ILLINOIS TECH
MINDS FOR MARINE ENERGY

2024 MECC Final Report

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Report portion	Word Count
Business Plan Challenge	7320
Technical Design Challenge	2779
Build and Test Challenge	3725

Table of Contents

Executive Summary

The usage of renewable energy sources has become more prevalent in recent years with the innovations made in the industry along with the transition of society's sentiment towards products that are environmentally friendly. This has allowed for multiple innovations in products that utilize solar and wind as their main resource for energy production. However, the innovations in wave energy technology has been few and far between with there being a stark contrast between the quantity of available products that utilize wave energy in comparison to other renewables on the market today. There are many reasons for this disparity, ranging from the geography of where wave energy can be utilized to the cost of developing a product that can contend with other forms of renewables that can be deployed on the ground. Our team believes that wave energy can become a contender in the market of renewables in terms of cost and utilization especially in the sectors that utilize microgrids. Multiple industries require copious amounts of water for their operations, these include but are not limited to: transportation of goods, process water, and industry specific uses (agriculture, offshore drilling etc.). This forces multiple industries to reside in areas in which there is access to sources to large amounts of water, placing them nearby lakes and rivers. These large bodies of water provide the water necessary for their operational needs and could also be utilized in order to transition these industries towards renewables, more specifically towards the usage of wave energy as a form of renewable energy. Transition towards renewables does not just seem practical but feasible as well as a certainty for a lot of these industries. Industrial manufacturers such as steel manufacturers are looking to move away from their usage of nonrenewable sources that not only prove to be dangerous to the environment and the public health of the resident living nearby, but will most likely have to stifle the usage of their nonrenewable systems so that they may comply with legislation that aims to protect the environment (e.g Biden’s Green New Deal). In this transition to renewables, we aim to develop a product that can meet the energy needs of these industries as they transition towards renewables as well as provide greater efficiency and reliability compared to other renewables that are currently on the market.

There are currently two renewable sources that dominate the renewable energy market. Solar and wind are the main focus of renewable energy products out in the market today. As most energy corporation’s renewable portfolios contain products for solar and wind. Solar and wind have multiple benefits as renewables and the ability to install solar or wind based products on land (solar and wind farms) and potentially on water as well (solar powered boats and offshore wind farms). However, we believe that the limitations of these types of renewables outweigh the potential benefit to be gained from these products. Solar and wind are easily forcastable, but they are not consistent in supplying a continuous source of energy. The energy that is produced from these sources are from processes that are recurring but not perpetual (unless deployed in certain areas of the world). It is due to this that solar and wind cannot provide energy during the down periods in which no energy can be generated. Another major problem for these renewables is that in order to generate a sufficient amount of energy for the current demand these products would require installations within large amounts of space. These installations require large capital expenditures and ruin the aesthetic of a natural setting. These are major concerns if solar and wind energy are to be used for emergency or industrial purposes. Our product aims to resolve these inefficiencies through the usage of wave energy.

The product will capture the kinetic energy of the wave and transform it to electrical energy for utilization by the consumers. Doing so will provide us with the benefits mentioned above as waves and wave generation do not have refractory periods allowing for constant energy generation as long as the product remains operational. The product will have to be installed within large quantities of water where wave generation is possible but this provides the benefit of the product needing not be on land. With most industries being strictly land based, transitioning away from solar and wind and towards wave energy will allow for more space that can be utilized towards the global economy's most important industries and/or the conservation of natural land. These benefits that our product will provide to consumers will set a precedent for the foreseeable future of renewables. Phasing out land based products for more efficient and reliable sources of energy.

With the introduction of our product, the area of service that we believe our product will be most useful within the microgrid space. Microgrids are electrical grids that are controlled by a singular entity, one that aims to provide energy to itself. Our team believes that this area will be the best space to introduce our product; as the implementation of microgrids increases with industries attempting to meet the restrictions from new legislation. The benefits of microgrids are twofold. One benefit is that they are allowed to power a system in the event of a failure to connect to the main grid. Allowing provisional power to the entity controlling the microgrid in the event there is disconnection from the main grid. Paired with the consistency of wave energy there will be a continuous production of energy for the consumer even in the event of an emergency. A second benefit is the introduction to remote locations. There are many innovations in land locked countries in the energy distribution field limiting the product away from those. For water locked areas like islands where coastal waves are abundant our product can act as an energy generator for these locations. Allowing these areas ample amounts of energy in order to grow their economies or meet the energy needs of the residents living in these locations.

Our product will provide renewable energy that is competitive with the renewables products on the market currently. It has lower material and installation costs and provides much more energy per square foot compared to our competitors. With the world being 70% water we have the means of scalability to meet the needs of any of our consumers that wish to utilize our product. We will set a new precedent for renewable energy that will force renewable energy products to guarantee the efficiency, reliability and accessibility that our product provides as we continue to push for a completely green world.

I. Business Plan Challenge

A. Motivation and Background

Wave energy is a form of renewable energy that harnesses the kinetic energy generated by the natural motion of ocean waves. Devices like wave energy converters capture this energy and convert it into electricity, offering a sustainable and clean alternative to traditional fossil fuels. Wave energy has the potential to contribute significantly to global energy needs while reducing carbon emissions and dependence on finite resources, making it a promising solution for a more sustainable future. Wave energy has many advantages including:

1. **Consistent Energy Generation**: Waves are generated by wind patterns and are relatively consistent compared to wind and solar energy, which can be intermittent. This consistency provides a more stable and reliable source of energy production, enhancing grid stability and reducing the need for backup power.
2. **High Energy Density**: The energy density of waves is much higher than that of wind or solar energy. Waves carry a significant amount of energy, especially in coastal regions with strong wave activity, allowing for potentially higher power output per unit area of wave energy converters.
3. **Predictability**: Wave energy is highly predictable, as it is primarily driven by wind patterns and weather conditions. Advanced forecasting techniques can accurately predict wave characteristics and energy production, enabling better grid management and energy planning.
4. **Low Visual Impact**: Wave energy converters can be located offshore and are often submerged or partially submerged, minimizing their visual impact compared to wind turbines or solar panels. This makes wave energy a more aesthetically pleasing option for coastal communities and reduces potential conflicts over land use.
5. **Longer Lifespan**: Wave energy converters are generally designed to withstand harsh marine environments and have a longer operational lifespan compared to some renewable energy technologies. With proper maintenance, they can continue to generate electricity for decades, providing a stable long-term energy solution.

While these factors make wave energy attractive, it also has some challenges, namely:

1. **High Initial Costs**: The upfront capital costs of installing wave energy infrastructure, including wave energy converters and associated infrastructure, can be substantial. This high initial investment may pose a barrier to the widespread adoption of wave energy, especially compared to more mature renewable energy technologies like wind and solar.
2. **Technological Challenges**: Wave energy conversion technologies are still relatively nascent compared to other renewable energy solutions, leading to ongoing technological challenges and uncertainties. Designing efficient and

reliable wave energy converters that can withstand harsh marine conditions remains a significant hurdle for developers.

3. **Environmental Impact**: While wave energy has a lower environmental impact compared to fossil fuels, it can still have ecological consequences. Installation and operation of wave energy converters may disrupt marine ecosystems, affecting marine life habitats, migration patterns, and feeding grounds. Careful environmental assessment and mitigation measures are necessary to minimize these impacts.
4. **Limited Location Suitability**: Wave energy generation is feasible primarily in coastal regions with strong wave activity, limiting its geographical applicability. Areas with low wave energy potential may not be suitable for wave energy projects, reducing the overall availability of this renewable energy source.
5. **Interference with Navigation and Fishing**: Offshore wave energy installations may interfere with maritime activities such as navigation and fishing. Placement of wave energy converters in shipping lanes or fishing grounds could lead to conflicts with other marine users and stakeholders, requiring careful planning and coordination.

B. Concept Overview

In initial evaluations a number of different devices were investigated including oscillating water columns, attenuators, overtopping devices and point absorbers. The team found that point absorbers were an attractive option due to their simple design, potential for high energy extraction and low cost construction. In particular, the team’s design was inspired by the following two device structures.

Wave Energy Point Absorbers with Electromagnetic Generators (EMG)

Design Feasibility: EMG-based point absorbers typically consist of buoyant structures connected to linear generators that convert the mechanical motion of waves into electricity. These generators often utilize magnetic fields and coils to induce voltage and current in response to wave-induced motion. EMG-based point absorbers have been extensively researched and developed, with several prototypes and commercial-scale installations deployed worldwide. The technology has a relatively high level of maturity, with established design principles and engineering methodologies.

Predicted Energy Data: The energy output of EMG-based point absorbers depends on factors such as wave climate, device geometry, generator efficiency, and electrical conversion efficiency. Predicted energy data can be estimated through numerical simulations, wave tank experiments, and field trials. Studies have shown that EMG-based point absorbers have the potential to capture a significant amount of wave energy, especially in regions with favorable wave conditions. However, actual energy output may vary depending on site-specific factors and operational performance.

Wave Energy Point Absorbers with TriboElectric NanoGenerators (TENG)

Design Feasibility: TENG-based point absorbers utilize the triboelectric effect to generate electricity from the relative motion between different materials. These devices typically incorporate flexible structures or membranes that deform in response to wave action, leading to the separation and contact of triboelectric materials and the generation of electric charge. TENG-based point absorbers are a relatively novel and emerging technology, with ongoing research focused on materials development, device optimization, and integration into wave energy converters. Design feasibility depends on advancements in materials science, nanotechnology, and device engineering.

Predicted Energy Data: Predicting the energy output of TENG-based point absorbers is challenging due to the complexity of the triboelectric effect and the nonlinear behavior of TENG devices. The energy output depends on various factors such as device geometry, material properties, contact area, and wave-induced motion. Computational modeling, experimental testing, and theoretical analysis are used to estimate the energy generation potential of TENG-based point absorbers. While early studies have demonstrated promising results in laboratory settings, further research is needed to validate performance under real-world wave conditions.

In summary, while both EMG and TENG-based point absorbers have the potential to convert wave energy into electricity, EMG-based devices are currently more mature and widely studied, whereas TENG-based devices offer promise but require further research and development to realize their full potential. The choice between the two would depend on factors such as project objectives, technology readiness, and resource availability.

Point Absorber vs. other wave energy models

Determining which wave energy solution would have the lowest levelized cost of energy (LCOE), the least capital barrier to entry, and provide the most energy flux depends on various factors including technology maturity, site-specific conditions, and project scale. However, the team found some general insights based on current trends and characteristics of each wave energy technology:

1. **Least Levelized Cost of Energy (LCOE)**: Point absorbers have been one of the most researched and developed wave energy converter (WEC) types. They typically consist of floating buoys or structures that move with the motion of waves, driving a generator to produce electricity. Point absorbers can be relatively efficient in converting wave energy into electricity, especially in moderate wave climates. While their LCOE is attractive compared to other WEC options, their LCOE may still be relatively high compared to other renewable energy sources due to factors such as device complexity, maintenance requirements, and initial capital costs.
2. **Least Capital Barrier to Entry:** Oscillating water column (OWC) devices are relatively simple in design compared to other wave energy converter types. They consist of a partially submerged chamber with an opening to the sea, where waves enter and exit,

causing the water level inside the chamber to rise and fall. This oscillating motion drives air in and out of the chamber, powering a turbine or generator to produce electricity. OWC devices can be less capital-intensive to build and deploy compared to some other wave energy solutions, making them potentially more accessible to developers and investors.

3. **Most Energy Flux:** Attenuators are long, multi-segment structures that stretch perpendicular to the direction of wave propagation. As waves pass along these structures, they cause them to flex or oscillate, generating electricity through hydraulic systems or other mechanisms. Attenuators can potentially capture a significant amount of wave energy flux due to their large surface area and the ability to intercept multiple wave crests simultaneously. However, the actual energy flux captured depends on factors such as device design, wave climate, and site-specific conditions.

In summary, while each wave energy solution has its own advantages and challenges, oscillating columns may have the least capital barrier to entry due to their relatively simple design, while attenuators could potentially capture the most energy flux. However, it's essential to consider various factors, including technological readiness, resource availability, project location, and economic feasibility when determining the most suitable wave energy solution for a particular application. Additionally, ongoing research and development efforts aim to improve the performance and cost-effectiveness of all wave energy converter types, which could influence their relative competitiveness in the future.

An analysis comparing different wave energy technologies suggests that point absorbers, characterized by their floating buoy or structure design, could offer a more favorable investment outlook in terms of achieving a lower levelized cost of energy (LCOE). Despite their complexity and initial capital costs, point absorbers have undergone extensive research and development, showcasing efficiency in diverse wave scenarios. Conversely, while oscillating columns may present a lower capital barrier to entry due to their simpler design, attenuators exhibit potential for capturing the highest energy flux. Nevertheless, the choice among these technologies are still quite young depending on various factors such as technological maturity, site conditions, and project scale. As ongoing advancements aim to enhance the performance and cost-effectiveness of wave energy converters, the landscape of investment opportunities in this sector continues to evolve.

C. Process Overview

Designing, simulating, financing, and building a prototype of a wave energy converter (WEC) is a complex and multidisciplinary process that requires careful planning, collaboration, and execution. Here is a general outline of the steps the team took (Steps 1-4) and plans to take (Steps 5-6) to accomplish this:

1. **Conceptual Design and Feasibility Study**:
    - Conduct a thorough literature review to understand existing wave energy converter technologies, design principles, and performance characteristics.

   - Define project objectives, target performance metrics, and constraints (e.g., budget, timeline, resource availability).
   - Develop conceptual designs for the wave energy converter based on the team's expertise, available resources, and desired outcomes.
   - Perform initial feasibility analysis to assess the technical, economic, and environmental viability of the proposed WEC design.
2. **Numerical Modeling and Simulation**:
   - Utilize computational tools and software (e.g., MATLAB, ANSYS, OpenFOAM) to model and simulate the hydrodynamic behavior of the WEC design.
   - Optimize the WEC design parameters (e.g., geometry, materials, control systems) based on simulation results to maximize energy capture efficiency and minimize structural loads.
3. **Prototype Development**:
   - Translate the optimized WEC design into a physical prototype for testing and validation.
   - Source materials, components, and manufacturing services required for building the prototype.
   - Establish a prototyping facility and collaborate with external partners (e.g., fabrication shops, research laboratories) to manufacture the prototype components.
   - Assemble and integrate the prototype components according to the design specifications, ensuring proper functionality and safety measures are incorporated.
4. **Testing and Validation**:
   - Conduct a series of laboratory-scale tests and experiments to evaluate the performance and functionality of the prototype under controlled conditions.
   - Measure key performance parameters such as power output, wave energy absorption efficiency, and structural integrity.
   - Collect experimental data and analyze the results to validate the numerical models and assess the prototype's compliance with design requirements.
   - Iterate on the design based on test results and feedback to address any deficiencies or optimization opportunities.
5. **Financial Planning and Fundraising**:
   - Develop a detailed budget for the entire project, including expenses related to design, simulation, prototyping, testing, and project management.
   - Identify potential sources of funding and financial support for the project, such as research grants, sponsorships, crowdfunding, or institutional funding.
   - Prepare grant proposals, sponsorship packages, or fundraising campaigns to secure the necessary financial resources for the project.
   - Establish partnerships with industry stakeholders, government agencies, or philanthropic organizations to leverage additional funding opportunities and resources.

6. **Construction and Deployment**:
    - Once the prototype design has been validated and sufficient funding secured, proceed with final construction and assembly of the prototype.
    - Conduct rigorous quality assurance and safety checks to ensure compliance with relevant regulations and standards.
    - Plan and coordinate logistics for transporting the prototype to the testing site or deployment location, considering factors such as transportation, installation, and commissioning.
    - Deploy the prototype in a suitable marine environment or wave tank facility for field testing and performance evaluation, monitoring its operation and collecting data over an extended period.

Throughout the entire process, effective project management, communication, and collaboration among team members are essential to ensure project success. Additionally, engaging with relevant stakeholders, including industry partners, regulatory authorities, and local communities, can help address challenges, mitigate risks, and maximize the impact of the project.

D. Relevant Stakeholders

Steel Manufacturing

The team originally wanted to implement our product in the steel industry specifically supplying energy to steel mills either through the use of a microgrid or through product implementation with the mill's energy provider. Steel mills provided multiple advantages in our initial search for a viable market to introduce our product to the market. The advantages were described in greater detail in the midyear report but a concise list of the advantages are as follows:

- Large amounts of process water needed forces mills to be located near large bodies of water.
- 60% of steel produced is localized in the Great Lakes Area which are the perfect conditions for the team's product.
- Mills are attempting to transition away from coal usage and utilizing renewable sources for their processing.
- Recent legislation aims to curtail the emissions produced by mills unless they can meet emissions requirements in these new legislations (example: Biden's Green New Deal).
- Grids providing energy to these mills have yet to pursue wave energy in their renewables portfolio. Thus, there is an extra market potential through the distributors as well.

The biggest drawpoint to steel was regulations forcing steel and steel production to transition towards renewables. Since this concern has only been addressed fairly recently with public concerns over climate change taking top priority, it is likely that our product will have market introduction at the same time the steel industry would be forced to transition towards renewables. This would provide many benefits to both parties. For steel mills they would be able to cut down their emissions even drastically if the steel mill operated an Electric Arc Furnace (EAF). This judgment was made using data from the Worldsteel Organization stating that of mills that operated an EAF, 38% of the mills energy usage came directly from natural gas generators, which aside from electricity makes up the bulk of the energy usage within these mills. The team believed that if the new legislation manages to get passed and holds, mills would have to quickly transition to renewables. As they do so our product will have its introduction to the market. With our product able to outcompete wind and solar energy, steel mills transitioning to renewables will be able to see the advantages that wave energy will be able to provide them, especially due to their proximity to large bodies of water.

Microgrids

Microgrids can be defined as electric grids that are regionally controlled and possess the ability to disconnect from the main grid which allows them to function independently throughout a multitude of situations, including grid failures*.* The industry has brought about several benefits including a positive environmental impact due to the reduced reliance on fossil fuels for power, lessening greenhouse gas emissions. Being located in Chicago, it was no doubt there was a tremendous presence of microgrids being utilized. In fact, our own campus of Illinois Institute of Technology uses a microgrid that includes smart metering and a number of renewable energy sources in an effort to improve resilience, overall efficiency, and demand response. We have a number of buildings that have solar panels, wind turbines, and charging stations for electric vehicles - a hub for our microgrid's renewable power. There are developments making use of layers of management where operators oversee the paths of power. This shines the light on how the microgrid can receive power from a wave energy converter.

Potential Other Markets

While the team decided that microgrids would be our primary area of focus, we have explored other areas of interest. These other markets that we were looking into had areas in which we believed that could benefit from our product. However, they were not given a lot of consideration because we had found early on in the research process that these markets had issues that we would not be able to tackle until the product entered the consumer market. It does not deter us from exploring them later in the future but will only be outlined for the time being below.

1. **Municipal and Government Entities**:

Municipal and government entities in Chicago have a vested interest in promoting renewable energy and reducing carbon emissions to meet sustainability goals and combat climate change. Implementing wave energy projects aligns with these objectives, offering a clean and reliable energy source. Additionally, municipal and government facilities, such as water treatment plants or recreational facilities along the lakefront, could benefit from locally generated wave energy to power their operations, potentially reducing energy costs and reliance on the grid.

2. **Utilities and Energy Providers**:

Utilities and energy providers operating in the Chicago area are increasingly seeking to diversify their energy portfolios and incorporate more renewable energy sources. Wave energy presents an opportunity for these entities to expand their renewable energy offerings and enhance grid resilience. By investing in wave energy projects, utilities can tap into the consistent energy generation potential of Lake Michigan's waves, contributing to a more sustainable and reliable energy supply for the region.

3. **Commercial and Industrial Sectors**:

Commercial and industrial sectors in Chicago, including manufacturing facilities, data centers, and commercial buildings, have substantial energy demands. Implementing wave energy solutions can help these entities meet their sustainability targets while potentially reducing energy costs and enhancing energy security. By integrating wave energy into their energy mix, businesses can demonstrate environmental leadership, attract environmentally conscious customers, and differentiate themselves in the market.

4. **Research and Academic Institutions**:

Chicago is home to several research institutions, universities, and academic centers with expertise in energy, engineering, and environmental sciences. These institutions can serve as key stakeholders and partners in the development, research, and testing of wave energy technologies. By collaborating with industry partners and government agencies, research institutions can contribute to advancements in wave energy technology and drive innovation in the renewable energy sector. Additionally, implementing wave energy projects on university campuses or research facilities can serve as living laboratories for studying the environmental, economic, and social impacts of wave energy deployment.

E. Market Opportunity

Each market identified in the previous section was investigated. The team upon further research found that steel mills were in fact downsizing and moving operations away from large bodies of water. Legislations that would directly affect mills seem to have a much more adverse effect on these mills where the mills are downsizing instead of switching to renewable energy. Forcing steel mills to shut down and discontinue production. This downsizing of the market heavily impedes the range in which we can introduce our product if we focus primarily on steel.

The team also attempted to communicate with these mills and large mill corporations. The team hoped that by establishing communication we would be able to gain a better understanding of the energy needs of a mill and to see if our product would be a good fit to introduce into their energy systems. However, even after exhausting every mill/ corporation that we could find in the Great Lakes area we were unable to establish communication with any of the sources that we had contacted. The team ran into a problem of not having a response back or the respondents unable to answer questions about the mill's energy needs and were unable to redirect to a source that could provide our answers. Thus, the team decided that it would be best to broaden our scope in terms of market opportunity and have decided to transition to establishing our product in the microgrid space.

The team held interviews with MISO, or Midcontinent Independent System Operator, which is an independent, non-profit organization that focuses on managing the flow of high-voltage electricity across a significant portion of the United States that ranges between 15 states and Manitoba, Canada. A meeting with the executive vice president of MISO proved to be greatly insightful. It was described that markets looked to apply solar and wind renewable power as their first choice, however, in regards to reliability, wave energy soars above the two:

- Wind: 15% reliable capacity with 2.2 MW per windmill which takes at least 40 acres
- Solar: 50% reliable capacity with 1 MW per solar array and requires 8 acres. It is economically feasible with high efficiency rates

- Wave: 100% reliable capacity where triboelectric nanogenerator (TENG) and distributed embedded energy converter technologies (DEEC) are proven to be optimal models for low energy flux wave environments

It is to be noted from the MISO interview that there is no present industry that is significantly implementing and developing WECs but it remains an important consideration for many. The application of WECs may not be implemented to large water systems; however there has been an abundance of studies that have successfully transferred their microgrids to wave energy and continue to thrive off of them.

There are a multitude of coastal communities that have experimented with microgrids being powered from wave energy converters. For example, a remote community located in Igiugig, Alaska conducted a trial where a marine microgrid displaced diesel power for a short period of time. The study consisted of two Ocean Renewable Power Co 35-kW marine generators that were connected to river and tidal currents which worked with Schneider Electric's energy storage and microgrid system. Another study was conducted at Massachusetts Institute of Technology where marine energy is being tested on the island of Cuttyhunk. The goal is to gradually replace diesel generators as well as compete with solar and wind renewable sources. Because wind and solar energy does not consistently provide energy around the clock, it is important to realize the potential of WEC filling the gaps that those sources cannot provide. Overall, WEC connecting to microgrids is the next step to become more cost effective, environmentally friendly, and power efficient.

Municipal and government entities, utilities and energy providers, commercial and industrial sectors, and research and academic institutions in Chicago represent target markets that would consider implementing wave energy projects. These markets align with the city's goals of promoting sustainability, reducing carbon emissions, and diversifying the energy supply while offering opportunities for economic development, innovation, and collaboration. While the team saw challenges for initial implementation in these markets, they should be considered for later expansion.

F. SWOT and PESTLE Analysis

In developing the business plan, the team conducted both a SWOT and PESTLE analysis as detailed in this section.

SWOT Analysis

1. Strengths

- **Innovative Product:** Offers a unique solution by harnessing the consistent and predictable energy of wave motion, distinguishing it from the intermittent nature of traditional renewables like solar and wind.
- **Environmental Compliance:** The product aligns with current environmental legislations like Biden's Green New Deal, offering steel mills and other industries a renewable energy option that can help them reduce emissions and comply with regulatory demands.
- **Efficiency and Reliability:** Wave energy provides a constant source of energy, unlike solar and wind, which are subject to fluctuations. This could ensure steady power supply especially beneficial in microgrid applications.

- **Cost-Effectiveness:** Lower material and installation costs compared to other renewable sources, with higher energy output per square foot, enhancing competitiveness in the renewable market.

2. ***Weaknesses***
   - **High Start-Up Costs:** Although it's cheaper in the long run, starting a wave energy project needs a lot of money upfront, which might prevent people from trying it out early on.
   - **New Technology:** Wave energy technology, especially some advanced types, is still being developed and is not as proven as solar or wind technology.
   - **Location Specific:** It works best near the coast, so it cannot be used everywhere.
   - **Market Entry:** There has been trouble talking to potential customers like steel mills, which suggests they might not know much about wave energy or see its benefits yet.

3. ***Opportunities***
   - **High Demand for Clean Energy:** More rules and a shift in how people think about the environment are creating a big demand for new renewable energy technology.
   - **Growing Use of Microgrids:** More places are setting up their own small power systems, especially where the main power grid does not reach or is not reliable. This is a great chance to use wave energy.
   - **Industries Near Water:** Businesses close to large water bodies need lots of water and could use wave energy to make their power right where they are, which is more efficient.
   - **Potential to Grow Worldwide**: Since most of the Earth is covered in water, there is a huge potential to use wave energy in many places, both now and in the future.

4. ***Threats***
   - **Strict Rules:** Getting permission to start wave energy projects can be tough because of the need to protect the environment, which might slow things down or limit where they can be built.
   - **Competition from Other Renewables:** Solar and wind energy are already well established and supported, making it hard to convince people to switch to wave energy.
   - **Economic Changes:** Money for new technology and projects can dry up if the economy goes down, affecting the start of wave energy projects.
   - **Newer Technology Might Emerge:** If other new technologies come along that are better or cheaper, wave energy might become less appealing.

PESTLE Analysis

1. ***Political***
    - **International Organizations:** International organizations such as the United Nations (UN) seek to meet goals of percent reductions in greenhouse gas emissions. The UN can implement wave energy as a renewable resource.
    - **Funding:** It is necessary for governments to provide funding for the research and development of wave energy converters which leads to funding communities to implement and enforce wave energy converters in their local environments.

2. ***Economic***
    - **Funding:** Wave energy converters must be subject to numerous research and development to be released for public use. They need to be invested in by financial institutions and influence.
    - **Private v. Public:** Potential private investors require significant interest from their public components to continue the momentum of wave energy convertors.
    - **Overall Cost:** The cost of a wave energy converter is significantly higher than investors would expect. The overall pricing needs to lower as findings from studies are produced.
    - **Future Profits:** As wave energy convertors become more common and are utilized in coastal communities, job opportunities increase as the machines are labor intensive throughout production and maintenance as long as the overall cost of the wave energy convertors becomes optimal.
3. ***Social***
    - **Public Demand:** As wave energy is a forthcoming renewable resource, local communities must be willing to transition from the traditional power sources to wave energy converters. That may lead to a change in the way of life which can bring about controversy and hesitance.
    - **Local Stakeholders:** The fishing communities, shipping companies, and recreational boating must be communicated with in order to avoid conflict of interest in their regular scheduled seasons. There is the potential of displacing marine life along with damaging property so appropriate information must be conveyed.

4. ***Technological***
    - **Early Developments:** Wave energy converters are in their early technological phases where power and efficiency are apparent but durability as well as cost of production remain significant.
    - **Risk:** There persists a challenge of developing technology accommodating tidal energy and its variable properties. It provides risks to invest in wave energy converters therefore further technological advances must be made.
    - **Key Processes:** The procedure of manufacturing, installation, connection, maintenance, removal and disposal of the wave energy converter requires many risks and processes to be considered and analyzed to ensure the product is cost effective.

5. Legal

- **Permitting:** Local communities and state federation require permits for the construction and installation of the wave energy converter product to be placed which will reduce legislative risk for developers.
- **Law and Order:** The “backyards” that will be chosen to implement the wave energy converters may enforce their right of property which will necessitate further documentation, time, and efforts.
- **Enforcement:** Each state and/or country is responsible for enforcing the legislation that concurs and will take on the responsibility upon conflict between interests of residents, officials, and developers alike.

6. Environmental

- **Decreased Greenhouse Gas Emissions**: The goal of wave energy converters is to reduce the amount of emissions. This must be accomplished to implement renewable wave energy as a competitive resource.
- **Marine Life**: There is a great quantity of both initial and long-term effects on the local marine life that wave energy converters that will be placed in. These include the artificial reef effect, water circulation, water quality, sound disturbance, electromagnetic fields, light disturbance, and collision risk.

G. Development and Operations

1. Development

Three different WEC designs were originally developed and a rubric was created to score and evaluate the designs. This process is described in detail in Section II.A. The device prototype was manufactured from 3D printed parts and off the shelf components. Manufacturing the full scale device will require specialized components and this poses a risk to the process. The device was intended to be leveraged in the Great Lakes and was tested at wave conditions comparable to those in the region as will be discussed in Section III. While the device showed promising results, its power output was still showing the need for further improvement before being fully operational. The current design also suffered some minor failures during testing. These issues would need to be addressed in order to ensure the device is resilient when operating in open water.

2. Maintenance and Operations

The device is intended to be used in the Great Lakes. Since the lakes frequently ice in the winter, the WEC would likely need to be removed from the water in the winter to ensure that it is not damaged. However, this down time also provides an excellent opportunity for yearly maintenance. During this time, the device should be thoroughly tested to ensure the linear generators are properly functioning and the device should be inspected for signs of excessive wear. As will be discussed in the Build and Test section, the prototype suffered from several minor breakdowns during testing. While all of these were easily fixed, they have helped the team identify areas of needed improvement before the device moves further toward scaled up testing and operation. Further testing would be required with an updated prototype to better address needed maintenance intervals.

3. Risks and Barriers

The team identified risks and barriers associated with the development and operation of the device as described below.

Technological Risks and Barriers

Development Stage: Wave energy technology, particularly newer models like TriboElectric NanoGenerators (TENG), is not as developed as other renewable technologies such as solar or wind. There's a risk that the technology may not perform as expected or may encounter unforeseen technical challenges.

Durability and Maintenance: Operating in harsh marine environments poses significant challenges for the durability of wave energy converters. Frequent maintenance or unexpected failures could increase operational costs and affect reliability.

Risk Mitigation: This risk could be mitigated by thorough testing and the setting of regular maintenance intervals along with more extensive device maintenance during the winter months when the device is not in operation.

Market and Commercial Risks and Barriers

Market Adoption: The acceptance of wave energy technology by the market is uncertain. Factors such as the downsizing of target industries like steel mills, and potential clients' hesitation to adopt new technologies, could limit market opportunities.

Competition from Established Renewables: Wave energy must compete with more established renewable energies like solar and wind, which are already widely accepted and have a mature market presence.

Risk Mitigation: Overcoming this risk will likely rely on government funding to help subsidize the development and initial operation of such a device.

Financial Risks and Barriers

High Initial Costs: The substantial upfront investment required for infrastructure development, including the installation of wave energy converters, could strain financial resources or deter potential investors.

Return on Investment: Given the emerging nature of the technology, there may be uncertainty regarding the return on investment, particularly if energy output does not meet expectations or if maintenance costs are higher than anticipated.

Risk Mitigation: As with the market risk, overcoming this risk will likely rely on government funding to help subsidize the development and initial operation of such a device.

Environmental Risks and Barriers

Impact on Marine Ecosystems: The physical presence of wave energy infrastructure could affect local marine ecosystems, potentially disrupting habitats and affecting marine species.

Extreme Weather Events: Wave energy installations must withstand extreme marine weather conditions, which could lead to damage or degradation over time, impacting energy production.

Risk Mitigation: Before finalizing the device design and taking it to market, thorough testing in more extreme conditions is needed. Yearly maintenance will also be required to check for damage and degradation.

Social Risks and Barriers

Public Perception: If not managed well, public concerns about the environmental impact of wave energy installations could lead to opposition and negative publicity, affecting social license to operate.

Impact on Local Communities: Installation activities and the physical footprint of wave energy projects could affect local industries such as fishing and tourism, potentially leading to conflicts with local communities.

Risk Mitigation: Early engagement with the community will be essential in order to understand their concerns and take steps to design a product that works within the needs and concerns of local communities.

H. Financial and Benefits Analysis

1. Revenue Plan

Initial capital expenditure

The prototype material cost came out to $1237 per device the team needed to build three to test under different configurations thus bringing our total material costs to $3711. The team was able to test the prototype in the University of Michigan Wave tank for three days. To test here the team used $5,575.72 from the competition and Illinois Tech funds and tested our device in differing wave conditions. In total the expenditure disregarding miscellaneous costs such as travel and meals the teams total expenditure ended up being $9,286.72. The breakdown of the main materials used and their costs can be found in Table 1.

The prototype and the actual product are on a scale of 1:100. The diameter of our prototype buoy is 300mm. For the actual product we would like to raise our buoy size to 3m as in Lake Michigan we believe that the greatest power generator is half the size of the distance between each wave. This distance in Lake Michigan is 6 meters thus our materials expenditures come out to be around USD $123,700 per device. However this cost is under the assumption that our materials costs are static as we scale them up however this is not the case. Some materials come with variable costs, these being:

- Springs as they would have to increase in length proportionally to depth of the that the device is installed in
- Power line connectors will increase proportionally with respect to distance from device to customer
- Buoy connectors will increase proportionally with respect to depth and distance from device to buoy (main structure will not change)

We will use the assumption that our material costs are static when they are scaled for the LCOE which will be shown in the calculation of the Capital Expenditure.

Table 1. Materials Breakdown of Prototype.

Item	**Item specifications**	**Link**	**Cost per item**	**Quantity needed**	**Total cost**
Watertight enclosure	3in 300mm	link	$326	2	$652
Magnets	19mm-OD & 8mm-ID 3mm thick	link	$19	4	$76
Coil holder		printed	$0	2	$0
Wire		link	$12	1	$12
Collars	8mm ID	link	$9	1	$9
Magnet spacers		link	$8	1	$8
Wetlink		link	$12	2	$36
Bellows seal		link	$45	2	$90
Joints		link	$10	2	$20
Carbon Fiber Rods		link	$15	1	$15
Jacketed Cable	4 conductor ping cable, 3 meters	link	$5	6 meters	$30
Plugs (M10 thread)		link	$6	14	$84
Rubber Seal		link	$7	0	$7
8mm x 20mm Dowel Pins		link	$8	0	$8
Heavy 2.4 in Ball		link	$9	0	$9
Stiff spring		link	$6	4	$24
lighter spring		link	$11	4	$44
12x2mm O-ring		link	$6	1	$6
62x2mm O-ring		link	$7	1	$7
Hose Clamps		link	$5	1	$5
Extension Spring		link	$12	1	$12
M4 screw		link	$8	1	$8
M4 nut		link	$6	1	$6
Acrylic Glue		link	$16	1	$16
Heat shrink Tubing		link	$13	1	$13
Silicone Tape		link	$10	4	$40
				Total	$1,237

Levelized cost of energy (LCOE)

To calculate LCOE there are some initial assumptions that need to be made. These are laid out in Table 2 and based on a 5 year cycle.

Table 2. Assumptions lists for LCOE calculations.

Assumption		
Rate of inflation is constant	Rate of inflation	0.0348
Federal interest rate is contant	Federal interest rate	0.055
Discount rate is consistent	Discount rate	0.09303771239
Consistent energy output during all 5 years		
1 Volt per prototype (from testing)		
7.5 amps to 13.5 amps (from testing)		
Wattage per device [7.5 W to 13.5W]		
scale prototype:end product is 1:100 (diameter of buoy scaled 1:10)		
2 different AWGs once scaled		
12 AWG for lower end conditions max capacity is 20 amps		
8 Awg for higher end conditions max capacity is 50 amps		
The monthly mean wave power reaches up to 9 kW/m.		
3 meter system so mean is 27 kW/m		
Assume 27 kWMonths are in 1 meter in a 3 meter system 19730 kWh annually then there is to be captured with no refractory period		
Great lakes waves are consistent		
With max wattage we should be able to completely capture all the wave energy generated		

Calculations needed for assumptions

r: $discount\ rate$

$r_{inflation}$: $inflation\ rate$

r_{loan}: $loan\ rate\ (federal\ US\ interest\ rate\ is\ used)$

$$r = \frac{r_{inflation} + r_{loan}}{1 - r_{inflation}}$$

Discount rate is needed due to the time value of money as the benefits and costs in the future are going to be worth less than they are in the present.

These assumptions may seem like assumptions for a highly idealized system however without proper market implementation it would be difficult to get the raw data to undertake a calculation like this. For example, our R&D cost only came from outsourcing our testing because we did not have the facilities to do it at IIT. If we were to build this product commercially we would have to pay for R&D ourselves. However, this is a project and without that commercial element it is difficult to estimate how much expenditure is needed if we were to design this product in a commercial setting.

The template for the CAPEX is the template used for the 500 MW wave farm assumptions. Our CAPEX calculations under that are given in Table 3.

Table 3. Total CAPEX Breakdown.

CAPEX		
Category	Value	Cost
Wave energy converter	33% of CAPEX	$123,700
Development Cost	6% of CAPEX	$22,500
Balance of Plant	36% of CAPEX	$134,950
Installation and Commision	13% of CAPEX	$48,740
Decommissioning	10% of CAPEX	$37,480
	TOTAL CAPEX	$367,370

The OPEX (Operating Expenditure) from the same template was also used; however, the template gave us a range of for the OPEX being between 5% - 15% of the CAPEX. Thus we took the lowest and highest values to give us an OPEX range as laid out in Tables 4 and 5.

Table 4. Lower End of OPEX.

LOW END OPEX (5% OF CAPEX)		
Category	Value	Cost
OPEX	5% of CAPEX	$18,740
Insurance	1% of CAPEX	$43,750
Annual O&M	29% of OPEX	$5434.6
Overhaul	15% of OPEX	$2811
Replacement	45% of OPEX	$8433
Insurance	11% of OPEX	$2061.40

Table 5 Higher End of OPEX

HIGH END OPEX (15% of OPEX)		
Category	Value	Cost
OPEX	15% of CAPEX	$56,220
Insurance	1% of CAPEX	$3750
Annual O&M	29% of OPEX	$16,303.8
Overhaul	15% of OPEX	$8433
Replacement	45% of OPEX	$25,299
Insurance	11% of OPEX	$6184.20

WIth this we can calculate our LCOE. (Note: there are 2 LCOE calculations one for higher OPEX estimation the other for lower OPEX estimation)

Equations used for LCOE

$CAPEX\text{: } Capital\ Expenditure$

$OPEX\text{ : } Operational\ Expenditure$

$r\text{: } Discount\ factor$

$t\text{: } years$

$AEP\text{: } Annual\ Energy\ Production$

$$LCOE\ =\ \frac{CAPEX + \sum_{t=1}^{5} \frac{OPEX}{(1+r)^{T}}}{\sum_{t=1}^{5} \frac{AEP}{(1+r)^{T}}}$$

Table 6 Lower LCOE Valuation

Lower OPEX Valuation			
	Capex	OPEX	AEP
1	367370	18740	19730
2	0	17144.87962	18050.61232
3	0	15685.53347	16514.17158
4	0	14350.40465	15108.51034
5	0	13128.91997	13822.49685
TOTALS	367370	79049.73771	83225.79109
		LCOE	5.363959079

Table 7 Higher LCOE Valuation

Higher OPEX Valuation			
	Capex	OPEX	AEP
1	367370	56220	19730
2	0	51434.63886	18050.61232
3	0	47056.60041	16514.17158
4	0	43051.21395	15108.51034
5	0	39386.75991	13822.49685
TOTALS	367370	237149.2131	83225.79109
		LCOE	7.263604289

Thus our LCOE under our assumptions come out to be USD $5/kWh - $7/kWh.

Pricing and analysis

Admittedly, these LCOEs are too high to currently compete with the market which aims to be at around USD $0.17/kWh if we are comparing it to offshore wind. Most likely our actual LCOE is even higher due to variable costs, and non perfect energy generation (lower AEP). This will be a huge hamper in bringing the product to commercialized use as it will be hard to attract customers to pay such a large premium for their energy with the only benefits being to become more renewable. There are 4 ways to price our product for commercial use but they come with multiple disadvantages with our high LCOE. These are:

- Sell our product with no cost to energy generated, however this strategy would need to cover the capital expenditure in a single purchase which is a big ask especially if the customer needs multiple devices.
- Lease the product with no energy charge, Again the CAPEX is still too great by leasing we would have to discount how many years we are leasing the product for which means that the lease price needed to break even will be in total greater than selling our product.
- Charge for energy in order to breakeven we would need to charge $17 dollars per kw under the higher range assumption which is a big price tag for users.
- Combinations of the 3 mentioned could alleviate the problems mentioned above but they will still be present. It is difficult to estimate the size of the customer base that we can capture with a complex selling strategy.

Due to the limitation of generating energy equivalent to the monthly energy production in Lake Michigan we can really only lower our LCOE by finding strategies to lower our costs. However our assumption also assumes that we are scaling our prototype to the scale that it would be in practice. Thus we may be able to find cost reductions as we develop into a full fledged commercial product.

I. Conclusions

Participating in MECC has been a journey to a new frontier of renewables. Marine energy is still in its budding stages but we believe that potential for marine and wave energy is greater than that still of the current renewables on the market. Water is a resource that is underutilized in the energy space but because of its abundance and consistency it has the potential to become a bigger player even to the point of competing with nonrenewables one day. Thus, even with the cost setbacks our team has shown that the innovation and proof of concept are available and the next steps are to break down the economic barriers that have barred many wave energy products from coming into the market. We see the potential in our product and hope that in the end of its development we will have a product that will be a staple in the energy field.

II. Technical Design Challenge

A. Design Objective

The Illinois Tech team aimed to create a point absorber system that could harness energy from multiple directions of motion and as such, improve energy capture beyond current designs that mainly focus on just the vertical movement of the buoy. Three designs were proposed in Fall 2024.

- Flower Design which utilized pontoon device principles. This design floated on the water and used rotary generators to provide power. The design was loosely based off of the Hoberman sphere children's toy. While the design was judged to be quite innovative, it was complex and the team had concerns about the ability to construct the device as well as its durability.
- Bowl Design which was centered around the point absorber principle. This design was a point absorber with a bowl shaped upper buoy to attempt to enhance the motion of the buoy. The buoy was connected to linear generators for the PTO mechanism.
- Buoy with spring design which also operated on the point absorber principle but Incorporated a mechanical spring as the Power Take off(PTO) mechanism.

The team created metrics on which to score the designs and these included 1) anticipated efficiency/power output potential, cost, design complexity, durability, environmental impact, ability to test, anticipated range of operation, and innovation of the design. The team decided that efficiency/power output, cost and durability should be weighted twice as much as the other metrics. With this rubric in place, the team voted for the design they thought had the best potential in each category and the following scoring resulted (Table 8).

Based on this evaluation, the team decided to move forward with the bowl shape design. The design aimed to extract more motion by facilitating a mechanism that shifts how the weight of the buoy itself is distributed, while also minimizing the number of complex parts to lower the maintenance cost. As the team expanded on this design, they came up with multiple options for creating this shifting weight in the buoy. One potential implementation for this was to intake and expel water on the inside of the buoy (siphon design). Another was to use a hollow buoy with a ball inside that could freely move. Three small scale versions of the buoy were 3D printed and tested including a hollow option with no ball, a hollow option with a ball inside, and the siphon based design. These were tested in a 50 gallon tank with simple student made waves. It was found that the hollow option with the ball appeared to have the most motion but was similar to the hollow option with no ball. The siphon based design could get overly filled with water and sink and as such, was not used in further designs. As such, a simplified model was selected where a ball was placed on the inside that would roll around, changing the center of mass.

The specific design calls for a large buoy, which enables the attachment of multiple generators across the lower surface, as opposed to just one generator per buoy. The overall design was selected such that the environment where the system is located reflects that of Lake Michigan or other great lakes. The prime means of power generation for each generator is achieved through electromagnetism, such that magnets with alternating polarities are attached to the translator which passes through fixed coils in a three-phase configuration, and thus, the wave oscillations result in power.

Table 8. Initial Design Evaluation.

	Flower Design	Bowl Design	Buoy with Spring Design
Efficiency/power output potential (x2)	8	10	0
Lowest cost (x2)	0	10	8
Lowest design complexity	4	9	2
Durability (x2)	3	4	5
Lowest environmental impact	9	6	6
Best ability to test	0	9	9
Largest anticipated range of operation	1	2	10
Innovation	10	1	1
Total Score	46	75	64

Ideally, the point absorber could be deployed with as many generators as desired, but the team focused on testing different positional configurations to find what would best maximize the output from the vertical movement. As there was a strong emphasis on creating the buoyancy force, it was important to design the buoy to displace as much volume as possible while being light, which is why it was chosen to manufacture the buoy via 3D printing. The 3D-print was accomplished by separating the buoy into two pieces, the top, and the bottom, which allowed for easy access to the interior where different balls would be placed depending on what configuration is desired. Such modularity was a major design requirement the team imposed upon themselves, as not only did it aid in testing the system, but it also demonstrated how such a device could be deployed and modified for an end user. In a similar vein, constructing the base was done by cutting multiple holes that gave predetermined locks where any generator could be attached or positioned.Figure 1 illustrates an overview of how the entire system appears. Engineering drawings are given in Section II.F and the design process for the final device is given in Section III.A.

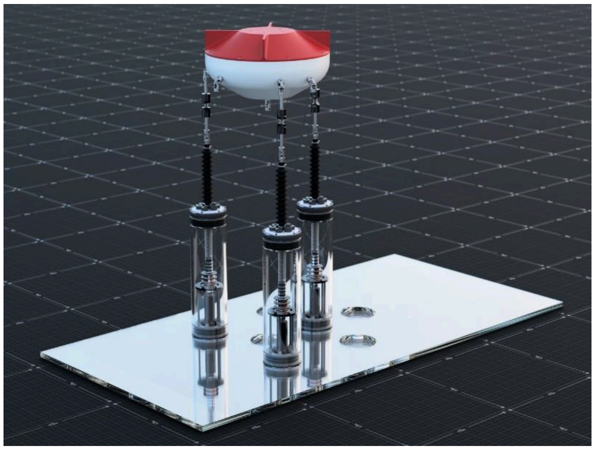

Figure 1. System Overview.

B. Performance Analysis

The device operates with linear generators as the PTO mechanism and these linear generators were constructed by the team. These were tested to understand their expected power output. Bench tests were originally conducted with the stator coil and later total power output was evaluated with the whole prototype. Performance of the entire device is discussed in the Buld and Test section of the report. The power performance of the WEC was recorded in real-time, so an average value for the current, voltage and power were all calculated. Firstly, the AC voltage produced was not used to ensure the voltage readings were as accurate as possible, as AC voltage is unstable and needs to be converted into DC voltage to be usable. The DC conversion produced a peak voltage reading of 3V, 7.5 - 13 A, and roughly 40 – 45 Watts for the entire system. It is important to keep in mind that these are the output numbers recorded under the peak conditions, meaning that for lower powered waves a lower power output can be expected. In capturing the system's electrical values, multiple tests were done with the oscilloscope probes attached to the stator coils to capture the system's voltage reading by sampling the output of a single coil. Figure 2 shows the reading of a later design of the stator coil and the voltage produced. The scale used for the oscilloscope below was 2V with a peak AC voltage of 2.5V, for the entire system the peak AC voltage was 7.5V (for all three coils). Therefore, the DC voltage value of 3V that was calculated directly correlates with the measured value as the DC voltage value should be roughly half of the measured AC waveform i.e. 3.75V. This ensures the accuracy of the electrical measurements during the final stages of development.

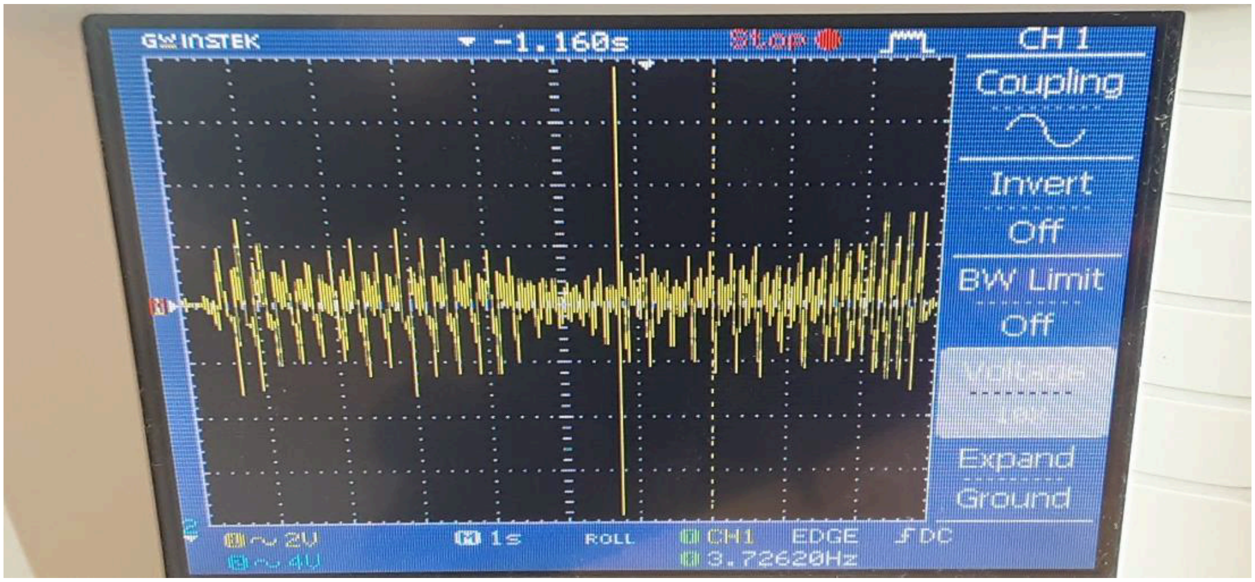

Figure 2. Single Coil Voltage Waveform.

C. Mechanical Loading, Power/Load Profile Analysis and Demonstration

For the mechanical load and safety factor, the buoyancy force must be considered. The volume of the buoy can be found to be 2,641cm^3. Using this to calculate the buoyancy force to be 25.9 Newtons which means when the device is fully extended to a large wave if the rods from the generator to the buoy will have to withstand a 26-Newton force to prevent the buoy from floating away. Using 5 generators as initially theorized instead of the 3 generators used during testing meaning 5 connecting rods to the buoy and putting a force pulling down at 25.9 Newtons and running a simulation will show the factor of safety. The following figure shows the analysis after simulating the 5 rods pulling against the buoyancy force of 25.9N. The max pressure ends up being 0.0759 MPa on the underside of the buoy while the yield strength of the plastic is around 40 MPa meaning this design has a safety factor of 527. This means that the buoy should almost never fail structurally due to a strong storm or a big wave ripping it apart. Instead, the points of failure will be due to repeated fatigue and other outside factors such as debris hitting the buoy in the water. Due to the design's simplicity, the only moving parts, being the rod with magnets, worked as far as sturdiness. This analysis cannot be 100% accurate since it does not consider the fact the walls are not 100% dense when printed and there are gaps to make the printing of the buoy take a shorter amount of time. This fact means the actual safety factor of the buoy cannot be simulated but it is safe to assume that it is much less than the 527 simulated but not so much less that it should matter for structural integrity. Even with the gaps in the walls it can be stated that the joints of the rods or the connection to the generator will fail way before the structure of the buoy does.

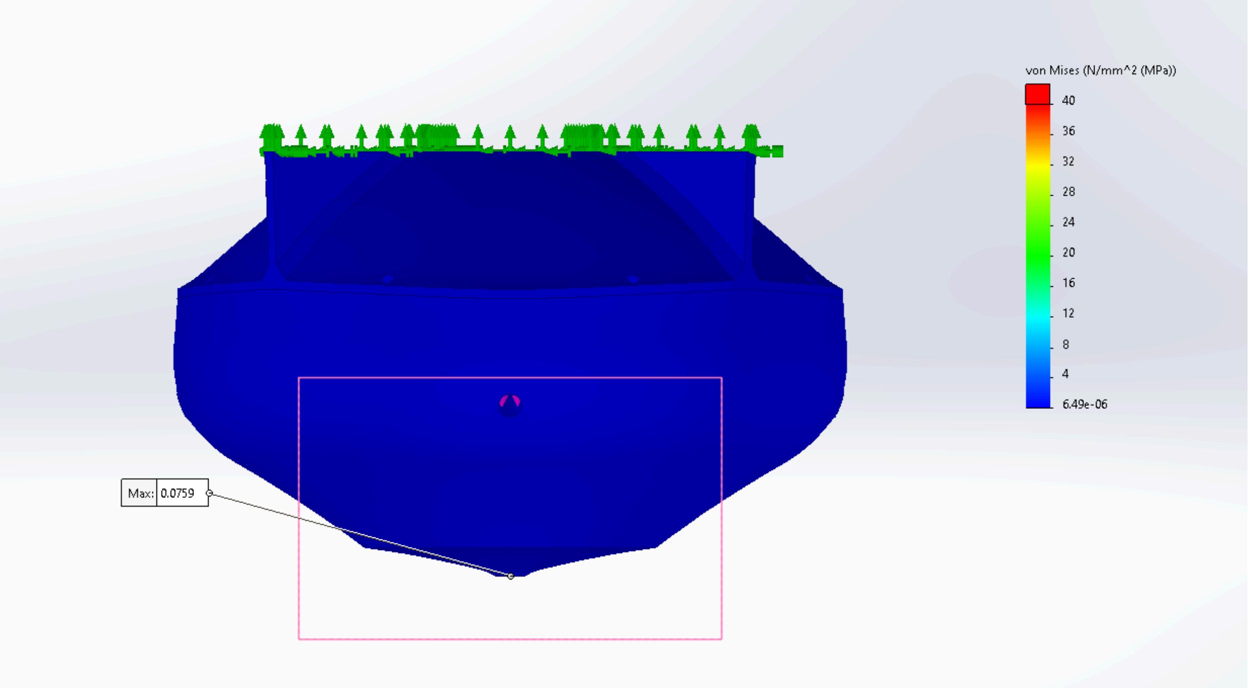

Figure 3. Buoy Finite Element Analysis.

For the electrical side of the design, the team did not incorporate an electrical load. However, regarding the safety factors considered in the design, the main safety concern was the wiring. It had to be ensured that all wires in the process were properly insulated, while also being underwater. Due to this having to be considered in the design, all the wires from the coils were properly insulated and covered while connecting to the generators. The other main factor on the electrical side that had to be considered was to make sure that the wiring could withstand the electrical load that the system can generate. With this risk in mind, it was determined that a safer route could be chosen by using copper wiring which can withstand a great deal of load that cannot be produced by the buoy. Overall, the safety concerns that were associated with the electrical parts of the design process were addressed and handled properly with correct insulation and wiring to withstand the load that could be produced by the buoy.

D. System Optimization

Two different magnet orientations on the translator were considered, alternating polarities and non-alternating. Fig. 4 shows the magnetic flux of the alternating configuration on the left and the non-alternating configuration on the right using 5 pairs of magnets in each. The non-alternating configuration has a larger magnetic flux; however, it does not change much along the translator so the entire group of magnets would need to enter and exit the coils for the flux to change significantly. Therefore, the alternating polarity configuration would more reliably produce energy in small wave conditions where the entire magnet assembly does not leave the coils.

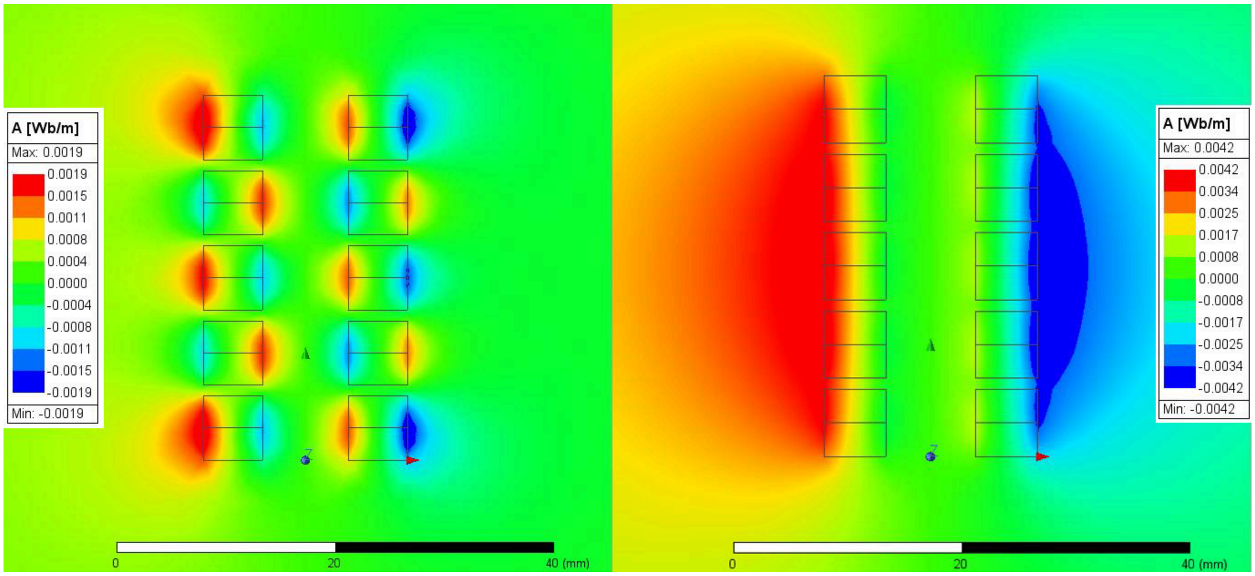

Figure 4. Magnetic flux with alternating and non-alternating polarities.

The alternating polarity configuration has a much smaller total flux, especially as the distance from the magnets increases. For this reason, the distance from the coils to the magnets was minimized. The total magnetic flux change along the translator is much larger on the alternating polarity configuration. This configuration also lends itself better to increasing the number of magnets used. Since the change in magnetic flux is the most important aspect for inducing current in a coil the alternating polarity configuration was chosen for the final design. Both configurations were tested by moving the translator with each configuration through a set of coils and measuring the induced voltage to confirm the models. For the final design the number of magnets was increased from 5 pairs to 10.

E. Meeting Power/Operational Needs

1. Sustainability of Design

This point-absorber, and wave-energy converters in general, offer many sustainable and environmentally friendly benefits, especially compared to other power sources. The system here is low-profile and in the designed environment of Lake Michigan, should not pose a threat to the native ecological life. To further that point, because the system is sealed/watertight, there is no danger that life might get trapped anywhere; such a scenario is possible with other wave-energy converters that rely on the potential energy of the water itself, like a gear motor creating torque from the pressure difference. The materials themselves that were used in the system are also an important consideration, such as how materials are selected to not corrode, or if needed, can be easily serviced in the event of maintenance being required. Along with being a renewable source of energy, wave-energy converters such as this one can produce power throughout an entire day, making them more consistent compared to that of solar panels.

2. Addressing User Needs

The system was designed to be used in Lake Michigan. For example, the average wavelength and amplitude were taken into consideration while selecting the scale. Materials were chosen to be resistant to corrosion and electrolysis. One of the main focuses of the design was to be easily assembled/disassembled. Its modularity allows for customization as seen fit to the circumstances, or by the end user. The interior can be easily modified to fit needs as required. Springs and coils can easily be replaced, making the system simpler to maintain. Additionally, there are 7 spaces for generators that are accommodated for on the base and buoy. However, only 5 generators can be attached to the buoy at a time. It was designed for 5 different testing configurations, one generator in the center, three in a row both parallel and perpendicular to the wave flow direction, three in a triangular orientation, or 5 in a cross orientation. Other orientations would be possible as well during real world implementation.

F. Lessons Learned

In the beginning of the academic year, students in the technical team started off by researching different types of pre-existing marine energy devices. The technical team was broken up into many small groups focused on further researching and developing their device of choice. Slowly, the number of groups converged until there were 3 designs remaining. Then, a vote was held to select the design that the team would continue with to the prototype stage. During the later months of development, the technical team was split into simulation, electrical, and building teams; during this period, teamwork and cooperation skills were refined as time went further on. The members in each group learned their own respective skills such as simulation software (WECSIM), CAD (Fusion 360), MATLAB, GitHub, 3D printing, laser cutting, etc. Students also learned rapid prototyping, materials selection, and other problem-solving and collaborative skills. The success of the project was demonstrated by the results produced while testing the device at the University of Michigan’s water tank as will be discussed in Section III.

G. Engineering Diagrams

The final design of the buoy and generators is discussed in more detail in Section III.A, but the major components and their diagrams are provided here. The device utilizes a buoy as shown in Fig. 5 that has fins and a hollow structure with a ball inside. Both of these features were added to increase the motion of the buoy. The buoy has multiple connection points at its base to allow for different attachment configurations to the linear generator PTO elements. A cross-section view of the buoy is given in Fig. 6.

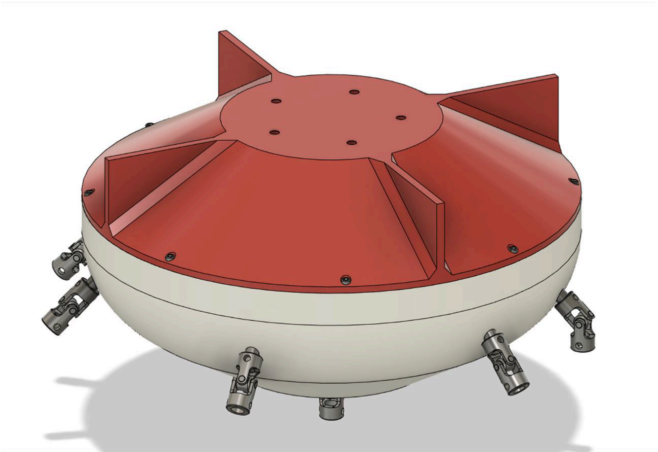

Figure 5. Buoy model.

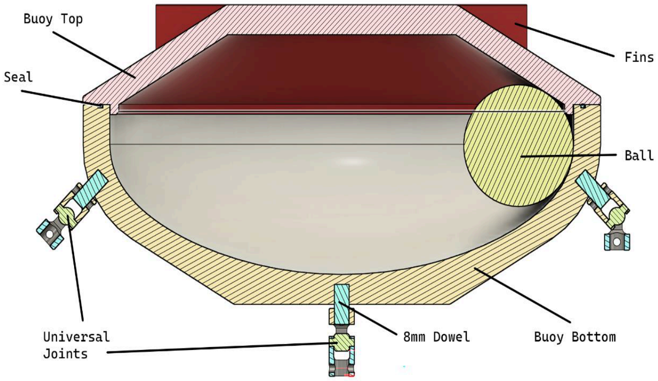

Figure 6. Buoy cross section.

The buoy is attached via the universal joints to a linear generator pictured in Fig. 7. The internal mechanism to the linear generator is shown in Fig. 8. This clearly shows the coils and magnets that were studied and discussed in Section II. B and D.

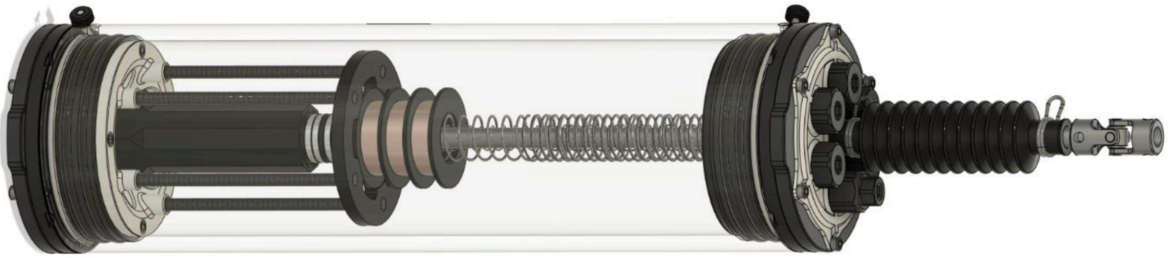

Figure 7. Linear generator model.

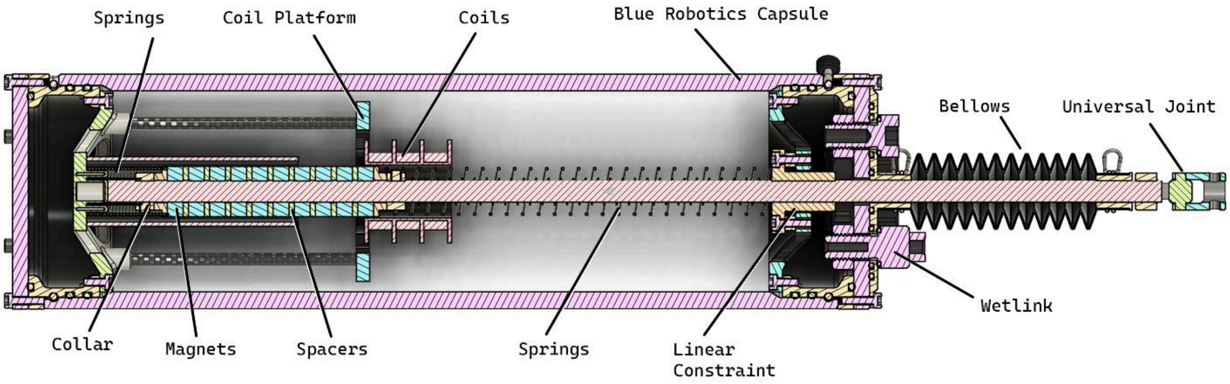

Figure 8. Linear generator cross section.

One critical concern with the linear generator was ensuring it was watertight. To enable this a bellows was introduced with a seal as shown in Fig. 9. This connection was tested and improved prior to full prototype testing at the University of Michigan.

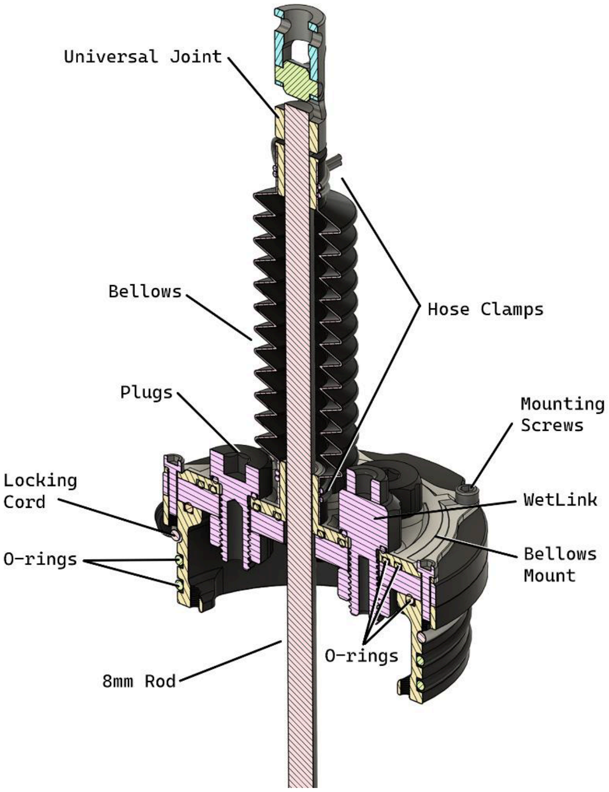

Figure 9. Bellows seal.

The bottom of the linear generator has a 3D printed coil platform that is shown in more detail in Fig. 10. This piece holds the coil and spring and ensures that the rod moving up and down stays on a set track. The top of the linear generator has a plate with a linear bearing as shown in Fig. 11.

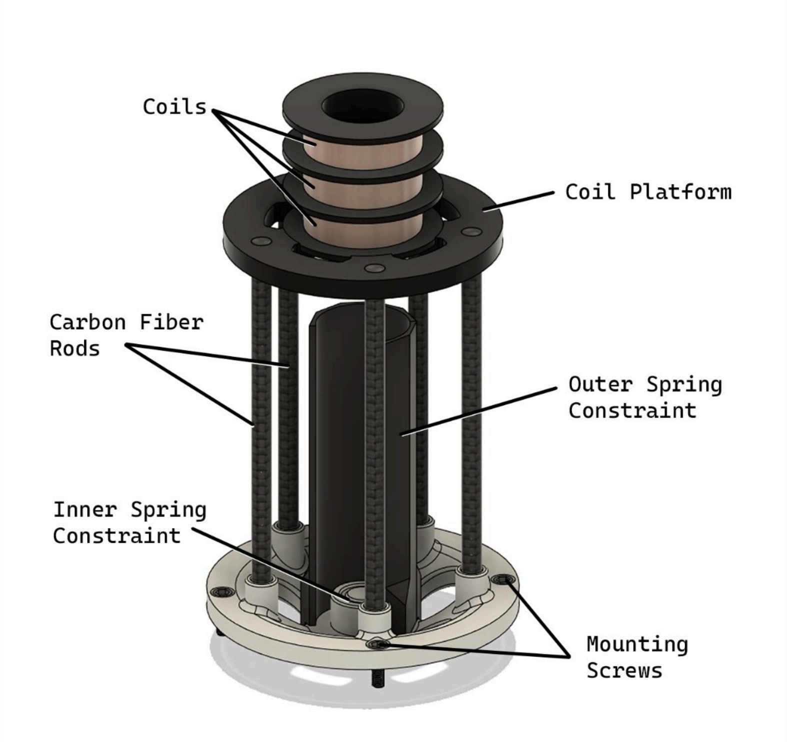

Figure 10. Coil platform.

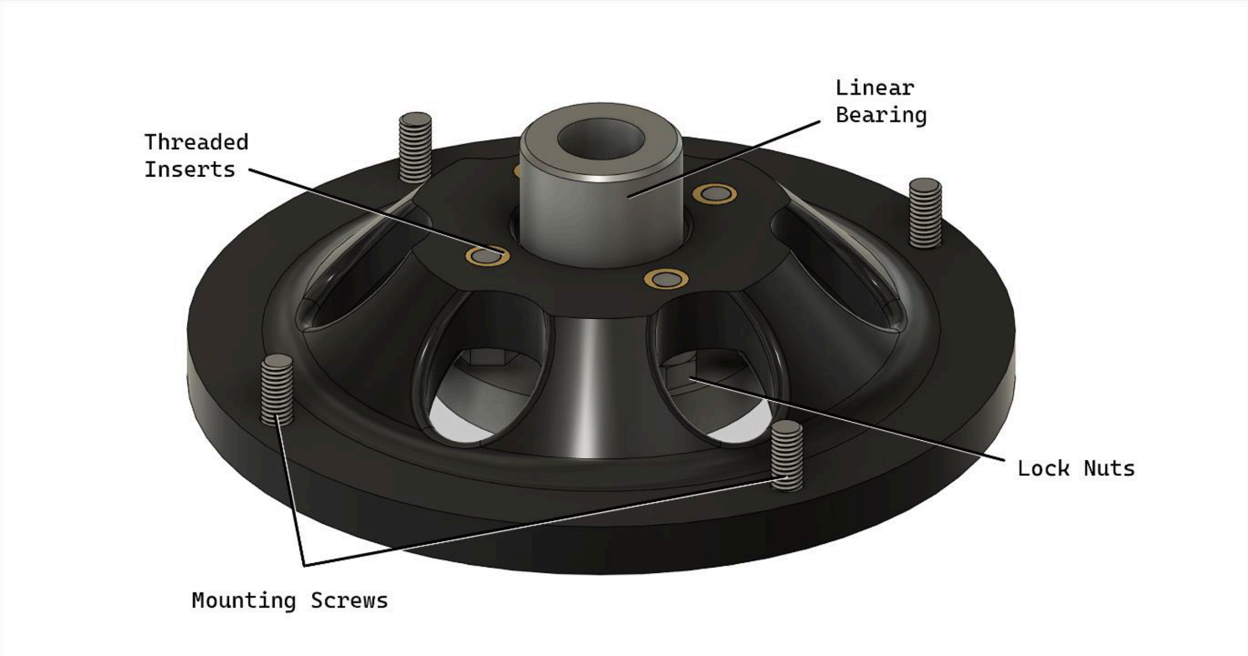

Figure 11. Linear constraint.

The linear generators are connected to a base (Fig. 12) that allows the linear generators to be placed into different configurations. Three linear generators were made and used for testing. The generators, buoy and the base are shown in their complete configuration in Fig. 12.

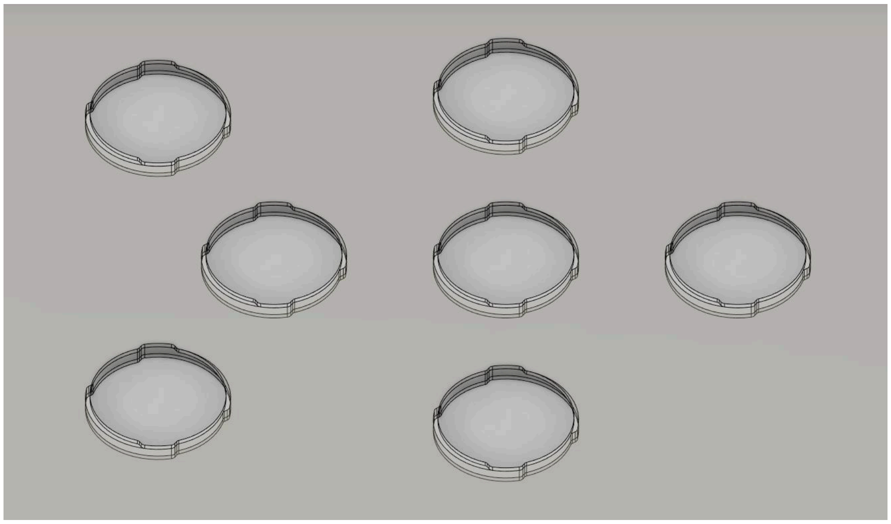

Figure 12. Base design.

Figure 13. Complete device during testing.

III. Build and Test Challenge

A. Design Process

The earlier designs and the design iterations that led to the prototype have been discussed in Section II.A. As such, this section focuses on the final design and development of the prototype used for testing.

As was illustrated in Figs. 5 and 6, the device has a hollow buoy. A ball is placed inside the buoy to roll around in the buoy and increase the pitch and roll motion of the buoy. The inside of the buoy is curved to allow the ball to roll back to the center and prevent it from tilting the buoy and becoming stuck in that position. Fins are included at the top so that any waves flowing over the buoy will push against them and tilt the buoy. The buoy is designed to increase the pitch and roll motion when interacting with waves. Multiple linear generators are connected to the edges of the buoy to harness the energy from the pitch and roll motion as well as the heave motion. The universal joints also allow for surge motion which pulls the buoy sideways compared to the generators and pulls the generator translator up, generating power. The universal joints are connected to the buoy with a steel dowel that is glued into holes in the buoy. The buoy was scaled to be half the wavelength of the average incoming wave.

Fig.8 shows a cross section of the linear generator design. Ten pairs of ring style magnets are arranged with alternating polarities near one end of the translator (the moving part of the linear generator). Spacers are placed between them to reduce the opposing forces of the magnets. The magnets are arranged so that four sets span three coils. Pairs of magnets are used so that the coils are taller, allowing more coil windings to be placed closer to the magnets. If the same number of coil windings are used with a thinner magnet the coils would be wider resulting in the outer windings to be farther away from the magnets. The magnets are attached to the rod using collars at each end. Springs are used at the top and bottom of the translator along with a spring connection between the buoy and the translator to try to increase the oscillatory motion of the translator. The translator and coils are enclosed in a container to isolate it from the water since the entire generator will be submerged. A Blue Robotics enclosure was used to encapsulate the generator since they are proven to work reliably.

Fig.9 shows the connection between the translator and the rest of the generator. A bellows style seal was used to seal the joint between the rod and the Blue Robotics capsule. This was used to minimize friction between the rod and the container compared to other types of seals such as an O-ring seal. Due to the small clearance between the rod and the top of the capsule, a connection was designed that was sandwiched between the capsule lid and the plugs. O-rings were placed around each of the holes in the cap along with a large O-ring around the entire top to seal off the connection. The translator rod was connected to the bellows with a 3d printed ring that was placed between the rod and bellows with silicone adhesive applied on both sides. A constant pressure hose clamp was also attached around the bellows to seal the opening and apply pressure to the bellows as the glue dried. The bellows seal was attached to the bellows mount the same way. A universal joint was attached to the top to connect to the buoy and allow the connecting rod to rotate as necessary as the buoy moved. A Blue Robotics WetLink was used to route the cables through. This section is connected to the acrylic tube with two O-rings to seal it. A cord is inserted into a groove to lock the top in place.

Fig.10 shows the coils and the connection to the Blue Robotics enclosure. Three coils are used to demonstrate a three-phase generator design. The coils are connected to a platform raised above the bottom of the container with five carbon fiber rods. This leaves room under the coils for the translator to move through and for the springs to be compressed. At the bottom there is an inner coil constraint to hold the springs in place. There are two different sized constraints to allow different sizes of spring to be tested. The springs had to be long and thin due to the size of the coils and the translator's design range of motion; Therefore, the springs buckled when the translator was at its bottom position. To keep the spring from buckling an outer constraint was added. Four screws are used around the outside of the mount to attach the coils to the enclosure.

Fig.11 shows the linear constraint that is used to constrain the translator. The platform is connected to the enclosure with four screws around the outside of the platform. A linear bearing is attached to the mount with threaded inserts that are heated up and pressed into holes in the 3d printed platform. A lock nut is placed between the linear bearing and the platform so that the screws can be loosened to adjust the level of the bearing so that the translator can be aligned with the coils below. This is done since there is only a small clearance between the translator and the coils to maximize power production. There are six holes around the platform to feed wires through and to reduce the amount of material needed.

The team designed the base of the prototype (Fig. 12), made of three layers of acrylic to meet the thickness of the bottom piece. Each one was laser cut individually so that the generators could be rotated and locked in place. The base was made with two extra spots to try different iterations and see if there are any changes to the output results that are obtained from testing it.

B. Prototype Fabrication

Our prototype featured the following components that required fabrication:

1. Buoy: The design features a spherical ball housed within it, aimed at amplifying pitch and roll movements during wave interaction. The buoy's interior curvature facilitates the ball's return to the center, thus preventing potential obstructions. To expedite the design's complexity within a limited timeframe, the team opted for 3D printing technology. Fig 14 shows the base of the buoy being printed.

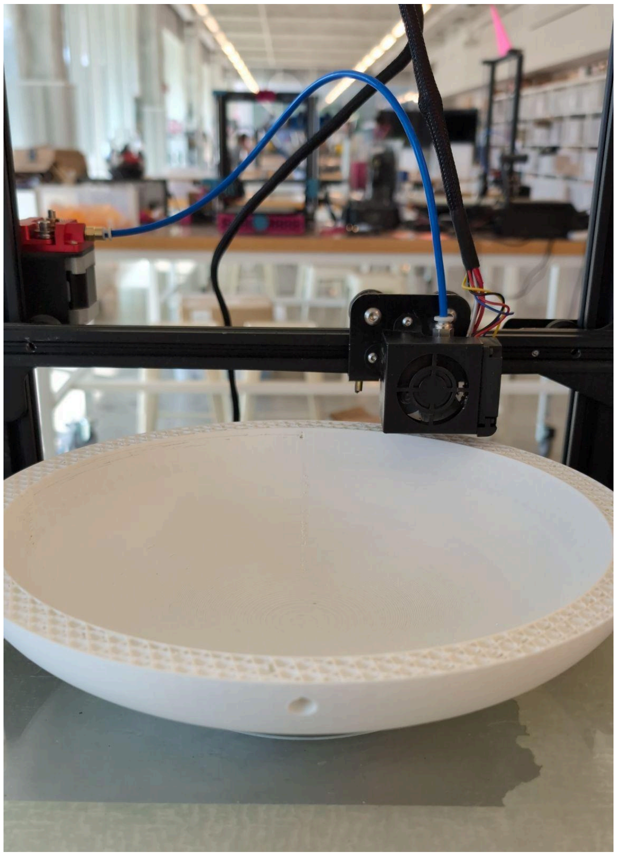

Figure 14. Buoy bottom printing.

2. Base: This design consisted of three rectangular -shaped fiberglass components interconnected using acrylic material to ensure a sturdy bottom section. Laser cutting was employed to precisely shape. This provided a structure to support the system's generator's effectively and allowed the generators to be placed in different configurations.

3. Coil platform: Figure 10 illustrates the coil platform, which was fabricated using 3D printing to meet the intricate requirements of the design within the designated timeframe for the prototype production.

Other components of the system including the magnets,springs, enclosures and waterproofing for electrical devices were stock components that were ordered and assembled. Figure 8 illustrates the assembled cross section of our PTO which in our system is referred to as a linear generator. Figure 14 shows the fully assembled linear generator and Fig. 15 shows that part being bench tested at Illinois Tech.

Figure 15. Assembled linear generator.

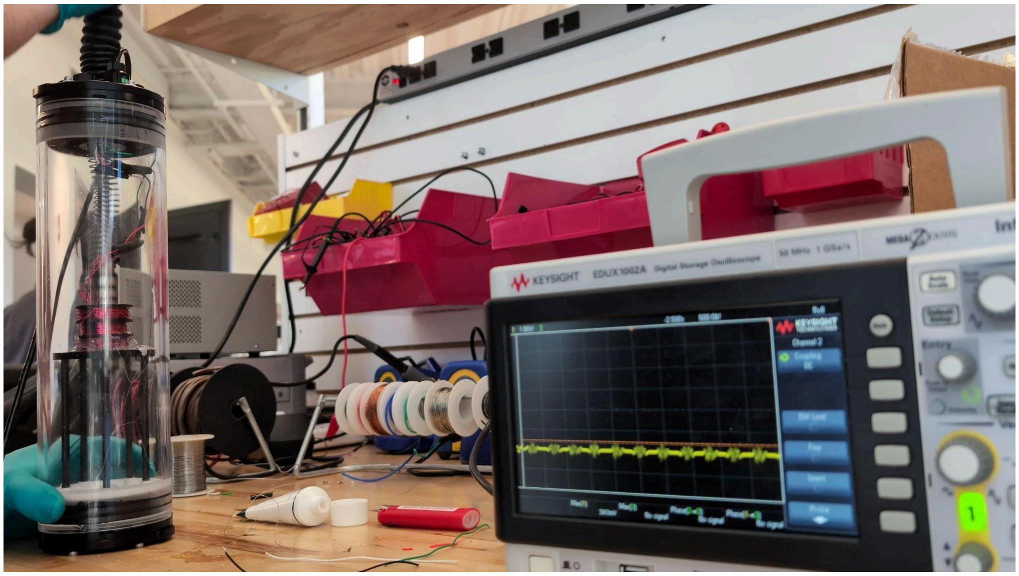

Figure 16. Linear generator during bench testing.

Figure 17 shows the team at work on the final prototype construction before it was taken to the University of Michigan for testing and Fig. 18 shows final adjustments being made at University of Michigan prior to tank testing.

Figure 17. Prototype construction at Illinois Tech.

Figure 17. Prototype adjustments made on site at University of Michigan.

C. Testing

After prototype construction, the device was taken to the University of Michigan for testing in their wind-wave tank. Four students led the testing with the faculty present as well.

1. Scaling Considerations

The full-scale size of the device was based upon the buoy diameter being one-half of the average wavelength of waves in Lake Michigan. With these considerations, the full-scale device would have a buoy diameter of 3 meters, with the base being 3x3 meters, and the height of the device would be approximately 6 meters. When constructing the prototype, the scale-down dimensions were determined by considering the limiting factors of the Wind Wave Tank (WWT) that testing would be conducted in. Using Froude scaling principals, the ideal prototype scale came out to be 1/10. At this scale, the largest prototype was produced which would still be able to be tested against the range of wave conditions that the device would be exposed to in Lake Michigan, given the wave height limitations of the WWT at UMich.

2. Development of Test Plan

To conduct testing at the University of Michigan Ann Arbor using their WWT, a couple things needed to be in place. First, a set of wave conditions representative of the range of wave conditions in Lake Michigan needed to be formulated. To achieve this, the South Haven Buoy, MI data was loaded into MatLab, then the period and amplitude was collected for 15 data points at percentile 15, 20, 25, 30, … , 85. These amplitude and period values can be found in Table 1 below. All tests were conducted at the 15 conditions laid out in the table.

The test plan needed to account for the physical design constraints of the WWT. The WWT can only generate 2D waves and a device diameter of 600 to 605 was recommended. The aim was to target a normal wave height of 0.15m and wave period ranging from 1.265-1.581s with stormy conditions captured by a 0.6m wave height and 1.897s period. Initial feedback was received from the University of Michigan that their WWT's wavemaker was capable of producing wave heights of about 0.120 meters for the 1.265 second wave, 0.100 meters for the 1.581 second wave, and 0.090 meters for the 1.897 second wave. Based on this feedback, the testing plan was finalized.

The tests conducted focused on evaluating the devices performance. Safety was evaluated but emergency shut down procedures were not created at this point as the team was first concerned with having an operational device and evaluating any critical flaws with the design. Durability issues were seen as part of the testing as several failures developed over the testing time. Consideration of these will allow the team to improve their design in the next iteration.

Table 9. Scaled down wave period and amplitude testing values.

Period (sec)	Amplitude (mm)
0.829	15.0
0.866	16.0
0.908	17.0
0.964	18.5
1.028	19.5
1.091	21.5
1.161	23.5
1.227	26.0
1.297	28.5
1.360	31.5
1.455	35.0
1.565	39.0
1.692	44.0
1.825	51.0
2.043	62.5

Three sets of experiments were conducted. The first experiment tested three different generator configurations, with connections on the base and the buoy. The base was designed such that the generators could be removed and replaced easily, and many slots were included such that many generator configurations could be tested. There were 3 orientations that were tested against the wave conditions in Table 1. The first orientation, called the parallel orientation, placed the 3 generators in the center 3 slots, parallel to the direction of wave propagation. The next orientation, called the perpendicular orientation, placed the 3 generators in the center 3 slots, perpendicular to the direction of wave propagation. The final orientation, called triangular, placed the 3 generators in a triangular orientation, with 2 generators downstream and 1 generator upstream. The goal of this experiment was to find which orientation produced the greatest voltage output. These three configurations are shown in Fig.18.

Figure 18. Parallel, perpendicular and triangular generator configurations.

The second experiment tested a spring connection between the buoy and generators against a rigid rod connection. Data was collected for each test group against the wave conditions in Table 1. The goal of this experiment was to determine which connection produced the greatest voltage output. In the last experiment, light weight balls in the buoy were tested against heavy weight balls in the buoy to determine which has the greatest power output.

3. Execution

The device was transported to the University of Michigan Ann Arbor with students from the testing group to commence testing. Over a three day period, troubleshooting and all of the above tests were performed by the students with help from the University of Michigan staff. Prior to testing, the team went over their MECC safety and technical inspection form with the staff as given below. The university staff was satisfied that the device was safe to operate.

MECC 2024 Safety and Technical Inspection Form

Team: IIT Minds for Marine Energy

SAFETY

☐ Wiring is deemed safe and uses adequate gauges—no electrocution or overheating hazard

☐ Electrical systems are tied to earth ground with 100 kiloohms or lower resistor

☐ Energized electrical components are adequately shielded—both electrically and mechanically

☐ Proper heat rejection

☐ Voltage is under electrical load limits for the data acquisition system at all times

☐ All mounting fixtures fit without having to be forced

☐ For any electrical load: all charging or bulk energy storage follows industry-accepted best practices (i.e., safe circuitry overvoltage/undervoltage protection, flame/spill containment)

Electrical

☐ All electrical components outside the wet testing space are contained in enclosures (no tape)

☐ Cable passthroughs in enclosures provide strain and chafe protection (e.g., cable glands)

☐ Marine energy model device electronics and load electronics are in separate enclosures

☐ All external wiring is in cable form and utilizes commercial connectors

☐ All electrical components are mechanically secured to enclosures

Marine Energy Model Device

☐ Capable of installation in the wet testing facility in one assembly to minimize the chance of shifting pieces in the water.

☐ Designed to be safely lifted by no more than two team members. If the device weighs more than what two team members can safely lift, adequate lifting points for a crane or equivalent hoist will need to be designed and inspected. Each team will need to evaluate each member’s ability and fitness for physical work and material handling.

☐ Able to be fully assembled outside of the wet testing facility to allow for mechanical and electrical system checks to be completed before entering the water. It may be necessary for a team to design a dry test stand or mount where the device can be attached without risk of accidental movement (do not simply place on a tabletop).

Mechanical

☐ Review model design, installation, and test plan to minimize pinch points, sharps, entrapment, entanglement, etc.

☐ Review model design, installation, and test plan to ensure there are appropriate safety measures in place if using an energized system (hydraulic pressure, compressed air, etc.)

Personal Protection Equipment (PPE)

☐ Verify that all team members working on the Build and Test Challenge have access to appropriate PPE, such as gloves, eye protection, closed-toe shoes, appropriate work clothing, basic medical kit, etc.

Environmental

☐ Review installation and testing plan to account for the additional risk of working in or near water.

☐ Ensure all materials, oils, fluids, etc. used in the build are test are properly handled and disposed of at completion.

Wiring

☐ Wiring will reach the data acquisition system for measurements that are made outside of the wet testing facility.

Load

☐ Team-supplied electrical or other load is certified for desired use

D. Performance Data Analysis

Having conducted several tests for the prototype with several configurations, analysis of the device performance can be conducted to compare the various ways the prototype can be made to produce the most output. The data given was that of the measured voltage produced by the prototype for every millisecond over a 200-second test period. Tests were also conducted at various period lengths to compare how different waves could generate different amounts of energy.

Figure 13 shows the root-mean-square (RMS) of the total output of the data at three different configurations. These configurations were those where the prototype was placed parallel to the motion of the tank, perpendicular, and triangular. The data shows that longer periods would generally increase the electric potential generated, and that the perpendicular configuration had the best power output, with the triangular configuration generally having the worst at longer periods. Additional analysis can be conducted on comparing the standard perpendicular configuration against some adjustments made to the prototype, such as having a lighter weight setup.

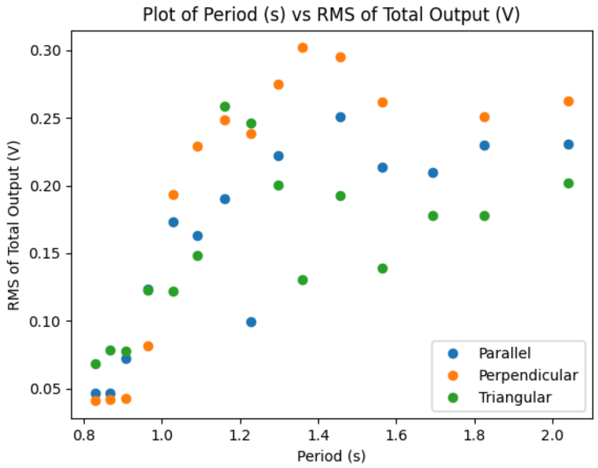

Figure 13. Parallel vs. Perpendicular (Heavy Weight, Spring) vs Triangular.

Figure 14 plots the resulting RMS voltage output with lightweight balls in the buoy and heavy weight balls in the buoy. Both were tested with the perpendicular configuration as this was shown to have the best power output as seen in Fig. 13. It can be concluded that the light weight design produced greater results at certain periods.

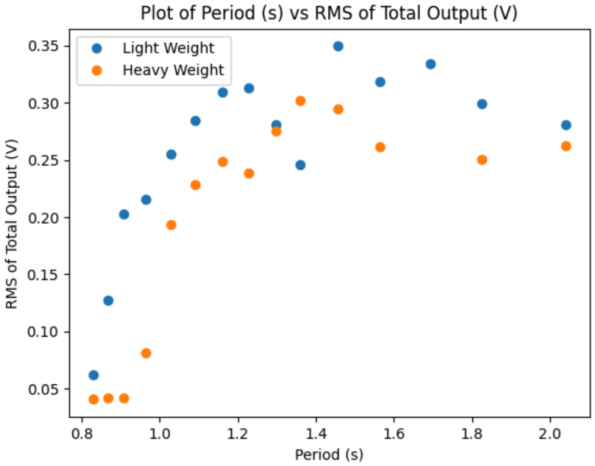

Figure 14. Light Weight vs. Heavy Weight (Perpendicular).

Figure 15 shows the effect of modifying the prototype to use a rod instead of a spring at the connection between the generator and buoy. The rod installation generally resulted in an increased performance from the test data.

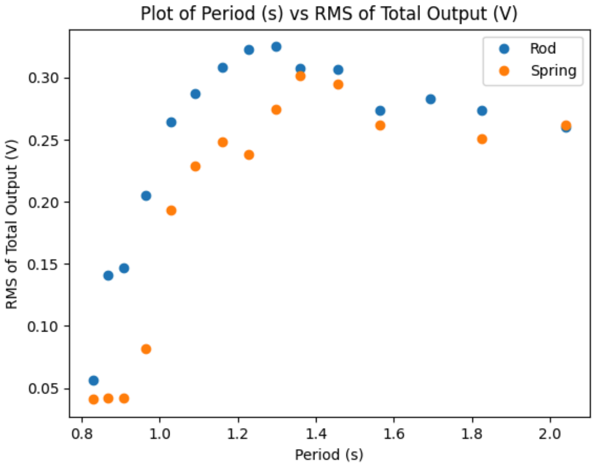

Figure 15. Rod vs. Spring (Perpendicular).

While additional tests were planned to examine irregular wave conditions, testing time did now allow for these additional tests and as such, only regular wave conditions were examined. The team recommends that future testing include irregular wave conditions with the most promising configuration.

In data post-processing, the plot shown in Fig. 16 was generated by taking the integral of the absolute value of the voltage output for each 3 minute run, for each wave condition, then plotting them against the corresponding frequency values. In this data, we were concerned with deciding upon the best conditions and configurations for the device. The conclusion based upon the above plot was that the generator configuration which places the three generators perpendicular to the direction of wave propagation, paired with a light-weight buoy and stiff connections between the buoy and generators produces the highest potential for energy output.

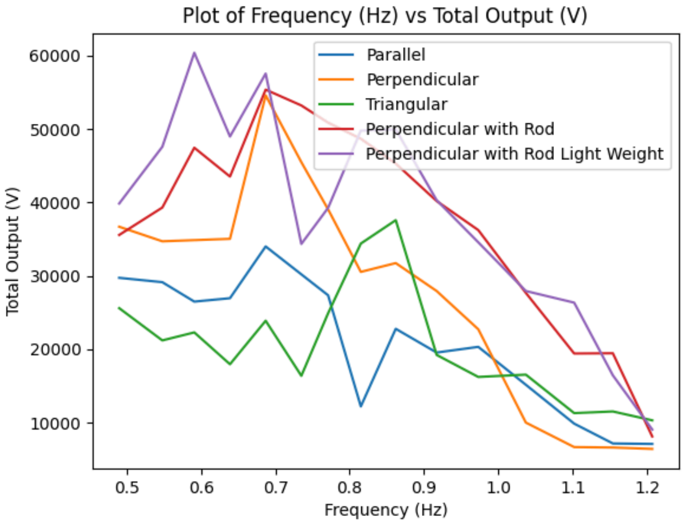

Figure 16. Plot of the total voltage output (V) vs. Frequency in Hz (x-axis).

E. Durability

The team recommends a future set of tests that examine the durability of the device with an updated configuration based on the results of the performance tests. During the tests two main failure modes were observed. The most frequent failure was the disconnection of one of the linear generators from the buoy at the flexible connection points. These were made to be easily changed so the prototype could be tested with different attachments but did prove to be a weak point. Since the team has now found that a rigid (rod) connection performs best, the next iteration could target a more rigid connection between these points with more secure fasteners. The second type of failure observed was a disconnection of the linear generator from the base plate. During testing, the generators could move a bit in the base and work themselves loose. A revised base design with a mechanism to lock the generator in place should be considered in the next version to avoid this issue.

F. Device Safety

Although not examined at this stage, an emergency procedure should be developed in future work to ensure the device is not damaged in extreme conditions or when a failure is detected.

G. Lessons Learned

While at the University of Michigan Ann Arbor for Wind Wave Tank testing, a detailed record was kept regarding what was completed and the challenges faced. On the first day at UMich, some design problems needed to be addressed before testing began. There were leaks in the generators that needed to be resolved. After placing the generator in water and observing the source of the bubbles, it was clear that the source of the leak was a thin, 3D printed piece which was supposed to seal the bellows to a flange from blue robotics. The material was not stiff enough, so it would flex with the movement of the rods, allowing water to enter the generator. To address this issue, the flange was machined to fit a Morris gland, which would provide a water-tight connection to the bellows when secured with silicone along the threads. After replacing the clamps on the bellows, the generators were water tight. On this day, the wiring of the device was also finalized, soldering the coil from each generator to a 12 position solder cup. Another, new piece was machined to combine the three 12 position solder cups in the final output. On the second day, testing began. Data collection was completed for the parallel configuration and began for the perpendicular configuration. There was one generator which was not moving much throughout data collection. There is also much improvement to be made in reducing the friction between the rods and coils. Some suggestions for further work would be to implement “tracks” for the rod to move in, so that the motion is only vertical, reducing the chance that it will make contact with the coil. The coil diameter could also be increased slightly to the same end. The buoy also caused a lot of wave reflection upstream, which is undesirable of a point absorber- indicating low efficiency. In future work, solutions could be implemented so that the generators do not put so much downward force on the buoy, allowing it to move freely with the waves. A potential solution may be in adding less stiff springs underneath the magnets. On the final run of the second day, one generator disconnected from the buoy. Once the buoy connections are finalized, permanent connections will be implemented as opposed to the current connections which must be able to be moved easily, which should prevent this issue.

On the third day, all testing- except for the lightweight buoy test- was completed. The issue of the generator disconnecting from the buoy occurred again on this day, though the issue was quickly resolved. The test that was not completed was carried out by the staff at the University of Michigan in the next week.

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