MECC 2024 Business Plan, Design, Build and Test Final Report

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5/1/2024

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Executive Summary

Marine energy has great potential to help reduce greenhouse gas emissions and mitigate climate change, which also can help improve national energy security by diversifying the sources of energy used to generate electricity. In this project, a marine energy system is designed and tested, which leverages an innovative electro-mechanical drivetrain to efficiently harness the oscillating power of ocean waves for renewable electricity generation. The design incorporates adjustable geometry allowing operation across a wide range of wave heights and tidal conditions. A buoyant surface component couples the wave motion via a sliding piston to an underwater four-bar crank mechanism driving a generator's rotating shaft. Critical features include a dual-crank configuration capturing power from both upstrokes and downstrokes, a flywheel providing inertial energy storage for consistent generator operation, and a gearbox boosting the input speed to the optimal generator rpm. The system's ability to conform to varying wave amplitudes yet decouple in extreme storms, combined with corrosion-resistant offshore-grade materials and components, enables reliable long-term electricity production from this renewable ocean energy resource. Meanwhile, the simplicity of the designed operation mechanism can enhance the reliability of whole system in the complicated wave conditions. With a projected 27.8% overall wave-to-wire efficiency, this marine energy converter shows technical and economic potential for utility-scale deployments.

I. Business Plan Section

Concept Overview

Our team's goal and vision are to build a low-cost, reliable, and scalable ocean wave energy harvesting system by using simple operating mechanism and robust design. California is paradise for renewable energy technology's development, the business model of this project design aims to compete with other renewable energy solutions. In comparison with solar and wind, the proposed marine energy system harnesses renewable wave energy to provide a long-term, cost-effective energy solution. After the initial capital investment, the operating costs are relatively low since the energy source is free and abundantly available in coastal regions of California. Investors and stakeholders can expect significant returns on investment through government renewable energy support, reductions in energy costs, and potential earnings from supplying energy to grids. As the global market for renewable energy continues to expand, investing in marine energy technology positions our team to benefit from market growth and emerging opportunities in the green technology sectors.

Besides, the introduction of the developed marine energy system can bring benefits to local communities as well. By providing a reliable source of clean energy, the system aids the development of infrastructure and supports economic activities that depend on a stable electricity supply, such as local businesses and hospitals. Through the involvement of residents in both the development and operation stages, the project promotes inclusive participation. Training programs can be initiated to equip locals with the necessary skills for system setup, maintenance, and monitoring, preparing the local workforce for the growing green economy. Additionally, replacing dirty energy sources with clean marine energy improves the local population's health by significantly reducing air pollution and associated lung and heart diseases. Furthermore, the system increases resilience against energy security threats and climate change by providing a dependable power source that continues to function throughout extreme weather events common in coastal regions.

Relevant Stakeholders

Various stakeholders and end users stand to benefit from the establishment of a new marine energy system, encompassing government agencies, energy corporations, environmental groups, and the public reliant on electricity in their daily lives. For example:

1) Government bodies at the local, regional, and state/national levels have a vested interest in marine energy systems (if marine energy is available) due to their potential environmental impacts, energy production capacity, and economic benefits. These systems contribute to environmental sustainability and help governments meet their emissions reduction targets by producing electricity without emitting greenhouse gases or air pollutants. Additionally, the development, installation, and maintenance of marine energy systems create employment opportunities in various sectors, stimulating economic growth. Many governments have established renewable energy deployment targets as part of their climate action plans (e.g. CA state government), and marine energy systems aid in achieving these targets and meanwhile fulfilling international commitments under agreements like the Paris Agreement.

2) Energy corporations (e.g. PG&E in California) can diversify their power generation sources, reduce reliance on traditional fossil fuels, and enhance resilience to market fluctuations by incorporating marine energy into their portfolio. Investing in marine energy projects offers energy corporations the opportunity to secure long-term revenue streams, as these systems can generate electricity for decades with minimal fuel costs, providing a stable source of income. Participating in the development and deployment of marine energy technologies allows energy corporations to demonstrate innovation and technological leadership in the renewable energy sector, enhancing their reputation and competitiveness in the market. Additionally, energy corporations can forge partnerships and collaborations with technology developers, research institutions, and government agencies involved in marine energy projects, leading to knowledge sharing, cost reductions, and accelerated project development.

3) The general population and end users of electricity will greatly benefit from the utilization of marine energy systems. Reducing air pollution and greenhouse gas emissions will improve air quality and mitigate climate change impacts for everyone. As marine energy technology matures and economies of scale are realized, the cost of electricity generated from these systems is expected to decrease, leading to lower electricity costs for consumers and improving affordability. Marine energy systems offer a reliable source of electricity, enhancing energy security and reducing the risk of power outages, ensuring a stable supply of electricity for households and businesses.

To gain a comprehensive understanding of the end-user needs and inform the design of our marine energy harvesting system, our team conducted several interviews with industry professionals and experts in the field of water & energy. These interviews provided valuable insights into the current state of the technology, potential challenges, and opportunities, as well as the specific requirements and considerations for developing a successful design.

One of the interviews was conducted with Chirag Parmar, a Senior Hull Land System Engineer in Marine Technical Projects at Chevron Shipping. With 13 years of experience in marine system design, Parmar emphasized the importance of education and experience in this highly technical field, which involves working with pumps, compressors, turbines, and other complex systems. He highlighted the need for new innovative engineering minds in the marine energy market, as well as the importance of staying focused and being aware of industry trends such as reducing carbon emissions, clean energy system innovation, new fuel sources, net-zero design, AI, and emerging technologies.

We also interviewed Ramon Rodriguez, a Senior Consultant at Roderick Consulting Inc., who has over 33 years of experience in the oil and energy industry. Rodriguez currently works with the development and implementation of renewable energy technologies, particularly in the marine environment. He recommended focusing on interdisciplinary studies that combine engineering principles with environmental science, as well as gaining hands-on experience through internships or projects related to renewable energy. Rodriguez also highlighted the differences between near-shore and vessel-bound marine energy systems, with near-shore systems being more accessible for maintenance but less exposed to harsh marine conditions, while vessel-bound systems are mobile and can be deployed in deeper waters but face more rigorous engineering challenges.

Additionally, we obtained insights from John W. Tauriac, the Founder of Santa Cruz Waveworks. Tauriac's company provides real-time monitoring of wave data, including the direction, period, height, and other relevant information. This real-time data is useful not only for surfers but also for engineering disciplines, as it helps locate potential sites for wave energy conversion devices. Tauriac emphasized the importance of skills in circuit design, data analysis, troubleshooting, project management, programming, and mathematical analysis methods for individuals interested in this field.

Besides, because it was not easy to find industry professionals who are willing to participate in our interview, to gain more information, insights, and knowledge, we also did research online and searched for the available public interview videos in the water energy fields.

We have found: 1) an interview was conducted with Jason Hayman, CEO of Sustainable Marine, in 2022 regarding the use of tidal energy, and this interview can be found on YouTube (https://youtube.com/watch?v=lXq0SCgd6Gk). In this interview, Hayman explains that the reliability and predictability of tidal energy make it ideal for energy generation. Hayman continued to explain that since Tidal energy is based on the orbit of the moon, we can predict the output of tidal energy systems for decades based on known tidal patterns. He pointed out that marine energy systems like the ones his company produces are in their "teenage years" compared to other types of energy generation, but that the technology is progressing well. He predicts that tidal energy solutions could be implemented across the US and Canada to add to the renewable energy in those regions. 2) an interview with AWS Ocean Energy CEO, Simon Grey, was conducted about the development of a floating wave energy collection system (https://www.youtube.com/watch?v=TjqZreAxG2A). Grey described this system as highly innovative because it is designed to function in normal conditions and storm conditions. He described the work being done by AWS as “breaking the rules” to truly create something new. The system uses a rubber membrane attached to a barge to capture the power of waves. 3) an interview with Foerd Ames, CEO of Ocean Wave Energy Company, was conducted regarding their technology (https://www.youtube.com/watch?v=LKq-5jwEcKU). Ames discusses the possibility of using rising sea levels as a source of energy rather than only looking at the negative side of this effect of climate change. His company uses marine energy to produce electricity and to produce clean hydrogen gas. This solution could be particularly useful if coupled with hydrogen-based fuel cell vehicles.

Through these interviews and research activities with industry professionals, we identified several key end-users needs and technology considerations for the design of our marine-energy-powered system:

- Reliability and durability: The system must be designed to withstand harsh marine environments and extreme weather conditions, ensuring continuous operation, and minimizing downtime.
- Adaptability to local conditions: The system should be capable of adapting to the specific conditions of the installation site, such as water depth, wave amplitudes, and tidal ranges, to maximize energy generation efficiency.
- Integration with existing infrastructure: The system should be designed for compatibility with existing energy infrastructure, such as electrical grids and hydrogen fuel cell technologies, to facilitate seamless integration and utilization of the generated energy.
- Environmental sustainability: End users value solutions that prioritize environmental sustainability and minimize negative impacts on marine ecosystems, biodiversity, and habitats.

By considering these end-user needs, and technology considerations identified through our outreach and engagement efforts, we developed the design of a wave energy harvesting system that addresses the specific requirements of the coastal area communities, ensuring its effectiveness, sustainability, and long-term viability.

Market Opportunity

Driven by the need to mitigate climate change and reduce dependence on fossil fuels, the global demand for clean and sustainable energy sources is continuously increasing. However, traditional renewable energy sources, such as solar and wind, have limitations in terms of their geographic availability and intermittency. This creates a market gap for reliable and consistent renewable energy solutions, particularly in coastal regions where the potential for harnessing marine energy is significant.

Our project design of harvesting wave energy aims to contribute to the solutions which can address this market gap by providing an economic, scalable, and efficient system for converting wave energy into electricity. By leveraging the consistent and predictable nature of ocean waves, this system offers a viable alternative to traditional renewable energy sources, catering to the growing demand for sustainable and reliable energy solutions in coastal areas. The important features of our design that differentiates itself from existing solutions include: i) adaptability to varying wave conditions: The system incorporates a dynamic length-adjustment mechanism, enabling it to efficiently capture energy from waves of different heights and adapt to tidal fluctuations; ii) dual-generator design: The dual-generator configuration with separate slider arms enhances the system's reliability and robustness, ensuring continuous power generation even under challenging conditions; iii) modular and scalable design: The modular nature of the system facilitates easy installation, maintenance, and scalability, allowing for tailored deployments based on specific energy requirements and site conditions.

Hence, based on our team’s research, we think our product can mainly target following market opportunities:

1. Coastal communities and islands: These areas often face challenges in accessing reliable and affordable energy sources, making them ideal candidates for implementing marine energy solutions. The proposed system can provide a consistent and sustainable source of electricity, improving energy security and reducing reliance on fossil fuels.

2. Offshore installations and marine vessels: The marine energy system can be adapted to power offshore platforms, such as oil rigs, research stations, and marine vessels, reducing their carbon footprint and increasing their energy self-sufficiency.
3. Grid-connected coastal regions: In areas where the electricity grid extends to coastal regions, the marine energy system can contribute to the overall energy mix, complementing other renewable sources and reducing the reliance on fossil fuel-based power generation.

Since our design has a scalable structure and relatively simple operation mechanism, the cost of manufacturing, installation, ongoing maintenance, repairs, and personnel expenses will be predictable and controllable. The financial incentives and subsidies offered by state/federal government for renewable energy projects could potentially further reduce the overall system cost and contribute to a more competitive pricing strategy, which will be determined through a comprehensive analysis of production, installation, operation, and maintenance under selected location and ocean wave conditions. Although it is difficult for the team to estimate the total cost, the potential high initial investment of such renewable energy project can be recovered by the long-term cost savings and benefits compared to traditional energy generation.

The global marine energy market is projected to experience significant growth in the coming decades, and according to a public report, the marine energy market is expected to reach $6.7 billion by 2028, with a compound annual growth rate of 15.6% during the forecast period of 2021-2028. Given above features of our design and market potential analysis, we believe the proposed wave energy harvesting system offers unique advantages, such as its adaptability to varying wave conditions and dual-generator design, which can help position itself as a viable and competitive solution in the growing marine energy market.

<u>Development and Operations</u>

To ensure successful implementation and long-term viability of the proposed design, the manufacturing, deployment, and operation phases require careful planning and consideration of various factors. In the manufacturing and fabrication stage, our design has a relatively simple structure and operation mechanism, and its key components, including turbines, generators, control system, and structural elements, can be produced, where the funds would be needed for material costs, labor expenses, and production overhead. Since we only developed the bill of materials (estimated cost) of a full-scale system, next step of manufacturing and implementation will need explore collaborations with established energy corporations or governmental organizations to leverage resources, expertise, and funding for scale-up and accelerated development. As a new design, we also believe that it is critical to mitigate risks associated with initial technology adoption costs, competition from other renewable sources, and saltwater exposure through strategic trials, proof of concept demonstrations, and corrosion-resistant materials. Besides, repair and maintenance costs, insurance, regulatory compliance, and personnel expenses should also be well assessed and evaluated as part of the operational expenses before moving into manufacturing and implementation phase. We think the main technical barrier for our project implementation is the how to maintain the structural durability under the harsh ocean environment. We found it was very challenging to conduct optimization design without sufficient knowledge on the ocean environment of selected installation locations and cyclic loading in real seawater. In addition, we think the transmitting the generated power from the energy system to shore-based distribution systems may require complex and costly subsea cabling infrastructure, which is also an uncertain technical barrier in our current design.

The maintenance schedules for our designed systems may vary with locations and operating conditions due to the unique challenges posed by the marine environment as mentioned above. Different from other non-marine-energy power sources, we might have to consider the impact of saltwater exposure and potential corrosion. In average, we estimate that an annual maintenance would be sufficient for our design to ensure the system's continued efficient operation based on our fatigue and cycle life modeling analysis.

This developed design will bring social impact, regulatory compliance, and environmental impact. It can provide reliable and clean energy sources to local communities, supporting economic activities and infrastructure development, but meanwhile, it could bring disturbances to marine habitats. It is important to implement measures to minimize impacts, including site selection, collaboration with environmental organizations, low-impact installation methods, exclusion zones, and habitat restoration initiatives.

Financial and Benefits Analysis

The proposed marine energy system presents a promising opportunity for sustainable and cost-effective energy generation, offering both financial benefits and ancillary advantages. To provide an overview of the financial potential and associated benefits, the required capital, financing considerations, and key assumptions are summarized in below for this proposed project:

The initial capital investment could be composed of R&D, manufacturing expenses, site preparation and infrastructure installation. Based on our bill of materials, we estimated the initial investment for research, design and testing would cost $0.2M, while the manufacturing and fabrication expenses might depend on how many systems will be installed, roughly estimated cost of multiple systems could be $2M. The revenue generation and operating expenses depend on the selected location, which are hard to estimate, but the marine energy system will generate revenue through the sale of electricity to local communities, utilities, or national grids. Besides, depending on the region, the system may be eligible for renewable energy credits or incentives, providing an additional revenue stream, and various government programs may offer financial incentives or subsidies to support the development and deployment of renewable energy technologies, further enhancing the project's financial viability.

In this financial analysis, the key assumptions we made is scaling up from single system to multiple systems, which requires additional capital investments but will lead to cost reduction through economies of scale and technological advancements. The ancillary benefits of this design project include environmental sustainability, energy security and resilience, and local economic development.

II. Design Section

Design Concept and Objectives

The goal of our design is to convert the up and down motion of waves into consistent and harness-able mechanical power using a four-bar mechanism (as shown in figure 1). The mechanical power generated by the waves will serve as input to a generator which will convert it into electrical energy.

The design components include:

1) Power Production Component - A buoy moves up and down with the wave motion, driving a four-bar mechanism with a rotating crank arm; The four-bar mechanism has a length-adjusting cylinder to accommodate varying wave heights and tidal changes; The rotational motion from the crank is transmitted through a gearbox to step up the speed for the generator input.

2) Power Needs and Load Analysis - The design is intended to operate at 30 feet depth with ideal 2-foot wave heights every 14 seconds; A 6-foot diameter buoy with 3000 lbs maximum buoyancy force was used for mechanical load analysis; The torque on the generator input shaft is calculated to be 3,407 W maximum power under ideal conditions; The overall system efficiency is estimated to be about 30.9% based on the theoretical wave power (the harvested energy is 100% from marine energy).

3) Power Storage and Consistency - A flywheel is included on the generator input shaft to provide energy storage and maintain a consistent rotational input to the generator; Ensuring a consistent power supply allows the generator to operate at maximum efficiency and prevents damage from fluctuations.

Our design utilizes the wave motion through the buoy and four-bar mechanism to generate rotational mechanical power, which is then stepped up and transferred to a generator for electricity production. The length-adjusting cylinder, gearbox, and flywheel components enable handling varying wave conditions while providing consistent power input to the generator.

In the past year, there was one team from our university joined MECC 2023, but their design was trying to harvest deep-sea current energy and is a quite different concept from our team's design, which targets wave energy. We are completely new to the MECC and don't have any previous team members in the team, although we learned from them regarding the competition event and educational opportunities.

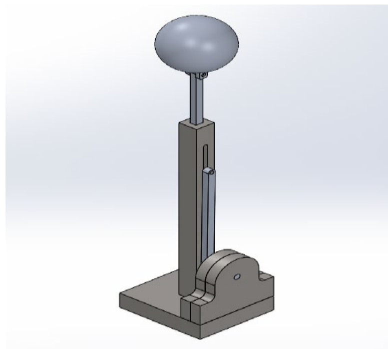

Figure 1 A SolidWorks model of our design

Performance Analysis

The wave energy converter is designed to operate at depths of 30 feet with ideal wave heights of 2 feet every 14 seconds. The rotating arm that inputs the rotational energy into the gearbox is 2 feet in length to match the wave height. With a wave period of 14 seconds, the gearbox was designed to speed up the rotation to the 180 RPM typical hydro generator requires. The gearbox consists of two 45 toothed gears, two 15 toothed gears, one 80 toothed gear, and one 16 toothed gear each with a pressure angle of 20. This results in a gear ratio of 1:45 from the input of the arm to the generator. The diametral pitch of 5 was chosen for the gears as it provided enough of a face width for the contact stress to be within a reasonable amount. For the scale model developed, a diametral pitch of 12 was used, resulting in smaller gears. When determining the mechanical loading of the full scale 30-foot model, a buoy with a diameter of 6 feet and maximum buoyancy force of 3000 lbs was used as the load in the SolidWorks simulations. This force of 3000 lbs was applied to the top of the piston in an upward direction to simulate the pull of the buoy onto the piston. The factor of safety on the driving arm that is attached to the piston from this force was found 4.6 with a maximum stress of 4.6 MPa. Assuming the maximum buoyancy force is exerted on the rotating arm of the gearbox, the torque the input gearbox shaft experiences is determined with the following equation,

$$P = \tau * \omega \quad (1)$$

Where is the torque applied to the shaft in N*m and is the angular velocity in rad/s. Under ideal conditions, the maximum power sent into the input shaft is 3,407 W. A typical spur styled gearbox has an efficiency of 95%, resulting in a total power of 3237 W. The total energy that can be captured by a wave can be formulated by,

$$P_{max} = \rho g H^2 Tp/16 \quad (2)$$

The H, in the equation represents the height of the wave measured from its trough to its crest or twice that of the wave's amplitude. The period of the wave is represented with the Tp variable. The maximum accessible power potential of a wave with an amplitude of 2 feet was found to be 10,465 W. This results in an overall system efficiency of 30.9%, and the harvested energy is all from marine energy. The generator itself will have its own conversion efficiency in turning that mechanical power into electrical power. Assuming an off-the-shelf permanent magnet generator with 90% efficiency, the full waves-to-electricity system efficiency is: 30.9% * 90% = 27.8%. While not outstanding, this level of overall energy capture is reasonable for a wave energy system capturing power from the oscillating waves. It leaves room for further optimization of the design, such as optimizing the buoy size/shape to better couple with the incoming wave energy, using a nonlinear rack and pinion geometry to better match the oscillating wave motion, and reducing frictional losses in the mechanical drivetrain.

Cost Competitiveness Analysis

The capital costs for constructing and deploying the marine energy system are significant upfront. However, the long-term operational costs are relatively low since the "fuel" (ocean waves) is free. This tilts the economics in favor of the system in markets with high electricity prices and strong renewable energy incentives/subsidies. Based on our study, there are several key cost factors:

- Capital costs: System manufacturing, installation, grid interconnection, permitting, etc. Estimated at $3-5 million per MW of capacity for current wave energy technologies.
- Operating costs: Primarily maintenance/repairs of the offshore equipment. Roughly $100k-$200k per MW per year.
- Energy storage costs: Integrating battery storage to mitigate variability can add $200-$400 per kWh of storage capacity.
- Revenue streams: Sales of electricity, renewable energy credits/certificates, tax incentives, etc.

For the potential markets of island/coastal communities with electricity prices of $0.25-$0.40/kWh and strong government support for renewables, the marine energy system could be cost-competitive compared to fossil generation over its 20–30-year operating lifetime.

If supplemented with low-cost battery storage to improve consistency (e.g. 2-4 hours at rated output), the system could reliably supply demand at a levelized cost in the range of $0.15-$0.25/kWh depending on financing rates. This is likely higher than current solar PV-battery systems in areas with good solar resource but could be cost-effective for coastal markets with poor solar insolation.

In summary, we believe the developed the marine energy system has the potential to be an economically viable renewable source in the target markets if capital costs can be reduced through technology maturation and scale. Securing financing and optimizing the conversion capacity to storage ratio for each deployment site will be critical.

Mechanical Loading, Power Requirements and Load Profile

As described above, our wave energy harvesting system is designed to operate at 30 ft depth with ideal wave conditions of 2 ft wave height every 14 seconds. Its key mechanical loading and power parameters include:

1) Buoy diameter of 6 ft with maximum buoyancy force of 3,000 lbs, which is applied vertically upwards on the piston and results in a factor of safety of 4.6 on the driving arm (max stress of 4.6 MPa);

2) Torque on input gearbox shaft calculated as 3,407 W assuming max buoyancy force, and after 95% efficient gearbox, 3,237 W power can be transmitted to generator, which likely operates most efficiently around 3,000 W output.

Although the power input might be discontinuous resulting from the oscillating wave motion, generator can still operate at relatively constant 3kW output by balancing flywheel inertia on generator input shaft. The connection between the buoy and drivetrain uses a sliding cylinder with holes to let water in/out. This accommodates the +/- 0.1% wave height variations while still providing relatively constant force transmission for >99% of each wave cycle.

Besides, to withstand operating forces and moments in the ocean, the buoy size/shape is designed for hydrostatic stability (6ft diameter and >3000lbs of buoyancy force). The gears in the gearbox will utilize 20° pressure angle and diametral pitch of 5 to ensure faces can handle transmitted forces without pitting or wear, while the shafts and bearings selected will be based on transmitted torques and operating speeds.

In summary, we think the design has sufficient structural safety factors to handle the wave loading forces. The gearbox steps up the input speed to the generator's optimal operating range. And the flywheel provides inertial energy storage to smooth the oscillating input into steady generator output.

<u>Technical Design to Adress the Power</u>

The primary concept behind this design is converting each up and down motion of a buoy into one rotation of a crank using a four-bar mechanism. One issue identified with using a four-bar mechanism to convert wave motion is that a four-bar mechanism has a specific length that must be reached to continue through its rotation. Ocean waves will each have some variation in height between each wave, as well as a large overall difference between low tide and high tide height: if the wave height difference is less than the critical four-bar length, the crank will wobble back and forth but not rotate. If the wave height exceeds the critical four-bar length, the buoy will be pulled underwater, the rotational motion of the four-bar would be lost, and if the wave does not drop low enough then the four-bar would not rotate forwards or backwards. For these reasons, a four-bar mechanism with all fixed lengths would not be sufficient to provide consistent power to the generator.

To remedy this issue, one of the links of the four-bar has been designed to vary in length and adjust for wave height and overall tide differences. This is done by including a cylinder on the link that is open to the ocean on both sides of the piston (figure 2). The compression and extension of the cylinder is limited by the amount of water that can escape through the holes in the cylinder. A maximum allowable compression or extension of the cylinder link was calculated based on the predicted number of waves per tide. Roughly 1500 waves are expected per tide cycle based on an estimate of 14 seconds between each wave, and 6.25 hours between tides. To allow for the cylinder to reliably adjust to a full tide, one-thousandth of the total height was selected to be the maximum height adjustment with each wave. The force exerted by the buoy was calculated using the buoyancy of the buoy when half-submerged. While the force from the buoy would lag or lead the system depending on its location during the wave cycle, these values would require complex analysis, so a more generalized value was used. The actual force could be determined to model a real situation to create a system more suitable to the regional needs. The velocity of the water leaving the cylinder, the piston dimensions, and the power lost during a height adjustment of 0.01% were used to inform the size of the holes which would allow water to escape from the cylinder. Since the maximum distance the piston can travel is limited by the inflow and outflow of water, which can be modeled as an incompressible fluid, the piston can still provide force and act as a rigid body during motion. Calculations support that the loss of energy associated with 0.1% height adjustment per wave is small, falling at 24 W per wave cycle or rotation of the crank.

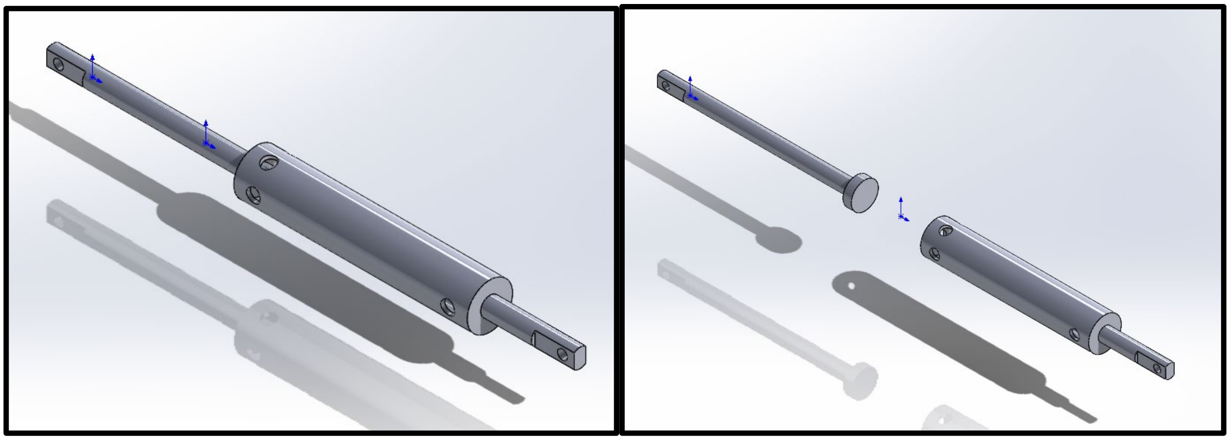

Figure 2. Cylinder Design

The slow rotational motion of the crank is passed through a gear train to step-up the rotational speed to a workable speed for the generator. The presence of a large flywheel on the input shaft of the generator will provide energy storage and maintain a constant rotational input to the generator. Providing the generator with a consistent supply of power ensures that the generator is working at the speed where it is most efficient and minimizes the wear and risk of damage to the generator.

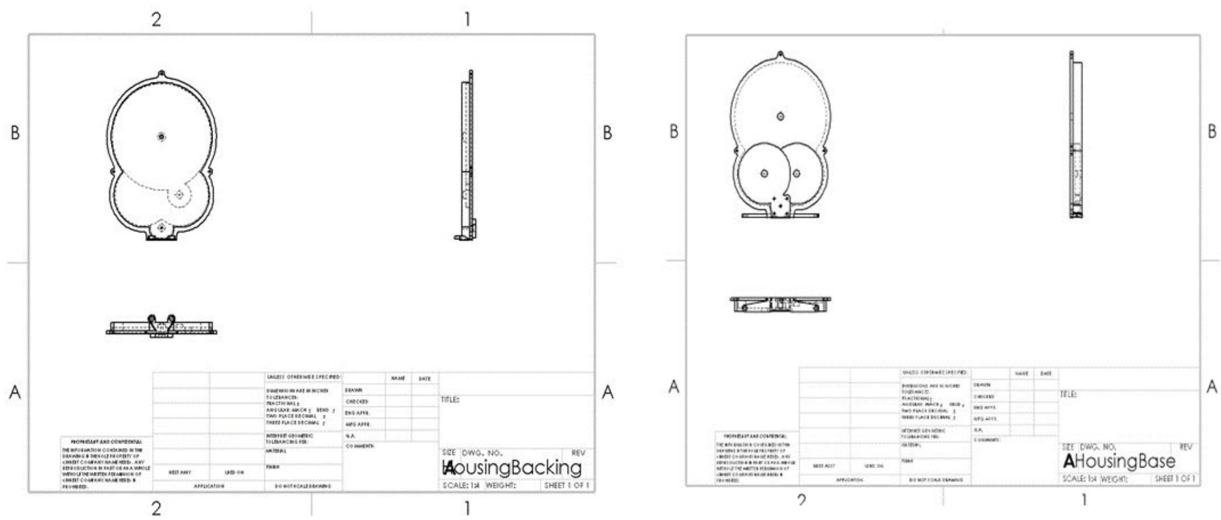

Figure 3 Gearbox Housing

The detailed engineering drawings of our design are based on a 1/15th scaled prototype of the 30-foot design with a gearbox and stepper motor to function as the generator. The gearbox housing is split into two and has three small bolts attaching the sides together. In addition to this, each side has two downward facing bolts to secure each side of the gearbox to the base (as shown in figure 3). A diametral pitch of 12 was used with a shaft diameter of 5/16 of an inch. The final gear in the gear train has a shaft diameter of ⅛ of an inch so that it can fit onto the shaft of the stepper motor. The gears can be seen in the figure 4,

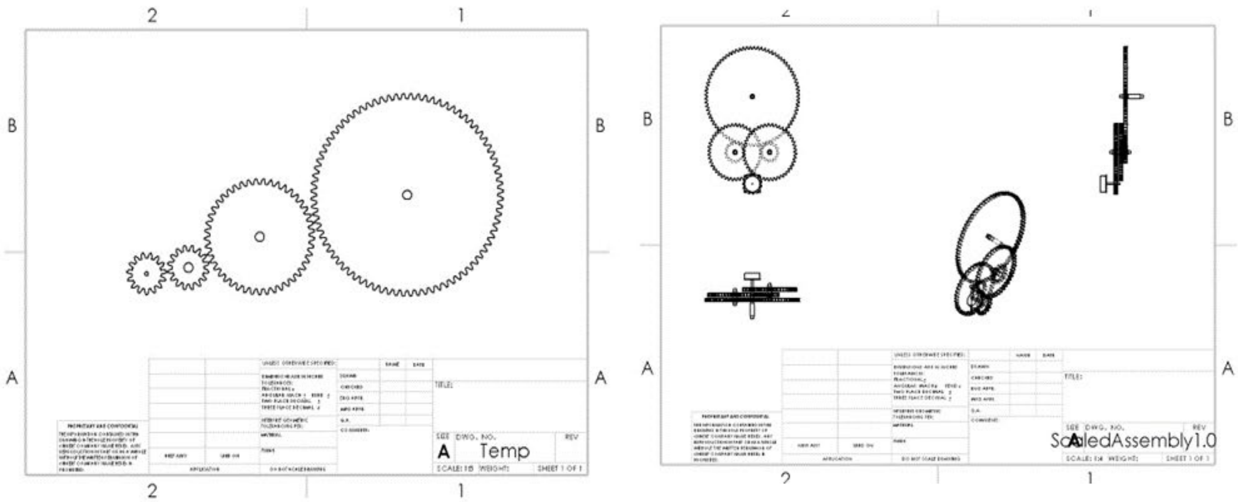

Figure 4 Gear train of the system

In addition to these components, a housing for the stepper motor was also constructed and designed so that it can be bolted on the back of the gearbox and to the base (figure 5, 6). The design also allows the use of gaskets between the components to allow for a watertight seal. The bearings used in the scaled model are double sided ball bearings with an inner diameter of 5 mm and an outer diameter of 11 mm. These bearings are to be placed within the gearbox and will enable gear shafts to rotate freely. The overall design is shown in figure 7.

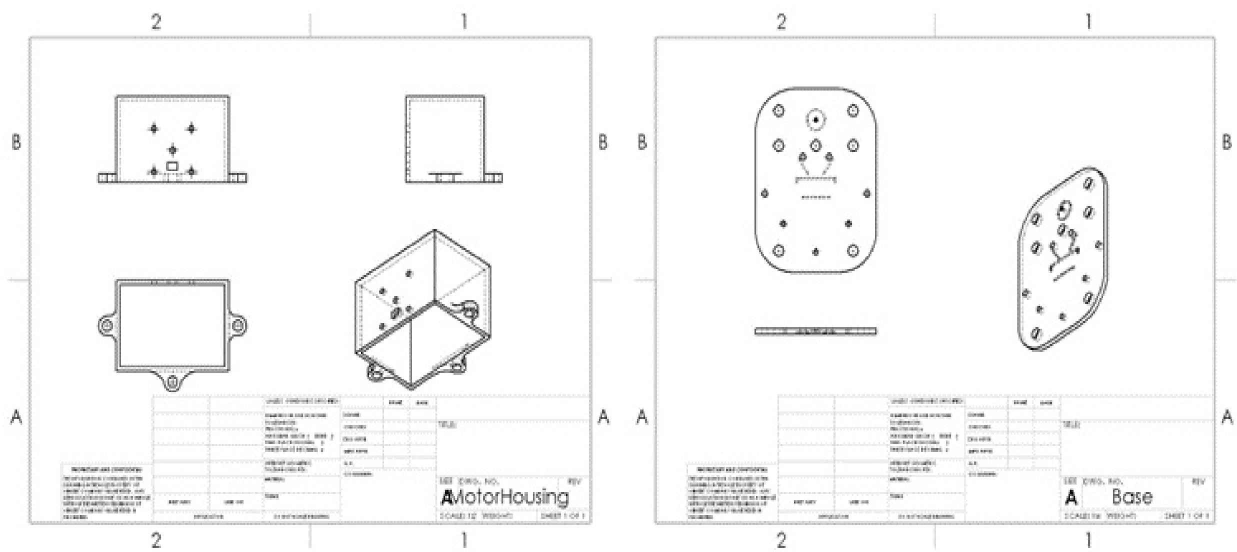

Figure 5 Motor Housing and Mounting base

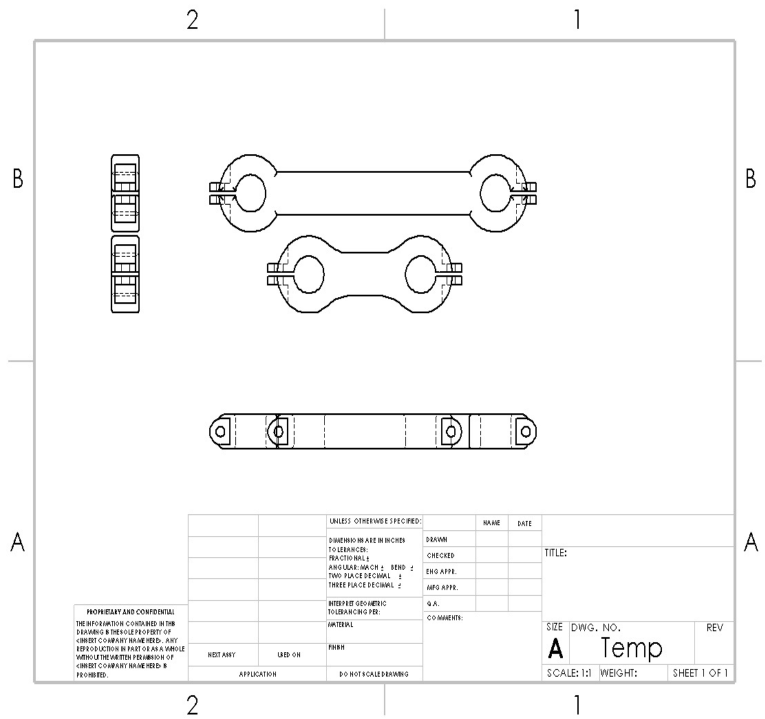

Figure 6 Four bar mechanism arms in prototype

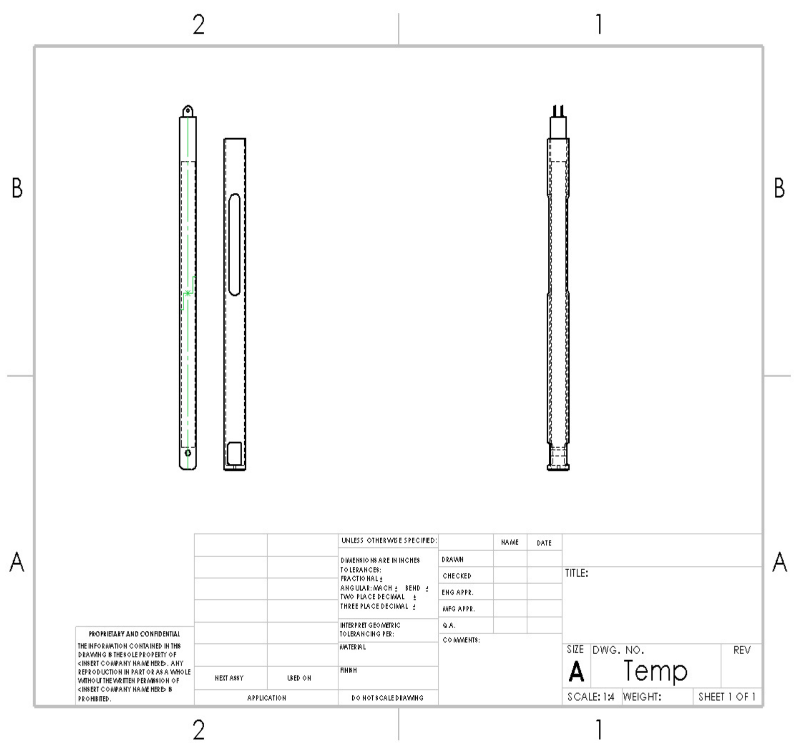

Figure 7 Piston and piston sleeve in 1/15th scaled model

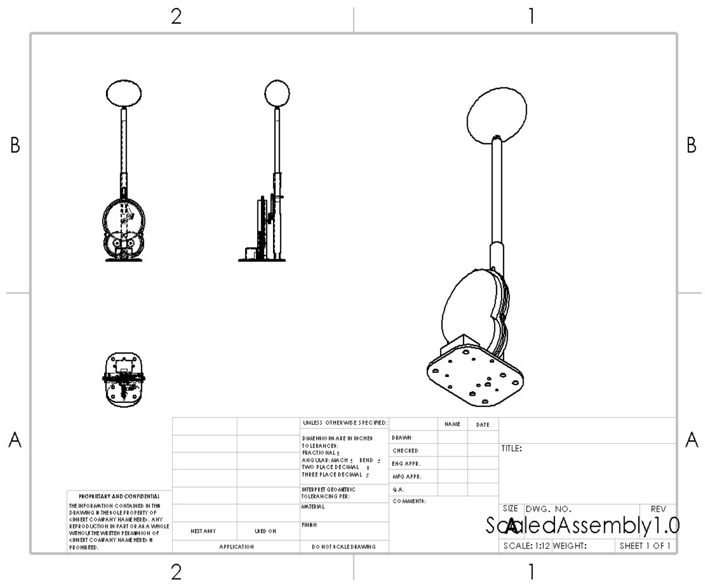

Figure 8 Drawing of overall design

Design Summary

In this design, our team developed an energy harvesting device to convert ocean wave motion into electricity through an innovative design a sliding piston and four-bar mechanism connected to a buoyant surface buoy. As waves raise and lower the buoy, the adjustable geometry can accommodate varying wave heights by the controlled cylinder. This oscillating motion drives a dual-arm crank mechanism that spins a flywheel coupled to an electrical generator. The flywheel smooths the power input to enable consistent generator operation. A gear train with a ratio of 1:45 steps up the crank rpm to the generator's optimal speed. The overall mechanical drivetrain is designed with appropriate factors of safety per offshore codes, while the buoy and mooring provide hydrostatic stability. The design allows broad operation across varying wave conditions while decoupling for storm survivability.

III. Build and Test Section

Fabrication Plan

As described in our design section, we developed two prototype designs: a 1/15th scale prototype design for initial testing and proof of concept and a full-scale design intended for ocean deployment. The scaling factors employed here for small-scale prototype allowed the team to cost-effectively produce and test a working physical model before committing resources to the full-scale deployment. While the small-scale utilizes different materials, the underlying mechanical design, motions, and energy conversion principles remain like the marine-rated version. The detailed fabrication plan of both designs is summarized below:

For the 1/15th scale prototype, we used 3D printer to print parts and components, and its detailed fabrication plan is: 1) Make sure the 3D model is printable, considering print orientation, overhangs, support, and assembly. 2) Split large components into sections if they are over the printer's volume. 3) Select a suitable material for printing, PLA is sufficient for prototyping purposes, ABS is another specialized filament for functional parts exposed to water. Polypropylene(PP) is also another filament that is considered water resistance. 4) Ensure the printing parameters for each component, including height, infill density, thickness, and printing speed. 5) Start printing individual components with the selected material and specifications. 6)

For the gear train and flywheel, use a material with high wear resistance and greater weight respectively. 7) Test assembling components to ensure alignment and functionality. 8) Assemble the printed components, for permanent joints, use adhesives for the material and for non-permanent use hardware. 9) Install any bearings, shafts, or other motion components. 10) Mount the gear train and make sure it's free to move. 11) Use a small motor to generate power. 12) Test the mechanical movement of the prototype to make sure the four-bar mechanism and piston are functioning properly. 13) Conduct load tests to see how they handle stress. 14) after assembled, place the system in a small body of water that has waves and ensure that it is working as intended.

For the full-scale design, it will utilize dimensions and materials suitable for harsh marine environments, such as 316 stainless steels for major structural components like the 10ft x 10ft base plate, center post, piston arm, and pinned joints. The 8ft diameter buoy is designed to be constructed from a durable plastic composite. The developed fabrication plan is: 1) The base plate is a 10 ft by 10 ft plate that will be made of 316 stainless steels to ensure durability and strength of the system. 2) The thickness of the base plate will be 9.144 inches of 316 stainless steel. 3) The gear ratio for this design is 1:45 and we'll be using a compound gear train. The material for the gear train will be made of duplex stainless steel. 4) The housing for the gearbox will allow also be made of stainless steel. 5) The fly wheel that will be utilized in the system will be made of 316 stainless steels. 6) The center post that will be placed on the base plate will be made of 316 stainless steel and will stand at a height of 244 inches. 7) The base plate and the center post will be welded together. 8) The piston arm that will be holding the circular buoy is also going to be made of 316 stainless steel and will be 6.1 inches thick. 9) The circular buoy will be 8 ft in diameter and will be made of a plastic composite. 10) The pins that are utilized in this assembly will also be made of stainless steel. 11) After assembling this contraption will be placed in the ocean and a test will be run to ensure that power is being generated. 12) An ideal place for this contraption to be placed is in the depth of the ocean where there is a strong ocean tide to allow for the system to generate the maximum amount of power.

Testing Plan

To validate the design's ability to effectively convert wave motion into rotational mechanical power, the team developed a comprehensive testing plan for the 1/15th scale prototype model: 1) Initial Testing: assemble and test movement of the 4-bar mechanism and adjustable cylinder link to conduct basic load testing by applying forces to simulate buoy motion and Ensure smooth operation of the gear train, flywheel, and generator coupling; 2) Wave Pool Testing: construct or utilize a small wave pool or tank to produce repeatable wave conditions, then install the prototype model and buoy at the appropriate scaled depth and measure rotational speeds achieved at the generator input under various wave frequencies/amplitudes. At last, quantify power output and overall cycle-to-cycle efficiency. 3) Instrumentation and Measurements: utilize a marine load cell to measure forces applied by the simulated buoy, employ rotary encoders or tachometers to measure rotational speeds at key points, then record generator output characteristics like voltage, current, electrical power, and utilize a wave probe or depth gauge to quantify wave conditions.

By executing this test plan in a controlled wave environment, the team can collect critical data to characterize the performance of their scaled prototype across a range of simulated sea wave conditions. This allows comparison against theoretical predictions and identifies areas for design improvement before scaling up.

Prototyping and Testing Results

For the initial prototype, the primary objective was to validate the mechanical functionality of the design. Considerations regarding material durability in saltwater conditions were not prioritized at this stage. The fabrication process employed 3D printing using polylactic acid (PLA) filament to create a scaled-down iteration of the system. This additive manufacturing technique facilitated rapid prototyping, design adaptability, and minimized material waste. The fabrication process involved identifying key functional requirements, designing a gear train system to meet those requirements, and scaling down the parts for 3D printing. An Ender 3 Pro 3D printer with a 0.4 mm nozzle and 220 mm x 220 mm print bed were utilized. Some components required sectioning due to the limited print bed size and were reassembled after printing. The slicing software UltiMaker Cura was used, with optimized settings such as a print speed of 50 mm/s, printing temperature of 210°C, and build plate temperature of 75°C to ensure consistent print quality. In addition to the 3D printed parts, off-the-shelf components like bearings were sourced from third-party vendors and integrated into the prototype assembly using fasteners for a streamlined process.

A scaled-down prototype facilitated experimental testing and design refinement. Table 1 has listed the materials used for this small-scale prototype. The use of PLA filament, although not suited for prolonged saltwater exposure, was appropriate for evaluating the prototype's functional mechanics. Additive manufacturing enabled rapid iteration and optimization of the design through cost-effective and precise prototyping.

Table 1 Material list for the Prototype

Component	Part Number	Manufacturer	Vendor
Ball Bearing 7 mm x 14 mm x 5mm	a18060900ux0385	Uxcell	Amazon
Ball Bearing 5 mm x 11 mm x 5mm	a18062800ux0226	Uxcell	Amazon
Phillips Screw 3-56 Thread Size	91772A905	McMaster-Carr	McMaster-Carr
Steel Socket Head 3-56 Thread Size	9004A249	McMaster-Carr	McMaster-Carr
Low-Strength Steel Hex Nut 3-56 Thread Size	90480A041	McMaster-Carr	McMaster-Carr
PLA Filament 1.75 mm	HJ-PLA Pro-175W1KG -US	3DHoJor	Amazon

The prototype was tested in a small pool environment, with manually simulated waves created using a ring buoy at a rate of five waves per minute, approximately half the rate of typical coastal waves. This slower rate allowed the system to complete its motion cycle before the next wave. The primary objective was to ensure consistent rotation of the crank mechanism to generate power. To evaluate the gearbox efficiency, the input arm was rotated at the expected 4 RPM induced by waves, and the voltage and current output of the motor were measured using a multimeter. The gearbox housing was marked to track the arm's position during testing (figure 9). The minimum torque required to initiate rotation in the gear train was determined by securing weights onto the large gear until motion was achieved. The torque was calculated based on the weight and moment arm length. Additionally, the buoy's buoyancy force was tested by submerging it in a water-filled bucket and adding weights until it reached equilibrium near full submersion. The maximum supported weight indicated the buoy's upward force potential (figure 10).

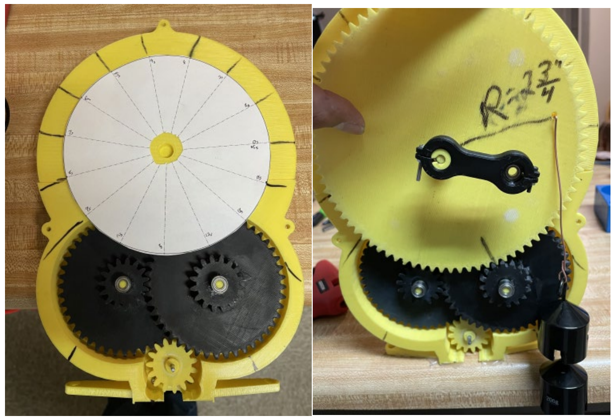

Figure 9. Gear train and torque tests.

Figure 10 Buoy completely submerged and stationary (left), Buoy with weights attached (right)

Numerical simulations using SolidWorks software were also conducted to assess the buoyancy force on the buoy and analyze the structural integrity of the connection point based on the calculated force (figure 11). This prototyping and testing phase allowed the team to verify the functionality of the four-bar mechanism, identify areas for improvement, such as reducing friction and accounting for material density differences, and gain insights into the potential challenges of the full-scale system implementation.

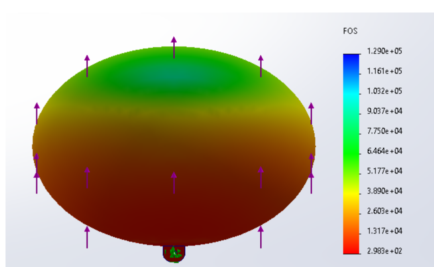

Figure 11 Numerical calculation of prototype buoyancy force

The experimental analysis of the gear train showed that many improvements can be made on the design and highlighted some of the drawbacks of using PLA filament as the material. Three trials were conducted to determine the voltage and current output of the system when given an input rotational speed of 4 RPM.

The following two equations allow for the input power to be calculated with the torque applied and angular velocity of the arm and for the output power of the motor to be calculated from the voltage and current readings:

$$P = 2\pi (N\cdot\tau)/60, \; P = I\cdot V$$

where τ is torque in Newton-meters and N is rotational speed in RPM in the first equation; and I is current in amps, and V is voltage in volts in the second equation. The ratio of the power output to the power input to the system provides the efficiency of the gearbox:

$$\epsilon = (I\cdot V)/(2\pi (N\cdot\tau)/60)$$

The testing results are summarized in the table 2 below,

Table 2 Power output of motor

Trial Number	Voltage (mV)	Current (mA)	Power (μW)
Trial 1	39	0.01	0.39
Trial 2	45	0.01	0.45
Trial 3	42	0.01	0.42
Average Power Output			0.42

The actual power inputted to the system is found by calculating the torque applied to gear by the weights and applying equation (1). The moment arm used for the experiment had a length of 2.75 inches and the mass needed to induce motion was 400 g. The mass of the weight multiplied by the acceleration due to gravity gives the force on the gear of 3.924 N, which results in a required torque of 0.274 Nm. With this information, along with an expected speed of 4 RPM, the power inputted into the system was found to be 0.1148 W. This indicates that the efficiency of the gearbox is extremely low. This means that most of the power is lost to vibrations in the gearbox and fiction between gears, gear shafts, and gearbox housing. The results from the buoy test showed that the buoy should produce enough buoy force to rotate the gearbox. The maximum mass that the buoy was able to support was 1090 g before sinking to the bottom. Since the gearbox required 400 g to rotate, the buoy shows promise that it will be able to provide the upward force necessary to operate the small scaled generator. The drastic difference in results from the analytical buoyancy result and the experimental might be due to the trapped air inside the buoy that provides additional upward force.

Build and Test Summary

Throughout the build and testing process for the initial 1/15th scale prototype, the team gained invaluable experience that will inform future design iterations:

- Explore alternative 3D printing materials like Nylon for increased strength and thermal resistance.
- Implement a modular multi-piece design for the larger scale to simplify manufacturing.
- Investigate investment casting or other production methods for the stainless components.
- Develop a more sophisticated wave generation system capable of programmable profiles.
- Implement wireless sensors and data acquisition to improve measurement accuracy.
- Explore installing a torque transducer to directly measure power transmission.

The design improvement should consider optimizing gear train design for higher efficiency power transmission, investigating alternative buoy geometries for increased energy capture, and adding a reactive spring/damper system to help smooth the buoy motion.

By applying these lessons learned from the successful prototyping phase, the team can refine their marine energy system design for enhanced real-world performance and preparedness for large-scale production. A second design iteration incorporating these improvements would undergo another thorough build and test cycle before finalizing for commercial deployment.

Acknowledgement

We gratefully acknowledge the support from MECC24 (NREL & DOE) on this project. Team also thanks our faculty advisor's great support and help. We also acknowledge our industrial mentors' valuable advice and discussion during the project.