mitigate these challenges, the product uses wave energy to generate electricity which powers a ham radio repeater. To provide power to the radio antenna, a round float follows the surface level of the water which drives an attached magnetic translator. This moves relative to the stationery spar which uses a heave plate and batteries at the bottom of the device help keep it stable. This relative motion drives the magnetic translator through a linear generator which can generate adequate power for the communication array. This product would supplement or provide all communications infrastructure for primarily first responders in an area after a natural disaster. This eliminates the need for portable land-based antennas, which are expensive and can be difficult to deploy and maintain. The product can be easily deployed from a small fishing boat or larger vessel, by an independent contractor or member of the community. If local small boats are disabled following a disaster, rigid inflatable boats (RIBs) can be brought in and used by first responders for deployment. With the product deployed offshore, it will not be in the way of any disaster relief cleanup efforts and can be easily towed and removed from the area once communication infrastructure has been restored. After conducting a detailed analysis of the SWEC design, it was determined to be stable in wave forcings of the Caribbean, have a power output of 1000W, withstand multiple deployments within a 25-year lifespan, and be 100% marine powered while not harming the aquatic life.



Figures 1 and 2: The WEC deployed offshore would have a wave following buoy and a stationary spar.

3. Stakeholders

Stakeholders include all who would be impacted by the product. This includes communities where the devices would be deployed, other users of the ocean such as fishers, and includes environmental concerns. The deployment would be temporary and would have the significant benefit of re-establishing communication.

First Responders: First responders require fast and reliable communication to help those in need following a natural disaster. Oftentimes, natural disasters compromise telecommunications systems which can last for weeks or months. Currently, when the electrical grid is without power, generators are used which only have fuel for a few days. However, these can be required to be used for months. These generators create a logistical nightmare for first responders who need to be constantly refueling them. Once SWEC is deployed it can provide reliable access to ham radio signals and is self-sustaining.

Community Impact: People living in coastal areas that are prone to natural disasters could be the most significant stakeholders for SWEC. Their safety and security would be the primary concern, and the device could help mitigate the damage. Having reliable access to a communication system has the potential to save many lives by connecting citizens with first responders faster. The product can also help rebuild the community more quickly by allowing logistical planning and overall communication.

Environmental Groups: Environmental groups may have reservations about adopting our product and how it may interfere with aquatic life potentially advocating for an alternative solution. These concerns have been researched and the product has been modified to prevent environmental risks as discussed in the "Environmental Risk" section. Overall, however the device will have a minimal environmental impact due to its short time in the water and thorough design.

4. Customer Discovery

Following a natural disaster, including hurricanes, earthquakes, or volcanic eruptions, many islands or coastal areas' infrastructure suffers including their communication systems. Inadequate communication systems make it challenging for first responders to properly aid those in medical need. Potential customers are therefore countries that are impacted by natural disasters, emergency relief agencies like the Federal Emergency Management Agency (FEMA), or companies who do large scale disaster relief projects under government contracts. Researchers had the opportunity to speak with John Robinson Jr, a disaster communications specialist in FEMA Region 1. He provided a large amount of information regarding emergency communications and stated that in the event of a large-scale natural disaster, most communication systems have backup generators with about 3 days' worth of fuel. However, if power is not restored in this period, the generators would need to be refueled or communication is lost. This is often problematic in remote regions, such as Puerto Rico, where fuel or the generator themselves are not accessible following a disaster. Fuel may also be inaccessible as it would be simultaneously used for other disaster relief missions.

Robinson discussed ham radio and said that while it is not used in New England, it is much more common in other parts of the country and in Puerto Rico. It is often found in places with a weaker communications infrastructure. After Hurricane Maria, ham radio was essential for providing communications to disaster relief organizations. He suggested that continuing with ham radio would be more logical and feasible for Swellular's project goals compared to cellular. This is because ham radio has a larger range and lower power requirements. However, SWEC could be easily upgraded to a cellular communication system in the future by simply requiring a different antenna and transmitter. Although a cellular network would require more devices to be deployed, and have a shorter range than radio towers, more information (video, etc.) can be sent across a cell network, and it does not require people to have separate radio devices to utilize the system.

The team also had the opportunity to meet with Brian Teague, a Branch Chief in FEMA Region 4. He has extensive experience in emergency response and natural disasters. Teague explained that the limiting factor for operating communication systems following a natural disaster is the power for the systems, rather than damage to the towers themselves. Although radio repeaters would be particularly useful for first responders doing search and rescue, Teague also claimed that there are many other groups that use radio communication as well. He noted that deployment of the WECs may be delayed as storm surge can drag debris, resulting in ports being shut down. He explained however that ports are usually assessed within 48 hours from when the storm hit. Since most backup generators for communication towers have fuel for 3 days, this would act as a buffer time to allow the product to be deployed before total loss of communication.

Overall, both FEMA representatives supported Swellular's concept and project goals and believe the market is large and lucrative. They encouraged that the devices are designed so they can be easily upgraded so when cellular technology advances, the product can be continually updated in that direction. Permitting required for environmental and communication regulations would need to be carefully reviewed.

5. Market Opportunity

5.1 Target Market

Since 1950, 511 disasters worldwide have hit small states, of these, 324 were in the Caribbean (Ötker, 2017). The Caribbean's vulnerability is characteristic of small island states, but this region has typically suffered more damage than others. The Caribbean states are seven times more likely to be hit by natural disasters than larger states and twice as likely as other small states. Also, the average estimated disaster damage as a ratio to GDP was 4.5 times greater for small states than for larger ones, but six times higher for countries in the Caribbean (Ötker, 2017). Additionally, climate change is worsening, leaving natural disasters to continue growing demand for sustainable solutions to disaster-driven problems. Swellular's target market is Caribbean disaster management services (governments, disaster relief organizations, private companies, etc.), more specifically the early adopters will be those serving in Puerto Rico.

Puerto Rico was chosen as an early adopter due to the moderate wave field's energy of 5-15kW/m under typical conditions. This was done so that the device is marketable to a vast variety of locations since hurricanes mostly occur in regions with moderate wave fields as seen in Figure 3 (the blue regions are considered moderate). While locations with a high wave power energy potential like Alaska and Greenland were also analyzed, the team decided that these locations were too extreme; with freezing temperatures, frequent storms, and icebergs, the wind energy would be more practical than wave energy in such locations. Therefore, for the purpose of designing and testing, Puerto Rico was used as a case study for the product for its wave energy potential and proven need for the product due to frequency of storms and remoteness.

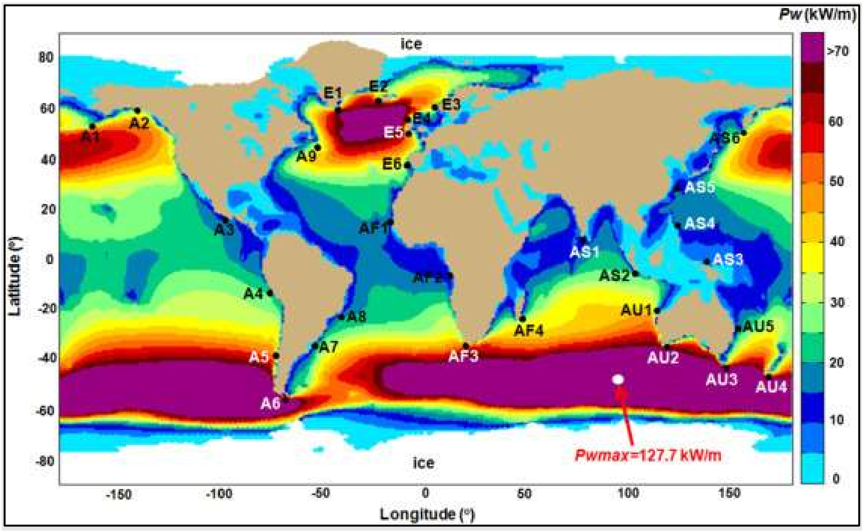


Figure 3: Global Wave Power Potential (World Wave Resource Map, 2015). Blue regions are considered moderate and are the target regions for this product.

The global disaster preparedness systems market size was valued at $146.03B in 2020 and is expected to expand at a compound annual growth rate (CAGR) of 7.4% from 2021 to 2028 (Disaster Preparedness Systems Market Size, n.d.). The rise in natural disasters is one of the major factors driving the need for disaster preparedness systems. Additionally, the Natural Disaster & Emergency Relief Services in the US Industry has revenue of $14.4B and profit of $1.0B (IBIS World, 2023). The industry has low concentration, low competition, and the opportunity for high revenue growth from 2023-2028. Lastly, following Maria, a Category 4 storm that hit Puerto Rico in 2017, the mayor of San Juan said that renewable sources of energy that feed into isolated microgrids are the way for Puerto Rico to protect itself from future natural disasters. “It's admittedly a long way off, but the island has undertaken a plan to switch to 100% renewable energy by 2050”, providing Swellular the opportunity to be successful in the market (Neuman, 2022).

Markets in the southern hemisphere have larger proven near-coast wave power that is steadier than that of markets in the northern hemisphere and along the equator. While the device will be designed specifically for the Caribbean market, additional markets along the coasts of Chile, Argentina, South Africa, and Australia should be explored as potential stakeholders, due to their proven wave energy potential. However, there are fewer disaster relief opportunities available in these locations. Potential stakeholders in these regions may be less likely to invest as the proven energy resource is higher, but the need for such a communication device is reduced.

Markets in the northern hemisphere, such as Greenland, northern Europe, and the northern Atlantic and Pacific Coasts of North America, present significant wave energy potential and additional disaster relief opportunities. However, many northern hemisphere potential markets have more robust communication and emergency response infrastructure, making the team's selection of the Caribbean market more promising. Additionally, potential investors for the Caribbean region may be more likely to invest as the need for communication infrastructure is needed with frequent natural disasters occurring.

5.2 Competition

Swellular's primary, and only, competitor is AT&T FirstNet which is the nationwide cellular platform dedicated to America's first responders and public safety community. They are a direct competitor with Swellular since FEMA and the United States government make up most of their market. However, their services are different from Swellular's as they implement a cellular network while Swellular implements a ham radio network. Their product is also primarily powered by fossil fuel generators. Although some of their products utilize solar energy, Swellular is powered by 100% renewable energy. FirstNet's deployment process is extensive as it requires a large vehicle and trailer and is dependent on generators which need to be refueled. Additionally, their deployment is limited to accessible roads, which is often a problem following natural disasters. While these can be deployed quickly in accessible areas, they require many more devices per unit area as they use a cellular system. FirstNet's strictly land-based vehicles limit their market from the rest of the globe as it would be difficult to quickly transport a vehicle to an island community such as Puerto Rico or the US Virgin Islands.

It is difficult to analyze the profitability of AT&T FirstNet independent of AT&T. However, their partnership with the US government is profitable. FirstNet grew 60% year-over-year in 2021 to generate $1.7 billion in revenue. Jenifer Roberston, the AT&T mobility executive vice president and general manager, stated "We've expanded the market and will continue to do so through incremental new connections like body cams, connected cruisers, school buses, biometrics and 2-way radio devices." This means that FirstNet hopes to merge into the same market as Swellular, and if Swellular introduced wave powered cellular towers in the future then the two companies will directly compete (Jackson, 2022).

5.3 Barriers to Entry

The barrier to entry is high for this market considering the high concept technical aspects of the product as well as the cost to model, test, and build this type of product. Initial funding from investors would be required to begin testing and designing. Another major barrier to entry is the challenges that come with developing an efficient product that can withstand prolonged periods of time while maintaining self-sustaining power supply. It is extremely difficult to make renewables efficient enough for the product to compete against non-renewable options. While there are many challenges that come with designing a product for harsh and unpredictable ocean conditions, wave energy is a great option due to its high potential energy density. As a result of these difficulties, a team of experienced engineers with various types of engineering backgrounds will be required to create a thorough, efficient, and robust design competitive enough for the market.

5.4 Other Possible Markets

The wave energy converter that Swellular is developing can be marketed beyond its target market of first responders in natural disaster relief as well. The wave powered communication system could also be a competitor in solving remote communities' telecommunications needs by implementing a permanent system. In certain coastal communities, such as the East Cape of Baja California Sur, Mexico, there is no cellular service and a lack of infrastructure for sufficient electricity. Installing a ham radio system in a location like this with a SWEC would be a great solution to their communication needs. Swellular's initial goal was to avoid developing a permanent ocean structure since it comes with more technical risks and costs for maintaining. However, by redesigning the SWEC's mooring system to include more lines, increasing its full range of motion to allow a larger wave forcing, and creating a solution to submerge the device in the event of a storm, there is potential for Swellular to enter this market.

6. Development and Operations

6.1 Decision matrix and design

Before determining which WEC type to use for the design, extensive research was conducted on existing designs currently in the market. After researching all potential existing designs, a list of design alternatives was created. A decision matrix was created with the alternatives described below, and parameters for the decision and score were decided on as a group, with the actual decision matrix being filled out individually. The decision matrices were scored on a 1-3 rating scale, 1 being the least viable option, and 3 being the most viable option. The team used the following parameters for each value on the decision matrix for each device conducted. These parameters will help to give a greater understanding to anyone outside the project of why the team picked this device, and what specifically the device has that makes it the most viable for the project.

Table 1: Justification for parameters on decision matrix

	Justification		
Parameters	**3**	**2**	**1**
Power Generation	> 1MW	500W-1MW	0-500W
Capital Cost	< $2,000,000	$2,000,000-$4,000,000	> $4,000,000
Environmental Impact	Corrosion Resistant, Sound Deadening, No external cables	Combination of corrosion resistant materials, sound deadening, and mooring methods	Frequency Disruption, Complex & Impactful mooring method,
Overall Efficiency	> 25%	10-25%	0-10%
Cost of O&M	< $100,000	$100,000-200,000	> $200,000
Accessibility for Maintenance	Basic Mechanic & Engineer required	Diver and Basic Mechanic & Engineer required	Diver, Expert mechanic, & engineer required
Ease of Deployment	15-25 foot Inflatable or Commerical Vessel	25-150 foot Commercial Vessel or NOAA Vessel	> 150 foot Commercial Vessel
Size	< 10 meters tall	10-20 meters tall	> 20 meters tall
Lifespan & Durability	>20 Years	10-25 Years	0-10 Years
Simplicity	Few moving parts required, simple mechanisms used	Combination of multiple moving parts and complex systems	Many moving parts required, complex mechanisms used
Survivability	Up to Beaufort Number 12 Sea State	Beaufort Number 7-12 Sea State	Beaufort Number 0-7 Sea State

The team looked at the following alternatives:

WEC Alternative 1: Point Absorber Wave Energy Converter with Antenna Attached

The first design alternative was to use a point absorber to produce energy for a radio antenna attached on top of it. This design benefits from simple access, portability, limited environmental impact with no undersea cable, and a long lifespan, however it doesn't generate a large amount of power, and has a limited survivability.

WEC Alternative 2: Oscillating Water Column (OWC) Wave Energy Converter with Antenna Attached

The second design alternative uses a floating OWC to produce energy with a radio antenna situated on top of it. This design benefits from little to no environmental impact, large power generation, and is easily accessible, but it can be difficult to scale down to a small size without compromising energy production, meaning it has limited use in a disaster relief scenario.

WEC Alternative 3: Tidal Turbine with Antenna Platform Floating Above

The third design alternative considered was a tidal turbine, which is bottom mounted with a floating antenna platform attached. This design can produce a large amount of power and is efficient but has many drawbacks. Primarily, there needs to be a sufficient resource, which severely limits deployment locations. including large environmental impacts, no portability, and a high capital cost, meaning it would be ineffective in a disaster relief scenario.

WEC Alternative 4: Attenuator Wave Energy Converter with Antenna Attached

The fourth design alternative uses an attenuator to produce energy with a radio antenna attached on top of it. The device has a low environmental impact, but otherwise is insufficient in all other categories. With assistance from the Project Sponsor, the team decided this alternative would not be feasible for the project's scope, based on its commercial availability and success, cost overruns, efficiency, and faulty parts.

6.2 Final Design

Table 2: Compiled decision matrix for WEC Final Design

	Alternatives			
Parameters	**Point Absorber**	**Oscillating Water Column**	**Tidal Turbine**	**Attenuator**
Power Generation	1	2	3	2
Capital Cost	3	2	1	1
Environmental Impact	3	3	1	1
Overall Efficiency	2	2	3	2
Cost of O&M	3	3	2	1
Accessibility for Maintenance	2	3	2	1
Ease of Deployment	3	1	1	1
Size	3	2	2	2
Lifespan & Durability	3	2	1	1
Simplicity	3	3	2	1
Survivability	1	2	2	1
Final Score	**27**	**25**	**20**	**14**

Based on the results from all individual decision matrices, the team selected a WEC system that used a point absorber with the antenna situated on top of the wave follower. The team felt that wave energy was the right choice for this project opposed to tidal, with point absorbers being the better choice due to their size, deploy-ability, power generation, and simplicity. The OWC WEC cannot be sized down as easily, which impacts ease of deployment, a considerable parameter for the team. Additionally, the point absorber is a good match with the electricity required to power a radio antenna. A small boat could deploy the point absorber device after a natural disaster, and carry the supplies needed, adding commercial value to the device. In a disaster scenario, multiple Point Absorber WEC devices could be deployed across an area, to boost communication signals across the island.

6.3 Alternative Applications

When developing an application for wave energy, it is important to choose one that has advantages in water as opposed to using a traditional method on land. The first application considered was electricity for a power grid. During a natural disaster, a design would be needed to produce enough energy to power essential utilities until the island can restore its power network. However, to deliver the power to the shore, cables need to run from the device to the location. Free-floating electric cables in the water would pose a hazard, and cables should be trenched into the ocean floor. This is not compatible with a system that must be quickly and easily deployed.

The second application considered was desalination. This could be integrated in two diverse ways: generate electricity to power a desalination system or pressurize seawater to pump through a desalination filter membrane. The desalination system could be on the WEC or shore. Regardless of how it is implemented, a desalination application would require either an electrical connection or a water pipe going to shore, which is again problematic for quick deployment.

When considering the relief efforts after a natural disaster, it was found that communication is a major need. Regarding tropical cyclones in the Caribbean, each year there are 11 named storms and 6 hurricanes, with two being category 3 or higher. Following a storm or natural disaster, first responders have limited time to find out who needs medical assistance. During many storms, failing communication systems lead to more deaths. In 2017, Hurricane Maria left most of the island without communication methods for months hindering recovery, isolating residents, and making it difficult for survivors to seek out aid. The U.S. Virgin Islands were left without communication services for 2 weeks (Frank, 2019). The point absorber designed will be used to power a self-powering ham radio system. This system will be designed to be easily deployed in short-notice situations. No underground cables will be needed because these do not require fiber optic cables, and the device can be deployed by boat.

7. Environmental Risk

7.1 Overview

When designing a wave energy converter, environmental risk is a key factor to consider. Even though the energy needed to power a communication system is small compared to the total energy needed in a town, the SWEC will reduce environmental risk by not using fossil fuels. Fossil fuels are the leading cause of greenhouse gas emissions in the United States. There are many opportunities for the United States, as well as worldwide to harness more energy from renewable energy sources to reduce fossil fuel consumption and reliance. With greenhouse gas emissions increasing, and these emissions accelerating climate change effects, additional countries must utilize more renewable energy sources worldwide. With increasing population and urbanization around the world, this can lead to more energy requirements, proving that now more than ever, renewable energy is needed. A wave energy converter is one way to supply this needed energy sustainably, focusing on providing the energy for present generations, while ensuring that the device is also applicable to and for future generations.

7.2 Ecosystem Considerations

Deploying a wave energy converter in any region is bound to face major ecosystem obstacles, as many natural environments can be extremely fragile. Many aquatic animals rely on sound for communication underwater in the world's oceans, and a potential concern is that our project could create noise that could impair wildlife communication. A solution the team has employed is gaskets between the different moving parts of the device such as between the spar and the translator, which is part of the power take off system. Additionally, inside the spar will be noise canceling insulation to help to reduce any generated noise. This will help the device maintain a quiet profile in the water, while still creating the energy necessary to power the communication array.

Another ecosystem consideration is the mooring system of the device, as any mooring system must interact with the seafloor, potentially disrupting ecosystems. The team has decided to use a single-line catenary mooring system as this type of mooring is typically used in the Caribbean and is a simple, cost-effective mooring. The catenary mooring line has a small surface area on the seafloor, allowing for minimal impact on the ecosystem. This is extremely important as the warm Caribbean waters are home to many coral reefs and aquatic populations living close to shore, meaning the margin for error and impact with the selected mooring is small. The strength and durability of larger moorings with solid anchors would not be needed as the device is relatively small and it will generally not face large storms, as the device would be deployed after a natural disaster. Additionally, having multiple lines would increase deployment complexity and costs. This device could also be paired with a Halas mooring system which would further reduce the impact on the ocean floor. This would also keep the buoy in high tension, further reducing ecosystem impact and risk of entanglement. The team has also explored nontoxic coating on the exterior of the device, to further reduce the impact the device would have on the environment.

7.3 Biofouling

Biofouling is an important environmental factor to consider when designing a device for marine use, as the marine environment can be extremely hostile to any foreign device placed in it. From an environmental perspective, it represents the natural progress of marine life and will lead to an increase in productivity and habitat for marine organisms. From an engineering perspective, it will increase drag and mass, alter dimensions, and contribute to degradation. On ships and mobile structures, biofouling may also contribute to the spread of invasive species (Swain, 2017). The UNH team has analyzed potential biofouling risks based on the region where such risks operate and has determined that since the device is temporary and would be deployed for a short time, biofouling would be less of an issue compared to alternative shore-based devices. However, after each deployment the SWEC will be examined and cleaned, with parts being replaced as needed. If there are several repeated issues with biofouling this can be investigated further.

8. Societal Risk

The use of wave power to harness energy reduces communities' dependence on non-renewable sources of energy, such as fossil fuels. This local source of renewable energy would allow a community to provide communication infrastructure while avoiding costly fossil fuels and the environmental risk that comes with them. A source of renewable energy helping a community would secure financial stability and improved quality of life, allowing for additional funds to be allocated to other areas in need of more immediate assistance. A major societal risk of non-renewable energy sources is the greenhouse gases released into the atmosphere because of combustion, resulting in climate change acceleration occurring. Climate change is a major societal concern because it can cause extreme weather events that are devastating to infrastructure, housing, and the members of the communities affected. Using energy from a WEC would drastically reduce this climate change acceleration from occurring, in the long term.

9. Technical Risk

When deploying any device into the ocean, there is always technical risk. To mitigate risk of vessel collision, which must be factored in with any ocean deployment, the WEC will have an omni-directional light located at the top of the device (higher than 8 feet) as according to Coast Guard regulations, any buoy must have a light above 8 feet and not obstructed in any direction.

Corrosion is often a large factor when deploying devices in the ocean as well. To combat this the SWEC was made exclusively of material that is corrosion resistant. This includes 316 stainless steel heave plates, 6061 aluminum framing, and galvanized 4130 anchor and chain. However, since our SWEC will be deployed in temporary emergency scenarios, it will likely not be in the water longer than a month at a time. After each deployment, the SWEC will be examined to ensure there is no damage due to corrosion or other effects.

Through an extensive design process, testing in WEC-sim, and scale model testing, various electrical and mechanical failures were identified and fixed. Given the limited time of this project and initial funding, the device is not perfected, but with future design considerations, and optimizations the device would be much more reliable. Listed below are all the potential risks, along with the effects and how they were mitigated.

Table 3: Technical Risks

Cause	Effect	Mitigation
Electrical Failure	Unable to transmit signals	Watertight spar and electronics, testing
WEC mechanical failure	Require maintenance, device failure	two-way communication, testing
Extreme Storms	Damage the WEC	Two-way communication to temporarily shut down
Mooring line failure	Damaged or Lost WEC	GPS
Vessel Collision	Damaged or Lost WEC	Navigation lights, reflectors
Theft	Damaged or Lost WEC	GPS
Saltwater Corrosion	Damaged WEC	Materials, short-term deployment, testing

10. Operation and Maintenance

To communicate and operate with SWEC while it is deployed, Iridium was selected due to its stability, worldwide range, and is a proven solution. Iridium is a global satellite communications company, that provides voice and data services. Iridium is known for being able to send data from some of the world's most remote locations because of its worldwide interconnected satellite coverage. Iridium has transfer rates of 2.4 kbs and has the ability for two-way communication. This is essential for the point absorber, as power output can be monitored, and if there are waves that are too big for the point absorber to handle, SWEC can be shut down remotely, to prevent damage to the device. In addition to Iridium, a GPS tracking system will be incorporated on SWEC for easy retrieval and tracking in the case of mooring system failure or theft.

11. Financial Benefit and Analysis

Wave energy is still a young industry compared to other types of renewable energy. The lack of research, testing, conceptual work, and harsh conditions create financial risks for the stakeholders and investors involved. With many prior projects failing, the team wants to avoid repeating the same mistakes. A method to decrease potential financial risk related to failure is to simplify the device involved. Point absorbers have a substantial history of success in the industry, due to their simplicity and high return on investment. Additionally, most communities hit after a hurricane do not have mechanics or technicians on hand, so by selecting a simpler device, it alleviates the need to have these specialists on hand. Keeping the WEC small and simple also allows it to be deployed or recalled by a small fishing or, adding to its potential for success from a financial point of view.

The research, development, and production of the WEC also come with inherent risks. Many WEC companies have gone out of business recently due to the lack of demand. However, the need for this communication device on the WEC has already been outlined in this report. Natural disasters will continue to be an inherent problem throughout the world and with increasing communication needs along with the shift towards renewable energy, this device will likely be attractive to investors.

11.1 Management

To ensure a successful business, the product must operate with a low operation and maintenance cost. Prioritizing output but having the design be complicated will make it hard to replace parts. Using specific parts will not only make it hard to obtain new parts but also could cause the product to be down for months at a time. Once the system is sold, the buyers will be professionally trained in how to maintain the system to prevent long-term failure.

11.2 Permitting

For any project, permitting is a vital task of the project, which must be considered before any materials hit the manufacturing line. For this project, the team understands that there are few permitting regulations that are relaxed following a natural disaster hitting. Therefore, extensive permitting and regulation investigation must be done prior to ensure the device is allowed to go into the water.

Through extensive research on previous WEC sites, the team has determined a Federal Energy Regulatory Commission (FERC) preliminary permit must be filed, and based on that permit, a set time “conditioned” license from FERC is given for the product, which allows the device to be in that area of the ocean for a certain amount of time. Also, the team would have to pursue any state regulations in the area and any additional federal regulations to deploy the device.

To operate a ham radio with the range necessary for the project, one must have a license to do so. With emergency situations, the license requirement is dropped, so a permit will not be required for the communications aspect of the project. The operating frequency will still be required to be investigated and we will likely work with local first responders to ensure there are no other communication regulation issues.

11.3 Revenue/Pricing Models

The main revenue stream for Swellular will be supplying WECs to companies that do large-scale disaster relief work under government contracts such as Honeywell, a company committed to the safety of first responders who help people during and after natural disasters (Ingersoll, 2022). Additionally, the International Federation of the Red Cross (IFRC), a company that acts before, during, and after disasters and health emergencies to meet the needs and improve the lives of vulnerable people (IFRC). When Swellular is undergoing full-scale operations, there is potential to secure our own government contract with an agency such as FEMA and similar Caribbean agencies with foreign governments. Once a company has navigated its way into the government market, it can be a highly lucrative and reliable revenue stream (Federal Contracting 101, n.d.). Currently, we estimate the base sales price to be $25,000 + shipping and maintenance. The initial cost to build one unit is $14,508, leaving us with a gross profit margin of 46.2%, and putting us in a good position to earn steady revenue. At the beginning of year (4), we will break even at 93 WECs sold.

11.4 Sales/Distribution

Subcontracting our WECs to companies such as Honeywell will be done through applications into databases that offer partnering opportunities. When looking to obtain our own government contract, Swellular will register with the System for Award Management (SAM), the government-wide vendor registration, as well as Unison Marketplace, a fully managed online marketplace for government procurement. The product will be built in the United States and distributed in shipping containers to their appropriate destinations. Weighing in at 226kg, it is possible to ship them by plane or ocean. Typically, it costs $2-$4/kg to ship items by ocean and $2.50-$5/kg to ship by plane. To increase sales, we plan to sell WECs prior to natural disasters in order for Swellular to be deployed immediately following a disaster. In this case, we would ship by ocean as it takes 20-27 days. However, we will ship by plane in response to a disaster once it has occurred, as it only takes 6-7 days.

11.5 Scaling

We plan to increase the units sold each year, which will lead to a decrease in the percentage of cost of sales. Our baseline financial projections show no decrease in cost of goods sold, however, as more units are sold, the plan is to reduce costs per unit over time through streamlining production by using capital equipment, outsourcing to less expensive areas, etc. In year (1), when we initially target Puerto Rico and its small surrounding islands, we expect to sell 6 units. As we scale our business to reach a larger target market including more of the Caribbean islands, and the rate of natural disasters increase, we expect our sales to grow exponentially each year, up to 250 in year (5). Another scaling opportunity for Swellular is to expand into new markets by developing a WEC that provides more versatility, eventually capable of hosting a cellular antenna. This would be done by replacing the radio device with an antenna and transmitter so that Swellular can capitalize on industries aside from disaster relief, such as research.

11.6 Financial Resources

We anticipate requiring $2,450,000 in equity funding in the first three years to advance the project to full commercial operations, at which point we will seek debt financing of $1,250,000 to be repaid in five years with a 7% debt interest rate, to bridge any additional funding requirements that may be needed. Distributions to equity will commence in year (5); the annual cash available for distribution will be $2.4M, increasing annually at a rate of approximately 10%. We intend to offer 40% of the company to equity investors through multiple fundraising over the first three years of operations. With this, we conservatively anticipate a return to investors of 35%. However, the upside potential of the business based on higher sales volumes could easily yield returns of more than 50%. While this amount of equity funding would allow for the team to get Swellular off the ground and in full operation, seeking grant funding could potentially reduce the amount of equity required. Funding opportunities are widely available through government agencies such as the Department of Energy (DOE), Department of Defense (DOD), Federal Emergency Management Agency (FEMA), National Oceanic and Atmospheric Association (NOAA), National Renewable Energy Laboratory (NREL), National Science Foundation (NSF), and Small Business Innovation Research (SBIR).

12. Sustainability Overview

Often products will claim they are more sustainable since they do not produce greenhouse gases while operating. However, the production for creating the product can be worse than the alternative. This is why a life cycle analysis is conducted. The purpose of a life cycle analysis (LCA) is to evaluate the environmental impact of a product or process from a holistic perspective, considering all stages of its life cycle.

The LCA measures the cumulative energy demand (CED) which accounts for direct and indirect energy use throughout the life cycle, including the energy consumed during the extraction, manufacturing, and disposal of the raw and auxiliary material. An LCA for Swellular's WEC was conducted and compared to a generator using SimaPro: a software tool for conducting LCAs. First, the complete list of materials with appropriate weights was inputted for the full-scale WEC model. The same was done for the alternative case of a small diesel-powered generator again accounting for extraction, production, and operation. To compare the SWEC solution to the traditional generator, a functional unit of 10 kW is used to compare how much energy goes into the life span for 10 kW to be created. The total kW the products can create in their lifespans is divided by the functional unit to create the adjustment factor. The total impact of each system is then divided by the adjustment factor to produce the adjusted impact. For Swellular's WEC assuming a 25-year lifespan its cumulative energy demand impact is .830 MJ whereas the generator of a lifespan of 30 years is 35.0 MJ. This shows that even though the SWEC has precious metals to extract for its battery, overall, it takes less energy to create compared to the traditional generator.

13. Technical Report

13.1 Summary for Technical Design

Swellular’s design consists of a two-body point absorber WEC that harnesses the waves’ heave motion to power a direct drive linear generator. The design's goal was to maximize efficiency while maintaining simplicity for deployment, cost, maintenance, and durability. See Figure 4 for an image of the design.

As previously mentioned, Puerto Rico was used as a target location for the device. As a result, the WEC was designed for Puerto Rico’s wave field. The wave parameters off the coast of Rincon, Puerto Rico were found by averaging the wave heights and wave periods in the month following the common hurricane season in 2021 according to the National Data Buoy Center. The average wave height found was 1.13 meters and 8.52 seconds.

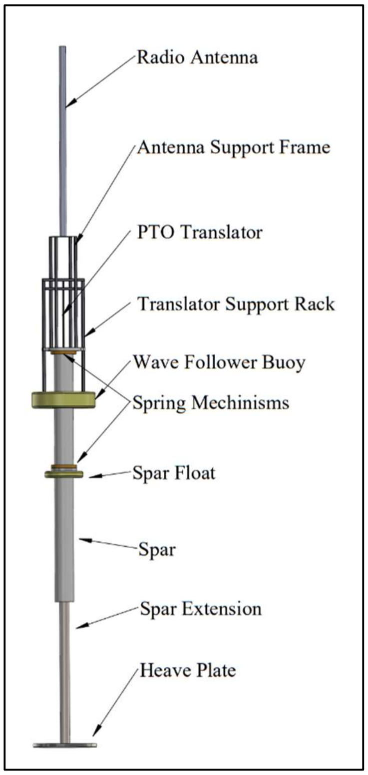


Figure 4: Full Scale Design

13.2 Hydrostatics

To design a point absorber capable of supporting a communication system, a detailed hydrostatic analysis was done on the two-body structure to ensure durability, stability, and efficiency. This process was long and tedious as any slight changes in materials, dimensions, or placement of the components on or within the structure affected the buoyancy of the device. SWEC consists of two bodies, a stationary spar and a buoy that moves relative to the spar. The two bodies were analyzed separately. The waterline sits 2.31 meters up from the base of the PVC spar at hydrostatic conditions, giving the buoy full range in the given wave parameters.

13.2 Construction

The spar consists of an 8-inch Schedule 40 PVC pipe that is 3.8 meters long. This is used as the PVC is lighter compared to the other alternatives. Within the PVC tube is the linear generator stator, secured 0.8 meters from the base of the PVC. Additionally, lithium batteries with 2000Wh of storage rest at the base of the spar. These were chosen since lithium batteries are much lighter compared to the lead-acid alternative. On top of the spar is an aluminum frame supporting the radio transmitter and antenna. The rack is 1.43 meters tall so that the buoy system can move in full range without interacting with the frame. There is 0.3 meters of buffer space between the buoy's highest maximum position on the spar and the top of the spar and a foam collar around the spar at the buoy's lowest maximum position on the spar. The collar adds stabilization to the spar to counteract the weight and height added with the communication system. A hollow aluminum pole extends 2.24 m from the bottom of the PVC spar and holds a stainless-steel heave plate on its end. These are separated by a non-metallic material.

The buoy consists of custom ultra-tough, super-cushioning ionomer foam with a 1-meter outside diameter and an inside diameter cut out to fit around the PVC Spar. The buoy holds an aluminum rack that supports the magnet pole. The rack is 1.44 meters long to account for the entire wave height and buffer space. The total mass of the fully constructed spar and float is 159.39 kg.

SWEC's simple design ensures that manufacturing costs would remain low. All the main components such as the PVC spar, stainless steel heave plate, aluminum framing, mooring, and antenna were all designed to be purchased off the shelf.

The two exceptions are the generator and the buoys, which would not be able to be purchased off the shelf. While the buoys would have to be custom-made, the manufacturer, Gilman Corporation, has already been contacted and has quoted Swellular for a reasonable price. The linear generator will cost the most in comparison to the rest of the system. While this may not need to be custom-made, linear generators are not extensively used on the market, which results in them being more difficult to find and often a higher price.

13.3 Power Take Off

SWEC's power comes from a direct drive linear generator which consists of a magnetic translator and a stationary 3-phase stator. This design was chosen due to its simple mechanical interactions. This allows the system to be less likely to result in failure and result in lower maintenance costs. These generators can have high efficiencies compared to other alternatives. This can be seen in the table below.

Table 4: PTO Efficiencies (Chozas, 2014)

PTO Type	Efficiency (%)
Hydraulic	65
Water	85
Air turbines	55
Mechanical drive	90

The direct drive linear generator consists of a stationary stator with copper wire windings. These windings were arranged in a 3-phase "Y" connection to maximize efficiency. This is coupled with a translator which consists of a tube filled with permanent magnets and steel spacers, arranged so that the magnets have similar poles facing each other, with a steel spacer between each. This arrangement allows each magnet to have its own magnetic field and the spacers allow each coil to only interact with one magnetic field at a time.

The relative motion between the stator and the translator results in a changing magnetic field which induces an electrical current in wire coils. This alternating current (AC) is then coupled with a 3-phase full wave rectifier which converts the AC into direct current (DC). This output would then be attached to a circuit breaker to ensure the batteries are not overloaded. This would be crucial to ensure the safety and longevity of the device. These would then be attached to the lithium-ion batteries which would store and provide electricity to the radio transmitter and antenna. An image of this design can be seen below in Figure 5.

The framework for the generator used in SWEC was based on a previous WEC project done at UNH by a 2016 team. This design had the magnets sit within a 1in PVC tube with their similar poles facing each other separated by steel spacers. The tube was sealed with a bolted nylon plug to keep the magnets contained within the translator.

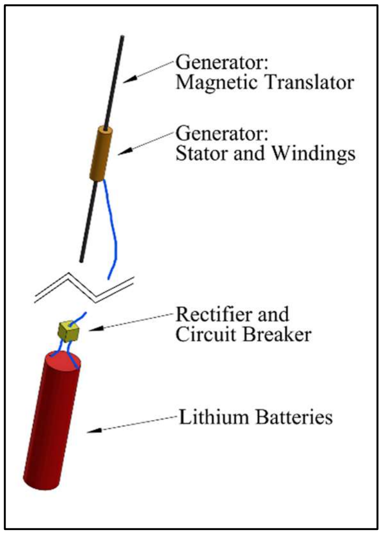


Figure 5: Exploded view of designed PTO

Copper wire was wrapped tightly onto a custom sized nylon stator. The stator has an inner diameter equal to the outer diameter of the magnet's tube so that the magnets can slide through the center of the spool with ease. The coils were wound with 20 AWG magnet wire in alternating clockwise and counterclockwise directions to maximize current. Each coil was then all attached to each other in parallel. Despite being nearly 1.5m long, their design did not prove to be very effective and was unable to generate more than a few watts of power. Although they were not able to identify the issues, it is likely because the coils were not arranged in a common 3-phase “Delta” or “Y” arrangements and there were cancelations in the currents. Additionally, their airgaps may have been too great within the generator.

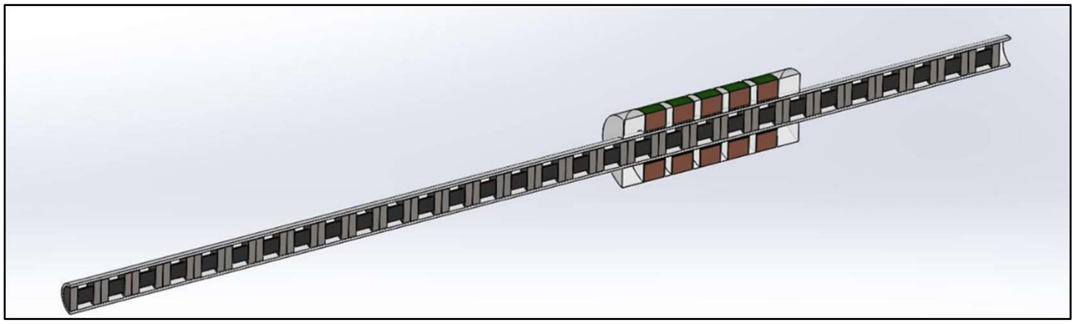


Figure 6: Cross-sectional view of linear generator (credits to the 2016 UNH WECB team)

13.4 Performance Analysis

In using a direct drive linear generator design, the friction between the translator and stator is negligible. Therefore, the damping coefficient is small, and the system is lightly damped. This means that the system will not lose excessive energy within the generator, and the buoy will have a greater response amplitude in the waves. This also results in an ideal wave field, the WEC system will contour the waves and act as a wave follower. A WEC that operates at these expectations is highly efficient and effective. The heave response amplitude operator (RAO) and buoy dynamics were calculated in MATLAB using linear wave theory in a code written by Chelsea Kimball, a current graduate student at UNH.

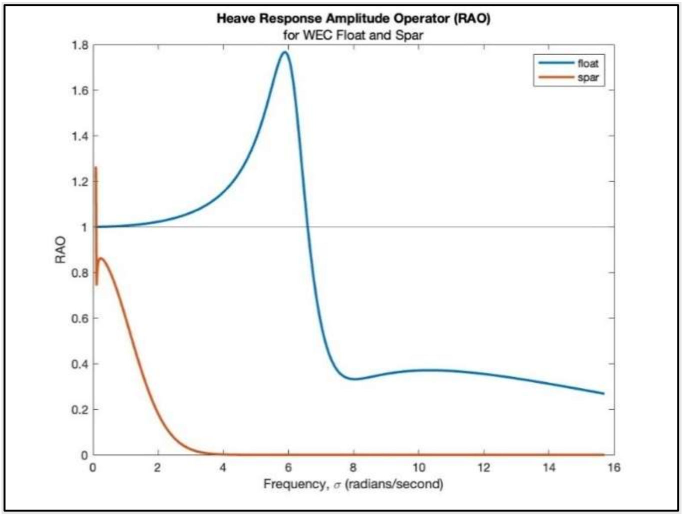


Figure 7: SWEC's heave RAO for the buoy (float) and the spar.

Figure 7 shows that the spar's RAO peaks at zero and decays rapidly, implying that the spar only has heave motion in extreme wave conditions. However, the buoy's RAO is equal to 1 while the frequency is equal to Puerto Rico's wave field (where the period equals 8.516 s). An RAO of 1 is ideal since it indicates that the buoy has maximum heave amplitude while maintaining steady power output. The RAO peaks at approximately 6 rad/s, a 1 second wave, which would not be seen in Puerto Rico's wave fields. Operating at peak RAO is not ideal as it could cause excessive loading and forcing on the device.

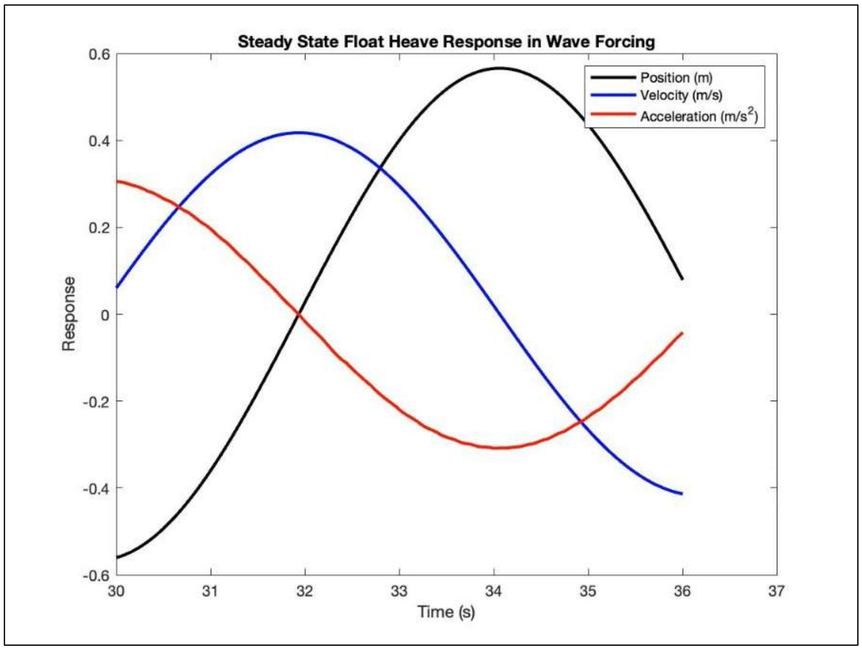


Figure 8: The SWEC buoy's displacement, velocity, and acceleration relative to the spar.

As seen in Figure 8, the buoy's position oscillates from just under 0.5658 meters to –0.5658 meters. This figure validates that the buoy would act as a wave follower since Puerto Rico's wave field has an average wave amplitude of 0.5645 meters.

13.5 Communications

Ham radio is used globally for long-range communication. Swellular's point absorber will power a ham radio repeater antenna, which will receive, and re-broadcast signals sent from ham radios, to extend their reach. The range and simplicity of ham radio is the main reason it was selected. The expected range of our system in open water is 100 statute miles. This range is subject to change due to high elevations such as mountain ranges and/or volcanic terrain, but with a ham radio FM repeater, handheld or mobile ham radio, operators on average can communicate 100 miles from the device. These ranges can be altered by the type of antenna, as the choices are omnidirectional, isotropic, and Yagi/directional antennas.

For the islands off Puerto Rico, Vieques (52.12 square miles) with a population of 9,350 people ,and Culebra (11.62 square miles) with a population of 1,792 people, one repeater could provide communications for these entire islands. These islands' only sources of electricity are directly from Puerto Rico, so when a storm hits and Puerto Rico loses power, the islands lose all communications also. In years prior, storms such as Hurricane Irma and Maria, Puerto Rico, and its islands lost all communications, the death toll was between 3,000 – 5,000 people, and many point towards the collapse of communications as a contributing factor. The ham radio repeater cannot reach the entire island by itself (the area of Puerto Rico is 3,512 square miles), so linked repeaters could potentially provide communications for the island. However, a single device would provide communications for the entirety of San Juan (Puerto Rico's capital) since it is located on the coast with an area of 77 square miles and a population of 326,953. Many of Puerto Rico's major cities are located on the coast, so providing communications for these areas could save lives. Ham radio repeater towers usually use between 10-250 watts, and Swellular's point absorber is expected to produce more than 1000 watts (assuming a 10% overall efficiency) so there will be more than enough power to provide for the ham radio repeater. The device will have battery storage, as ham radio requires a constant power supply, so the excess power produced will go to storage in the event of flat seas.

13.6 WEC-Sim

WES-Sim is a simulation software through Matlab used for modeling a WEC in various wave conditions. This was achieved by creating simple geometry files of both the spar and float bodies and converting them into nemoh files via mesh magic which may be used to run the bodies through wavefields. This wavefield data was created via Spyder as a nc file which was then converted to an h5 file via Bemio from the WEC-Sim source code. This h5 file allowed us to simulate the device on Matlab. WEC-Sim advance features were used to allow for the Simulation of our direct linear drive PTO.

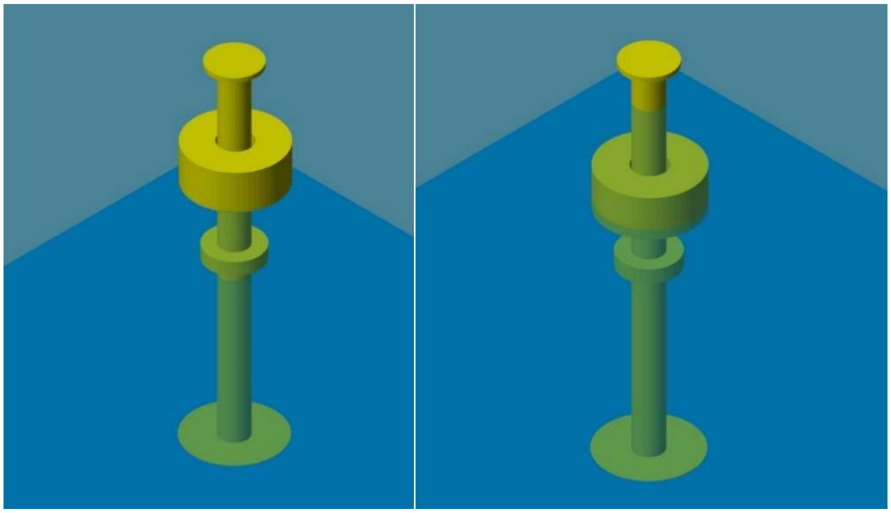


Figure 9: Sim Mechanics simple geometry model of two body point absorbers in wave conditions. The left image of the device is at the wave peak and the right image is at the trough.

As can be seen in Figure 9, there is good relative motion between the spar and float of the two bodies between the peak and trough of the wavefield. The two bodies are acting as expected in the simulated wave space. The direct linear drive PTO requires several inputs which can be viewed in the table below as well as the associated formulas. These variables were calculated based on the estimated stipulations of the device.

Table 5: PTO equations

PTO input	Equation	Variable names
winding resistance [ohms]	$R = \frac{\rho \cdot L}{A}$	ρ - resistivity of wire L - wire length A - cross-sectional area
friction coefficient	$\mu = \frac{F_f}{F_n}$	F_f - force of friction between the moving parts of the generator $F_n F_n$normal force between the moving parts
magnetic pole pitch [m]	$p = \frac{\pi \cdot D}{N}$	D – diameter or rotator N – number of poles in stator
flux linkage of stator d winding due to flux produced by rotor magnets [Wb-turns]	$\lambda = B \cdot I \cdot N \cdot A$	B – magnetic flux density I – length of stator core N – number of turns in stator winding A – area of stator core
inductance of the coil [H]	$L = \frac{\mu \cdot N^2 \cdot A}{l}$	- permeability μ A – cross-sectional area l –coil length
load resistance [ohms]	$R = \frac{V}{I}$	V – voltage I - current

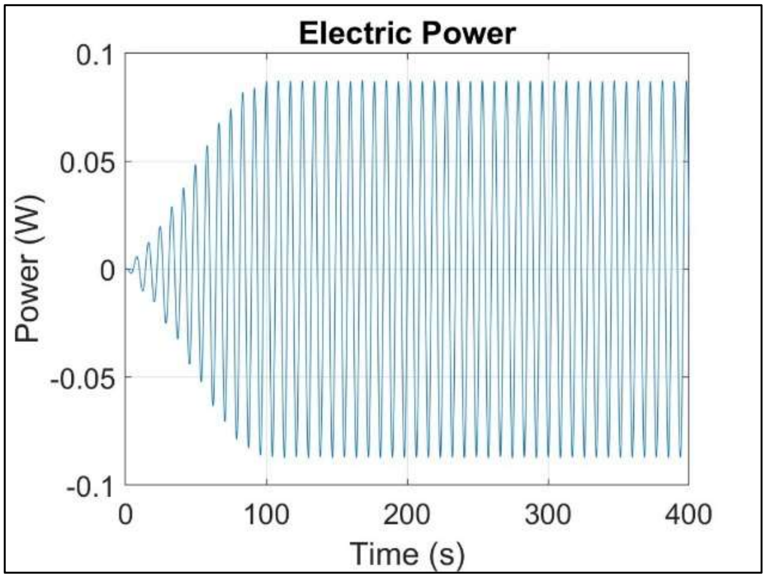
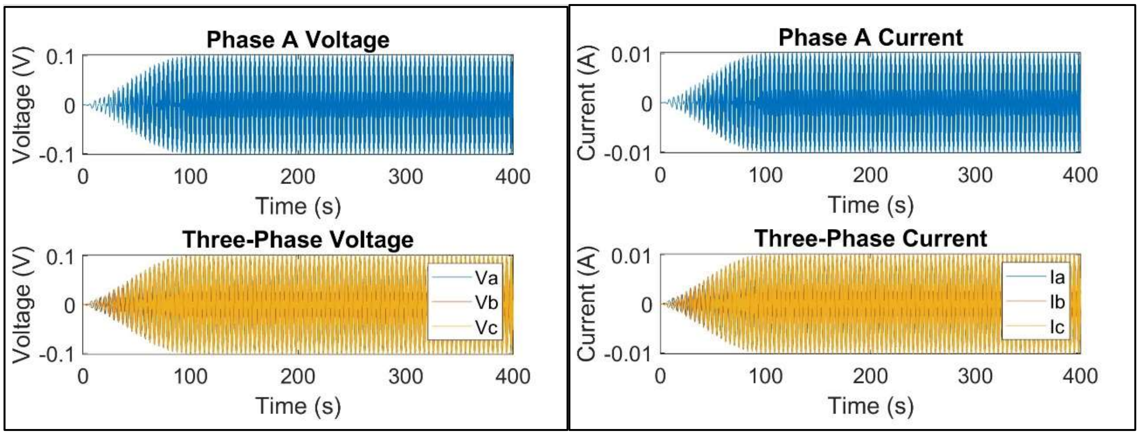


Figure 10: simulated power output via WEC-Sim



Figures 11 and 12: Simulated voltage and current outputs via WEC-Sim

Figures 11 and 12 show smaller than expected current voltage and power outputs. This is due to flawed input values for the PTO simulation. Despite these lower-than-expected results the oscillations of the power output match our 8.52 second wave period exactly. With improved PTO input values, we expect that our simulation can produce a feasible amount of power for our needs.

13.7 Heave Plate Dynamics

To maximize the efficiency of our WEC it is important to minimize the motion of the spar. A heave plate is used to create a drag force in the water below the spar which minimizes the vertical motion of the body. The stainless-steel heave plate also adds ballast, which lowers the spar's overall center of gravity and minimizes tipping motion. The vertical velocity of a wave can be found using the equation:

$$w = \frac{H}{2}\frac{gT}{L}\frac{\cosh\left[\frac{2\pi(z+h)}{L}\right]}{\cosh\left[\frac{2\pi h}{L}\right]} sin\theta$$

where H is wave height, T is wave period, L is wavelength, z is device depth, and h is water depth. As can be seen in Figure 13, the vertical wave velocity decreases as the water depth increases. This means that the farther down in the water column the heave plate is extended, the less overall motion the spar will have.

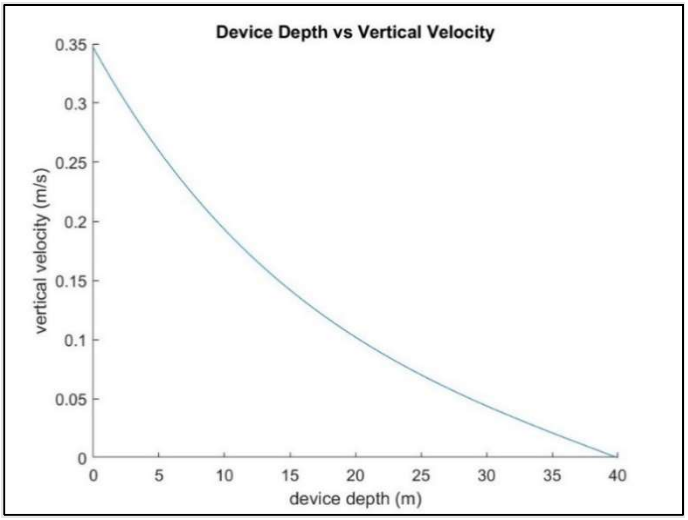


Figure 13: Vertical wave velocity as a function of water depth for the target location's (Rincon, PR) wave field.

In choosing the shape and size of the heave plate, it was important to maximize drag force. For this reason, a flat circular heave plate was chosen. This has a coefficient of drag of 1.17 in both heave directions. While other more complex shapes such as cones have larger drag coefficients in one direction, they will have smaller coefficients in the opposite directions (Hoerner, 1965). As any motion is discouraged in our design, a flat circular heave flat seemed most appropriate. In addition, this is easier and cheaper to manufacture. A large 1.5m diameter was chosen to increase the drag, however, the stainless-steel plate would only have a thickness of 0.0064 meters (¼ inch), to maintain a tolerable mass for the device. With this heave plate, the maximum tipping of SWEC in the chosen wave field and average wind forcing was calculated to be 2.33 degrees.

13.8 Mechanical Loads and Analysis

To ensure the durability of the WEC, a simple mechanical load analysis was done for its major components. This analysis was done by calculating load and impacts forces at critical failure points. The analysis of the spar was done by calculating the horizontal loads on the spar such as the wave and wind forces. The anchor and mooring line were calculated from the maximum horizontal wave and wind forces as well. The impact force for the buoy on the spar was then found. See Table 6 below for the results.

Table 6: Mechanical load analysis values

WEC Component	Material	Yield Strength	Maximum Calculated Stress	Factor of Safety
Spar	PVC Schedule 80	13.8 MPa	1.1 MSPa	12.5
Anchor	Galvanized 4130 Steel	435 MPa	4.6 MPa	92
Mooring Line	Galvanized 4130 Steel	18,900 N	4229 N	4.4
Buoy	Ionomer Foam	276 kPa	212 N	16.47

13.9 Power Performance

The power performance of SWEC was estimated by assuming 10% overall efficiency of the device and analyzing the available power of a chosen wave field. As discussed previously, Rincon, Puerto Rico was chosen as a target location for SWEC to be deployed and used.

The energy flux of a wave field is the rate of energy transfer through a unit area perpendicular to the direction of wave propagation. This equation is given by

$$\mathcal{F} = E \cdot Cg$$

where E is the wave energy per area given by

$$E = \frac{\rho g H^2}{8}$$

and Cg is the group celerity of the waves. When assuming deep water,

$$Cg = \frac{gT}{4\pi}$$

where T is the wave period, H is the significant wave height, ρ is the density of seawater, and g is the gravitational acceleration. The energy flux multiplied by SWEC's buoy diameter gives the available power for the WEC in the wave field. By multiplying the available power by efficiency, the maximum power output is calculated. After applying these equations to the SWEC in the averaged Puerto Rico wave field mentioned above, it was determined that the full-scale maximum power output for Swellular is 1053 watts. Since the radio system requires 10-250 watts, the SWEC will be more than able to produce the sufficient power needed. Despite this, the SWEC would be equipped with 2000Wh of battery storage again to allow it to operate for at least 8 hours if it could not generate any power from the wave field.

13.10 Mooring

The mooring configuration for this device would consist of one catenary mooring line attached to a surface buoy, which is secured to the SWEC's buoy using a cleat. This allows for easy deployment and retrieval of the device and is sufficient since SWEC is not intended to be deployed for long durations of time.

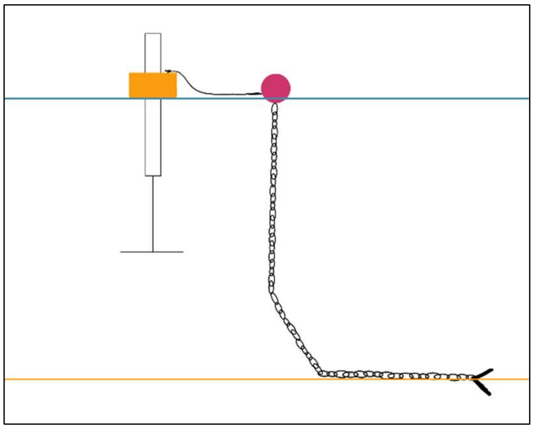


Figure 14: The mooring line would attach to an anchor that is dropped from the vessel during deployment.

The wave field in Puerto Rico was used to calculate the average horizontal wave forcing and drag force on the buoy and including a tolerance for average wind forces in the region, a 16lb Danforth Anchor with a holding strength of 1300lbs in sand could hold the system in place. However, it is logical to use a larger anchor than necessary in a mooring system because the cost difference is minimal, and the sea state can be unpredictable. A 70lb Danforth Anchor, with a holding strength of 3000lbs in sand, would be a safer option for this device and deployment location.

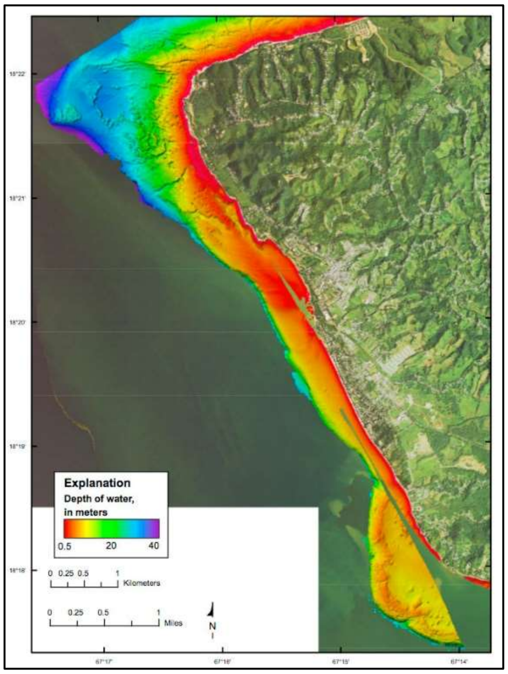


Figure 15: Bathymetry plot in Rincon, PR. Photo from U.S. Geological Survey Open-File 2007-1017 showing average depth of 12 meters at 0.5 miles offshore.

To minimize potential tension on the anchor, plenty of the mooring line must lie on the seafloor. A reasonable scope is 3:1 between the length of the mooring chain and the water depth of the deployment location. The water depth varies around Puerto Rico's coast, but an average water depth of 12 meters at 0.5 miles offshore would call for a mooring chain length of 36 meters.

13.11 Deployment and Storage

There are two main options for deployment, using a vessel of substantial size that is designed for ocean deployment, or utilizing a boat and inflatable raft to deploy the device. A vessel of substantial size that could be of use would be the *Hi'ialakai,* which is a NOAA vessel, that has been used to deploy buoys much larger than SWEC. The vessel travels at about 10 knots, so deployment would take ten hours from the dock departure to the buoy going off the stern. This method works great for areas that have access to boats like the *Hi'ialakai,* but in places where such vessels are not so easily available, one would use the boat and inflatable raft combination to deploy SWEC. The inflatable raft holding the SWEC would be towed behind a boat to the deployment location. Because it is inflatable, shipping would have significantly reduced costs. An inflatable boat that can sustain the SWEC would need to be around 16 feet in length. According to Defender (yacht broker), an inflatable around this size would cost around $4,000, and with its capacity of over 2000 pounds, it could sustain the SWEC. The boat required to tow the inflatable would not require more than 200 horsepower to reach 15 knots, so the deployment time would be similar, but much more cost effective with this combination. The heave plate and extension pole, mooring line and anchor, and radio antenna would be detached and kept on board during the towing process. Once at the deployment location, the crew members could easily reach the SWEC while it is on the raft to assemble the remaining components. They would attach the anchor line to the cleat atop the buoy, throw the anchor and chain overboard, thread on the heave plate and extension pole, and secure the antenna. Once that is done, the SWEC could be unhooked and slid off the raft by tipping it upwards. Due to its buoyancy characteristics, the SWEC would naturally assume the correct upright position in the water.

To ship the SWECs from their manufacturing location, likely in the US, to their deployment locations, shipping containers would be used to hold the devices. Four SWECs could fit inside an average 20 ft shipping container after disassembling the heave plate and extension pole from the spar. These containers could then be shipped to the Caribbean, or other locations, by sea or air. The SWECs would ideally be stored in the target locations, most likely in FEMA's Disaster Recovery Centers, prior to a natural disaster for quick deployment.

13.12 Optimization & Future Considerations

There are several future considerations that should be considered when trying to further optimize this design. This includes a more robust buoy and linear PTO design as well as the potential integration of an upgradeable transmitter and antenna, solar panels, and a control system. These changes will allow the device to generate more power and allow it to become more marketable and accessible.

As described in section 13.4 Performance Analysis, the buoy's amplitude response did not match the corresponding period of Puerto Rico's waves. Although this was experimented with, the team was unable to produce a more accurate result. To better optimize the power output of the design, the buoy would have to be redesign

One of the limitations of this design is that of the direct drive linear generator. The proposed design above includes a very simple geometry with a cylindrical translator and stator that uses permanent magnets. This was done as there was limited knowledge and expertise on the subject matter. If this were to be designed moving forward, a linear generator expert would be required to help maximize the efficiency. Some improvements that could be made would include more complex translator and stator geometries, electro-magnets, and more optimal materials.

Another improvement mentioned is to design a SWEC capable of supporting a cellular system in replacement of the ham radio. Currently, the public and private sectors of the communication sector are pushing for better cellular networks. Not only are they seeking faster speeds, but also more access. This drive will result in the expansion of cellular network capabilities and their ranges. When these have better range capabilities, Swellular will quickly upgrade their devices so that they can be outfitted to support cellular networks. Although ham radio on SWEC would remain crucial for first responders, creating a wave powered cell tower in addition to radio will grant access to the public as well.

It is likely that these cellular towers will require much more power than the current radio solution. As a result, it may be required to increase the full-scale model's size. This would require a total design change and adjustment to the financial, environmental, and deployment plans. One way to avoid this is that solar panels could be added to the SWEC to help generate additional needed power. These could be easy to install on the SWEC, with plenty of space around the frame that supports the antenna.

Lastly, an important consideration is design control. While the current team did not have the resources or knowledge to implement a control system in the SWEC, this would be vital for a full-scale design. An advanced control system has the potential to increase the energy absorbed by a SWEC by 200% (Coe, 2017). This is done by obtaining resonance for the incoming waves. Although there is limited expertise in this area, any control system can help the SWEC generate more power.

If these changes were able to be accurately implemented, it could significantly increase the absorbed energy by the SWEC and its communication potential.

14. Build and Test

14.1 Abstract

To better evaluate SWEC's design, a scale model was constructed and tested in the Chase Ocean Engineering Laboratory at the University of New Hampshire. The testing involved hydrostatic, durability, RAO, and power output in various wave states. Like the full-scale design, the scaled model was a point absorber consisting of two bodies: a buoy, and a spar. The buoy's heave motion around the neutrally buoyant, stationary, spar drives a direct drive linear generator. The generator consists of a magnet translator moving through a stator with copper coils. There was no communication system on the model, as this component would be outsourced, and it would be difficult to accurately scale.

14.2 Model Development

Using Froude scaling the model was constructed to be 1:3 to the full-scale design. Froude scaling was used to maintain the hydrodynamic properties between the prototype and the full-scale model. This also allows the wave field to be accurately scaled within the wave tank and for the model's performance to accurately represent the performance of the full-scale design within the waves. The 1:3 scale was chosen so that some repurposed parts of previous WECs such as a foam buoy and heave plate with an attached extension pole could be used in the model's development. This allowed the team to decrease the time of building the model and make the project more sustainable.

The following equation was used to scale the full-scale wave period to the tank testing wave period:

$$\frac{T_{full\,scale}}{T_{model}} = \left(\frac{d_{full\,scale}}{d_{model}}\right)^{\frac{1}{2}}$$

Where $d_{full\,scale}/d_{model}$ is equal to 3. The following two equations were also used to Froude scale dimensions with units' length and mass.

$$\frac{H_{full\,scale}}{H_{model}} = \left(\frac{d_{full\,scale}}{d_{model}}\right)$$

$$\frac{M_{full\,scale}}{M_{model}} = \left(\frac{d_{full\,scale}}{d_{model}}\right)^{3}$$

The total height and mass were Froude scaled to determine the accurate properties of the device. It was calculated that the model device should be 1.21 meters with a total mass of 5.90 kg.

14.3 Build

This model was next built as seen in Figure 16 with many repurposed parts such as the buoy and spar extension with heave plate.

The spar was made with 4in Schedule 40 PVC pipe, with both ends fitted with a threaded end cap. This allowed a watertight seal, yet still making the spar accessible. On one end of the spare, was the attached spar extension and heave plate. The other end was fitted with lightweight aluminum framing which would prevent the buoy from spinning and theoretically hold the antenna. The buoy that was used had a 0.32 meter outside diameter. This was then attached to lightweight aluminum framing which the translator was secured to. Inside the spar, ballast was placed to replicate the weight from the batteries. e mooring system was replicated using a small surface buoy and 35lb anchor.

Figure 16: 3:1 Scale model

The linear generator PTO system was created as well. Although difficult to Froude scale completely and accurately, the lengths were the primary variable used for scaling. The stator core was made of 3D-printed PLA plastic and the wrapped coils were made using 20 AWG coil wire. These were arranged to create a "Y" connection three-phase AC output. The three-phase AC current was designed to be converted into DC current using a 3-phase full wave rectifier. This, however, was not possible due to a series of administrational issues resulting in the delay and inability to order parts. This was then installed into the spar. See Figure 17 below for an image of the stator and windings.

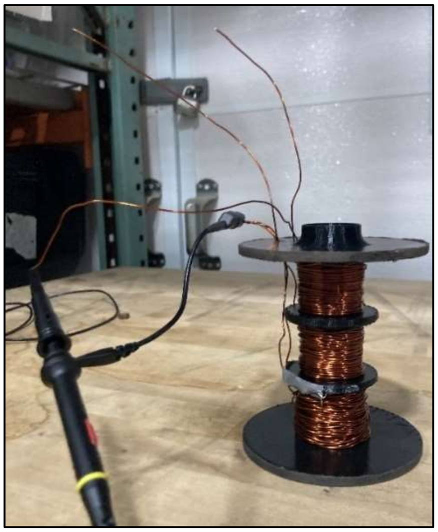


Figure 17: Scale model PTO stator

The follower buoy has an aluminum rack attached to which the magnet translator was secured. This was made from a thin Garolite tube. Like the full-scale design, magnets were inserted into this tube separated by steel spacers and oriented so their similar poles were facing one another. These were sealed using Nylon plugs and pins. During deployment, the relative motion of the buoy provides the forces which drive the translator through the PTO stator, which is fixed in the stationary spar.

14.4 Methods

Prior to any testing, the team worked with the MECC and testing facility staff to ensure that the proper safety measures were in place. This included a review and verification of safety standards as outlined in the Safety and Inspection Sheet.

14.4.1 Hydrostatic Testing

After constructing the model SWEC, testing was done to determine the accuracy of the expected performance. By calculating the center of gravity of the spar, and assuming hydrostatic conditions, the draft of the spar was determined. This waterline height was marked on the spar with a black line and the structure was placed into the Chase Laboratory's deep test tank as seen in Figure 18. The calculations were validated since the waterline was within 0.5 inches of the marked line on the spar.

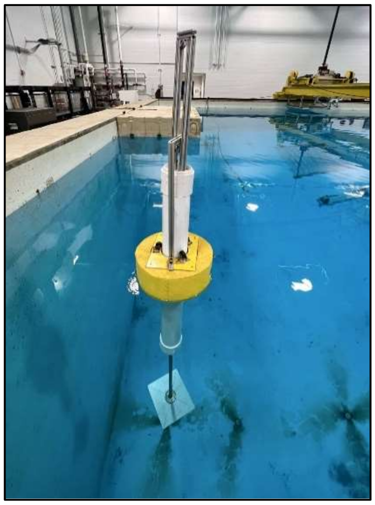


Figure 18: Scale model hydrostatic validations in the deep-water test tank.

After testing the hydrostatics of the model, the RAO and durability was tested in the Chase Laboratory's wave tank. On one face of the buoy, a black circular marking was drawn along with a matching marking on the spar directly above it. These two markings were captured in a video during testing and were later used in a pixel-tracking software, Kinovea, to determine the heave RAO of the device. After calibrating the software using the reference measurement and markings, it can calculate the buoy's distance, velocity, and acceleration.

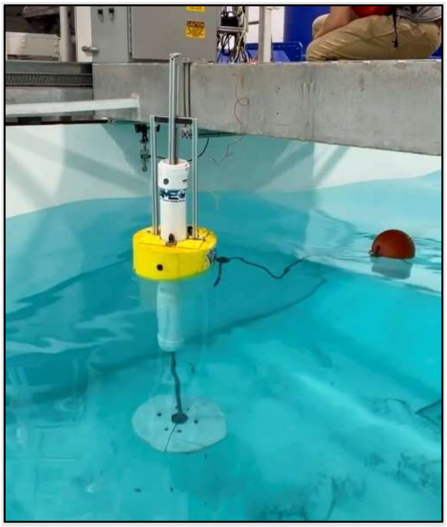


Figure 19: Scale model being tested in the UNH Wave Tank

The surface buoy was secured to the SWEC's buoy perpendicular to the circular markings. This orientation was done so that when the waves forced the buoy forward, the markings would face the side of the tank, and a camera could capture the markings during testing.

Seven different wave fields were tested on the SWEC model, and the wave parameters can be found in Table 7. A large wave field was tested to analyze the SWEC's durability and performance at maximum range. The wave tank restricted certain size waves due to its capability, so the various wave height and period combinations gave a variety of wave fields to analyze. The wave fields tested were chosen based on percentages of Puerto Rico's Froude-scaled wave field. Puerto Rico's full-scale wave field Froude scales to 37cm at 4.9 seconds.

Table 7: The wave fields generated in the UNH wave tank for SWEC model testing

			Wave Height (cm)	Wave Period (s)
Wave Field 1	25% Height	29% Period	9.3	1.4
Wave Field 2	100% Height	43% Period	37	2.1
Wave Field 3	100% Height	39% Period	18	1.9
Wave Field 4	75% Height	41% Period	28	2
Wave Field 5	100% Height	33% Period	37	1.6
Wave Field 6	25% Height	50% Period	9.3	2.5
Wave Field 7	50% Height	71% Period	18	3.5
Wave Field 8	100% Height	100% Period	37	4.9

14.4.2 Generator Calibration

Before power testing the generator was first calibrated to calculate its efficiency and understand its potential for power generation. This was done by comparing the calculated applied power into the generator and measuring out electrical output. The input power was found by measuring the acceleration of the translator while being displaced. To measure and record the electrical power generated an oscilloscope was used. See below for an image of the setup.

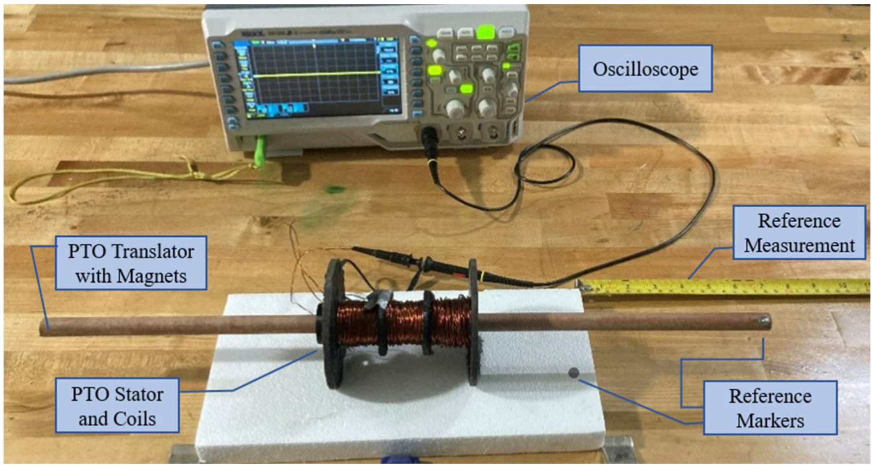


Figure 20: Calibration Test Setup

The stator was fixed with the translator remaining free to move. A reference measurement was placed in the background to provide a calibration length used for the Kinovea software. The generator output was attached to an oscilloscope which measured and recorded the voltage data. The translator was pushed once, and the data was recorded.

First, the acceleration of the translator was calculated, and this was then multiplied by the mass of the translator to find the applied force. By integrating the applied force with respect to the distance that the translator traveled, it was then possible to find the required work. Dividing this work value over the change in time of movement resulted in the power input into the system.

Since it was not possible to obtain a rectifier and the only available oscilloscope had one working channel, it was not possible to measure the three phases out at once. As a result, only one phase was measured and then the two others were replicated after applying an appropriate phase difference.

The peak voltage values between all three phases were then calculated and stored. The AC power could be calculated by assuming the peak current values equaled the peak voltage divided by the system's resistance.

$$P_{AC} = \frac{3V_{peak}I_{peak}}{2} = \frac{3\left(V_{peak}\right)^2}{2R}$$

Similarly, the DC power was calculated by making the same assumption that the peak current values were equal to the peak voltages divided by the resistance of the system. This can be seen in the equation below.

$$P_{DC} = \frac{3\sqrt{3}V_{peak}}{\pi} \cdot \frac{3\sqrt{3}I_{peak}}{\pi} = \frac{27\left(V_{peak}\right)^2}{\pi^2 R}$$

14.4.3 Performance Test

Now that the efficiency of the generator was calculated, it was reinstalled inside the SWEC. This then began the phase of measuring the power output in 8 different wave states as seen in Table 7 above. The model SWEC was deployed in the wave tank at the Chase Laboratory. The SWEC then was subjected to a variety of wave states. During each, the resulting electrical power output was recorded. Like the calibration, the DC power was calculated using the voltage data and the known resistance of the system. Each test was recorded via camera so that they could be analyzed with Kinovea as well.

14.5 Results

14.5.1 Heave Response Results

After testing the SWEC model in the various wave fields and recording the testing with a stabilized camera, Kinovea was used to produce the following figure.

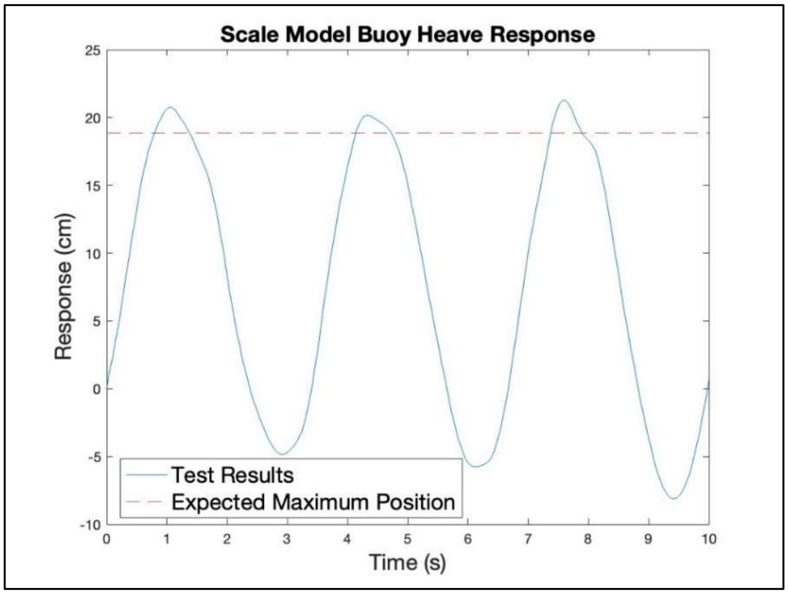


Figure 21: Kinovea produced model-scale displacement of the buoy relative to the spar in wave field 4.

Figure 21 represents the buoy's vertical displacement relative to the spar in wave field 4 (27 cm at 2s). As seen in the figure, the buoy had a maximum heave response of 27.27cm which is just 2.4cm greater than the maximum expected displacement of the buoy, which was calculated by scaling the expected heave response of the full-scale buoy in Puerto Rico's wave field. The testing result's closeness to the expected results validated the calculated hydrodynamics for SWEC. Wave Field 4 was analyzed in Kinovea because it produced the second-largest power output with the first being Wave Field 5.

14.5.2 Durability Test Results

The durability testing took place during wave field 5 with the 37cm waves at a 1.6 second period. Unfortunately, no data was able to be obtained in Kinovea due to the rapid movement of the buoy and slight spinning motion because of a shorter surface mooring line. Although data was not obtained, it was observed that the buoy did not tip very much or get damaged in any capacity, and the buoy moved the maximum range in this wave field.

14.5.2 Power Output Results

The calculated AC and DC power data from the calibration can be seen below. From the DC power, an average efficiency was found. This was done by calculating the average DC power and dividing by the calculated input power. This resulted in an efficiency of 50.6%

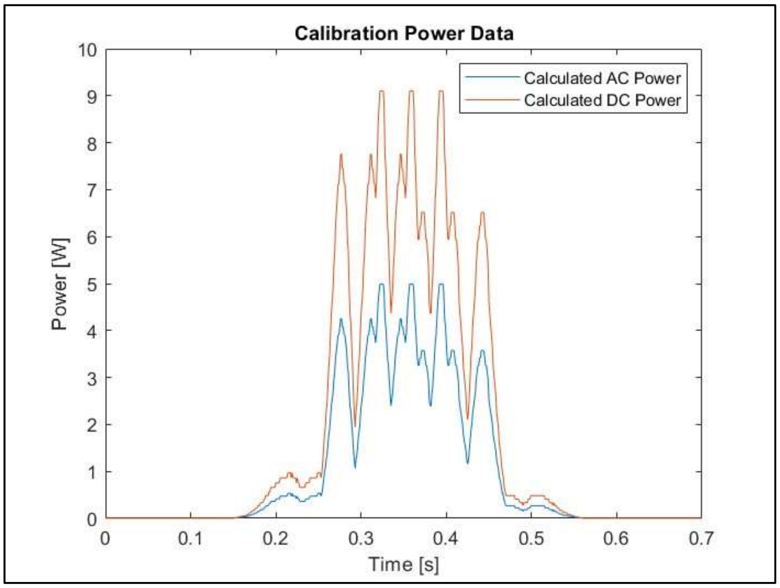


Figure 22: Calculated Calibration Power Output

A plot of the calculated DC power for one of the wave states during power testing can be seen below. This test gave the best performance with the maximum power output.

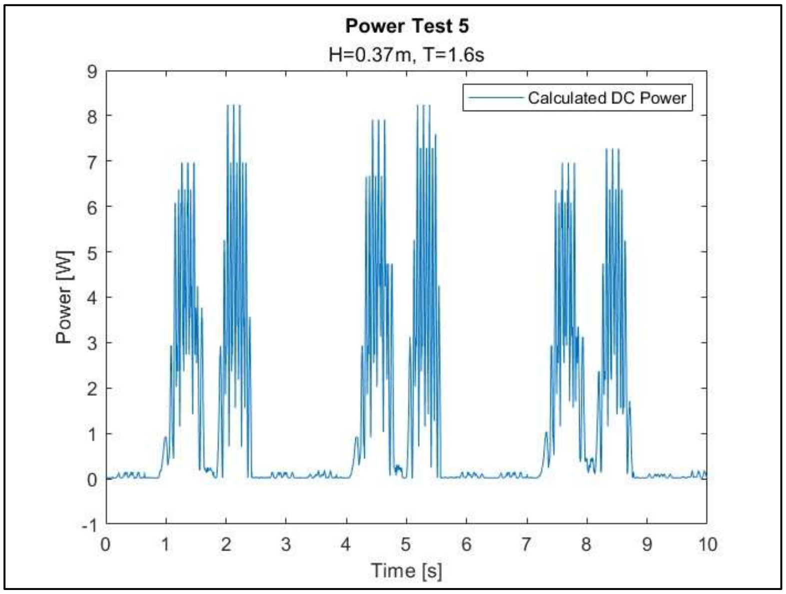


Figure 23: Calculated DC Power during Testing

The average DC power value was then calculated and plotted for each of the wave states in the power matrix below. Although the power matrix is not complete, it demonstrates the general dynamics of the system. Note that all values labeled as 0 were not tested.

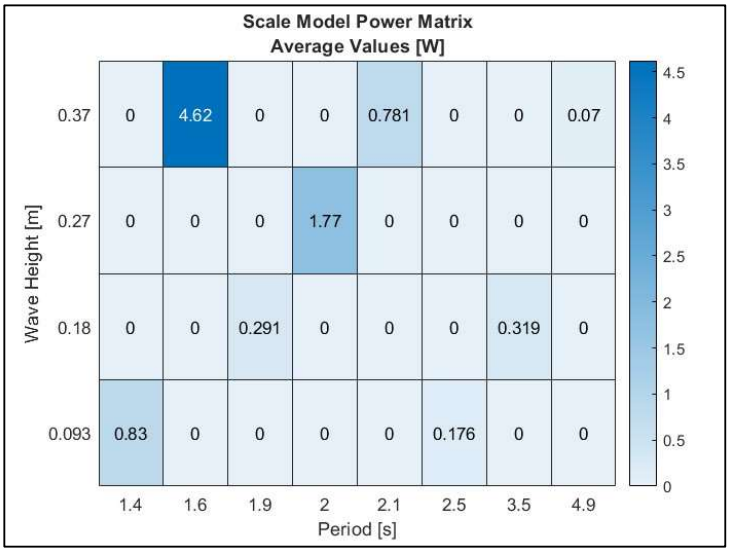
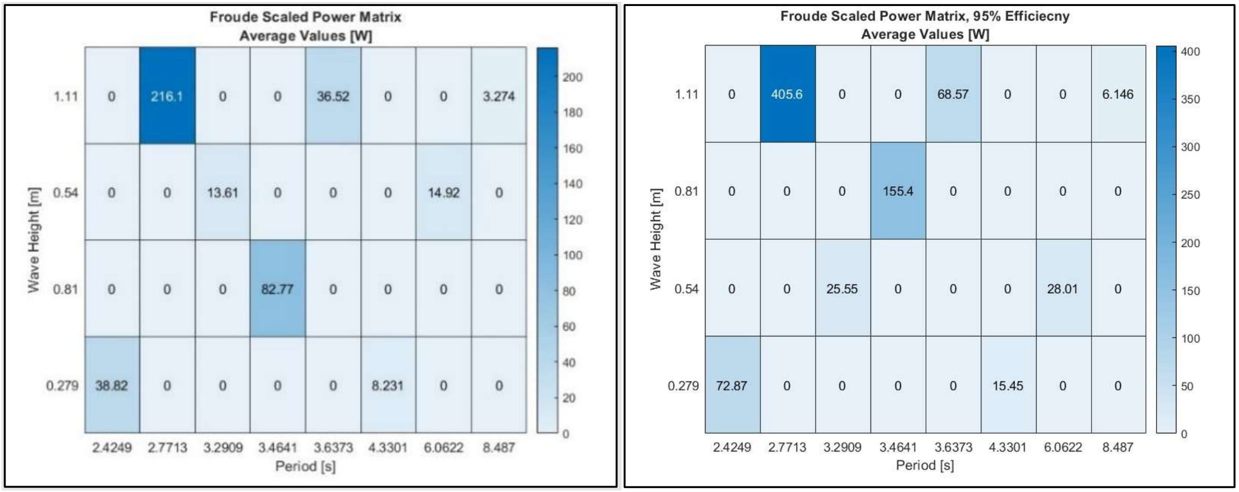


Figure 24: Calculated Average Power Matrix for Testing

To better compare this to a full-scale model, the values were all Froude scaled accordingly. This was done using the same efficiency of 50.6% and 95%, which would replicate the highest end commercial linear generator's capabilities. These can be seen below.



Figures 25 and 26: Calculated Average Power Matrix for Full Scale with Varying Efficiencies

Wave Field 8, which represents Puerto Rico's wave field after Froude scaling, produced the lowest power output. This output was unexpected and caused full-scale reconsiderations. The low power output can easily be explained since the longer wave period caused less drive of the generator. Considering the power output of a point absorber is a function of the buoy diameter and wave period, the simplest solution would be to create full-scale SWECs with variable buoy diameters depending on the average wave period of the deployment location. This solution would not affect any other components of the design since the SWEC is made up of two independent bodies and would have a negligible cost difference. Another solution as mentioned above would be incorporating an advanced control system for the PTO to improve power capture over a broader range of wave periods. This, however, would be beyond the scope of this build and test.

14.6 Conclusions

The general functionality of the linear direct drive PTO and the design of the SWEC were able to be validated.

First, the heave response was measured using Kinovea. The relative motion of the buoy to the spar closely matched the results that we anticipated for our full-scale model. The SWEC was able to be durability tested. It survived the most extreme wave field that the wave tank could generate, and it did not experience any damage, serious tipping, leakage, and still produced a significant power output.

A scaled version of the PTO system was designed and prototyped. Although it was not possible to obtain a 3-phase full wave rectifier, the full PTO power was calculated. By comparing the calculated input and output power of the PTO system, it was possible to calculate efficiency. This was estimated to be 50.6%. Note that this system was rapidly designed and prototyped. If fully scaled, this would be a component that would be outsourced, and this would result in much higher efficiencies.

With the PTO installed, it was then possible to then power test the SWEC in 8 different wave fields in the wave tank of the Chase Laboratory. When these power values were Froude scaled, we gathered a better understanding of how the full-scale SWEC would operate. Assuming that a more efficient generator was used it was calculated that this could generate at least an average of 405.8W of power. This, however, occurred at a different wave state than what it was designed for. Ideally, the maximum power generation would have occurred at a wave height of 0.37m and a period of 4.9s, however, it occurred at a wave height of 0.37m and a period of 1.6s.

14.7 Future Testing

If the team were to conduct a second round of experimental testing, it would also be a smaller model. This would be done as the wave states were largely limited by the facility's capabilities. By decreasing the size of the model, a greater variety of wave states would be possible to test. When the optimal power is reached at the correct state. The team would create a full-scale prototype and perform a durability test in the ocean. This could also give an opportunity to create a more complete power matrix.

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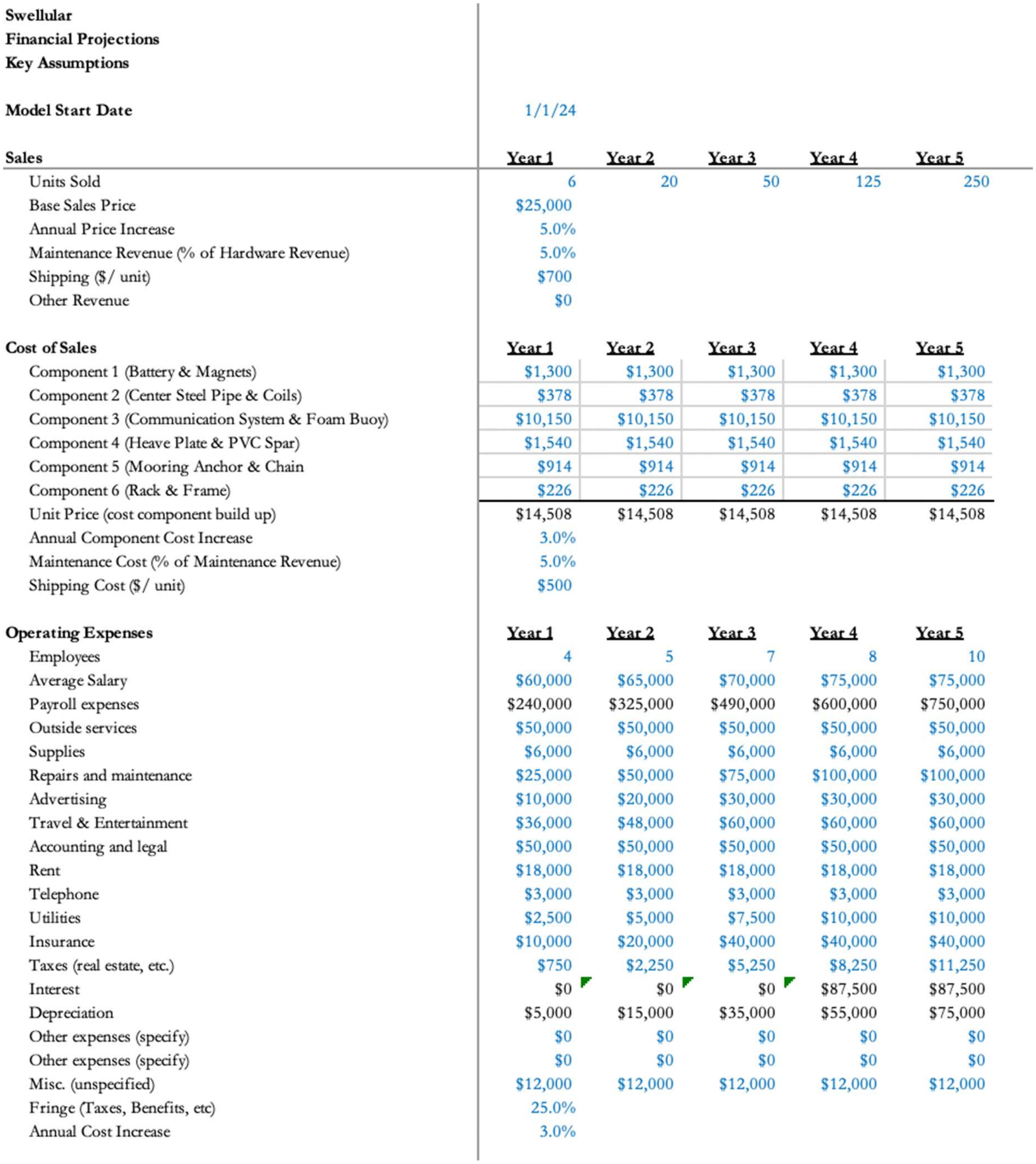
16 Appendix



Swellular
Financial Projections
Key Assumptions

Model Start Date 1/1/24

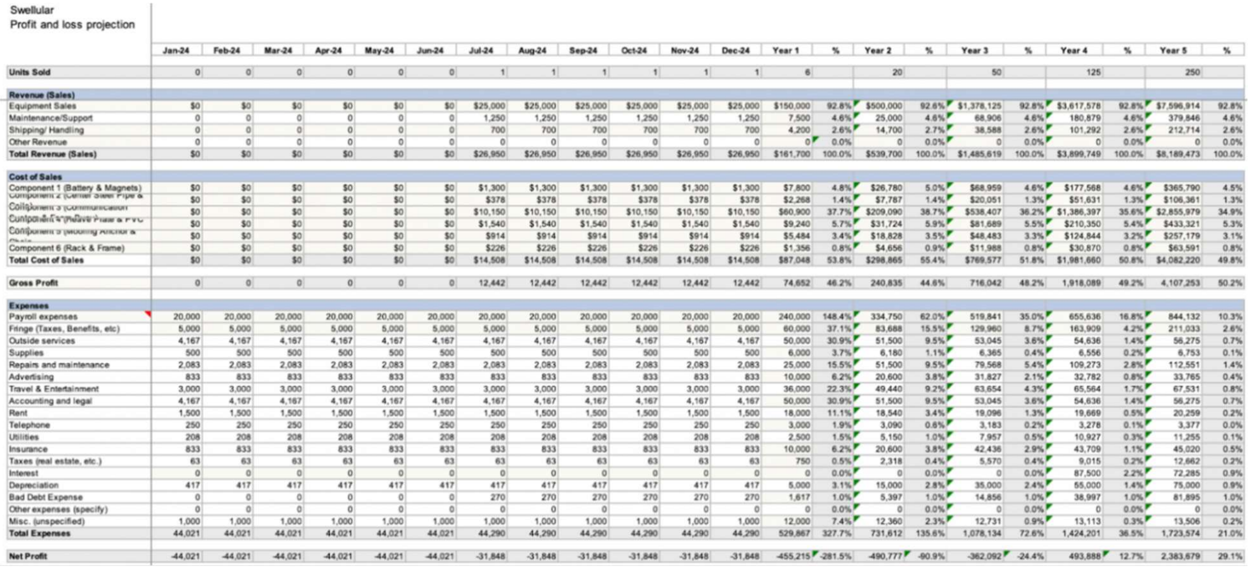
Sales	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**
Units Sold	6	20	50	125	250
Base Sales Price	$25,000				
Annual Price Increase	5.0%				
Maintenance Revenue (% of Hardware Revenue)	5.0%				
Shipping ($/ unit)	$700				
Other Revenue	$0				

Cost of Sales	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**
Component 1 (Battery & Magnets)	$1,300	$1,300	$1,300	$1,300	$1,300
Component 2 (Center Steel Pipe & Coils)	$378	$378	$378	$378	$378
Component 3 (Communication System & Foam Buoy)	$10,150	$10,150	$10,150	$10,150	$10,150
Component 4 (Heave Plate & PVC Spar)	$1,540	$1,540	$1,540	$1,540	$1,540
Component 5 (Mooring Anchor & Chain	$914	$914	$914	$914	$914
Component 6 (Rack & Frame)	$226	$226	$226	$226	$226
Unit Price (cost component build up)	$14,508	$14,508	$14,508	$14,508	$14,508
Annual Component Cost Increase	3.0%				
Maintenance Cost (% of Maintenance Revenue)	5.0%				
Shipping Cost ($/ unit)	$500				

Operating Expenses	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**
Employees	4	5	7	8	10
Average Salary	$60,000	$65,000	$70,000	$75,000	$75,000
Payroll expenses	$240,000	$325,000	$490,000	$600,000	$750,000
Outside services	$50,000	$50,000	$50,000	$50,000	$50,000
Supplies	$6,000	$6,000	$6,000	$6,000	$6,000
Repairs and maintenance	$25,000	$50,000	$75,000	$100,000	$100,000
Advertising	$10,000	$20,000	$30,000	$30,000	$30,000
Travel & Entertainment	$36,000	$48,000	$60,000	$60,000	$60,000
Accounting and legal	$50,000	$50,000	$50,000	$50,000	$50,000
Rent	$18,000	$18,000	$18,000	$18,000	$18,000
Telephone	$3,000	$3,000	$3,000	$3,000	$3,000
Utilities	$2,500	$5,000	$7,500	$10,000	$10,000
Insurance	$10,000	$20,000	$40,000	$40,000	$40,000
Taxes (real estate, etc.)	$750	$2,250	$5,250	$8,250	$11,250
Interest	$0	$0	$0	$87,500	$87,500
Depreciation	$5,000	$15,000	$35,000	$55,000	$75,000
Other expenses (specify)	$0	$0	$0	$0	$0
Other expenses (specify)	$0	$0	$0	$0	$0
Misc. (unspecified)	$12,000	$12,000	$12,000	$12,000	$12,000
Fringe (Taxes, Benefits, etc)	25.0%				
Annual Cost Increase	3.0%				

Capital Expenditures					
CapEx Item 1	$25,000	$0	$0	$0	$0
CapEx Item 2	$0	$50,000	$0	$0	$0
CapEx Item 3	$0	$0	$100,000	$0	$0
CapEx Item 4	$0	$0	$0	$100,000	$100,000
Total Capital Expenditures	$25,000	$50,000	$100,000	$100,000	$100,000
Depreciable Life (in years)	5.0				
Balance Sheet Items					
AR Outstanding (in days)	30				
AP Outstanding (in days)	30				
Inventory on hand (future unit sales in months)	4	months			
Bad Debt Assumption (% of Revenue)	1.0%				
Financing Assumptions					
Initital Funding (Opening Cash Balance)	$2,000				
Equity Funding	$700,000	$750,000	$1,000,000	$0	$0
Debt Funding	$0	$0	$0	$1,250,000	$0
Debt Interest Rate	7.0%				
Repayment Term (in years)	5.0				

Debt Repayment Profile	Year	Beg Bal	Interest	Principal	End Bal
	1	$0	$0	$0	$0
	2	$0	$0	$0	$0
	3	$0	$0	$0	$0
	4	$1,250,000	$87,500	$217,363	$1,032,637
	5	$1,032,637	$72,285	$232,579	$800,058
	6	$800,058	$56,004	$248,859	$551,199
	7	$551,199	$38,584	$266,279	$284,919
	8	$284,919	$19,944	$284,919	$0
	9	$0	$0	$0	$0
	10	$0	$0	$0	$0



Swellular
Profit and loss projection

	Jan-24	Feb-24	Mar-24	Apr-24	May-24	Jun-24	Jul-24	Aug-24	Sep-24	Oct-24	Nov-24	Dec-24	Year 1	%	Year 2	%	Year 3	%	Year 4	%	Year 5	%
Units Sold	0	0	0	0	0	0	1	1	1	1	1	1	6		20		50		125		250	
Revenue (Sales)																						
Equipment Sales	$0	$0	$0	$0	$0	$0	$25,000	$25,000	$25,000	$25,000	$25,000	$25,000	$150,000	92.8%	$500,000	92.6%	$1,378,125	92.8%	$3,617,578	92.8%	$7,596,914	92.8%
Maintenance/Support	0	0	0	0	0	0	1,250	1,250	1,250	1,250	1,250	1,250	7,500	4.6%	25,000	4.6%	68,906	4.6%	180,879	4.6%	379,846	4.6%
Shipping/ Handling	0	0	0	0	0	0	700	700	700	700	700	700	4,200	2.6%	14,700	2.7%	38,588	2.6%	101,292	2.6%	212,714	2.6%
Other Revenue	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%
Total Revenue (Sales)	$0	$0	$0	$0	$0	$0	$26,950	$26,950	$26,950	$26,950	$26,950	$26,950	$161,700	100.0%	$539,700	100.0%	$1,485,619	100.0%	$3,899,749	100.0%	$8,189,473	100.0%
Cost of Sales																						
Component 1 (Battery & Magnets)	$0	$0	$0	$0	$0	$0	$1,300	$1,300	$1,300	$1,300	$1,300	$1,300	$7,800	4.8%	$26,780	5.0%	$68,959	4.6%	$177,568	4.6%	$365,790	4.5%
Component 2 (Center Steel Pipe &	$0	$0	$0	$0	$0	$0	$378	$378	$378	$378	$378	$378	$2,268	1.4%	$7,787	1.4%	$20,051	1.3%	$51,631	1.3%	$106,361	1.3%
Component 3 (Communication	$0	$0	$0	$0	$0	$0	$10,150	$10,150	$10,150	$10,150	$10,150	$10,150	$60,900	37.7%	$209,090	38.7%	$538,407	36.2%	$1,386,397	35.6%	$2,855,979	34.9%
Component 4 (Heave Plate & PVC	$0	$0	$0	$0	$0	$0	$1,540	$1,540	$1,540	$1,540	$1,540	$1,540	$9,240	5.7%	$31,724	5.9%	$81,689	5.5%	$210,350	5.4%	$433,321	5.3%
Component 5 (Mooring Anchor &	$0	$0	$0	$0	$0	$0	$914	$914	$914	$914	$914	$914	$5,484	3.4%	$18,828	3.5%	$48,483	3.3%	$124,844	3.2%	$257,179	3.1%
Component 6 (Rack & Frame)	$0	$0	$0	$0	$0	$0	$226	$226	$226	$226	$226	$226	$1,356	0.8%	$4,656	0.9%	$11,988	0.8%	$30,870	0.8%	$63,591	0.8%
Total Cost of Sales	$0	$0	$0	$0	$0	$0	$14,508	$14,508	$14,508	$14,508	$14,508	$14,508	$87,048	53.8%	$298,865	55.4%	$769,577	51.8%	$1,981,660	50.8%	$4,082,220	49.8%
Gross Profit	0	0	0	0	0	0	12,442	12,442	12,442	12,442	12,442	12,442	74,652	46.2%	240,835	44.6%	716,042	48.2%	1,918,089	49.2%	4,107,253	50.2%
Expenses																						
Payroll expenses	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	240,000	148.4%	334,750	62.0%	519,841	35.0%	655,636	16.8%	844,132	10.3%
Fringe (Taxes, Benefits, etc)	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	60,000	37.1%	83,688	15.5%	129,960	8.7%	163,909	4.2%	211,033	2.6%
Outside services	4,167	4,167	4,167	4,167	4,167	4,167	4,167	4,167	4,167	4,167	4,167	4,167	50,000	30.9%	51,500	9.5%	53,045	3.6%	54,636	1.4%	56,275	0.7%
Supplies	500	500	500	500	500	500	500	500	500	500	500	500	6,000	3.7%	6,180	1.1%	6,365	0.4%	6,556	0.2%	6,753	0.1%
Repairs and maintenance	2,083	2,083	2,083	2,083	2,083	2,083	2,083	2,083	2,083	2,083	2,083	2,083	25,000	15.5%	51,500	9.5%	79,568	5.4%	109,273	2.8%	112,551	1.4%
Advertising	833	833	833	833	833	833	833	833	833	833	833	833	10,000	6.2%	20,600	3.8%	31,827	2.1%	32,782	0.8%	33,765	0.4%
Travel & Entertainment	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	36,000	22.3%	49,440	9.2%	63,654	4.3%	65,564	1.7%	67,531	0.8%
Accounting and legal	4,167	4,167	4,167	4,167	4,167	4,167	4,167	4,167	4,167	4,167	4,167	4,167	50,000	30.9%	51,500	9.5%	53,045	3.6%	54,636	1.4%	56,275	0.7%
Rent	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500	18,000	11.1%	18,540	3.4%	19,096	1.3%	19,669	0.5%	20,259	0.2%
Telephone	250	250	250	250	250	250	250	250	250	250	250	250	3,000	1.9%	3,090	0.6%	3,183	0.2%	3,278	0.1%	3,377	0.0%
Utilities	208	208	208	208	208	208	208	208	208	208	208	208	2,500	1.5%	5,150	1.0%	7,957	0.5%	10,927	0.3%	11,255	0.1%
Insurance	833	833	833	833	833	833	833	833	833	833	833	833	10,000	6.2%	20,600	3.8%	42,436	2.9%	43,709	1.1%	45,020	0.5%
Taxes (real estate, etc.)	63	63	63	63	63	63	63	63	63	63	63	63	750	0.5%	2,318	0.4%	5,570	0.4%	9,015	0.2%	12,662	0.2%
Interest	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0%	0	0.0%	0	0.0%	87,500	2.2%	72,285	0.9%
Depreciation	417	417	417	417	417	417	417	417	417	417	417	417	5,000	3.1%	15,000	2.8%	35,000	2.4%	55,000	1.4%	75,000	0.9%
Bad Debt Expense	0	0	0	0	0	0	270	270	270	270	270	270	1,617	1.0%	5,397	1.0%	14,856	1.0%	38,997	1.0%	81,895	1.0%
Other expenses (specify)	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0%	0	0.0%	0	0.0%	0	0.0%	0	0.0%
Misc. (unspecified)	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	12,000	7.4%	12,360	2.3%	12,731	0.9%	13,113	0.3%	13,506	0.2%
Total Expenses	44,021	44,021	44,021	44,021	44,021	44,021	44,290	44,290	44,290	44,290	44,290	44,290	529,867	327.7%	731,612	135.6%	1,078,134	72.6%	1,424,201	36.5%	1,723,574	21.0%
Net Profit	-44,021	-44,021	-44,021	-44,021	-44,021	-44,021	-31,848	-31,848	-31,848	-31,848	-31,848	-31,848	-455,215	-281.5%	-490,777	-90.9%	-362,092	-24.4%	493,888	12.7%	2,383,679	29.1%