Wave Energy Converter for Data Buoys

DOE MECC Written Report 2024

University of California Riverside

Cover Sheet

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5,400-word report describing the Business Plan Challenge.
7,500-word report describing the Technical Design Challenge.
5,000-word report describing the Build and Test Challenge.

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1. Executive Summary

The UCR Marine Energy Harvesting (MEH) project represents a collaborative effort between multidisciplinary teams, encompassing mechanical engineering (ME), electrical engineering (EE), and business students. Our goal was to design, build, and test a prototype device capable of harnessing wave energy to generate electricity efficiently while also exploring potential market opportunities and business strategies. This executive summary encapsulates the key findings, challenges, and future directions derived from each phase of the project: business analysis, technical design, and build and test.

The business team undertook a comprehensive market analysis to evaluate the feasibility and potential market opportunities for our wave energy converter. We identified key market segments, including data buoy applications along the Pacific Coast, where our device could offer a reliable, renewable energy solution. Through industry interviews and market research, we gained insights into customer needs, competitive landscape, and regulatory considerations. Additionally, financial projections and cost-benefit analyses provided valuable insights into the economic viability of our venture.

The technical design phase involved intricate engineering considerations to develop a robust and efficient wave energy converter prototype that also has onboard battery storage. ME and EE teams collaborated closely to optimize the device's mechanical and electrical components. Initial challenges, such as incompatible motor torque requirements, were addressed through iterative design improvements. The EE team explored saltwater batteries as a potential energy storage solution, conducting experiments to assess feasibility and performance, subsequently selecting Lithium ion batteries for onboard energy storage. Through meticulous design iterations and prototype refinements, we achieved a functional device capable of converting wave energy into electrical power.

The build and test phase represented the culmination of our efforts, where the prototype was constructed and rigorously evaluated under various environmental conditions. The experimental setup allowed for manual manipulation to simulate wave action, enabling data collection on power input and output, operational performance, and efficiency. Analysis of test results revealed insights into the device's performance characteristics, highlighting strengths and areas for improvement. Despite challenges such as low efficiency and power output, the prototype demonstrated the potential of wave energy conversion as a renewable energy source.

In conclusion, the Wave Energy Converter project represents a significant step towards sustainable energy generation from ocean waves. Our multidisciplinary approach facilitated comprehensive exploration and development of the prototype device, underscoring the importance of collaboration across diverse fields. Moving forward, our team recognizes the need for further optimization and refinement to enhance efficiency and reliability. Future efforts will focus on improving drivetrain configurations, optimizing motor selection, and exploring alternative energy storage solutions. Additionally, continued market research and engagement with industry stakeholders will be crucial for commercialization and deployment of the wave energy converter in real-world applications.

To summarize, the UCR Marine Energy Harvester project has not only advanced our understanding of wave energy conversion technology but also highlighted the potential for renewable energy innovation to address global energy challenges. With continued dedication and collaboration, we are poised to contribute towards a more sustainable and resilient energy future.

2. Business Plan

2.1 Concept Overview

Our business model is centered around the development of a scalable and cost-effective WEC buoy system and onboard battery storage that addresses the pressing need for reliable, accessible, and renewable energy sources in the maritime sector. Our WEC device presents a pioneering approach to generate electrical energy from the relentless motion of ocean waves via direct mechanical drive, aiming to make significant contributions to the realm of renewable energy production. With a focus on both power generation and energy storage, our current device boasts a capacity to generate 20W, with the potential for scalability up to 100W. However, despite advancements in ocean exploration, approximately 80% of the ocean remains unmapped and unexplored, highlighting a critical gap in our understanding of marine environments. The growing demand for navigational and survey instruments underscores the need for reliable power sources at sea, a need echoed by recent initiatives such as the U.S. Department of Energy's funding for wave power research. Our value proposition lies in our proximity to market opportunities, leveraging the vibrant ecosystem of ocean technology entities in Southern California for collaboration and practical applications. Additionally, our device's capability to deploy sensors enhances the range of offshore projects, addressing the challenge of infrastructure limitations in marine energy endeavors. Through innovation and strategic partnerships, our marine energy harvesting device aims to harness the vast potential of ocean waves to drive sustainable energy solutions and advance ocean exploration.

2.2. Market Research

Market Needs

The international ocean observation market, though challenging to quantify precisely, is estimated to exceed $16 billion and is on a growth trajectory. Advancements in technology have led to a reduction in per-unit-sensor power consumption while simultaneously increasing the total number of sensors on platforms, resulting in a net power augmentation. Marine energy devices offer a compelling alternative to solar and wind solutions, presenting the advantage of providing longer-term and more consistent power by harnessing the very environment being measured by sensors. This capability extends to nighttime and high-latitude winter charging scenarios, where other renewable sources might falter. Recent trends highlight a significant uptick in the production of navigational and survey instruments, many of which find application in ocean observation and navigation. With the maritime industry's growing reliance on such instruments, there emerges a heightened demand for power. Marine energy stands poised to address this need by either supplementing power for existing instruments or enabling the deployment of new, higher-power applications, thus reinforcing its role as a vital component in the sustainable advancement of ocean observation and navigation endeavors.

Exhibit 1: Gaps in HF radar coverage

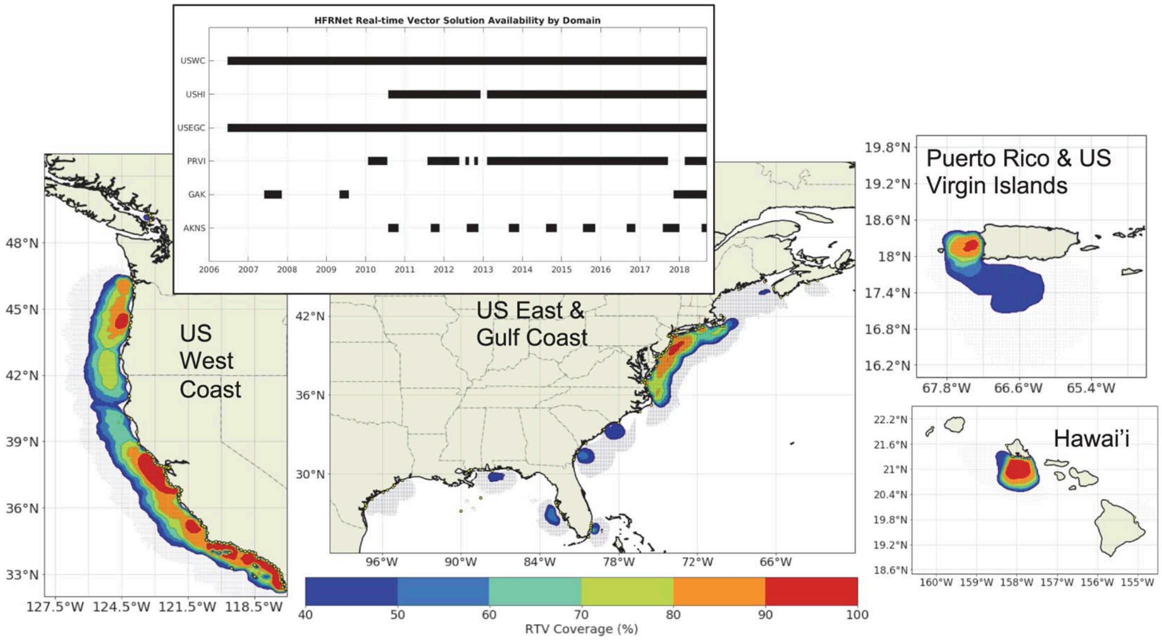


Figure 1: HF Radar Coverage Map. *Source: The Global High Frequency Radar Network*

This map outlines the Global High Frequency Radar Network's geographical coverage, technical design, and importance in collecting surface current data. The network's data is utilized by various federal, state, and local agencies for activities such as search and rescue, hazardous spill response, ocean tidal prediction, and water quality management. Additionally, research and development groups utilize the data to assimilate surface currents into numerical models for forecasting and prediction purposes. Noticeable coverage gaps are evident along the Northern California and Southern Oregon coastlines. This presents an opportunity for the wave energy sector to expand Real-Time Vector (RTV) coverage by deploying offshore power solutions.

Highlighting the imminent future of wave energy, the Biden administration's commitment to achieving net-zero carbon emissions by 2050 emphasizes the imperative of transitioning towards renewable energy sources. This initiative creates a conducive environment for the development and adoption of WEC devices by incentivizing clean energy projects and offering funding opportunities to support research, development, and deployment in the renewable energy sector. The increasing market demand for WEC devices is driven by the need to mitigate climate change, reduce reliance on fossil fuels, and enhance energy security. As governments worldwide implement policies to promote renewable energy adoption, there is a growing market for innovative solutions like marine energy harvesting systems. This demand creates opportunities for our product to address the energy needs of various stakeholders in the maritime sector.

California Senate Bill No. 605 (SB 605): SB 605, enacted in October 2023, mandates the evaluation of wave energy and tidal energy as forms of clean energy in California. The bill requires the State Energy

Resources Conservation and Development Commission to assess the feasibility, costs, and benefits of utilizing wave and tidal energy, in consultation with relevant state agencies. Additionally, the bill calls for the identification of suitable sea space for offshore wave energy and tidal energy projects. This legislation provides a supportive regulatory framework and potential funding avenues for the development and deployment of WEC devices in California. State and federal incentives such as grants, tax credits, and research funding can significantly reduce the upfront costs associated with developing and deploying WEC devices. By leveraging these incentives, we can lower the overall cost of our product and make it more competitive in the market. Additionally, regulatory support and policy initiatives like SB 605 provide market validation and increase investor confidence, enhancing the attractiveness of our product to potential customers and stakeholders. In summary, state and federal incentives, coupled with legislative initiatives like SB 605 and the Biden administration's clean energy goals, create a favorable environment for the development and commercialization of WEC devices. By aligning our product strategy with these initiatives and leveraging available incentives, we can effectively meet market needs, drive adoption, and contribute to the transition towards a sustainable energy future.

Competition: Solar Energy

During an interview with our industry contact Rolle Hogan, co-founder of Calwave's DolphinLabs, it was emphasized that solar energy falls short in ensuring continuous power generation. However, our larger WEC buoy device holds the potential to reach up to 100W with scaling. This highlights the growing viability of wave energy, potentially surpassing solar in the near future. Moreover, while solar power is gaining traction due to the increasing commercial availability of solar panels, its installation process is relatively straightforward. Nonetheless, a drawback of solar power lies in its reliance on a solar source, which can be unreliable in certain regions. As an alternative to solar, marine energy devices offer the promise of longer-term and more consistent power generation by harnessing the very environment they measure. The energy density of moving water far exceeds that of other renewable sources such as wind or solar, making marine energy devices efficient generators of power at sea. When compared to solar renewable power, wave energy presents advantages such as continuous power supply for aquaculture and suitability for operation around the clock, even in high latitudes during winter—situations where solar energy traditionally faces challenges.

Value Proposition

The team's concept aligns with the desires of the target market by offering a solution that mitigates the limitations associated with battery life, material fatigue, biofouling, and instrument calibration drift, which have historically constrained ocean observation systems. Our product enhances the capabilities of existing buoy systems and navigation aids by providing a continuous and sustainable power supply, thereby extending the useful duration of observation and navigation equipment. Our team's innovative device, with its current capacity to generate 20 watts and the potential to scale up to 100 watts, presents a promising solution to address the varying power requirements of ocean observation buoys and navigation aids. While installations typically demand anywhere from 10 to 600 kilowatts, many buoys operated by the National Oceanic and Atmospheric Administration (NOAA) require power in the range of 40 to 200 watts. Recognizing this diversity in power needs, our business model is founded on the development of an adaptable and economically viable buoy system. Engineered to cater to the lower spectrum of market demands, our system is poised to meet the escalating necessity for dependable, accessible, and renewable energy sources amidst the backdrop of ocean navigation data. By offering a solution that aligns with evolving industry requirements, we aim to revolutionize the landscape of marine energy harvesting while enhancing the sustainability and efficiency of ocean observation and navigation endeavors.

Potential Deployment Sites

Table 1: Buoy Data From Deployment Sites

Stations	Wave Height (WVHT)	Average Period (APD)
41113: Cape Canaveral Nearshore, FL	2.6 ft	3.7 sec
46244: Humboldt Bay, North Spit, CA	2.6 ft	4.4 sec
46251: Santa Cruz Basin, CA	3.3 ft	6.0 sec

Source: National Data Buoy Center

Our initial device design was informed by data from the National Data Buoy Center, particularly Station 41113 near Cape Canaveral, FL. This speculative deployment site provided valuable insights for the design and analysis of our device under specific wave conditions. However, subsequent research and market analysis led us to select the Pacific coast for deployment due to various factors, including market opportunities and geographical proximity to key stakeholders. Data from buoys along the Pacific coast, such as Station 46244 near Humboldt Bay, CA, and Station 46251 near Santa Cruz Basin CA, confirms similar sea states suitable for potential deployment sites. Further research will identify relevant wave data needed for site speculation along the Pacific coast, enhancing our market reach and deployment strategy.

Five Year Plan

Year 1:

- Further development and testing of the 1:5 scaled model (20W).
- Continue researching potential customers, focusing on ocean observation, navigation, and low power applications.
- Research permitting requirements and conduct risk assessment for deployment locations.
- Wave tank testing and analysis of the smaller scaled model.
- Secure research and development funding from UCR and other entities.
- Improve the design of the smaller model.
- Continue and finalize the design of the larger 100W model.
- Continue Wave Energy Converter (WEC) modeling and performance via WEC-SIM.

Year 2:

- Develop the scaled 100W model for modulated use or deployment as a farm.
- Deploy the smaller scaled model for low power applications and sensors.
- Conduct wave tank testing and WEC-SIM modeling of the larger 100W model.
- Continue permitting and wave tank testing of the larger model.

- Successfully deploy and grow the client base for the smaller model.

Year 3:

- Successfully deploy the larger 100W model to meet the power demands of high-power clients.
- Further testing and analysis of the larger model's performance.

Year 4:

- Continue deployment of the smaller model and improve its performance.
- Maintain business clients for smaller models.
- Successfully deploy the larger model in the market.

Year 5:

- Continue deploying the smaller and larger models.
- Conduct wave tank testing to improve designs.
- Conduct continuous customer feedback for application improvements
- Assess the feasibility of developing an even larger model to increase market opportunities.
- Consider continuing optimization of current models and focus on farming and modulating aspects.

2.3 Relevant Stakeholders

Stakeholder 1: Investors
During an interview with Jack Pan from Ocean Motion Tech, he highlighted their receipt of non-diluting funding from SBIR, which targets businesses with projects ripe for commercialization. SBIR aided them in securing intellectual property rights and accessing market introductions. This initial funding provided a solid foundation, attracting investor interest and subsequent funding offers.

The Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs, collectively known as America's Seed Fund, allocate over $1.3 billion from their Research & Development Funding specifically for small business initiatives. These programs, administered by the NIH, offer crucial support to early-stage small businesses across the country.

NOAA's Small Business Innovation Research Program (SBIR) is a fiercely competitive grant initiative aimed at encouraging U.S. small businesses to engage in federal Research/Research and Development (R/R&D) endeavors. The ultimate objective is to foster the creation of innovative and commercially viable products or services. By integrating qualified small businesses into the nation's R&D landscape, these programs spur high-tech innovation and cultivate entrepreneurial spirit, thereby addressing the nation's specific research and development needs. NOAA's SBIR focuses on product and service development aligned with its mission areas, offering valuable opportunities for prospective applicants to contribute to NOAA's diverse and essential mission objectives. Prospective applicants are encouraged to explore the provided links and the SBIR section of NOAA's website for comprehensive information on the application process for NOAA's upcoming SBIR funding opportunities.

Stakeholder 2: Permitting authority

To comply with permit requirements, our plan involves obtaining approval for Private Aids to Navigation (PATON), regulated by the U.S. Coast Guard under Title 33 of the Code of Federal Regulations, Part 66 (33CFR66). These aids, including buoys, lights, or daybeacons, are owned and maintained by entities other than the Coast Guard, such as private citizens, marinas, governments, and industrial companies. PATONs serve to mark privately owned marine obstructions or hazards to navigation and are required to be maintained by their owners as stipulated in the Coast Guard permit.

Stakeholder 3: Strategic Partnership with a Private Entity
In our long-term strategy, we aim to provide continuous power to CODAR Ocean Sensors' HF radar systems, which can operate off-grid with low power consumption. This collaboration aligns with our objective of expanding renewable power sources in their portfolio, provided it is financially viable and meets their power demand of 90W, information gained from a professional interview with Daniel So, an electrical test engineer currently working with CODAR. We aim to achieve this objective within the 5-year business plan timeframe.

Stakeholder 4: Strategic Partnership with a Research Facility
The Scripps Institution of Oceanography at UC San Diego holds a prominent position in global earth science research and education. Given our proximity to this esteemed institution, they emerge as a promising collaborative partner as we advance. Their affiliation with the National Data Buoy Center, a division of Scripps Institution of Oceanography, designates them as a crucial stakeholder. This partnership includes their Shore Stations Program, which features the LJAC1 station in La Jolla, California, hosted by NOAA's National Data Buoy Center. This station specializes in collecting meteorological data essential for weather forecasting by entities like the National Weather Service and other pertinent agencies. Through collaboration with them, we can actively contribute to data collection efforts aimed at long-term monitoring of sea surface temperature, salinity, and other ocean sensors along the California coast. The Shore Stations Program gathers and provides access to both current and historical daily sea surface temperature (SST) and salinity (SSS) measurements observed at shoreline locations across the west coast of the United States. Presently, there are only 10 active stations positioned along the California coast, spanning from La Jolla to Trinidad.

Stakeholder 5: Risk Mitigation and Insurance
Gallagher Energy Insurance and Consulting specializes in risk management and insurance solutions tailored to the energy industry, including marine renewables. Collaborating with Gallagher enables us to develop comprehensive risk management strategies to address potential liabilities associated with deploying and operating marine energy harvesting devices. Their expertise encompasses regulatory compliance, environmental risks, and operational challenges specific to marine energy projects, enhancing our project's resilience.

Stakeholder 6: Maintenance and Deployment Partner
Gravity Marine Services offers a fleet of custom vessels tailored for sampling and surveying marine environments. Partnering with them provides access to vessels suitable for deploying, maintaining, and servicing our marine energy harvesting devices. Their experienced staff and specialized resources, including custom sensors and sediment coring systems, are instrumental in optimizing the deployment and operational efficiency of our devices.

2.4 Development and Research

Research and Further Development

During an academic year at the University of California, Riverside (UCR), extensive research and development were conducted for the Wave Energy Converter (WEC) and battery storage devices. Collaborating across departments, teams of engineering students, under the guidance of faculty advisors from Mechanical Engineering and Electrical Engineering, worked diligently to create a scaled model demonstrating proof of concept of the direct mechanical drive WEC. Initially, the aim was to produce 1 kWh of electrical power from mechanical energy stored in waves, with matching onboard storage capacity.

However, practicality constraints led to the adjustment of design requirements to 100 Wh for both energy generation and storage, with an intended design capacity of 150 Wh to accommodate system losses and potential power needs. Market research, team discussions, and insights from existing WEC technologies informed the initial designs, which included considerations for sustainability, such as the use of salt batteries. However, feasibility assessments prompted the adoption of alternative battery storage concepts. The scaled model, approximately 1:5 the final design, was successfully created and tested, validating the proof of concept. CAD models and design specifications for the larger unit were also developed. While the smaller unit holds potential market applications in ocean observation, further improvements and testing are necessary.

Moving forward, additional research should be conducted at UCR, with a focus on flow modeling using software like Ansys fluid flow, and subsequently WEC-SIM, to assess performance in varying sea states, particularly the deployment sites along the Pacific coast. Collaboration with entities like UC Scripps for wave tank testing could expedite the testing process. Development efforts should include extensive waterproofing and testing in ocean or wave tanks to refine the design further. These steps are crucial for advancing the research and development of both the scaled and larger models of the WEC, ultimately paving the way for practical implementation and market integration, as well as development of a market ready product.

Manufacturing of the Smaller Scaled Model (1:5)

The manufacturing process for the smaller scaled model (1:5) will entail advancing upon the prototype design, prioritizing waterproofing and efficiency enhancements. Extensive efforts will be necessary to ascertain that chosen materials can endure harsh marine conditions while optimizing buoyancy. Improvements in manufacturing techniques and material selection will be indispensable to align with design specifications and performance criteria of the scaled-down model, ensuring its effectiveness in harnessing marine energy and practicality in the market.

Manufacturing of the Larger Model

Manufacturing the larger model will entail distinct methods, materials, and manufacturing processes in contrast to the smaller scaled model. The machining and fabrication of components for the larger model will incur greater costs and complexity due to its expanded size and scale. Collaboration with multiple manufacturers might become essential to procure the specialized components and materials needed for constructing the larger model.

Deployment Process

The deployment process will necessitate a vessel with a midsize engine capable of towing the device out to sea and deploying it at the designated mooring location. Considerations for deployment will involve ensuring that the vessel is equipped with the necessary equipment and personnel to safely transport and install the device. Mooring system selection will be crucial, with attention to factors such as sea bottom characteristics, buoyancy requirements, and environmental considerations. Proper spacing of mooring buoys and individual site selection will be essential for successful deployment, with attention to substrate suitability and potential impacts on marine ecosystems. Hydraulic drilling and cementing of anchor pins will be part of the deployment process, requiring skilled personnel and specialized equipment to ensure secure mooring of the device.

Significant Risks

Wave energy conversion projects hold promise for renewable energy generation but come with significant technical risks. This section discusses the identified risks and proposes an approach to managing them effectively. Based on the information provided from the electrical engineering and mechanical engineering team reports and insights from professional interviews, several significant risks have been identified in the project.

The project confronts significant risks, as outlined in the electrical engineering report and gleaned from insights shared during an interview with Rob Cavangaro, a WEC researcher at Pacific Northwest National Laboratory (PNNL). Firstly, there's a pressing concern regarding battery safety due to a lack of expertise in power electronics. Insufficient knowledge of battery circuitry and maintenance heightens the risk of incidents like overcharging or undercharging, potentially leading to gas leakage, fires, or explosions, posing a threat to both the system and personnel. Secondly, the challenge of transferring power from offshore wave energy converters (WEC) to onshore locations, particularly through underwater transmission, raises issues of potential power losses. This necessitates meticulous consideration of cable insulation, connectors, and the likelihood of transmission losses. Thirdly, the selection of suitable materials for the device entails various risks. While titanium offers ideal corrosion resistance for oceanic power transmission, its high cost presents a hurdle. Additionally, seals and washers are prone to wear and tear, which could result in water ingress and component failure. Addressing these risks involves employing non-conducting washers and seals, along with implementing regular maintenance practices. Lastly, mechanical components like mounting plates and sealing screws are vulnerable to fatigue and corrosion in marine environments. Regular maintenance and visual inspections are pivotal in identifying and preventing potential failures that could compromise the system's functionality and safety.

Moreover, the mechanical engineering assessment underscores additional risks crucial to the project's success. Through Failure Mode and Effect Analysis (FMEA), various failure modes across different components of the Wave Energy Converter (WEC) have been identified. These encompass mechanical breakdowns, electrical faults, corrosion, and structural integrity issues, emphasizing the paramount importance of robust design, material selection, and maintenance practices. Specific failure modes highlighted include fatigue-related issues in buoy structures due to cyclic loading, corrosion risks from

UV radiation exposure, and potential water ingress resulting from gasket corrosion. Furthermore, sealing screws are susceptible to corrosion in harsh environmental conditions, leading to structural damage, while mounting plates may experience fatigue-related failures due to cyclic loading. To mitigate these risks effectively, proactive measures such as regular visual inspections, the application of UV-resistant coatings, utilization of high-quality gasket sealants, and adherence to maintenance schedules are indispensable. By integrating insights from both electrical and mechanical engineering assessments, the project can formulate a comprehensive risk management strategy to mitigate potential failures, thereby ensuring the reliability and safety of the wave energy conversion system.

Approach to Risk Management

In navigating the complexities of wave energy conversion projects, a proactive approach to risk management is paramount. Collaborating with specialized entities such as Gallagher can provide invaluable insights and support in mitigating risks associated with battery safety, material selection, and mechanical failure. Implementation of Battery Management Systems (BMS) geared towards preventing overcharging, undercharging, and potential hazards is crucial for ensuring the safe operation of the system. Careful consideration of material properties, including corrosion resistance and durability, during the selection process enhances system reliability, with the utilization of marine-grade materials and design tips from professional interviews optimizing performance. Establishing maintenance schedules and inspection protocols enables early detection of potential failures, facilitating timely interventions and preventing catastrophic incidents. By integrating insights from professional interviews, reports, and leveraging specialized expertise, a proactive risk management approach enhances the safety, reliability, and success of wave energy conversion projects, thereby contributing to the realization of the full potential of renewable energy sources while ensuring operational safety and efficiency.

Technical Constraints

When addressing the question of technical constraints to implementation, several crucial factors come into play. Firstly, battery technology limitations pose a significant consideration, as the chosen batteries must meet energy storage requirements while ensuring safety and reliability. Technical constraints may emerge if the selected batteries cannot deliver the necessary power output and energy capacity needed for the wave energy conversion system. Additionally, power transmission presents challenges, including power losses, cable insulation, and underwater transmission, all of which can affect system efficiency. Material selection is also paramount, with the need for materials that can withstand harsh marine environments, such as corrosion and biofouling, while balancing performance and cost-effectiveness. Furthermore, the mechanical design must withstand wave forces and ensure structural integrity, with premature component failure due to fatigue or corrosion being potential technical constraints. Lastly, regulatory and environmental compliance add another layer of complexity, with requirements such as noise levels and marine habitat protection influencing system design and deployment, thus necessitating careful consideration and adaptation to ensure successful implementation.

Technical, Social, and Environmental Impacts and Opportunities

The integration of wave energy conversion systems into the data buoy sector presents a paradigm shift with significant implications across technical, social, and environmental dimensions. From a technical standpoint, the adoption of wave energy as a power source for data buoys represents a pioneering endeavor, fostering innovation in renewable energy technology tailored to ocean monitoring applications. While conventional power sources like diesel generators are prevalent, advancements in battery technology and the reliability of solar panels have dominated the field. However, the emergence of wave energy converters (WECs) offers a promising alternative, albeit with distinct challenges. Unlike established renewable sectors such as solar and wind, wave energy technology is still in its infancy, characterized by diverse device concepts and power take-off mechanisms. The variability and irregularity of ocean waves pose technical hurdles for conventional electricity generation methods, necessitating innovative approaches to harness wave power effectively. Nonetheless, recent developments by companies like Ocean Power Technologies (OPT) showcase the feasibility of wave-powered data buoys, underscoring the potential of this nascent technology to disrupt the status quo.

Socially, the integration of wave energy into data buoy systems holds promise for fostering economic development and community empowerment, particularly in coastal regions. By creating job opportunities in manufacturing, installation, and maintenance of wave energy systems, the project can stimulate local economies and drive employment growth, addressing pressing socio-economic challenges in Pacific coastal communities. Moreover, community engagement initiatives such as public consultations and educational outreach programs can enhance awareness about renewable energy and empower communities to participate in the transition to clean energy. The project's emphasis on inclusivity and community involvement is vital for ensuring its long-term success and sustainability.

From an environmental perspective, the adoption of wave energy for data buoy applications offers substantial benefits in terms of mitigating climate change and promoting marine conservation. By reducing reliance on fossil fuels and minimizing greenhouse gas emissions, the project aligns with global efforts to combat climate change and transition to sustainable energy sources. Furthermore, wave energy systems have the potential to minimize habitat disturbance and reduce dependence on environmentally harmful energy sources, thereby contributing to marine ecosystem protection. However, challenges such as marine fouling and the control paradox pose significant environmental and technical considerations that must be addressed through innovative design and engineering solutions. The control paradox is important when considering whether sensor data can be properly processed and utilized onboard a WEC that is not stable, such as our intended HF radar application.

In summary, the integration of wave energy conversion systems into data buoy applications represents a transformative initiative with profound implications for energy security, economic development, and environmental sustainability. By leveraging technological innovation, fostering social inclusivity, and prioritizing environmental stewardship, the project has the potential to drive positive change at local, regional, and global levels, ushering in a more sustainable and resilient future for ocean monitoring and renewable energy integration.

Maintenance Intervals

When considering maintenance intervals for UCR's marine energy harvesting device, it's crucial to strategize based on the life cycles of key components to ensure timely maintenance before any critical parts surpass their operational limits, insights gained from our interview with Ryan Coe, a wave energy &

fluid dynamics modeling specialist at Sandia National Laboratories. The goal of the design is to minimize maintenance requirements over the course of one year. The maintenance approach is guided by the mooring guide, which stresses routine inspections and prompt replacement of worn components to uphold system integrity. Maintenance for mooring buoys involves visual inspections, parts replacement, and availability of replacement components to swiftly address any issues. On average, hands-on maintenance for mooring buoys can range from 45 minutes to two hours per buoy per month, depending on specific conditions. Additionally, comprehensive inspections and component replacements should be conducted annually to uphold system reliability.

Comparing this maintenance approach to other power sources reveals distinct differences. Battery and solar-powered systems, prevalent in modern data buoy applications, offer lower maintenance requirements. Batteries used in conjunction with energy harvesting methods require replacement every few years, while solar panels necessitate periodic cleaning to maintain efficiency. While both options require maintenance, the frequency and complexity differ, with battery replacement being more infrequent but costlier, while solar panel maintenance is more regular but less financially burdensome. Therefore, the wave energy conversion project's maintenance strategy aims to strike a balance between reliability, cost-effectiveness, and environmental sustainability, ensuring optimal performance while minimizing operational disruptions.

2.5 Financial Analysis

Our Wave Energy Converter (WEC) and onboard battery storage device has the potential to facilitate the establishment of additional data buoy sites. Traditionally, oceanography has been characterized by discrete data points, with temperature readings and salinity samples collected sporadically. However, the contemporary landscape is witnessing an explosion of data, sourced from various sensors deployed on satellites, drones, buoys, and autonomous underwater vehicles. This influx of data presents both challenges and opportunities. The challenge lies in effectively managing and analyzing this vast information stream. Nevertheless, it also offers an unprecedented opportunity to gain insights into oceanic processes that were once inaccessible.

Furthermore, our WEC device aims to address the lower end of the power spectrum demanded by end-users. The global market for navigational and survey instruments experienced significant growth, more than doubling from $7.5 billion to $16 billion between 2001 and 2011 (Maritime Technology News, 2012). A considerable portion of these instruments are utilized for ocean observation and navigation purposes, indicating a rising demand for power at sea to sustain these systems. Our WEC device is positioned to meet this growing need, thereby capitalizing on the expanding market for maritime power solutions.

Scaled 1:5 Model

Table 2: Material/Component Costs of 1:5 Model

Component	**Approximate Cost ($)**
MEH-1: Buoy Mechanism	$350

MEH-2: Mechanical Drivetrain and Generators	$420
MEH-3: Mooring/Drage Plate/Supporting Structure	$550
Electrical Engineering Team - Battery Pack and Battery Management System	$550
Wave Tank Testing and Refabrication	$5000
Labor Expenses	$2400
Total cost:	$9,270

Description

In our financial analysis of the scaled 1:5 model, we estimated the material costs for each component required for its development. With a senior capstone project budget of $600 per team member, totaling $2400 for the entire project, each team successfully developed their respective components within this budget. However, additional expenses are expected, primarily for wave tank testing, additional re-fabrication, modification, and waterproofing, which we anticipate to be approximately $5000. While the manufacturing costs were minimized as parts were sourced off-the-shelf and pre-manufactured from suppliers like McMaster or sellers on Amazon, assembly and machining costs were not as prevalent. Totalling approximately 24 hours of work among the team members. Assuming an hourly pay rate of $25 for a team of 4, we calculate these costs accordingly.

Moreover, considering deployment and installation alongside existing data buoys would be more cost-effective than creating our own, as the latter would require assessing deployment and mooring costs, which would still be substantial despite the scaled-down model. However, the financial analysis for the larger model will include an assessment of deployment and mooring costs, albeit slightly less than those for the smaller model.

Financial Analysis: Larger Scaled Model

Table 3: Varying Costs for Larger Model

Component	**Approximate Cost ($)**
Stainless Steel (316)	$2750
Linear Low Density Polyethylene (LLDPE) Housings	$1100
AC Generators for Marine Environments	$2000
Battery Pack and Battery Management System	$550

Wave Tank Testing and Refabrication	$5000
Manufacturing Costs	$5000
Labor Expenses	$7200
Mooring Installation and Equipment Costs	$2060 - $31060
Total Estimated Cost	$23660 - $44160

Description

The financial analysis for the larger scaled model considers several factors, including material costs, manufacturing expenses, labor costs, and mooring installation and equipment costs.

Stainless steel (316) is chosen for its durability and corrosion resistance, with an estimated cost of $2750 based on the volume increase compared to the smaller model. Linear Low Density Polyethylene (LLDPE) is selected for the housings due to its strength-to-weight ratio and UV stability, costing approximately $1100. AC generators suitable for marine environments are budgeted at $2000. A new battery pack and battery management system are estimated at $550. Wave tank testing and refabrication expenses are expected to be $5000.

Manufacturing costs are estimated at $5000 to properly fabricate the components using precision techniques tailored for durability and resistance to harsh marine environments. Labor costs are calculated based on a team of four individuals working 72 hours at $25 per hour, totaling $7200 for machining, fabrication, and assembly.

Based on the Mooring Buoy Guide, installation costs for helical mooring anchors are estimated at $860, while Manta Ray anchor installation is budgeted at $1200. Maintenance costs per unit per year range from $10,000 to $30,000, depending on the location and environment.

Key Assumptions:

- Material costs are estimated by scaling up the weight of materials used in the smaller model for the larger scaled model.
- Research and development costs beyond wave tank testing and refabrication are not considered.
- Administrative costs are excluded from the analysis.
- The functionality and marketability of the larger unit within a 5-year business plan are assumed.
- Maintenance costs are based on estimates from the operation and maintenance of data buoys, including component replacement and routine inspections.
- The comprehensive financial analysis provides detailed insights into the anticipated costs of developing and deploying the larger scaled model, considering various factors and key assumptions made during the estimation process.

The comprehensive financial analysis provides detailed insights into the anticipated costs of developing and deploying the larger scaled model, considering various factors and key assumptions made during the estimation process.

3. Technical Design

3.1 Introduction

The introduction sets the stage for the technical report, providing a brief overview of the project, its objectives, and the multidisciplinary teams involved. It also introduces the context of the Marine Energy Collegiate Competition (MECC) within which the project is situated.

3.1.1 Overview of the Project and Objectives

UCR’s Marine Energy Harvesting project is situated within the 2024 Marine Energy Collegiate Competition (MECC) providing the structure, guidance and funding for the research. Offering opportunities to gain insight and real-world experience in the emerging blue economy. The project aims to address the pressing need for sustainable energy solutions in coastal regions, particularly focusing on powering data buoys or ocean sensors with wave energy technology. In response to this need, a multidisciplinary effort has been undertaken by members of UCR’s Electrical and Mechanical Engineering departments, along with a team from the Business school.

The primary objective of the project is to design and develop a mobile platform capable of efficiently converting mechanical wave energy into electrical energy with onboard battery storage. This platform is envisioned to provide a reliable power source for data collection systems deployed in coastal areas.

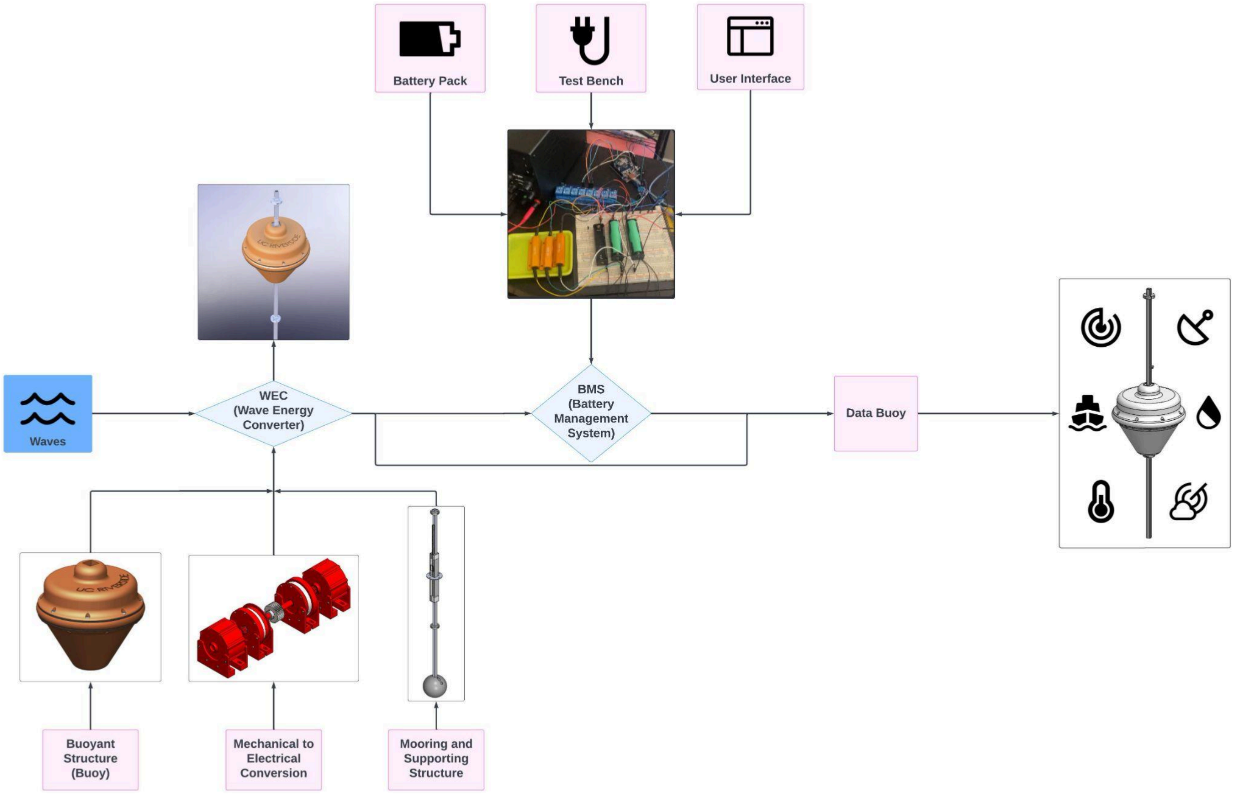


Figure 2: Diagram of the WEC Design Concept

3.1.2 Multidisciplinary Teams Involved

The project involves collaboration among three key disciplines: Electrical Engineering (EE), Mechanical Engineering (ME), and Business. Each team brings unique expertise and perspectives to the project, contributing to the development of a comprehensive solution.

Building upon previous research, the Electrical Engineering team focuses on the storage and delivery aspects of the energy system, developing a Battery Management System (BMS) to store and manage electrical energy efficiently.

In parallel, the Mechanical Engineering teams, represented by MEH-1, MEH-2, and MEH-3, are responsible for designing and implementing various components of the wave energy harvesting system to create the power generation aspect of the device. MEH-1 focuses on the buoy and stable platform, MEH-2 on the mechanical-to-electrical conversion system, and MEH-3 on the fixed structure, linear guide, and anchor system.

The Business team provides insights into market analysis, financial modeling, and project management, ensuring the viability and scalability of the proposed solution.

3.2 Background and Context

3.2.1 Overview of Previous Research

The research conducted in the preceding year serves as a foundational element in shaping the current project. Insights gained from previous investigations inform key design decisions and strategic directions, enabling the project to build upon existing knowledge and advancements in the field of marine energy conversion.

3.2.2 Market Need for Wave Energy Technology

The market need for wave energy technology arises from the need to power data buoys or ocean sensors reliably and sustainably in coastal regions. By tapping into the abundant and renewable energy potential of ocean waves, the project addresses this need, offering a viable alternative to conventional power sources. This aligns with the broader objectives of the blue economy, emphasizing environmental sustainability, resource efficiency, and economic prosperity.

3.2.3 Alignment with Blue Economy Goals and MECC

The project's objectives are closely aligned with the goals of the blue economy, which seeks to promote sustainable and responsible use of ocean resources for economic growth and environmental stewardship. By participating in the Marine Energy Collegiate Competition (MECC), the UCR marine energy harvesting project engages with a community of innovators and stakeholders committed to advancing marine energy technologies and solutions. Through collaboration and knowledge exchange, the project aims to contribute to the collective effort towards a more sustainable and resilient blue economy.

3.3 Mechanical Engineering Contributions

3.3.1 Introduction to ME Teams' Roles

The success of the project relies significantly on the collaborative efforts of the Mechanical Engineering (ME) teams, each contributing distinct expertise to various aspects of the wave energy harvesting system. In this section, an overview of the roles is provided as well as contributions of these teams, outlining their specific areas of focus and expertise.

The ME teams play crucial roles in the design, development, and implementation of key components of the wave energy harvesting system.

MEH-1 focuses on the design and development of the buoy and stable platform, aiming to provide a robust and stable foundation for the wave energy conversion mechanism. This team's expertise lies in structural engineering, hydrodynamics, and materials science, allowing them to address challenges related to buoyancy, stability, and durability in varying marine conditions.

MEH-2 specializes in the mechanical-to-electrical conversion aspect of the system, designing the drivetrain and DC motors used as generators. Their expertise in mechanical engineering, power transmission, and electromechanical systems enables them to develop efficient and reliable conversion mechanisms to harness wave energy effectively.

MEH-3 is responsible for the design and implementation of the fixed structure, linear guide, and anchor system, providing essential support and stability to the overall wave energy harvesting device. Their expertise in structural analysis, dynamics, and marine engineering ensures the integrity and functionality of the system in challenging marine environments.

Together, the ME teams collaborate closely to integrate their respective components seamlessly into the overall system, ensuring optimal performance and functionality. Their interdisciplinary approach and collective expertise contribute to the success of the project in addressing the critical need for sustainable energy solutions in coastal regions.

3.3.2 Problem Definition

Before delving into the specific contributions of each Mechanical Engineering (ME) team, it's essential to define the overarching problem that the project seeks to address. The problem definition outlines the functional, physical, environmental, life-cycle, human factors, and other requirements that the wave energy harvesting device must fulfill to meet the project's objectives.

Table 4: Functional Performance Characteristics

No.	Performance Characteristic	Description
1.	Wave Energy Harnessing	Ability to efficiently capture wave energy and convert it into mechanical power.
2.	Compactness and Lightweight	Suitable for deployment from small ships or helicopters, requiring compact and lightweight design.
3.	Durability	Capable of withstanding various deployment methods, adverse weather conditions, and seawater exposure.
4.	Regulatory Compliance	Compliance with all relevant regulations and safety requirements set forth by governments and organizations.

Table 5: Physical Requirements

No.	Requirement	Description
1.	Housing	Must house both the wave-to-mechanical energy system and the mechanical-to-electrical power conversion system.
2.	Stability	Must withstand typical force from shoreline waves without disturbing internal components.
3.	Weight	Must not exceed 100 lbs to facilitate easy deployment and retrieval.

Table 6: Environmental Requirements

No.	Requirement	Description
1.	Anchoring	Must be anchored to a stable point to allow relative motion with the ocean for energy production.
2.	Corrosion Resistance	Must withstand possible corrosion from saltwater.
3.	Positioning	Must maintain level positioning relative to shallow coastal waters.
4.	Wildlife Protection	Must be designed to avoid harm to marine wildlife upon contact.

Table 7: Life-Cycle Requirements

No.	Requirement	Description
1.	Operation Duration	Must operate smoothly for a minimum of one month per deployment cycle.
2.	Maintenance	Must easily undergo necessary maintenance and repairs after each deployment cycle.
3.	Reusability	Must allow for multiple deployments before being deemed unusable for future disaster relief efforts.

Table 8: Human Factors

No.	Factor	Description
1.	Portability	Must be portable enough for deployment by two individuals via helicopter or boat.
2.	Automatic Trigger	Must include an automatic trigger for the anchoring system upon deployment.
3.	Component Sealing	Must seal electrical and mechanical components to prevent water exposure and corrosion.
4.	Material Reflectivity	Must utilize non-reflective materials to minimize interactions with wildlife.
5.	Retrieval Ease	Must facilitate simple retrieval by two individuals with minimal training.

3.3.3 Approach to Solution

This section outlines the overarching approach employed by all Mechanical Engineering (ME) teams in the conceptualization and selection of design solutions for the Wave Energy Converter project. While each team may have unique methodologies and rationales, the fundamental process of concept generation, evaluation, and selection remains consistent across all teams.

Concept Generation and Ideation

The approach to ideation began with a comprehensive study of existing technologies and an analysis of the blue economy's landscape, with a particular focus on wave energy. Utilizing this knowledge base, teams initiated brainstorming sessions to generate a wide range of ideas, drawing inspiration from existing designs and industry innovations.

Various ideation techniques were employed, including brainwriting methodologies like the 4-3-5 method and the utilization of morphological charts. These techniques facilitated the exploration of diverse concepts and expanded the breadth of potential solutions.

Evaluation and Selection

Following the generation of multiple design concepts, teams meticulously evaluated each concept based on criteria such as technological readiness, feasibility, and alignment with project goals. This evaluation process included considerations of power requirements, structural integrity, operational efficiency, and scalability.

Teams then presented their top selections, backed by detailed rationales, to the broader team. Collective discussions and debates enabled comprehensive evaluations, considering technical merits, potential challenges, and alignment with the overarching project vision

Figure 3: Best Voted Team Design

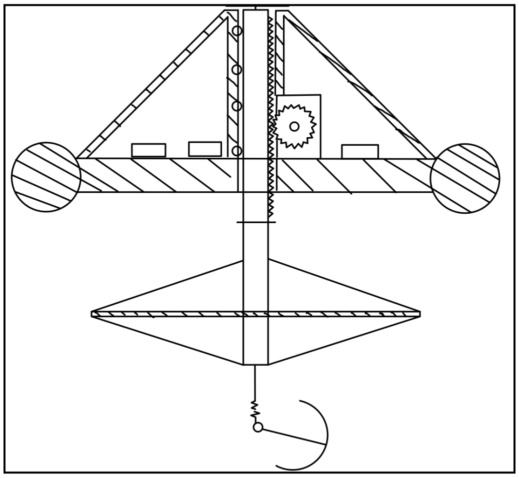


Figure 3: Team selected design idea, a heaving buoy attached to rack and pinion mechanism

Figure 4: WEC Design Concept

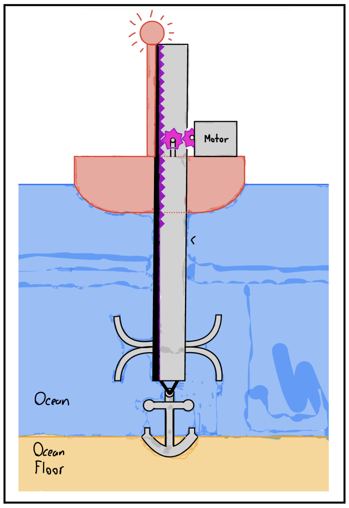


Figure 4: Visualization of WEC Design Concept

Consensus Building and Decision Making

Through a structured and rigorous decision-making process, teams collectively assessed and refined their ideas, emphasizing technological feasibility and scalability. The final selection was not arbitrary but the result of a comprehensive assessment considering multiple parameters.

The chosen design solution emerged as the pinnacle choice following a transparent and inclusive decision-making process, informed by iterative refinement and collaborative discussions. This solution represents the epitome of the team's collective effort, synthesizing rigorous ideation, systematic evaluation, and alignment with project specifications.

By comparing the design against the outlined specifications and showcasing the culmination of a meticulous selection process, the chosen design solution serves as the architectural cornerstone, poised for further refinement and eventual realization into a tangible, real-world solution.

3.3.4 MEH-1 Contribution: Buoy and Stable Platform

3.3.4.1 Design Solution

The heaving buoy wave energy converter (WEC) design solution entails the development of a buoyant structure, typically cylindrical or spherical, constructed from durable materials like reinforced polymers, to withstand harsh marine conditions while optimizing buoyancy and minimizing resistance to wave motion. This buoy, designed to move vertically with wave action, is coupled with mechanical systems to convert the buoy's mechanical motion into rotational motion, subsequently driving an electrical rotary generator to produce usable electricity. Environmental considerations, including impact assessments and end-of-life recycling, are incorporated to mitigate ecological disturbance. The design's scalability and modular construction enable easy deployment and maintenance across diverse wave conditions and power requirements, facilitating its potential as a renewable and sustainable energy source with minimal environmental impact.

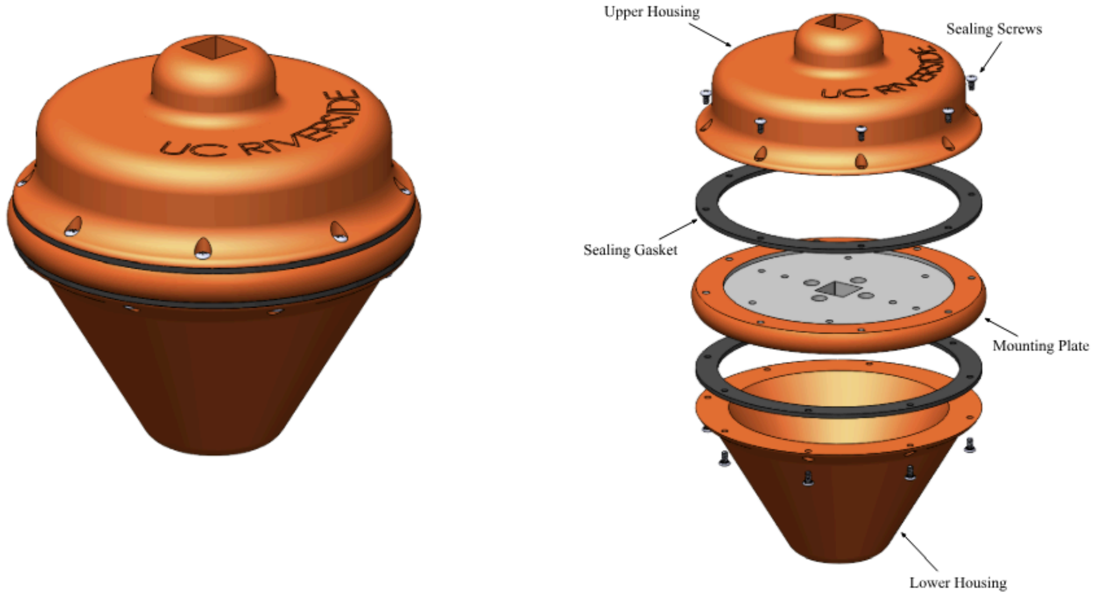


Figure 5: Pictorial view of assembly model (left) and pictorial view of exploded model (right)

Key features of the final design include modularity, impermeability, scalability and an overall aesthetically pleasing design. To keep the design modular the structure is divided into three main components that allow for easy assembly and deployment. The design consists of an upper electrical housing component and a lower conical housing component that are each fastened to the flat mounting plate as shown in figures below. The upper and lower components can be quickly and easily removed to gain access to the internals. A neoprene gasket on both the top and bottom of the mounting plate as well as stainless steel sealing screws will be utilized to ensure water can not leak into the internal structure of the buoy. As illustrated in the figures below, each component will be painted in high visibility safety orange to reduce the likelihood of accidental collisions.

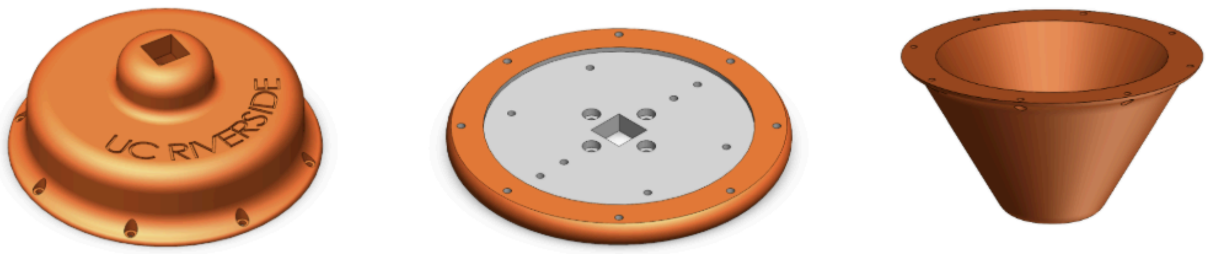


Figure 6: Upper housing (left), Mounting plate (middle), and Lower housing (right)

The mounting plate will act as the core structural foundation for the entire assembly as it will be the component that every other component is mounted to. Given the high stress the mounting plate will endure and it will be fabricated from 316 stainless steel. This material is an ideal selection for this component as it is high strength, corrosion resistant, affordable and abundant. The upper and lower housings will be made of linear low density polyethylene (LLDPE). Although LLDPE is more expensive than 316 stainless steel it possesses ideal material properties suited for this application. One of the key properties of LLDPE is its strength to weight ratio, it is lighter than steel while still maintaining enough strength to withstand high pressure and impact forces associated with an oceanic environment. Having the structure be as lightweight as possible is essential to generate sufficient buoyancy to operate the generators. Other ideal properties of LLDPE includes UV stability and requires little to no maintenance. UV stability is important in the material selection process because the buoy will be exposed to solar UV light for extended periods of time which can ultimately degrade the material and weaken the structural integrity. Finally, each component will be coated in anti fouling paint. This type of paint is primarily used to deter marine life such as barnacles and weeds from attaching themselves to the surface of submerged objects.

To ensure the highest strength possible, the mounting plate will be fabricated from a single stock of 316 stainless steel. Fabricating 316 stainless steel components for a heaving buoy involves several precision processes tailored to ensure durability and resistance to harsh marine environments. Initially, machining techniques such as cutting, drilling, and milling are employed to shape stainless steel sheets or bars into required buoy components. These methods ensure precise dimensions and smooth surfaces crucial for optimal buoy performance. The upper and lower housings will be manufactured by rotational molding. Rotational molding is a highly effective fabrication method used for linear low-density polyethylene (LLDPE), offering unparalleled versatility and durability in producing a wide array of hollow plastic components. This process begins with the loading of powdered LLDPE resin into a mold, which is then heated and rotated simultaneously in multiple axes within an oven chamber. As the mold rotates, the plastic resin melts and coats the inner surfaces evenly, conforming to the mold's shape. After the material has cooled and solidified, the mold is opened, revealing a seamless, hollow LLDPE product with consistent wall thickness and intricate details. Rotational molding offers advantages such as uniform material distribution, stress-free production, and the ability to create complex geometries with minimal waste. It is particularly suitable for manufacturing large, lightweight, and durable components, making it an ideal fabrication method for linear low-density polyethylene components. Detailed engineering drawings can be referenced in the appendix for exact dimensions of each component.

3.3.4.2 Design Verification

Physical and Virtual Prototypes

Team MEH-1 constructed a physical prototype as well as designing a virtual prototype using 3D CAD software. The purpose of virtual prototyping is to analyze the function and performance of the selected geometry to ensure the mechanisms involved will operate as expected. SolidWorks was used to determine and check many key aspects of the design including center of gravity and center of buoyancy. Static simulations will be utilized to check the force response, factor of safety, and displacement plots of the device to ensure it does not fail while in operation. The buoyancy force and dynamic analysis of the buoy will be assessed using MATLAB. As is the nature in the operation of the design, the displaced volume of the vessel varies with time, and in turn varies the buoyancy force. Volume and buoyant force versus time plots were generated to visualize this behavior and will aid team MEH-2 with associated power output calculations.

The goal of the physical prototype is to demonstrate the proof-of-concept that this device has the proper mechanics to generate a form of renewable energy. This includes delivering the required buoyant force to drive the motor as well as providing a stable platform so the device does not capsize. It will also verify the feasibility of manufacturing the design considering integration with the other MEH teams project. The physical and virtual prototypes will give a visualized idea of how the device will behave to address and design changes needed.

Design Evaluation

The virtual prototype will be used for design verification and evaluation by using MATLAB and SolidWorks simulation. By utilizing a static study, analysis of the force response of the device will be investigated. Displacement plots, von mises stress plots, and factors of safety will be assessed to verify the mechanism functions properly and is safe for use. Center of mass and buoyancy will be calculated through the software to determine that the buoy is stable and will not capsize as a wave passes through. Mass properties of the system and the volume of water displaced were used to calculate the buoyant force that is generated from the buoy. Dynamic analysis of the buoy was performed analytically and through MATLAB to verify the results found from SolidWorks.

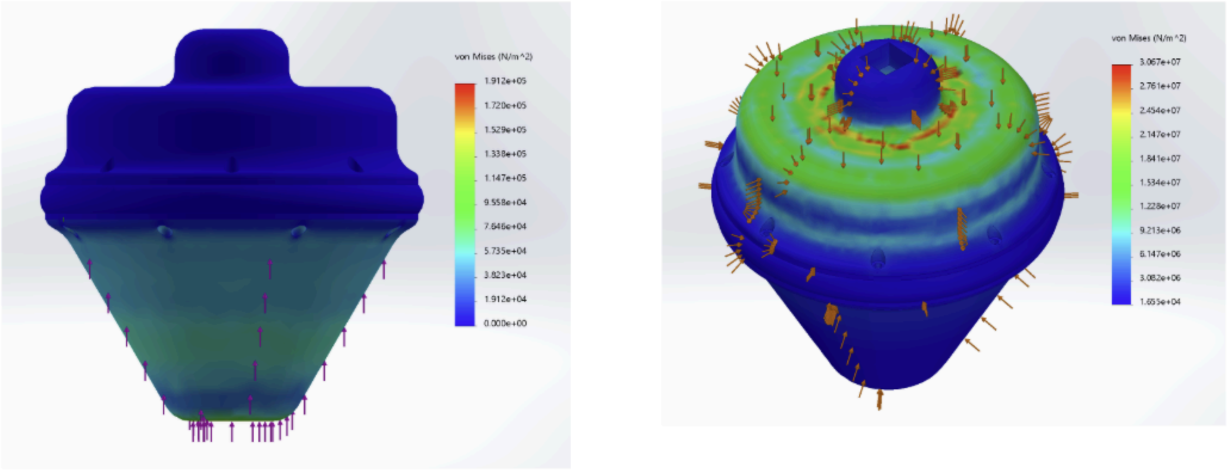


Figure 7: Solidworks static simulation 1 (left), Solidworks static simulation 2 (right)

The physical prototype evaluated the manufacturing and assembly of the system, as well as verifying the design was able to generate power. Through physically manufacturing and assembling the device with the other MEH designs, the teams ensured that it was easy to assemble and was a robust design. The heat set inserts integrated with the 3D printed buoy components as intended and allowed for ease of manufacturing. Mounts for the mechanical components fit together as intended with tight tolerances and slots designated on the motor mounts allowing for easy engagement between the rack and pinion system.

Differences From Detail Design Solution

Key differences between the virtual prototype and detail design are that the simulations and motion analysis does not depict the real environment of the ocean that the device is intended to be in. The virtual prototype is being simplified by assuming no friction between parts and drag associated with the ocean water. Small components like hinges, bolts, and screws have also been excluded from the virtual prototype as they are simulated by mates in SolidWorks. Mass properties associated in the software do not follow the exact properties that will be used in the detailed design, slightly altering weight, center of mass and buoyancy, as well as the forces experienced. Assumptions made concerning calculations in MATLAB were made that do not depict the real time effects the buoy experiences in the ocean. The dynamic analysis neglected any horizontal motion and only accounted for the vertical displacement of the buoy. The wave that was acting on the buoy was modeled as a constant sine wave whereas in reality it is constantly changing.

The physical prototype differs vastly from the final detail solution as it was only used to verify the physical mechanics and power output of the device. The physical prototype generated was scaled down (1:5) to allow for 3D printing and rapid prototyping. Other significant differences include the material and hardware used. Heat set inserts were used and melted into the plastic to assemble the parts together whereas the final design solution would need a drill press to create the threads required for assembly. The original design was made using a type of lightweight polymer known as polystyrene foam whereas the prototype was printed using ABS carbon reinforced filament. This greatly affects the weight and buoyancy force between the two systems.

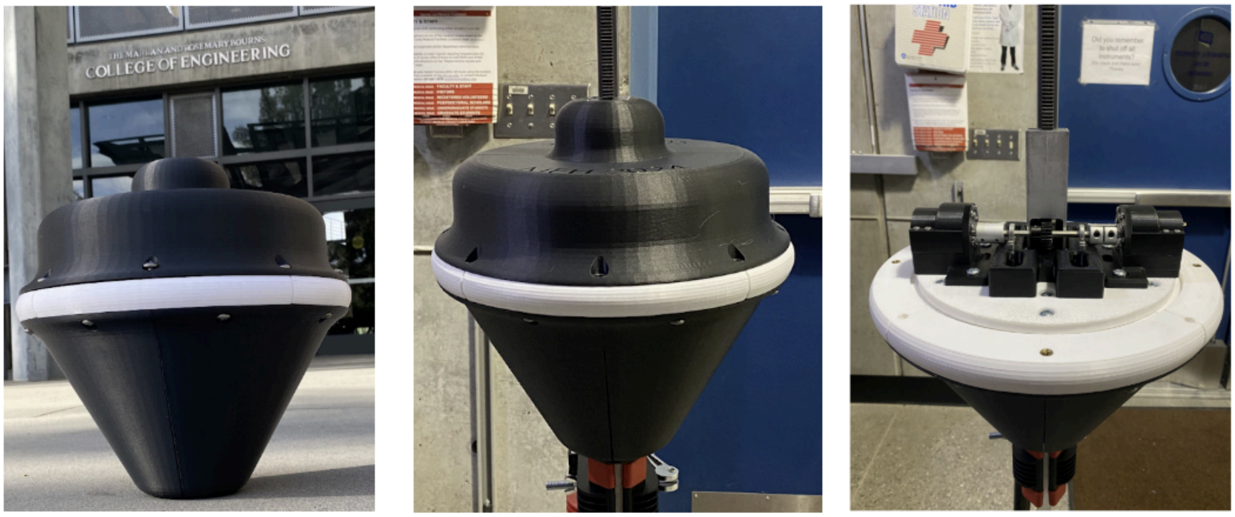
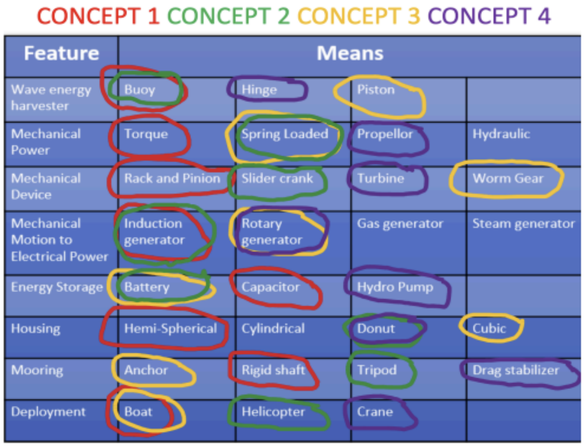


Figure 8: Scaled Down Physical Prototype of MEH-1 assembly

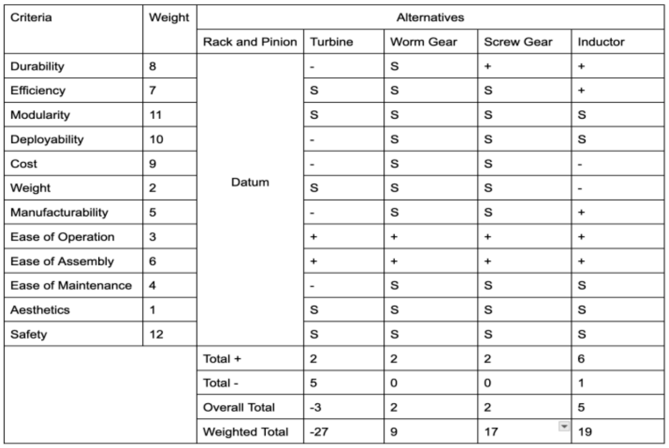
3.3.4.3 Approach to Solution

Once the team came to the conclusion of the conceptualization process there were 4 potential final designs for solving the problem. These concepts in the most general of terms were as follows: Helical Screw Rotation, Induction, Gear/Rotor Shaft, and Vertical Turbine. These concepts were generated through Brainstorming of ideas and also the use of a Morphological chart.



Feature	Means			
Wave energy harvester	Buoy	Hinge	Piston	
Mechanical Power	Torque	Spring Loaded	Propellor	Hydraulic
Mechanical Device	Rack and Pinion	Slider crank	Turbine	Worm Gear
Mechanical Motion to Electrical Power	Induction generator	Rotary generator	Gas generator	Steam generator
Energy Storage	Battery	Capacitor	Hydro Pump	
Housing	Hemi-Spherical	Cylindrical	Donut	Cubic
Mooring	Anchor	Rigid shaft	Tripod	Drag stabilizer
Deployment	Boat	Helicopter	Crane	

Figure 9: Morphological chart comparing sub-functions from different MEH-1 concepts



Criteria	Weight	Alternatives				
		Rack and Pinion	Turbine	Worm Gear	Screw Gear	Inductor
Durability	8	Datum	-	S	+	+
Efficiency	7		S	S	S	+
Modularity	11		S	S	S	S
Deployability	10		-	S	S	S
Cost	9		-	S	S	-
Weight	2		S	S	S	-
Manufacturability	5		-	S	S	+
Ease of Operation	3		+	+	+	+
Ease of Assembly	6		+	+	+	+
Ease of Maintenance	4		-	S	S	S
Aesthetics	1		S	S	S	S
Safety	12		S	S	S	S
		Total +	2	2	2	6
		Total -	5	0	0	1
		Overall Total	-3	2	2	5
		Weighted Total	-27	9	17	19

Figure 10: Decision matrix comparing alternative concepts

3.3.5 MEH-2 Contribution: Mechanical to Electrical Conversion

3.3.5.1 Design Solution

Within the energy conversion process, MEH-2 plays a pivotal role in transforming the mechanical wave energy harnessed by MEH-1 into storable electrical energy. Specifically, MEH-2 is responsible for converting the vertical motion of the buoy mechanism into rotational motion, facilitating efficient power generation and storage.

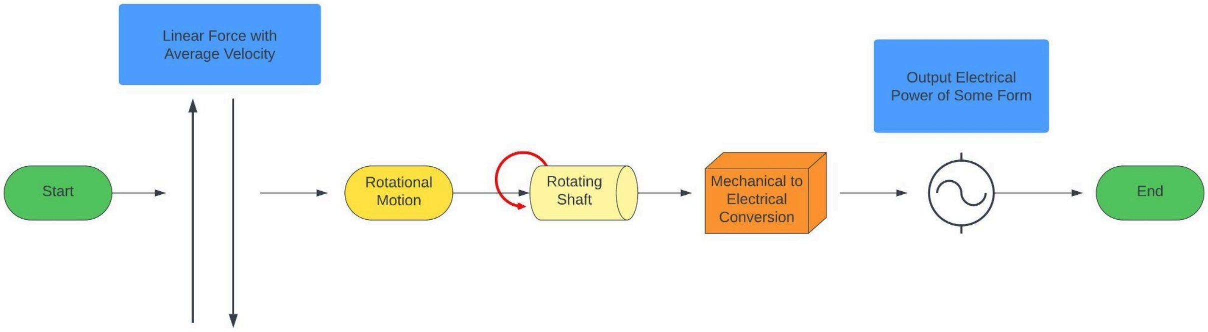


Figure 11: Architectural Design of Mechanical to Electrical Conversion

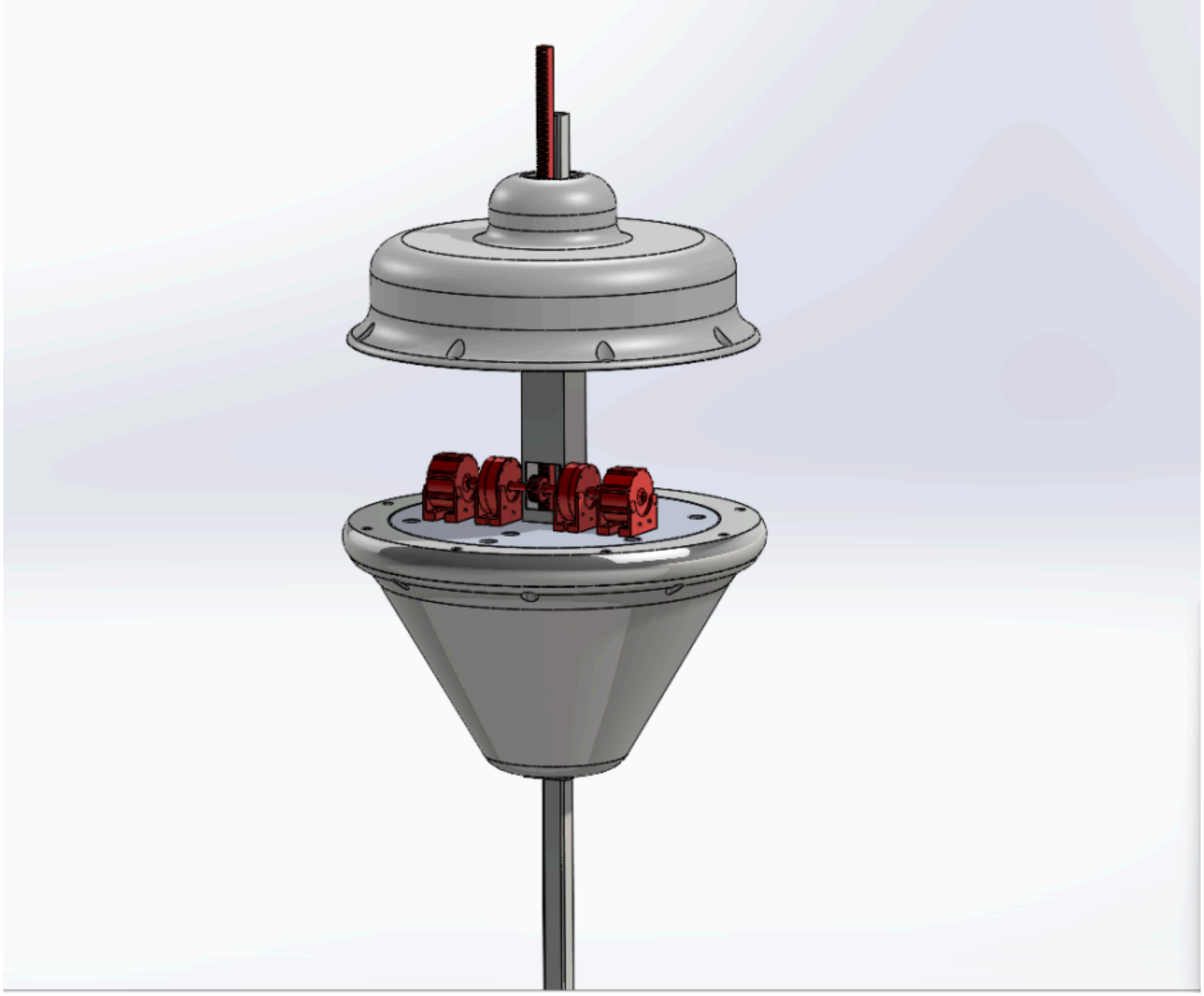


Figure 12: Design Solution with MEH-2 portion in red.

The design's focus on the mechanical to electrical conversion ensures efficient translation of the buoy's motion into rotational energy, priming the system for effective electrical power generation.

Mechanical to Electrical Design

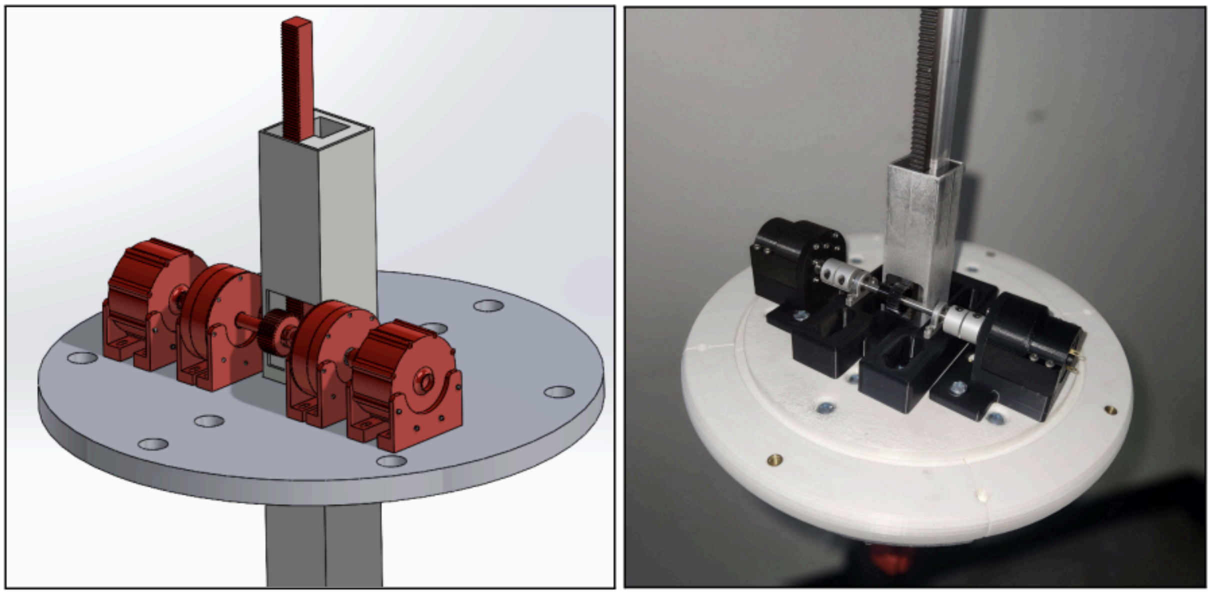


Figure 13: Final buoy design with MEH-2's converter highlighted in Red (left), Scaled prototype (right)

The Wave Energy Converter (WEC) operates by harnessing the kinetic energy of ocean waves through direct mechanical drive, via a rack and pinion mechanism integrated into a buoyant structure. As the buoy oscillates vertically atop the waves, it drives a pinion along a stationary rack, generating bi-rotational motion of the pinion shaft. This consistent rotation is essential for reliable power generation. The pinion shaft movement, with an initial low rpm and high torque is converted via drivetrain into high rotational speeds at low torques into the input torque and rpm of the selected alternator. The alternator subsequently produces the usable electrical power, AC or DC. This power will then be stored in some form of electrical storage. The mechanical drivetrain consists of a rack, pinion, d-shaft, two mounted bearings, and two shaft couplers, as well as the necessary screws and mounting brackets.

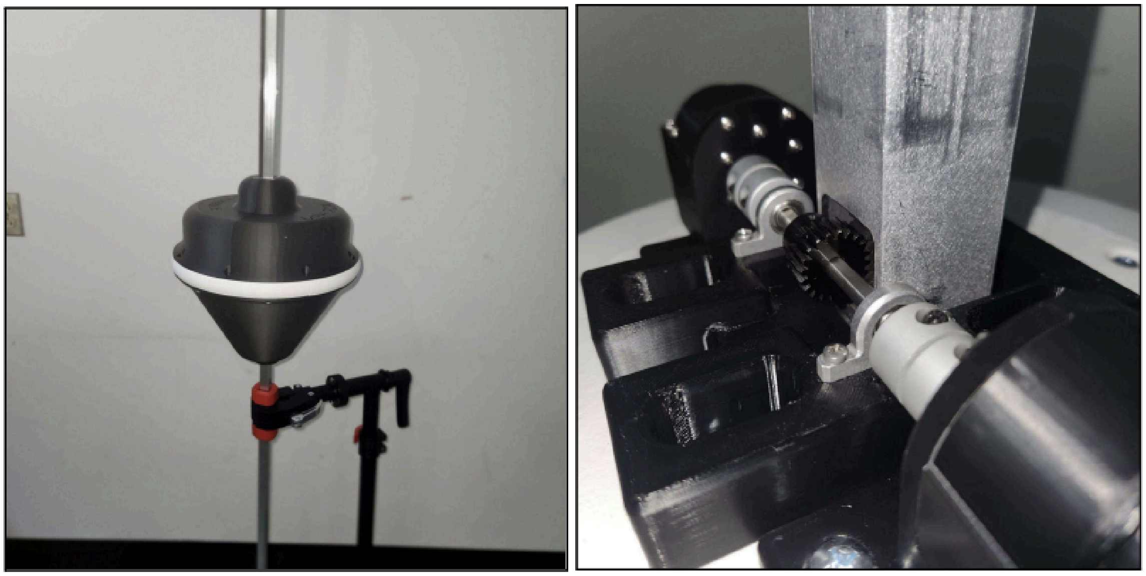


Figure 14: Scaled assembled prototype of WEC (left), Scaled prototype of MEH-2 Assembly (right)

3.3.5.2 Design Verification

The selected generator for the final solution was a low RPM, 1 kilowatt-hour device that required a starting torque of .42N-m to get spinning and could handle torques of 5 N-m, and rated to handle 600 revolutions per minute for angular velocity at the shaft. In order to achieve these torques, and RPM, MEH-1 had to provide us with a buoyant force of approximately 450 Newtons at our selected pinion size. The pinion size was determined by related the average velocity of each wave cycle to the equation $v = \omega r$ and rearranging the equation to solve for the radius (r) of the pinion as follows $r = v/w$. Doing so concluded that we needed to have a pinion of radius 20 mm. Based on an average wave speed of 1.33 ft/s we would obtain an average angular speed of 20.9 rad/s or roughly 200 RPM. In order to achieve higher revolutions per minute we needed to add in a speed increase gearbox to speed up our 200 RPM to 600 RPM. Using the equation *gear ratio = Output RPM / input RPM* a 1:3 gear ratio was obtained, meaning that output RPM's to the motor shaft have to be 3 times bigger than our input rotational speeds to the gearbox. In order to achieve this we designed a planetary gearbox which consists of 3 main components; a ring gear, sun gear, and planet gears, which are labeled in the figure below.

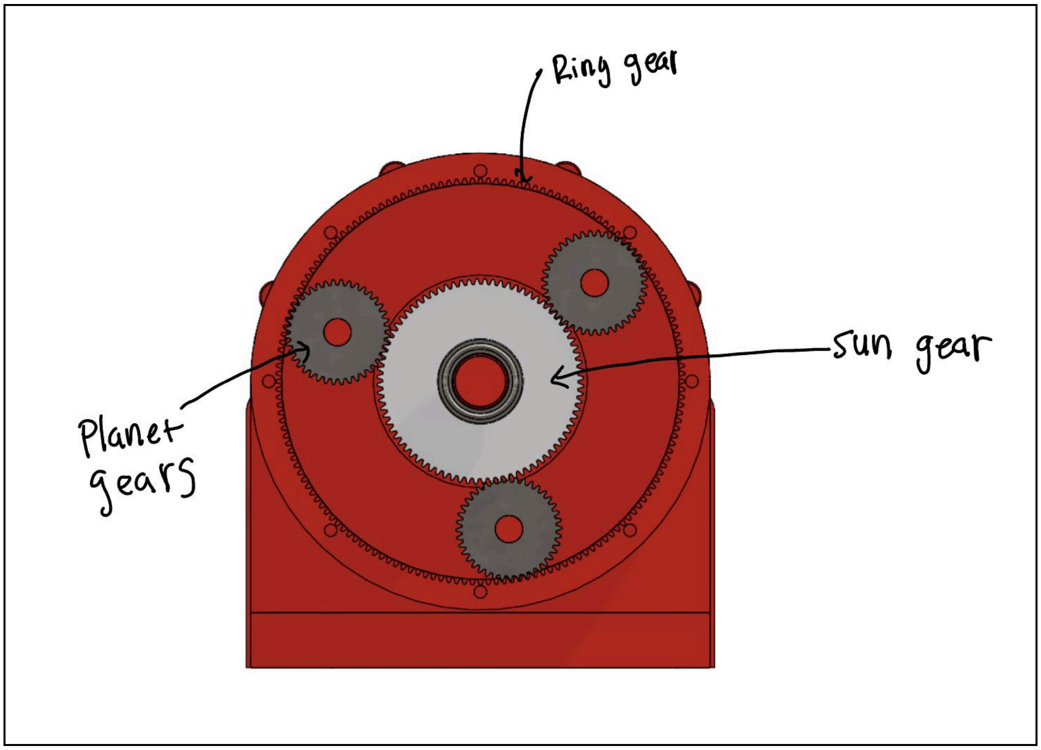


Figure 15: Planetary gearbox consisting of 3 main components; a ring gear, sun gear, and planet gears

The way in which this mechanism works in order to be a 1:3 speed increaser gearbox is that the ring gear must be fixed. The 3 planet gears are fixed into a plate that has the shaft that runs to the pinion that is meshing with the rack. The center shaft of the sun gear is connected to the generator we selected. By rotating the planet gears that are meshed with the sun gear we obtain a 1:3 gear ratio since the sun gear is 2 times the size of the planet gears. In conclusion, giving us the desired 600 revolutions per minute to the motor. The whole mechanism for this planetary gearbox is shown.

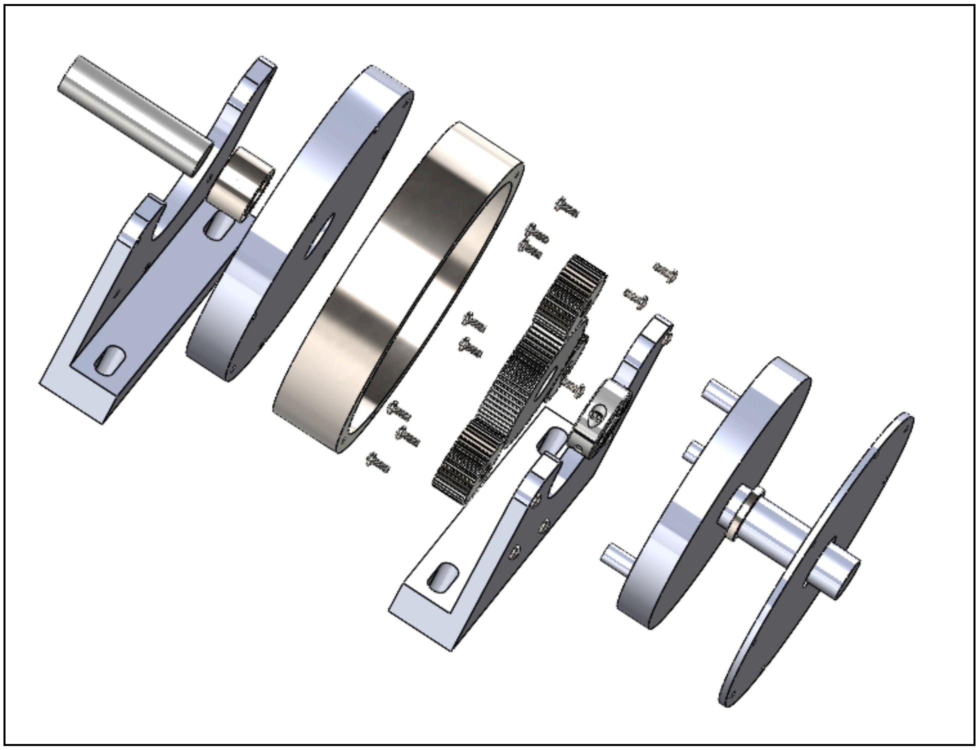


Figure 16: Planetary gearbox assembly

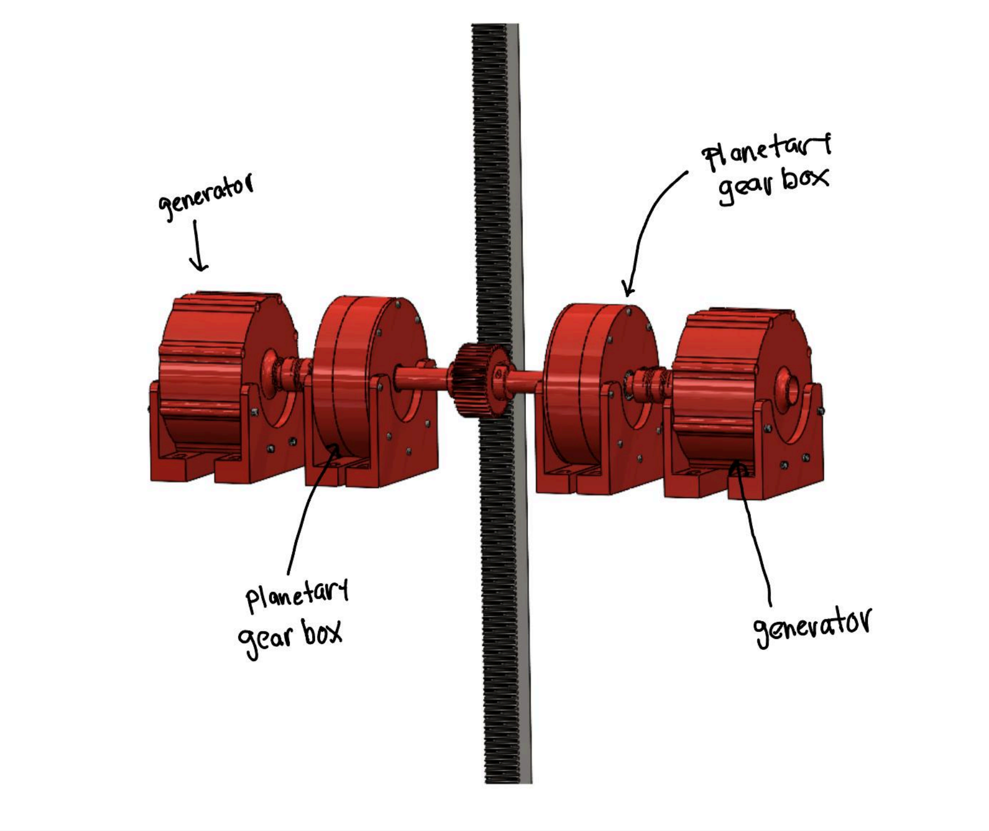


Figure 17: Planetary gearbox and generator drivetrain

3.3.5.3 Approach to Solution

Our team's approach to ideation began with an exhaustive study of existing technologies and an in-depth analysis of the blue economy's intricacies, focusing particularly on wave energy and its diverse forms. We briefly explored various technologies prevalent in the market, identifying their strengths and limitations. Utilizing this knowledge base, we initiated brainstorming sessions to generate diverse ideas, drawing inspiration from existing designs and industry innovations.

Figure 18: Preliminary Design Sketches

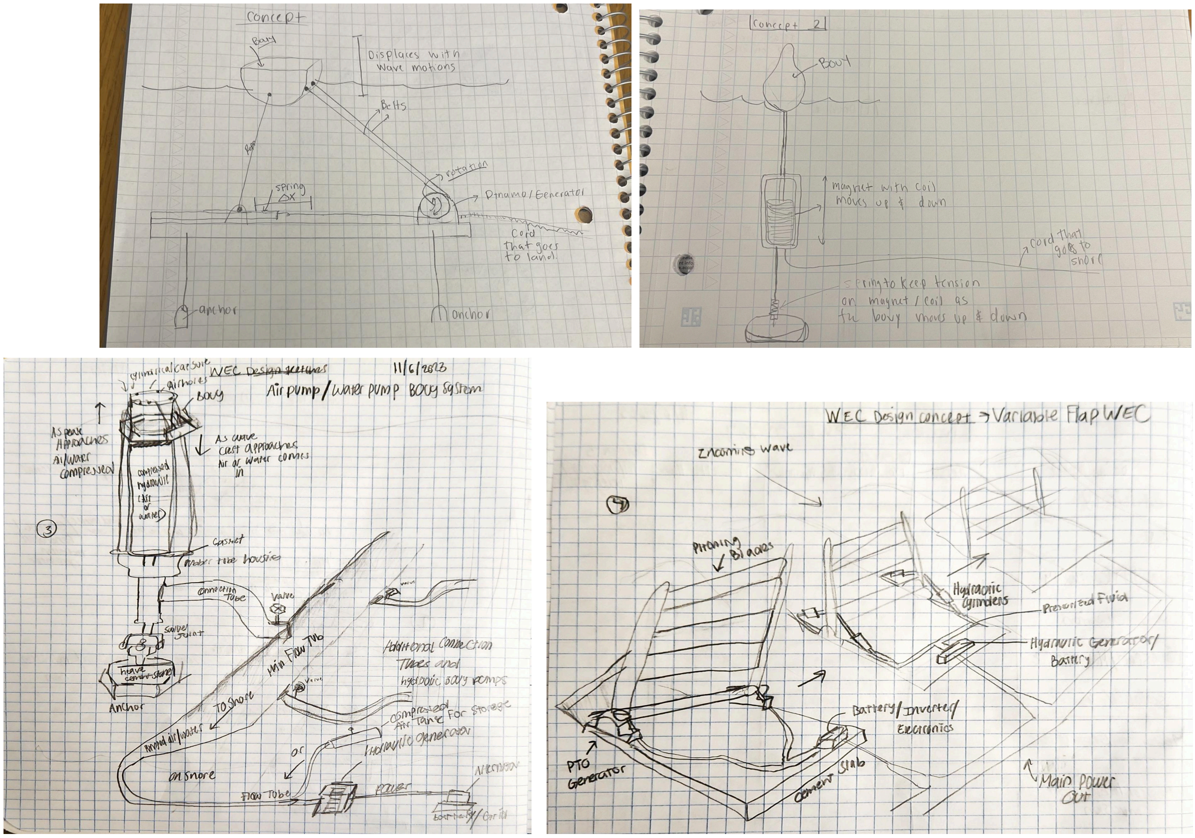
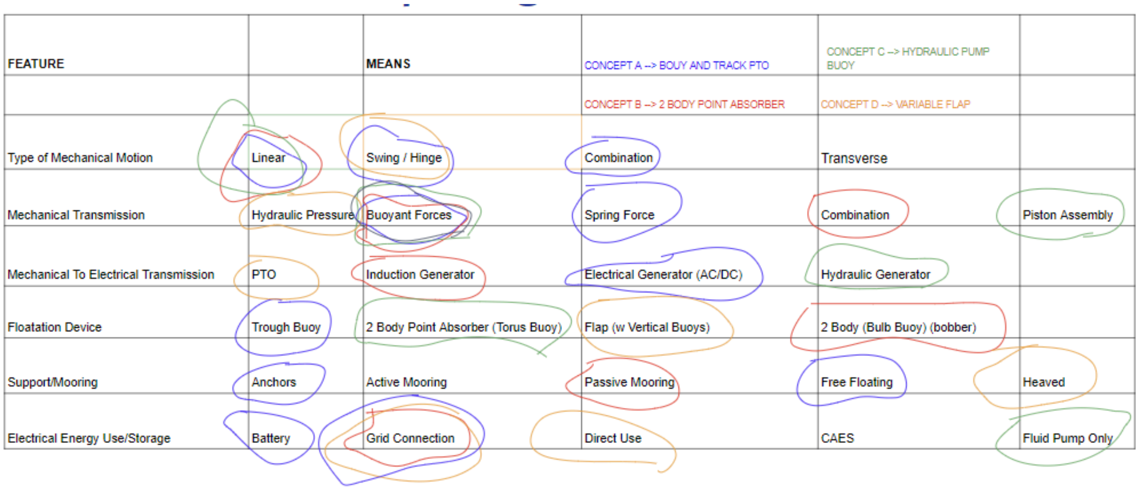


Figure 18: Shows the early design sketches (MEH-2) generated during the concept generation stage

Morphological Chart



FEATURE		MEANS	CONCEPT A --> BOUY AND TRACK PTO	CONCEPT C --> HYDRAULIC PUMP BUOY	
			CONCEPT B --> 2 BODY POINT ABSORBER	CONCEPT D --> VARIABLE FLAP	
Type of Mechanical Motion	Linear	Swing / Hinge	Combination	Transverse	
Mechanical Transmission	Hydraulic Pressure	Buoyant Forces	Spring Force	Combination	Piston Assembly
Mechanical To Electrical Transmission	PTO	Induction Generator	Electrical Generator (AC/DC)	Hydraulic Generator	
Floatation Device	Trough Buoy	2 Body Point Absorber (Torus Buoy)	Flap (w Vertical Buoys)	2 Body (Bulb Buoy) (bobber)	
Support/Mooring	Anchors	Active Mooring	Passive Mooring	Free Floating	Heaved
Electrical Energy Use/Storage	Battery	Grid Connection	Direct Use	CAES	Fluid Pump Only

Figure 19: Morphological chart of potential concept solutions

3.3.6 MEH-3 Contribution: Fixed Structure, Linear Guide, and Anchor

3.3.6.1 Design Solution

The final design solution for the fixed structure of the hydroelectric energy generator consists of a shaft with a mounted gear rack that rides along the inside of a housing in an up and down motion. This shaft is supported at the bottom with a buoyant sphere that applies an upward 9 force on the shaft that is large enough to overcome both the weight of the assembly and the torque of a motor that is supplied by MEH-2. The purpose of this upwards buoyant force is to keep the shaft static in the vertical direction so that the buoy supplied by MEH-1 can move up and down along the shaft. The device can then capture the sinusoidal motion generated by waves in the ocean and translate this into vertical motion that can be used to generate energy by using the rack attached to the shaft to rotate pinion attached to a generator supplied by MEH-2. Along with this main assembly, there is an additional sub-assembly which consists of a chain and an anchor whose purpose is to keep the buoy from drifting away from its desired location. The length of the chain is determined by the depth of the ocean, and the weight of the anchor is determined by the overall mass of the entire buoy created by all three teams.

As stated above, the main assembly contains a linear guide housing and a shaft. These two components are the most essential part of the design, as the relative motion between these two components is how the energy is generated. As shown in Figure 20, the shaft is located in the center of the linear guide housing, and it rests inside the two linear bearings located at the top and bottom of the housing. The rack is then mounted on the shaft with the teeth facing the same direction as the cutout on the housing. At the top and bottom of the shaft, there are two shaft collars whose distance is determined by the length of the rack along with the length of the housing. Finally, at the bottom of the shaft, there is a sphere whose purpose is to support the shaft while it is submerged in the ocean. A detailed exploded assembly drawing with a labeled parts list can be found in Appendices.

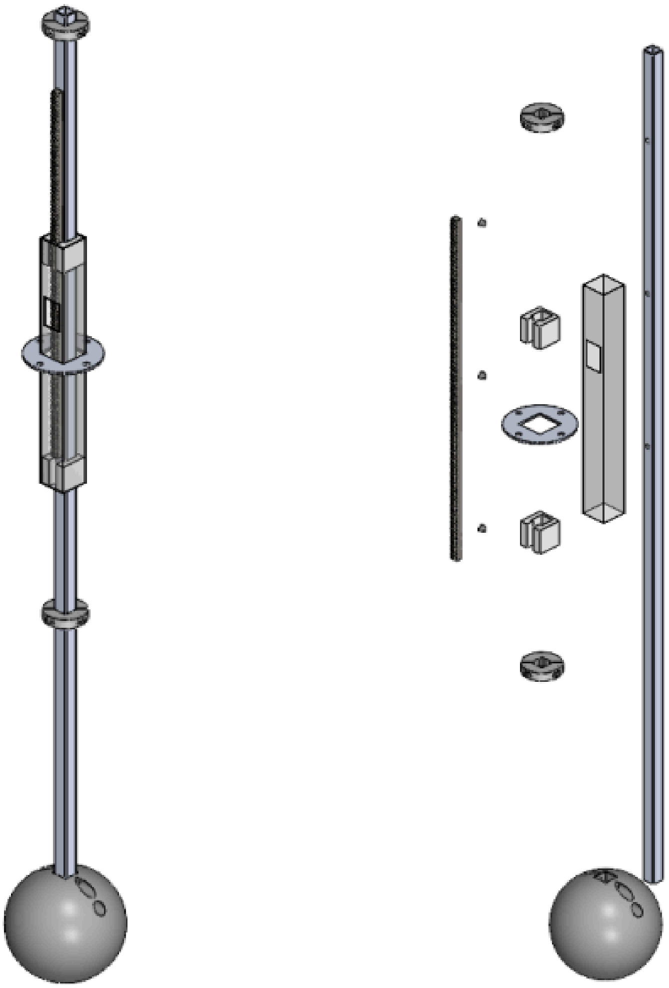


Figure 20: Picture of the full assembly in assembled and exploded views. The shaft housing is transparent in the assembled view in order to demonstrate the location of the linear bearings

Pictured in Figure 21 is the main housing of the assembly. The main purpose of this component is to house the shaft and the linear bearings so that the shaft is provided a straight line to move up and down. This component will be made from stainless-steel square tubing in order to prevent corrosion from the seawater. This component has a slot located on one face whose purpose is to leave an opening for the rack to have engagement with a pinion which is supplied by MEH-2. This component can be cut to size on a bandsaw, and the slot can be milled with a CNC milling machine. A detailed component drawing can be found in the appendices.

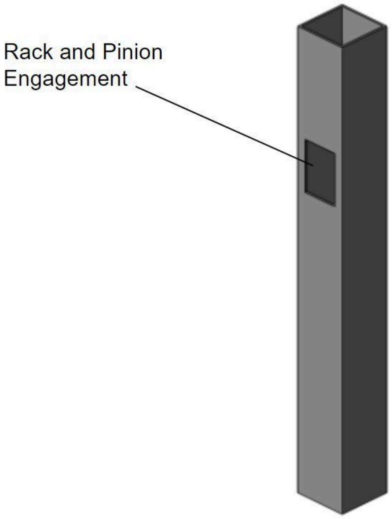


Figure 21: Picture of the shaft housing. The slot for the rack and pinion engagement can be seen on the left side of the housing.

The component pictured in Figure 22 is the mounting plate. The purpose of the mounting plate is to fix the shaft housing onto the buoy which will be supplied by MEH-1. This mounting plate will be manufactured out of stainless steel plate, so that it can be TIG welded onto the shaft housing. The holes on this plate can be machined using a laser cutter, as there are square holes which can not be milled on a CNC machine. This plate will be mounted to the buoy with four 12 5/16-18 grade 8 bolts (not pictured), as they are corrosion resistant and will not fracture due to cyclic loading. A detailed drawing of all components for manufacturing is located in the appendix.

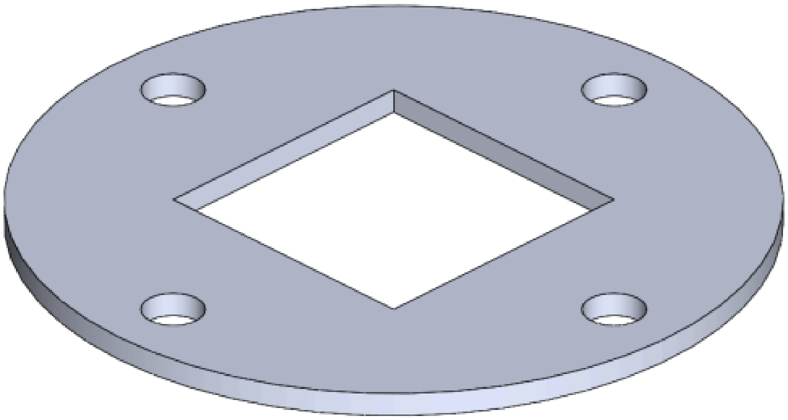


Figure 22: Picture of the mounting plate that is to be welded onto the shaft housing. It consists of a square hole for the shaft, and 4 circular holes for the 5/16 bolts.

The component pictured in Figure 23 is the linear bearing for the shaft. The purpose of this component is to supply support for the shaft in order to keep it in a straight line. The material chosen for this part is Polytetrafluoroethylene (PTFE), due to its low friction coefficient along with its environmentally friendly properties. The bearing can be manufactured on a CNC mill, and the press fit and glued into the shaft housing at the top and bottom of the housing. Since this component is susceptible to wear, it shall be replaced during yearly maintenance.

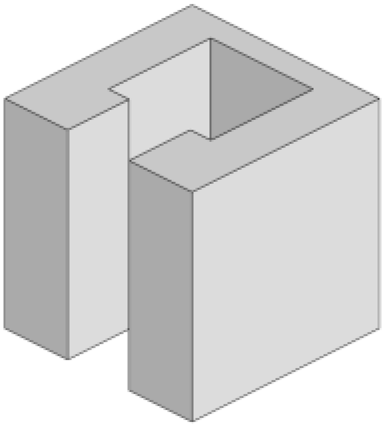


Figure 23: Image of the linear bearing used to support the shaft.

Pictured in Figure 24 is the square shaft collar. There are two collars in the assembly used to limit the motion of the shaft so that the rack stays engaged with the pinion. The collars can be purchased directly from McMaster-Carr, part number 3257K18. The collars are stainless steel to prevent corrosion.

Figure 24: Image of the square shaft collar that is located on the top and bottom of the shaft.

The shaft which acts as a locator for the gear rack is pictured in Figure 25. The shaft slides along the linear bearings pictured in Figure 23. The purpose of the shaft is to stay vertically static while the buoy supplied by MEH-1 moves up and down along the shaft. There are three counterbored holes on the shaft so that the rack can be mounted to the shaft. These holes are drilled for 1/4-20 button head screws. The shaft will be manufactured out of stainless steel in order to prevent rust and corrosion due to the seawater. Similar to the shaft housing, the shaft can be cut to size on a bandsaw, and the holes can be milled on a CNC mill. The shaft length can be modified for different wave sizes.

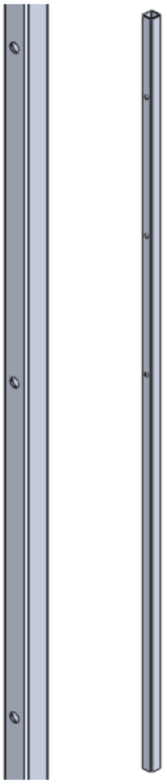


Figure 25: Images of the static shaft. The shaft is pictured on the right, while the image on the left is a close up image of the counterbored holes for the rack mounting screws.

Pictured in Figure 26 is the gear rack that is to be mounted on the side of the shaft. The purpose of the rack is to convert the vertical motion created by the relative motion between the shaft and the shaft housing into rotational motion. The rack has three tapped holes into the backside so that it can be bolted onto the shaft. The shaft will be manufactured from hardened steel to prevent rust and wear, and the holes can be machined on a CNC mill. The length of the rack can be altered in order to best fit the amplitude of the waves at a given location.

Figure 26: Image of the gear rack that is to be mounted onto the static shaft.

The final part of the main assembly is the buoyant sphere, pictured in Figure 27. The buoyant sphere is meant to provide an upward force on the static shaft in order to keep the shaft in equilibrium. If there were no upward force on the shaft, the shaft would simply fall to the bottom of its stroke, and there would be no relative motion between the buoy and the shaft. The sphere has a square cutout in the middle for which the shaft can slide into. Perpendicular to the square hole, there are two circular holes in order to mount the sphere onto the shaft. These holes are sized for 5/16 bolts. The sphere will be formed from ABS plastic using injection molding. The sphere's size is determined by the mass of the assembly and the depth of the ocean. A 16 graphical user interface was created in order to determine the size of the sphere for different power outputs. The GUI can also be found in the appendix.

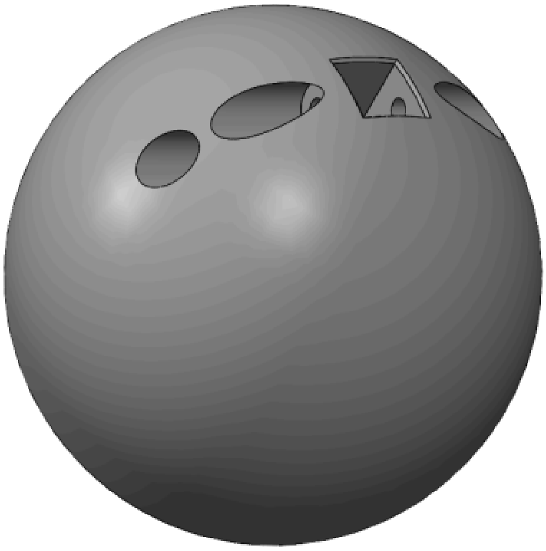


Figure 27: The buoyant sphere which supplies an upward force on the shaft. Constructed from ABS plastic and contains holes in order to mount itself to the shaft.

The depth of the ocean is an important factor in placing the buoy, as the length of the chain for the anchor must be chosen based on the given depth. The length of the chain is important as it affects the vertical position of the static shaft. If the shaft is either too high or too low relative to the average sea level, then the buoy will fail to capture the energy generated by the waves. The shaft should be located at a height such that the sphere portion of the buoy is approximately 4 feet underneath the average surface of the ocean. This will guarantee that the sphere stays submerged, but that the buoy will not be limited to a shorter range of motion. Schematics of the chain and anchor for the current model can be found below.

Figure 28: Illustration of the chain and anchor that will be attached to the bottom of the shaft and the ocean floor.

For MEH-3, a physical prototype was used to analyze how everything fits and moves, as well as a virtual prototype to test out the complex systems that the design calculations are relying on. An external flow simulation was used to verify the calculations on the buoyant forces needed for the design to function as intended. The physical prototype of the marine energy harvester was made for the purpose of verifying that the separate components designed by the three MEH teams would successfully fit together and create power. After considerable research and calculation conflicts, there were redesigns of the project which changed the requirements for verification on the first prototype. The primary objective being components seamlessly fit with other MEH team assemblies.

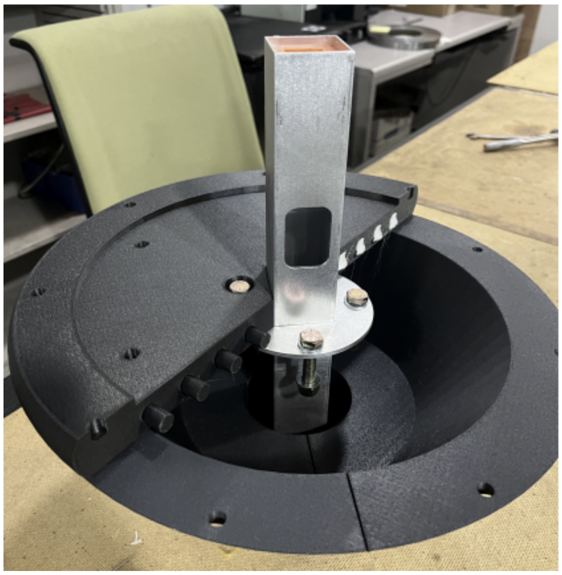


Figure 29: Physical Prototype of the shaft and mounting bracket with MEH-1 buoy attached

3.3.6.2 Approach to Solution (materials and rationales)

To determine the best solution, four methods were employed: brainstorming sessions, 4-3-5 brainwriting, go/no-go screening, and a Pugh chart analysis. Brainstorming yielded five designs, including flat buoyant platforms, pelamis-type devices, turbine propellers, floating platforms with linkage arms, and a single floating platform with a crankshaft. Criteria for evaluation included stability, anchoring system, efficiency, manufacturability, orientation, modularity, safety, mechanism type, reliability, and deployability. A failed design led to a new concept featuring a buoyant sphere for static force, offering greater feasibility and ease of manufacture.

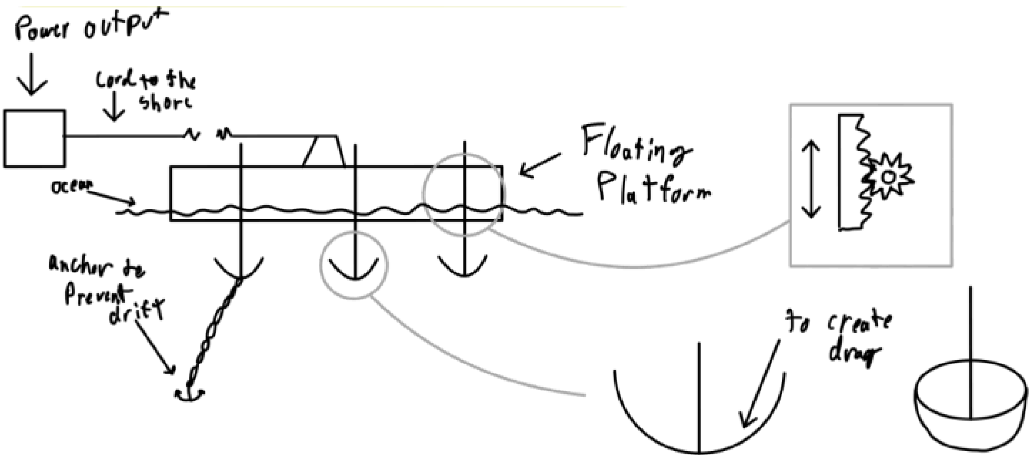


Figure 30: First design containing a buoyant platform with multiple rods.

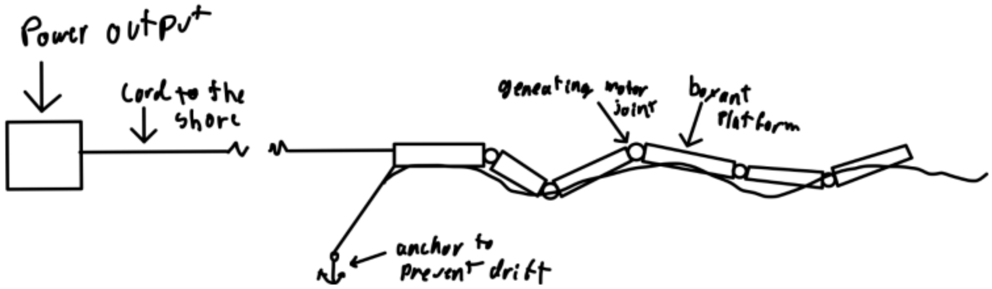


Figure 31: Pelamis type wave to electrical energy generator.

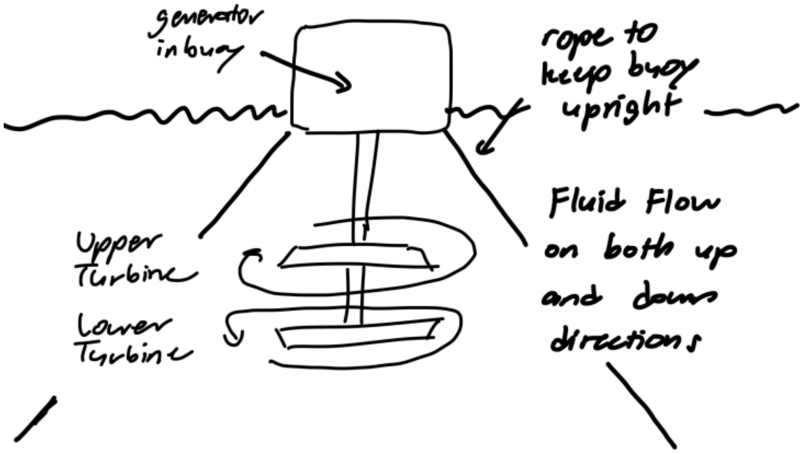


Figure 32: Turbine propeller wave to electrical energy generator.

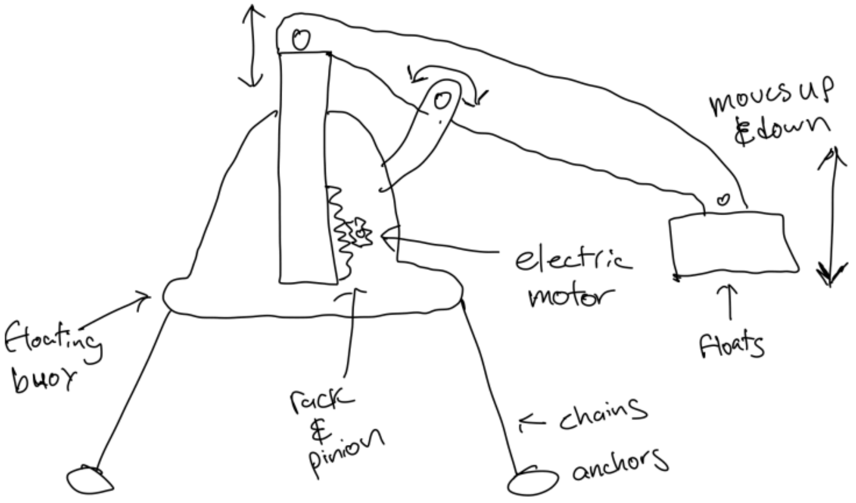


Figure 33: Relative motion between two buoyant platforms

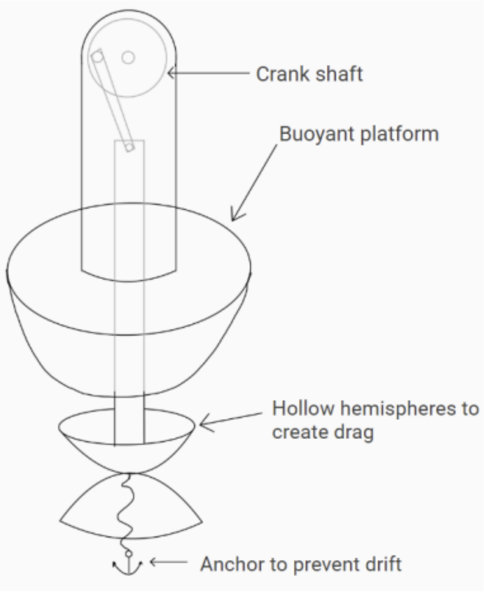
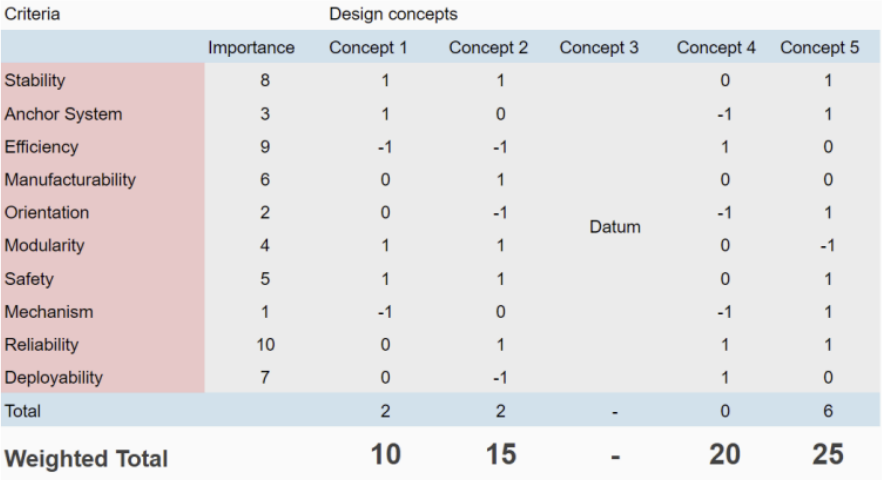


Figure 34: Crankshaft energy generator.



Criteria		Design concepts				
	Importance	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5
Stability	8	1	1	Datum	0	1
Anchor System	3	1	0		-1	1
Efficiency	9	-1	-1		1	0
Manufacturability	6	0	1		0	0
Orientation	2	0	-1		-1	1
Modularity	4	1	1		0	-1
Safety	5	1	1		0	1
Mechanism	1	-1	0		-1	1
Reliability	10	0	1		1	1
Deployability	7	0	-1		1	0
Total		2	2	-	0	6
Weighted Total		**10**	**15**	**-**	**20**	**25**

Figure 35: Pugh chart of the five proposed designs.

3.4 Electrical Engineering Contributions

3.4.1 Introduction to Electrical Engineering Role

Our Electrical Engineering (EE) team played a pivotal role in developing the storage and delivery aspects of the project. Focusing on creating a Battery Management System (BMS), we aimed to make irregular power supply usable. Initially, we explored using seawater for batteries to align with the project's eco-friendly goals, but ultimately reverted to Li-ion cells due to time constraints.

Battery packs with three cells each, were developed and wired into the BMS to monitor voltages and manage charging/discharging. To validate our prototype, the team built a testbench capable of simulating varied energy waveforms, ensuring our BMS could respond effectively. The prototype includes a microcontroller, relay switches, Li-ion cells, and voltage sensors, enabling precise voltage monitoring and control.

The next steps involve integrating the BMS with the Mechanical Engineering (ME) team's buoy-driven power generator. The scalable design can accommodate larger battery packs for increased capacity, positioned well for future phases of development and scaling.

3.4.2 Battery Storage and Management System (BMS) Concept Overview

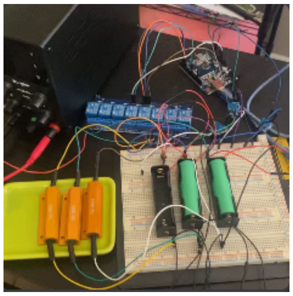


Figure 36: Picture of Battery Management System (BMS) Prototype

The design considerations encountered significant challenges due to time and budget constraints. These limitations impeded the incorporation of certain desired features into the Battery Management System (BMS). Extensive research into various BMS designs was undertaken, but accessibility to parts emerged as a recurring issue. Previous iterations relied on custom PCBs, which were unavailable for purchase due to parts being consistently out of stock. As a result, the team pivoted towards utilizing readily accessible components, facilitating scalability and modular expansion of our system, such as the integration of additional battery packs. Moreover, the project aimed to develop a standalone prototype with the anticipation of later integration into the Mechanical Engineering team's buoy generator, necessitating the creation of a functional and scalable prototype with limited insight into the companion project's specifics.

Regarding industry standards, the team adhered to the RS-232 Standard to ensure a "hardwired" yet straightforward execution of our design, circumventing complexities associated with wireless or microcontroller communication. Additionally, the utilization of Windows OS facilitated the operation of essential software tools such as the Arduino IDE, enabling control and management of both the Testbench and BMS. Furthermore, Python programming in the Visual Studio Code IDE was employed to develop a user-friendly graphical user interface (GUI) for enhanced readability and ease of comprehension.

Safety considerations are paramount within the project, particularly concerning battery handling and our team's limited experience in power electronics. With the aim of generating 150Wh, project specifications entail specific voltage and capacity requirements per battery pack. However, lacking expertise in battery circuitry and maintenance poses significant safety risks to both the system and personnel involved. The Battery Management System (BMS) is designed with a primary focus on battery safety, aiming to prevent incidents such as overcharging, undercharging, gas leakage, fires, or explosions. Automated features within the BMS are implemented to maintain safe battery conditions, mitigating potential hazards associated with unbalanced cells and ensuring even charging and discharging.

3.4.3 Architecture and High Level Design of BMS

The main design specification to accomplish was developing enough battery discharge capacity to store the power generation of our mechanical engineers' buoy generator. This requirement would then influence our other design specifications in the rest of our systems such as: battery pack configuration, BMS and testbench design. Based on research of Battery Management Systems, a couple basic features to function were needed such as: state of charge, voltage levels, current flow. To determine which batteries to charge or discharge to maintain nominal conditions, relay switches were used to close the circuit connecting it into a power resistor where our batteries could discharge in the form of heat dissipation or the switch would remain open exclusively charging the battery pack.

3.4.3.1 System Architecture and Design

The Testbench contains the power output regulation and a means of controlling it digitally with a computer interface. This allowed the systems input power to be varied over time to allow for the testing of the BMS under power fluctuations similar to what might be experienced once integration with the ME team's buoy occurs.

The BMS uses voltage sensors to monitor battery packs and relays to control the power flowing to and from the battery packs, to charge and discharge the batteries respectively, all of which are manipulated through an Arduino program.

3.4.3.2 Hardware Architecture

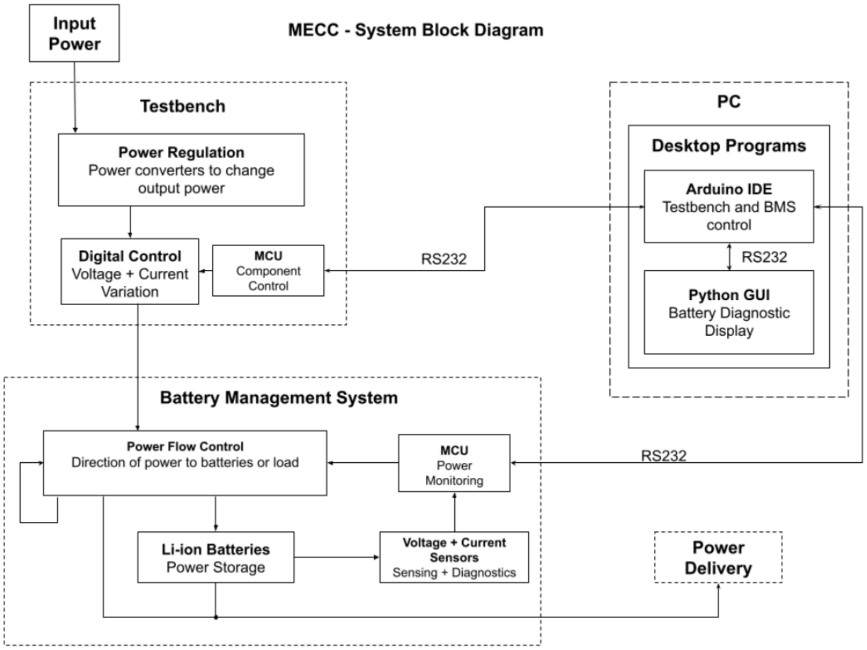


Figure 37: System Block Diagram

3.4.3.3 Software Architecture

Testbench Software Block Diagram

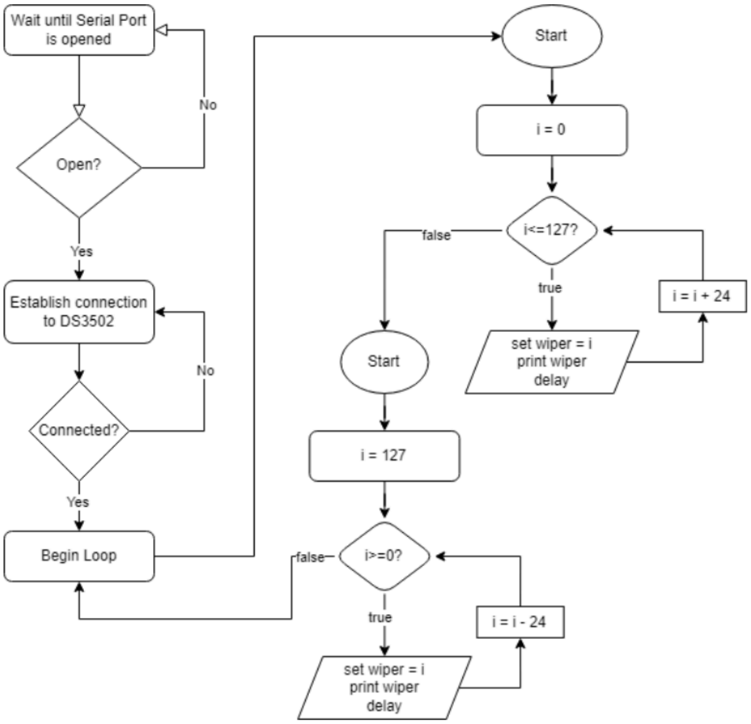


Figure 38: Testbench Software Block Diagram

Battery Management System Software Block Diagram

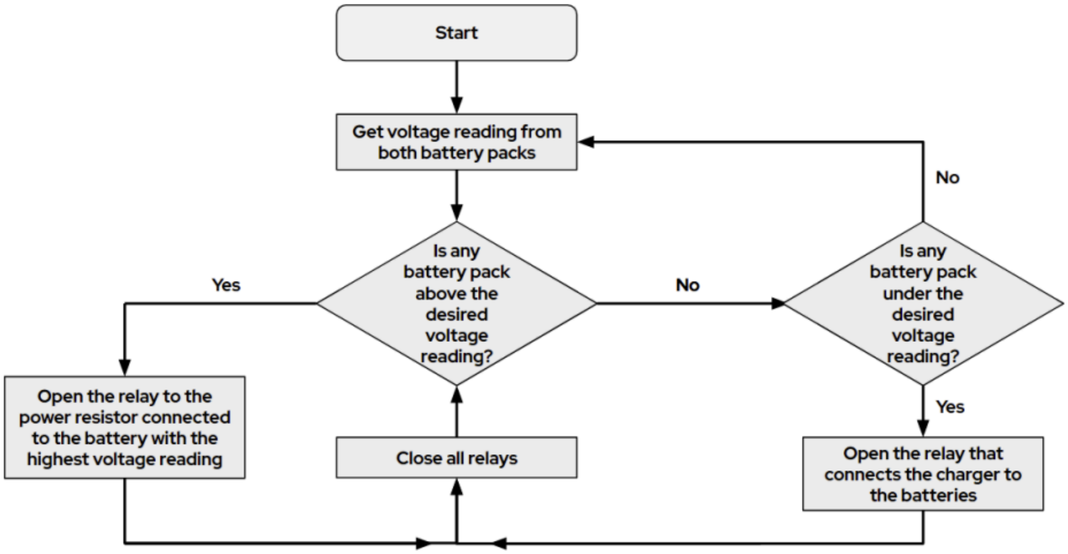


Figure 39: Testbench Software Block Diagram

3.4.4 Low Level Design of BMS

3.4.4.1 Testbench

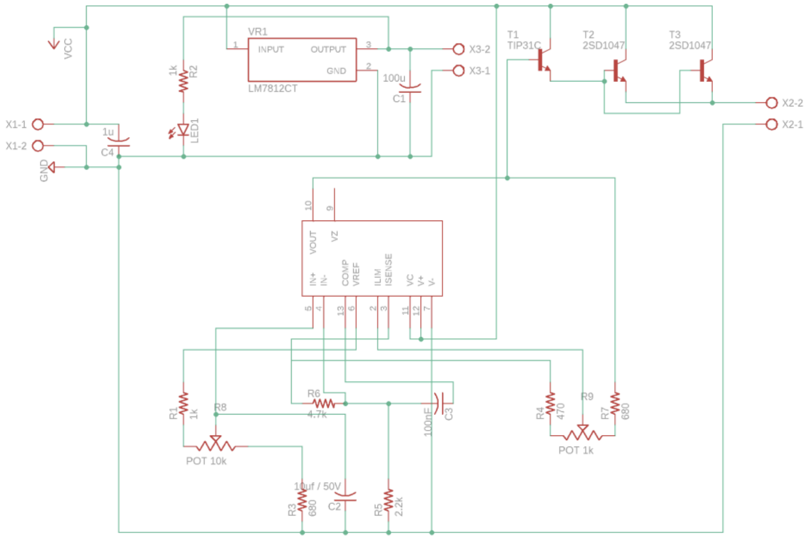


Figure 40: Circuit Diagram of testbench

Processing narrative for Testbench
The Testbench functions as such, it receives a fixed input power and with the use of voltage regulators and power transistors, it is able to output a range of power from 1 to its input minus about 1.77 volts. With the use of digital potentiometers the control can be automatic instead of manual.

Testbench interface description
The Testbench only needs an input source, in its current form it can handle an input of 1-30V and 0-1A. The voltage limitation was an intentional design, however, the current limitation is a constraint imposed by the breadboard it operates on.

Testbench processing details
As an example, supplying the Testbench with 20 V from a lab power supply, could output anywhere from 1V to about 18V. With the integration of digital potentiometers and software, this control can be automatic and run through a loop that can produce whatever waveform desired. As mentioned earlier the system has a voltage drop of about 1.77V as such, this voltage drop needs to be considered when calculating for the desired output voltage.

3.4.4.2 Battery Management System

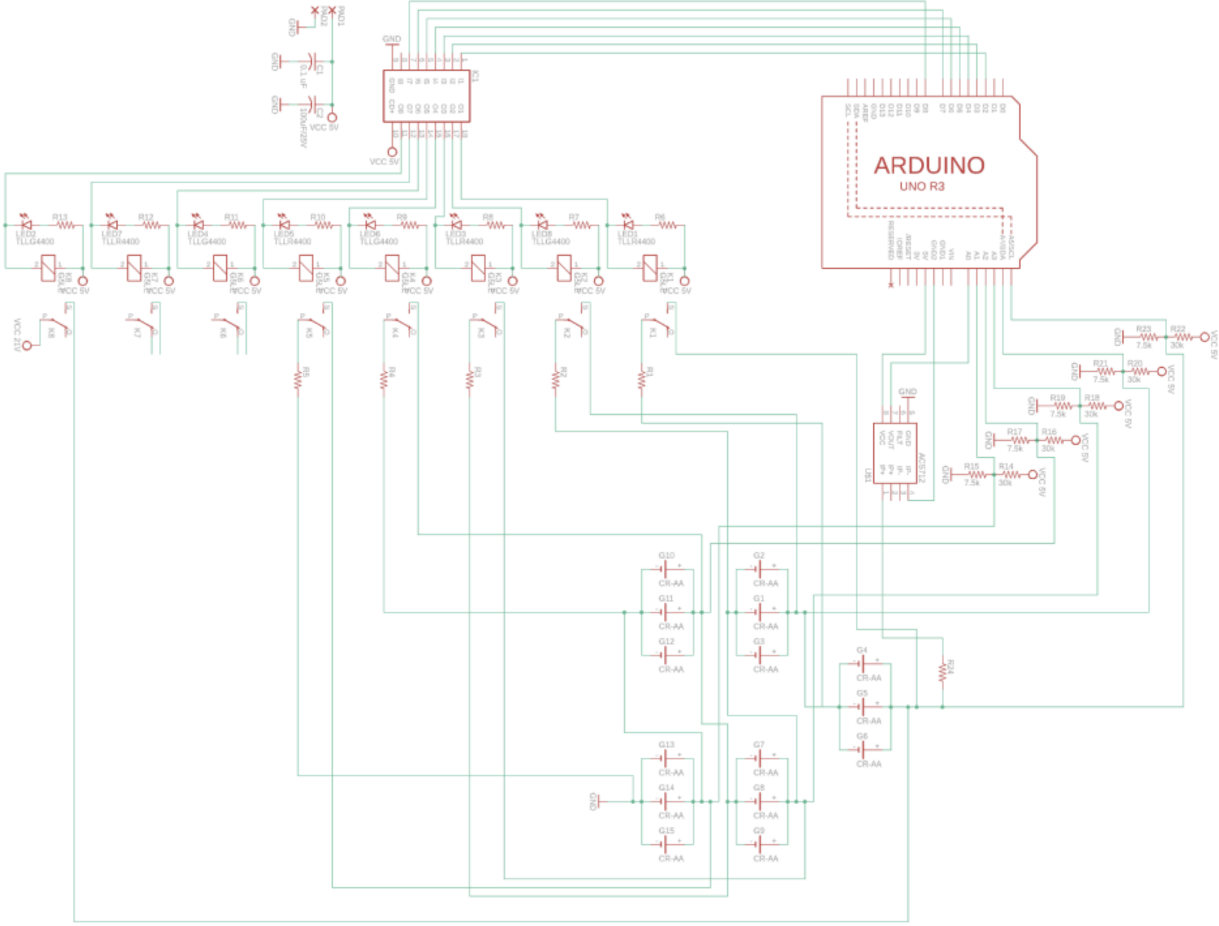


Figure 41: Circuit Diagram of Battery Management System

Processing Narrative for Battery Management System

The BMS overlooks the status of all battery packs, such as voltage, and automatically determines which battery pack needs to be charged or discharged. It will first prioritize any battery pack that needs discharging and if so, will connect that battery pack to the load (power resistors) to discharge the battery via relays that are controlled by the Arduino UNO. If there are multiple batteries that need discharging, it will prioritize the battery with the highest voltage to ensure safety. On the flip side, it works similarly to charging. If it recognizes that any of the batteries are too low, it will charge the entire battery system because they are connected in series. The system will prioritize discharging any batteries before charging.

Battery Management System Interface Description

The BMS receives variable power input from the test bench. This input is directly connected to a relay switch to be controlled via Arduino UNO. The input connects to the system whenever the batteries need to be charged. On the other end of said relay, it is directly connected to the positive terminal of the batteries (positive terminal of the “first” battery pack of the series) and the ground from the test bench’s power supply is connected to the negative terminal of the batteries (negative terminal of the “last” battery pack of the series).

Additionally, the output of the BMS is a GUI that displays the system's status (such as charging, discharging, stabilizing) and the live voltage readings of each battery pack. The GUI was programmed in Python on Visual Studios IDE and receives the data from the Arduino UNO via serial communication.

Battery Management System Processing Details

Due to the 8-channel relay module used, the system is limited to seven battery packs at most for the single system since one relay is needed per battery pack and one relay is dedicated as the charger. Though, beyond that point, the system can just be replicated and microcontrollers can communicate with each to create a bigger system.Some performance issues occur with the voltage sensors as the longer they run, the more inaccurate the readings are. When the system first starts up, things run perfectly but after extended periods of time, around 10 minutes, the voltage readings become exponentially smaller despite the battery voltages minimally changing. Thus, at the point the prototype is at currently, it optimally runs up to 10 minutes at a time, not including time for the system to "cool down".

3.4.4.3 Battery Pack Configuration

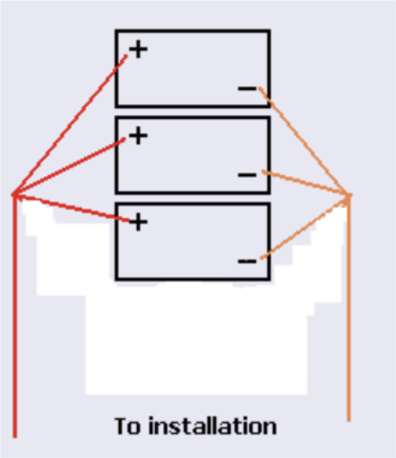
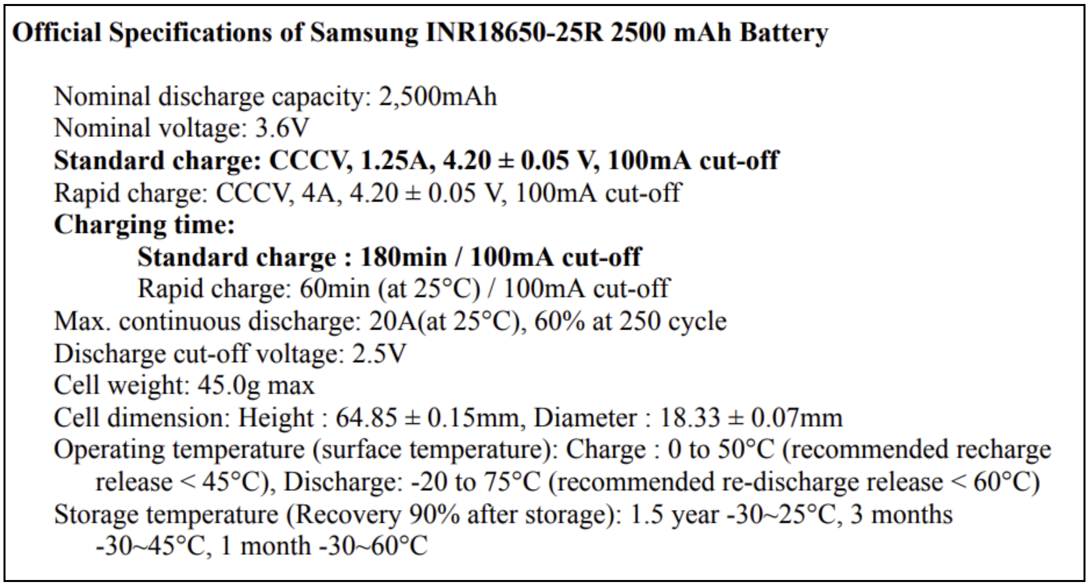


Figure 42: Battery Pack Wiring Diagram

Processing narrative for Battery Pack Configuration

Battery Packs: The battery packs were created by spot welding strips of pure Nickel (50mm x 6mm x 0.15mm) to the ends of the individual Li ion cells. The batteries used were the Samsung 25R 2500mAh 20A 18650 cells. The individual cells with attached electrode lengthening strips were then joined in parallel to a central electrode for both the positive and negative sides. These central electrodes were then connected to the BMS.



Official Specifications of Samsung INR18650-25R 2500 mAh Battery

Nominal discharge capacity: 2,500mAh
Nominal voltage: 3.6V
Standard charge: CCCV, 1.25A, 4.20 ± 0.05 V, 100mA cut-off
Rapid charge: CCCV, 4A, 4.20 ± 0.05 V, 100mA cut-off
Charging time:
    Standard charge : 180min / 100mA cut-off
    Rapid charge: 60min (at 25°C) / 100mA cut-off
Max. continuous discharge: 20A(at 25°C), 60% at 250 cycle
Discharge cut-off voltage: 2.5V
Cell weight: 45.0g max
Cell dimension: Height : 64.85 ± 0.15mm, Diameter : 18.33 ± 0.07mm
Operating temperature (surface temperature): Charge : 0 to 50°C (recommended recharge release < 45°C), Discharge: -20 to 75°C (recommended re-discharge release < 60°C)
Storage temperature (Recovery 90% after storage): 1.5 year -30~25°C, 3 months -30~45°C, 1 month -30~60°C

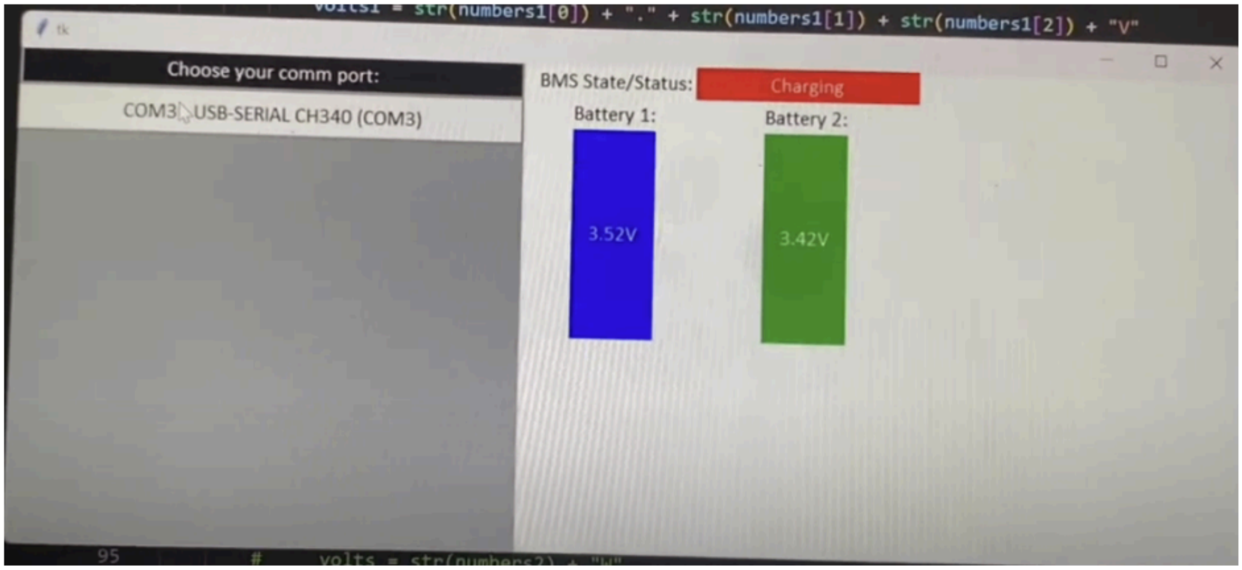
Figure 43: Samsung Battery Specifications

3.4.4.4 User Interface Design

Application Control

The user interface programmed for the BMS relatively stays constant throughout the entirety of the system running. On the left hand side of the screen is a menu to select which communication port the Arduino UNO is connected to. On the right hand side is the BMS logistics, such as what the system is doing (charging, discharging, or stabilizing) and the live voltage readings of each battery pack. All elements regarding the BMS automatically update so only one click from the user is needed to connect to the correct Arduino UNO. We programmed the entirety of the GUI system using Python and the libraries tkinter and pyserial.

User Interface Screens



```
volts1 = str(numbers1[0]) + "." + str(numbers1[1]) + str(numbers1[2]) + "V"
```

Choose your comm port:
COM3 USB-SERIAL CH340 (COM3)

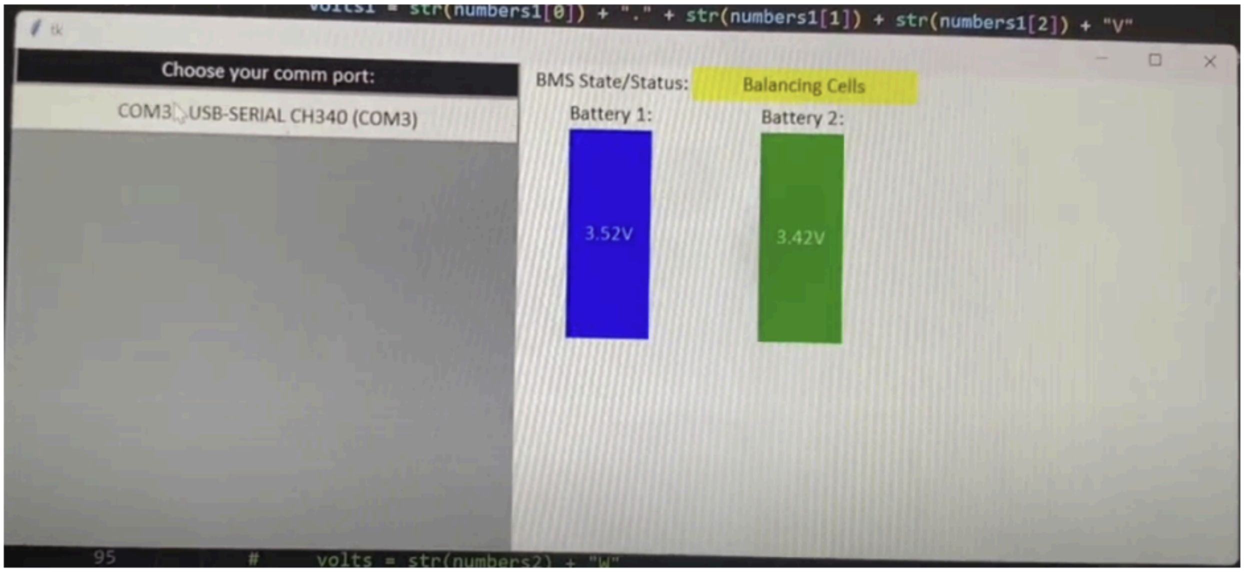
BMS State/Status: Charging

Battery 1: 3.52V

Battery 2: 3.42V

```
#     volts = str(numbers2) + "W"
```

Figure 44: The voltage readings of each battery pack are shown and labeled as well as the state of the BMS illustrating that the system is charging.



```
volts1 = str(numbers1[0]) + "." + str(numbers1[1]) + str(numbers1[2]) + "V"
```

Choose your comm port:
COM3 USB-SERIAL CH340 (COM3)

BMS State/Status: Balancing Cells

Battery 1: 3.52V

Battery 2: 3.42V

```
#     volts = str(numbers2) + "W"
```

Figure 45: The voltage readings of each battery pack are shown and labeled as well as the state of the BMS illustrating that the system is stabilizing (neither charging or discharging).

4. WEC and BMS Testing

4.1 Introduction to the Build and Test Challenge

In the testing and validation phase, the project underwent meticulous scrutiny to ensure functionality and safety across its key components. The testing was segmented into distinct areas, focusing on both the

Wave Energy Converter (WEC) power generation device and the Battery Management System (BMS) developed by the Electrical Engineering team.

Description of Build Process
The fabrication process for the prototype components is detailed in the technical reports provided by each individual team. Additional information, including parts drawings, can be found in the appendix.

4.2 WEC Power Generation Testing

4.2.1 MEH-1 Design Verification and Feasibility Study

The primary focus of physical prototyping was to verify the kinetics of the device with the other MEH groups designs..After constructing the prototype, it became evident that the design chosen from MEH-2 was incompatible. The main problem arose from the motors' demand for high torque, which the existing design couldn't provide. Additionally, the buoy required a considerable force to rise, but it didn't descend naturally. To address this issue, the team promptly revamped the drivetrain, opting for low rpm and torque DC motors, and adjusting the motor orientation.

As the MEH-1 team's primary concern is the buoyancy force, a dynamic analysis of the a virtual prototype was necessary. To start the analysis, wave data gathered from the National Data Buoy Center was collected to determine the wave height, speed, and period of oscillation that the buoy would be exposed to. With this information, the wave was modeled as a sine function that described the displacement over time. Assumptions were made that the buoy will follow this motion and that the cycle will stay consistent over an hour period. The position graph can be seen below.

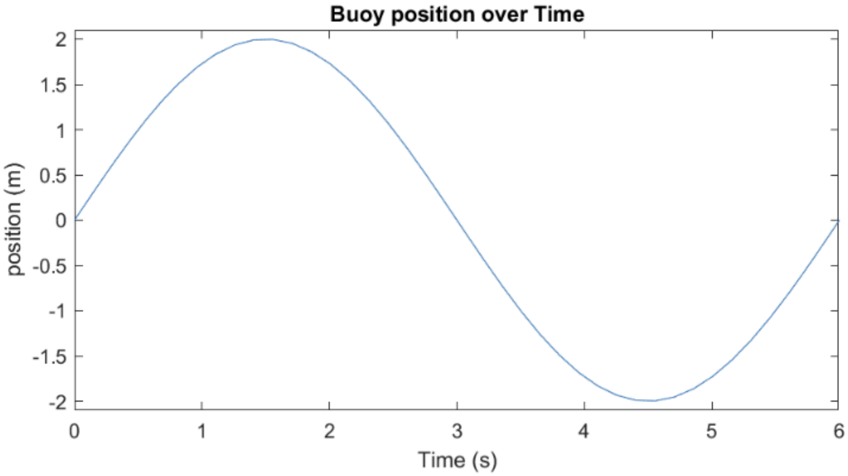


Figure 46: Buoy displacement versus time over one cycle of oscillation

A free body diagram was created to set up the second order differential equation that governs the motion of the device. MATLAB's ode45 function was used to solve the differential equation which was used to generate a graph displaying velocity versus time. The buoyancy force was then calculated and plotted against time to display the varying buoyant force corresponding to the changing volume displacement of the buoy. The associated graphs are displayed below.

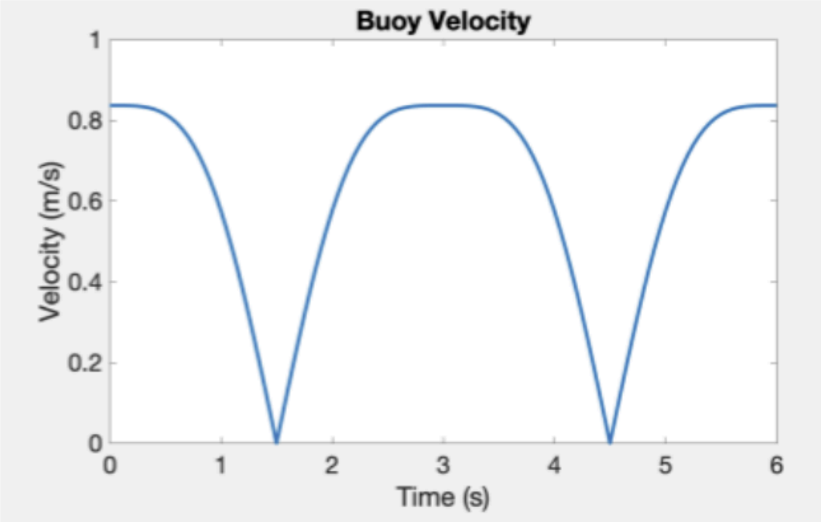


Figure 47: Buoy Velocity versus time over one cycle of oscillation

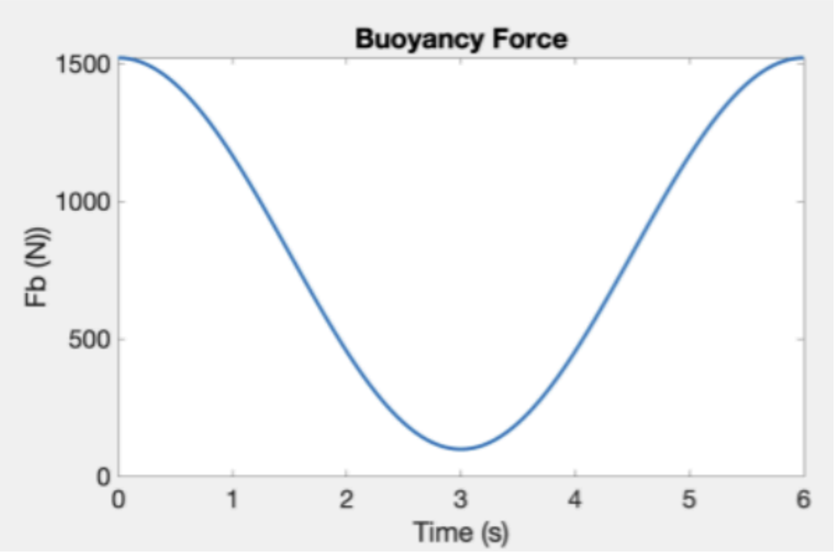


Figure 48: Buoyancy force versus time over one cycle of oscillation

With this information collected, the team was able to generate a plot of the mechanical power output of the buoy by multiplying the buoyant force array by the velocity array. The average power output of the device was found to be 741W with its corresponding plot shown below. The large discrepancy between the physical and virtual prototype power output is largely due to the different scale of each model. The virtual prototype was also simulated not taking into account the resistance from the drive train made by MEH-2.

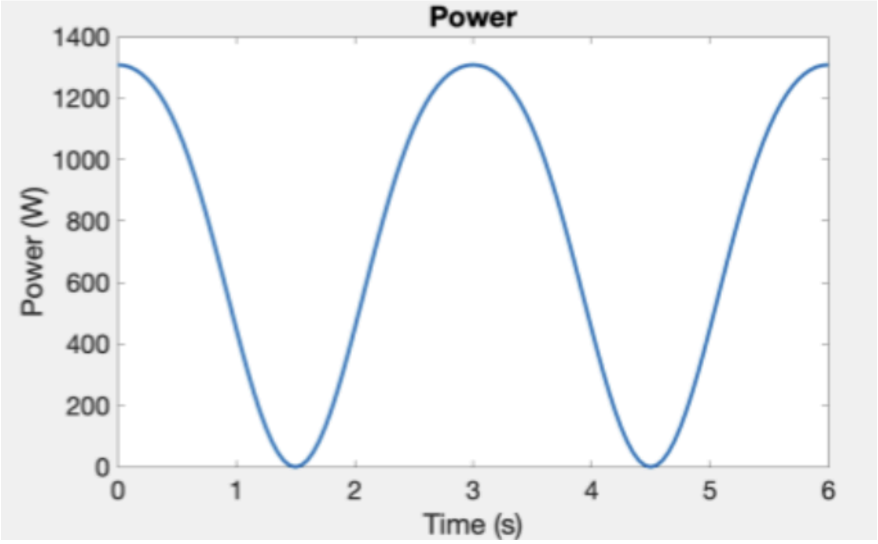
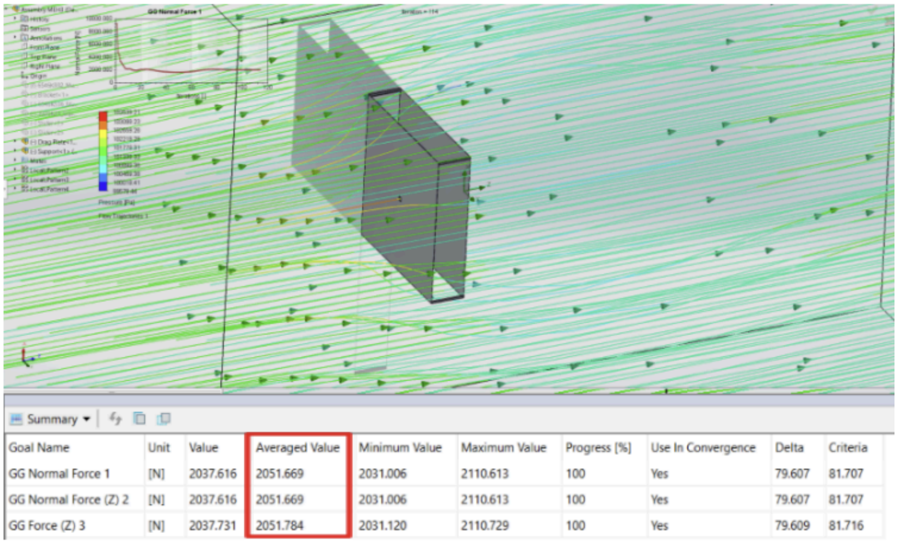


Figure 49: Power output versus time over one cycle

4.2.2 MEH-3 Design Verification and Feasibility Study

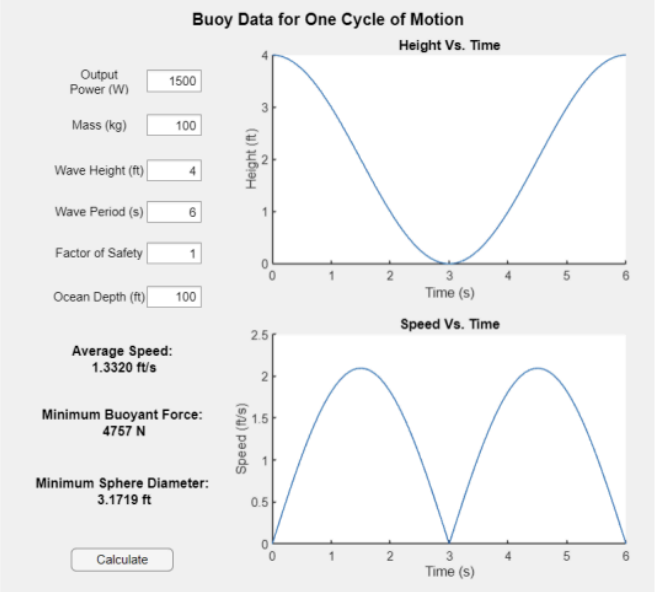
A virtual prototype was made for the purpose of verifying whether the design matched the calculations that were required. The hand calculations involved a necessary drag force on a 20 square plate to provide enough static support for a generator to create 1.5 kW of power. Using an external flow simulation, the team was able to simulate an accurate representation of the preliminary drag component design in action. The simulation gave results on the force experienced by the drag plate, which can then verify whether the drag plate was able to carry enough force to keep the device static. This virtual prototype also helped the team verify the feasibility of the original design, as scaling the size of the plate to match the desirable drag force was a helpful tool.



Goal Name	Unit	Value	Averaged Value	Minimum Value	Maximum Value	Progress [%]	Use In Convergence	Delta	Criteria
GG Normal Force 1	[N]	2037.616	2051.669	2031.006	2110.613	100	Yes	79.607	81.707
GG Normal Force (Z) 2	[N]	2037.616	2051.669	2031.006	2110.613	100	Yes	79.607	81.707
GG Force (Z) 3	[N]	2037.731	2051.784	2031.120	2110.729	100	Yes	79.609	81.716

Figure 50: Solidworks simulation to verify the drag force supplied by two drag plates.

Another virtual prototype used was a GUI made on Matlab which provided average speed of the wave, minimum buoyant force needed from the underwater buoy, and minimum sphere diameter of the underwater buoy. The parameters that must be given are desired output power of the system, expected mass of the entire device, maximum wave height, wave period, desired factor of safety, and approximate ocean depth. Using this GUI can provide insight towards 21 scalability on the main MEH-3 design, which is the underwater buoy. Assumptions and simplifications made regarding the GUI are that the wave height, wave period, and ocean depth would remain constant. The purpose of the GUI is to provide rough estimates that will be accurate enough to verify design feasibility as well as scaling feasibility


Buoy Data for One Cycle of Motion

Output Power (W) 1500

Mass (kg) 100

Wave Height (ft) 4

Wave Period (s) 6

Factor of Safety 1

Ocean Depth (ft) 100

Average Speed:
1.3320 ft/s

Minimum Buoyant Force:
4757 N

Minimum Sphere Diameter:
3.1719 ft

Figure 51: Matlab GUI for calculations of necessary parameters for the underwater buoy

The results of the physical prototype were a success regarding design verification. As mentioned previously, the main requirements that this first physical prototype needed was that the components could move seamlessly and that it could generate any power at all.

The results of the flow simulation were disappointing as it proved the feasibility of the drag plate design was impossible. The simulation resulted in the drag plate receiving a drag force of 2051 N on average, while the necessary drag force based on calculations was 3691 N. This was already under the assumption that the drag plate would have an area of 160 m^2, an area far too large to be manufactured. The large difference between the drag forces proved the calculations to be wrong, thus the necessary drag plate area was unable to be determined. It was for this reason that led to a design change where the underwater buoy was introduced and the drag plate idea was discarded. The calculations made from the GUI shows promising results as the buoy only requires a 3.2 feet diameter under the same conditions the drag plate was calculated with

As mentioned before, the predetermined requirements for the design consisted of producing a minimum of 1.5 kW of power, being portable, and having the ability to connect with nearby MEH’s. However, these requirements are for the final product and do not reflect the requirements made for the prototype.

4.2.3 Overview of Testing Procedures

Introduction

Our wave energy converter (WEC) prototype harnesses the power of ocean waves through an innovative design centered on the heaving buoy concept. The device operates via direct mechanical drive, featuring a stationary rack and onboard drivetrain equipped with a pinion for rotational motion. The primary objective of our experiment is to rigorously test the power input and output of the device, recording operational performance data to calculate operational efficiency under varying wave conditions. Through this testing process, we aim to validate the functionality and effectiveness of our WEC prototype.

Experimental Setup

To conduct our experiment on the wave energy converter (WEC) prototype, a comprehensive list of materials and equipment is required. Our testing environment comprises a controlled setting where we can manipulate the device manually to simulate wave action. Additionally, access to power sources, as well as adequate lighting for video recording is required. The testing area will be equipped with appropriate safety measures to ensure the well-being of the experimenters

Materials and Equipment:

1. WEC prototype: Includes stationary rack, buoy assembly, generators (DC motors), and associated components.
2. Cameras: To capture video footage for velocity tracking and data synchronization.
3. Laptop: For running video analysis software (Tracker) and data recording.
4. Tracker software: A video analysis tool to track the linear velocity of the device.
5. Two D-rig anchors: Used for tethering the device during testing.
6. Tarp straps: To secure the anchors and apply tension to measure starting upward buoyant force.
7. Two multimeters: For measuring electrical power output (voltage and current).
8. Breadboard and wire leads: To connect the multimeters to the circuit.
9. LEDs and resistors: Additional components for circuitry if needed.
10. Measuring tape and scale: For recording dimensions and weight of the device.
11. Phone mounts: To secure cameras in place for recording.
12. Luggage scale and spring clamp: For measuring starting upward buoyant force.

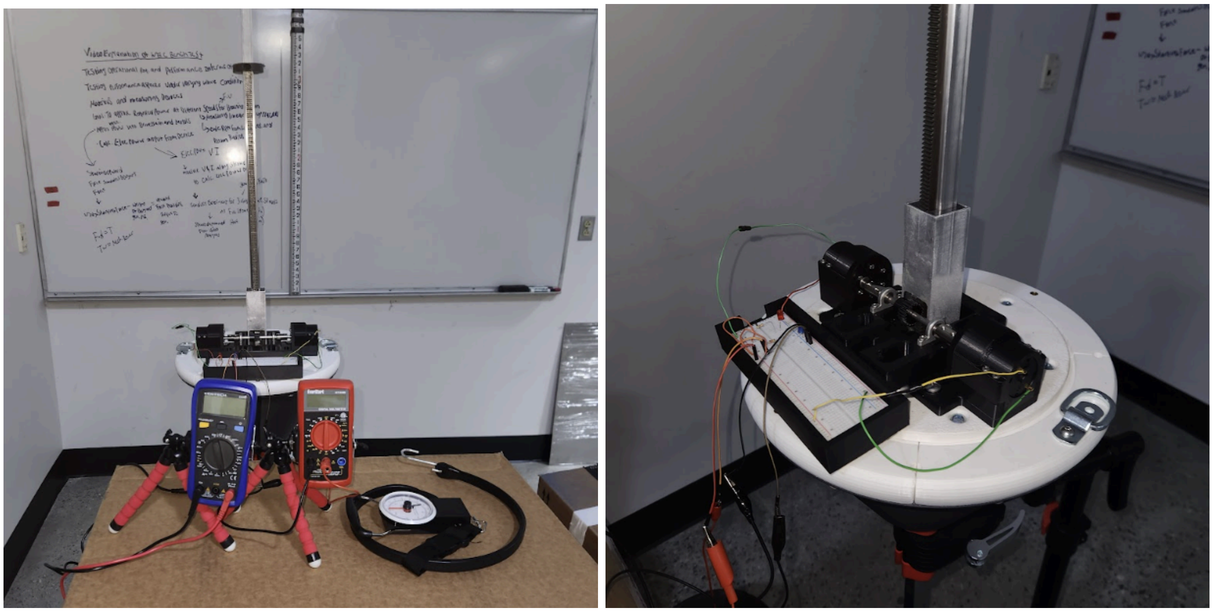


Figure 52: Photos of WEC power generation Test Setup

Procedure

Setup:
a. Place the WEC prototype in the testing environment, ensuring a clear and open space for full device motion.
b. Secure the D-rig anchors to provide stability and tether the device during testing using tarp straps.
c. Connect the cameras to their mounts and position them to capture video footage of the device's motion.
d. Connect the multimeters to the circuit and ensure proper functionality.

Calibration:
a. Calibrate the cameras and Tracker software to accurately track the linear velocity of the device.
b. Verify the functionality of the multimeters and ensure they are properly connected to measure electrical power output.

Data Synchronization:
a. Mark specific points along the device's stroke with colored tape for data synchronization.
b. Ensure that the cameras and multimeters are synchronized to record data simultaneously at these marked points.

Experiment Execution:
a. Manually move the device up and down starting from rest.
b. Record video footage of the device's motion using the cameras and Tracker software.
c. Measure the starting upward buoyant force using the spring clamp and luggage scale.
d. Record electrical power output using the multimeters connected to the circuit.
e. Repeat the process for different operational conditions, varying wave speeds and heights as per the MECC testing guidelines.

Data Collection:
a. Record weight measurements, dimensions, rpm, linear velocity, electrical readings, etc., as per the experimental setup.
b. Collect data at each marked point along the stroke to ensure comprehensive analysis.

Explanation of Measurement and Data Recording

- The velocity of the device will be tracked using Tracker software, which analyzes video footage captured by the cameras.
- Starting upward buoyant force will be measured using attached anchors, tarp strap, and luggage scale, providing insight into the device's initial power requirements.
- Electrical power output will be recorded using the multimeters connected to the circuit, measuring voltage and current.
- Data will be synchronized at specific points along the stroke using colored tape markers, allowing for accurate analysis and comparison across different conditions.

Relevant Equations

1. Mechanical Power

$$P_{mech} = \text{Force} \times \text{Velocity} + I\omega \text{ (}I\omega\text{ is neglected for simplicity)}$$

This equation calculates the mechanical power exerted by the device, where Force is the force applied to the device and Velocity is the linear velocity of the device.

2. Electrical Power Output

$$P_{elec} = \text{Voltage} \times \text{Current}$$

This equation determines the electrical power output of the device, where Voltage is the voltage across the circuit and Current is the current flowing through the circuit.

3. Efficiency (η)

$$\eta = P_{elec} / P_{mech}$$

Efficiency represents the ratio of electrical power output to mechanical power input, providing insights into the device's overall performance.

4. RPM Calculation

$$RPM = (\text{Linear Velocity} \times 60) / \text{Circumference of Pinion}$$

This equation calculates the revolutions per minute (RPM) of the rotating shaft attached to the pinion, based on the linear velocity of the device and the circumference of the pinion (40 mm).

4.2.4 Results of Performance Testing

Table 9: Experimental Parameters and Device Measurements

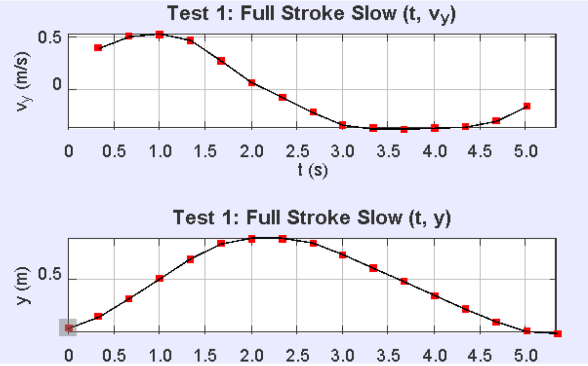
Parameter	Description	Recording
Device Weight	Total weight of the WEC prototype and buoy mechanism	11.4 lbs
Buoy Weight	Weight of the buoy mechanism and power generation assembly	9.2 lbs
Rack and Shaft Weight	Weight of the rack and shaft assembly	2.2 lbs
Rack and Shaft Dimensions	Length, width, height, of rack and shaft assembly	Max Length: 1.25 in Width: .75 in Height: 6 ft
Buoy Dimensions	Length, width, height, and diameter of the buoy mechanism	Length: 13 in Width: 13 in Height: 13.5 in Buoy Diameter: 13 in
Starting Upward Force	Initial force required to overcome static loads	Approx. 13.5 lbs ≅ 60 N
Wave Speeds	Speeds at which the device will be moved vertically	Determined from Video Tracking software (Tracker) and loosely controlled manually for slow, medium, and fast wave speeds
Wave Amplitudes	Amplitudes of the waves	Full Stroke (15 in) Half Stroke (7.5 in)

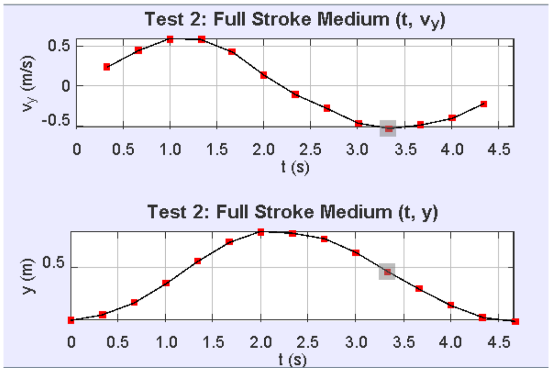
Table 10: Data Recordings

Condition (Wave Speed/Amplitude)	Stroke Position	Time (s)	Velocity (m/s)	RPM	Mechanical Power (W)	Voltage (V)	Current (A)	Electrical Power (W)	Efficiency (%)
Test 1 (Full Stroke)(Slow)	Position 1	0.334	0.40	190.99	24	0.6	0.91	0.55	0.02
	Position 2	1.001	0.53	254.01	31.92	2.6	5.95	15.47	0.48
	Position 3	3.337	-0.37	174.75	21.96	0.7	4.28	3.00	0.14
	Position 4	4.004	-0.36	173.32	21.78	5.53	0.8	4.42	0.20
Test 2(Full Stroke)(Medium)	Position 1	1.001	0.59	279.79	35.16	2.2	4.93	10.85	0.31
	Position 2	1.335	0.58	275.97	34.68	2.2	5.33	11.73	0.34
	Position 3	2.336	-0.11	51.09	6.42	0.58	1.4	0.81	0.13
	Position 4	3.337	-0.52	249.24	31.32	1	6.82	6.82	0.22
Test 3(Full Stroke)(Fa	Position 1	1.001	0.66	316.08	39.72	3.9	5.73	22.35	0.56

st)									
	Position 2	1.335	0.599	286.00	35.94	3.45	4.1	14.15	0.39
	Position 3	3.003	-0.683	326.11	40.98	1.7	8.35	14.20	0.35
	Position 4	3.337	-0.495	236.35	29.7	1.5	7.3	10.95	0.37
Test 4 (Half Stroke)(Slow)	Position 1	1.251	0.269	128.44	16.14	0.8	2.49	1.99	0.12
	Position 2	1.502	0.283	135.12	16.98	0.3	3.27	0.98	0.06
	Position 3	2.502	-0.139	66.37	8.34	1.3	0.22	0.29	0.03
	Position 4	3.253	-0.354	169.02	21.24	1.2	4.03	4.84	0.23
Test 5 (Half Stroke)(Medium)	Position 1	0.751	0.483	230.62	28.98	1.1	4.2	4.62	0.16
	Position 2	1.084	0.355	169.50	21.3	1.1	5.98	6.58	0.31
	Position 3	2.085	-0.478	228.23	28.68	2.7	1.93	5.21	0.18
	Position 4	2.336	-0.515	245.89	30.9	1.7	6.12	10.40	0.34
Test 6 (Half Stroke)(Fast)	Position 1	1.001	0.471	224.89	28.26	2	5.07	10.14	0.36
	Position 2	1.168	0.216	103.13	12.96	2	0.71	1.42	0.11
	Position 3	1.668	-0.339	161.86	20.34	3.3	2.12	7.00	0.34
	Position 4	2.169	-0.575	274.54	34.5	2.8	6.02	16.86	0.49
Average Efficiency									0.26

Tracker Software Data





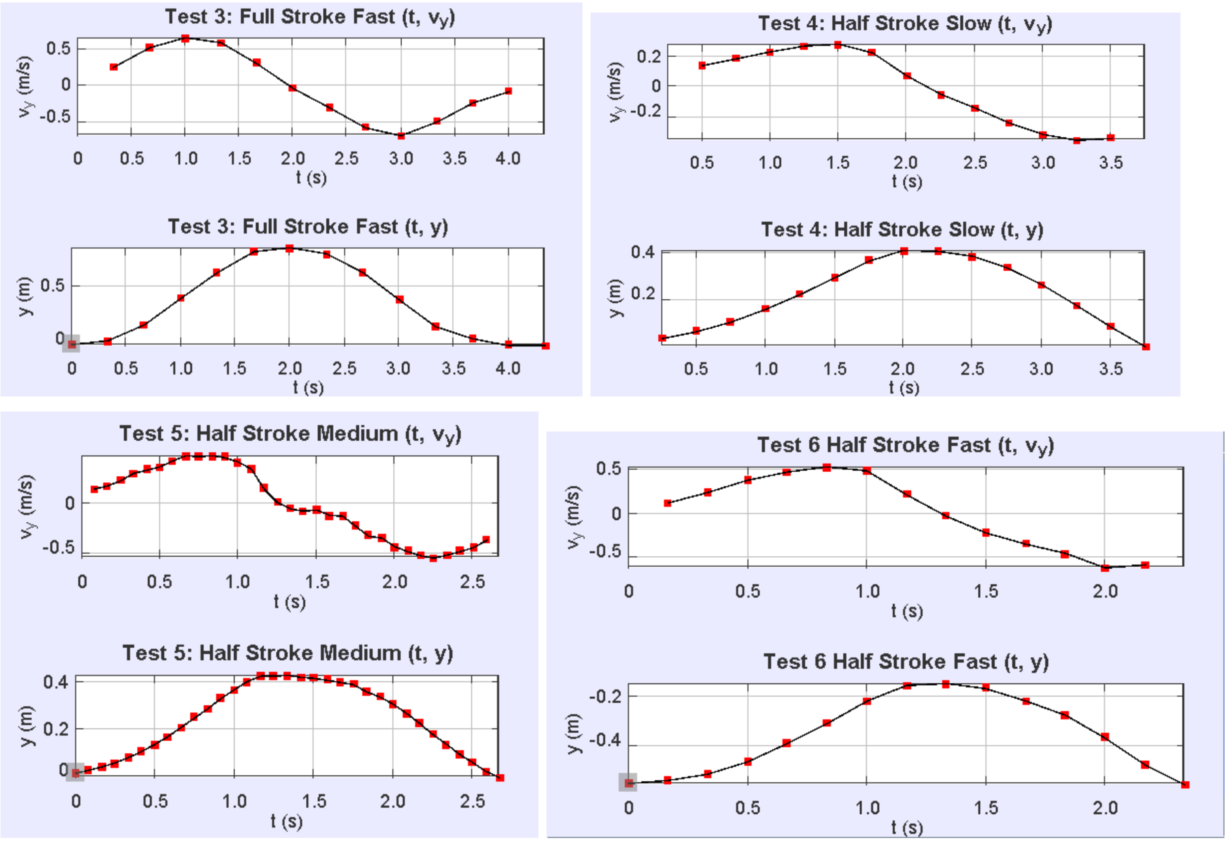


Figure 53: Screenshots of Tracker Video Software Trial Data

4.2.5 Analysis of Performance Testing

Output Power vs. Time Graph

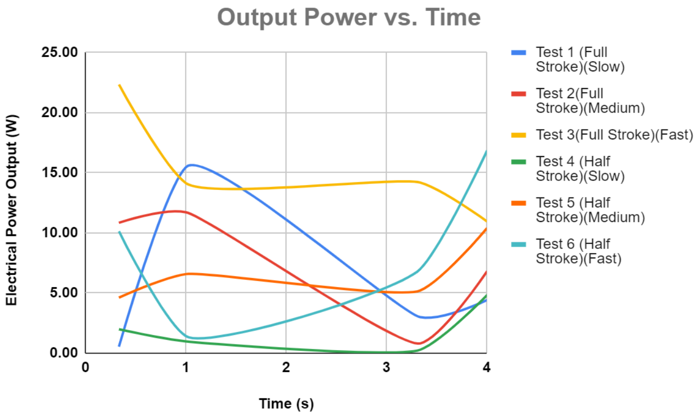


Figure 54: The graph illustrates the electrical power output over six trials conducted under different wave conditions, varying in stroke length and speed.

Each trial represents a specific combination of stroke length and wave speed, with full strokes (15 inches) and half strokes (7.5 inches) examined at different speeds. The analysis of electrical power output over time reveals significant insights into the operational dynamics of our wave energy converter prototype. Through six trials under varying wave conditions, it becomes evident that the device's performance is closely tied to stroke length and wave speed. Full stroke tests consistently exhibit higher power output compared to half strokes, indicating the device's preference for longer stroke lengths. Moreover, tests conducted at faster wave speeds demonstrate greater electrical power output, underscoring the device's optimal operating conditions. Test 3, in particular, conducted with a full 15-inch stroke at a faster wave period, stands out as the most effective, producing the highest usable power. These findings underscore the importance of optimizing wave conditions to enhance device efficiency and overall performance, providing valuable insights for further optimization efforts.

Power Input vs. Power Output Scatter Plot

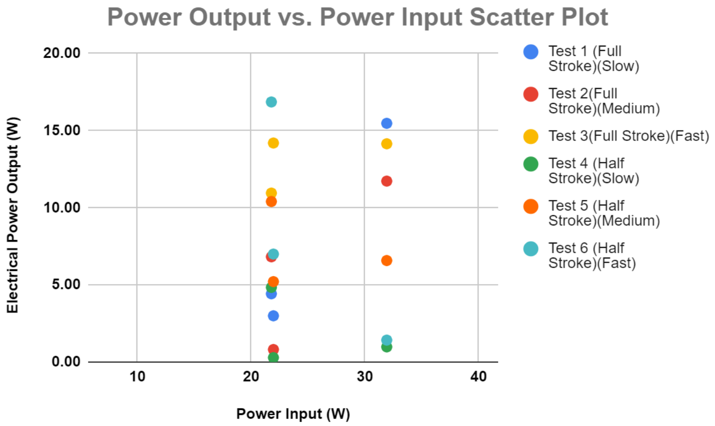


Figure 55: The graph illustrates the electrical power output over six trials conducted under different wave conditions, varying in stroke length and speed.

The analysis of the Power Input vs. Power Output scatter plot reveals important trends regarding the device's performance under varying conditions. The plot indicates a range of power inputs to the device, spanning from approximately 22W to 32W, while the power output varies from 0W to around 18W. Notably, the grouping of data points for each trial suggests distinct patterns: trials characterized by faster wave speeds and longer stroke lengths consistently exhibit higher electrical outputs compared to those with slower wave speeds or shorter strokes. This observation underscores the device's sensitivity to wave conditions, with longer strokes and faster wave speeds yielding more favorable outcomes in terms of power output. These findings highlight the critical role of stroke length and wave speed in optimizing the device's performance.

Output Power vs. RPM

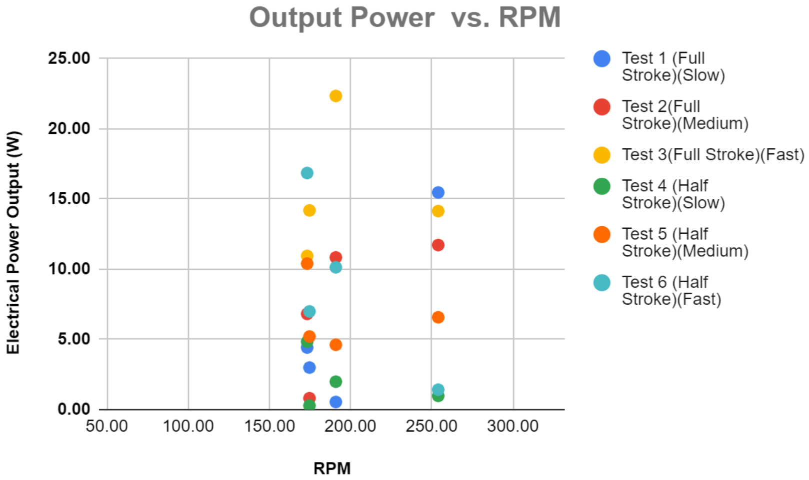


Figure 56: Graph displaying the electrical output power (W) versus RPM of the generators

The analysis of the Output Power vs. RPM plot reveals several notable trends regarding the device's performance under different testing conditions. Across all tests, there is a discernible relationship between RPM (Rotations Per Minute) and Electrical Power Output, indicating the influence of rotational speed on power generation.

In Test 1 (Full Stroke, Slow), Test 2 (Full Stroke, Medium), and Test 3 (Full Stroke, Fast), where the device operates at varying speeds under full stroke conditions, higher RPM values correspond to increased electrical power output. This trend suggests that faster wave speeds and longer strokes result in higher rotational speeds and, consequently, greater power generation. Conversely, in Test 4 (Half Stroke, Slow), Test 5 (Half Stroke, Medium), and Test 6 (Half Stroke, Fast), where the device operates with shorter stroke lengths, the RPM values and electrical power outputs are comparatively lower.

The scatter plot illustrates a direct correlation between RPM and electrical power output, emphasizing the importance of stroke length and wave speed in optimizing the device's performance.

Efficiency vs. RPM

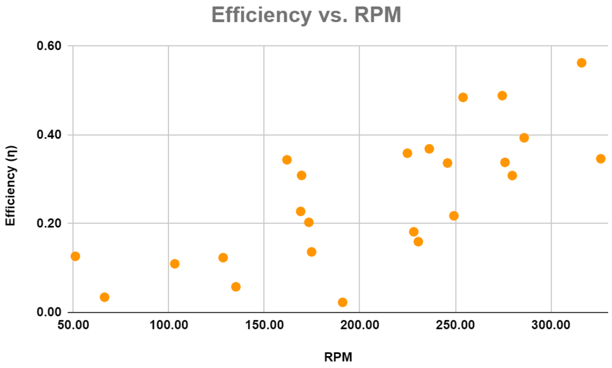


Figure 57: The scatter plot of the trial RPM recordings versus the efficiency of the device

The Efficiency vs. RPM plot illustrates a direct relationship between rotational speed and power conversion efficiency. Clearly showing that as RPM increases, so does efficiency. This clear trend indicates that higher rotational speeds lead to more effective conversion of mechanical power into electrical power. By analyzing efficiency across different RPM values along the stroke, the graph highlights optimal operating regions where the device performs most efficiently. This concise interpretation underscores the critical role of RPM in determining the device's overall performance and emphasizes the importance of optimizing operational parameters for maximum efficiency.

4.2.6 Lessons Learned and Future Improvements

The experiment's findings reveal key insights into the performance of the wave energy converter (WEC) prototype. Despite successfully generating usable power, the device's average efficiency of approximately 26% indicates significant room for improvement. The analysis underscores the importance of optimizing design parameters to enhance efficiency. One notable observation is the direct relationship between RPM and efficiency, suggesting that maintaining optimal rotational speeds is crucial for improving power conversion efficiency. Based on these results, future improvements could include integrating a flywheel mechanism to ensure continuous rotation of the motors at more productive RPM levels, closer to their intended operational speeds. Additionally, further research and development efforts should focus on refining the device's design to maximize efficiency and overall performance, ultimately advancing the feasibility and effectiveness of wave energy conversion technology.

4.3 BMS Electrical Engineering Testing

Feasibility Study

The EE team explored saltwater batteries for energy storage, testing different configurations and electrode setups. Experiments varied in saltwater volumes, electrode materials, and container sizes. Initial tests focused on voltage measurements, while later experiments assessed charge and power density. Results showed low voltages but promising increases when jars were connected in series. Challenges included electrode shorting, addressed by wrapping electrodes in cotton and using cardboard separators. Ultimately, this battery method was determined infeasible.

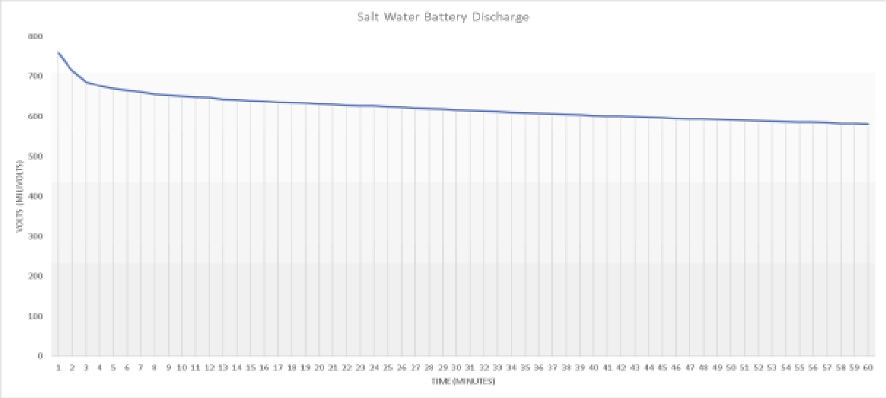


Figure 58: Test of page electrodes in Sea Water: 0.84 V

4.3.1 Overview of Testing Procedures

For the BMS testing, a comprehensive plan was devised, encompassing multiple test cases. The first test involved validating the conversion from analog to digital potentiometers, crucial for controlling output power akin to the WEC device. Subsequent tests evaluated the functionality of relays, battery packs, and the compatibility between the BMS and the Test Bench. Notably, bug tracking and quality control measures were meticulously implemented to ensure software integrity and system reliability.

Test Design

Test 1: Analog to Digital Potentiometers

1. Initial test objective was to build and confirm Testbench capabilities with analog potentiometers. Secondary objective was to convert analog potentiometers to digital and maintain the same overall functionality, but with better control and freedom using a microcontroller. Conversion was critical to overall system performance because proper BMS testing needed output power similar to ME's buoy.

2. Experiment consisted of: a regular power supply, a microcontroller, a multimeter, and a LED connected to the output of Testbench.

3. First iteration of the Testbench was constructed using analog potentiometers, one to control current and the other to control voltage. Once successful operation can be achieved using the above mentioned LED and multimeter. Second iteration of the Testbench can be built, replacing the analog potentiometers with digital. A microcontroller will be used to connect to digital potentiometer. With the use of the Arduino IDE, automatic control can be implemented once a loop is solved.

4. Expected Results:

    a. Voltage and Current control within input range
    b. Multimeter should read an output within expected range
    c. LED should either dim or illuminate when using potentiometers

Test 2: Relays

1. The objective of this experiment was to ensure that relays could be controlled properly via Arduino UNO as well as developing a better understanding of the general functionality of relay switches. This test is crucial to the entirety of the BMS so that the batteries can connect to either the chargers or power resistors for discharging.

2. The experiment consists of the 8-channel relay module, with three channels each connected to a breadboard circuit for an LED.

3. The Arduino is programmed to the three channels of the relay module and will open particular relays depending on the five different case scenarios: all batteries need charging, one battery pack needs discharging, the other battery pack needs discharging, both battery packs need discharging, or no charging/discharging needs to occur. Each scenario will be printed in the Serial Monitor on the Arduino IDE and the corresponding LEDs should turn on to ensure that power travels through the relay since it should switch open and connect the circuit.

4. Expected results are as follows:

    a. Red LED should turn on if the batteries need charging
    b. Blue LED should turn on if Battery 1 needs to be discharged
    c. Green LED should turn on if Battery 2 needs to be discharged
    d. Both the blue and green LED should turn on if both batteries need to be discharged
    e. All LEDs should be off if no charging/discharging is needed

Test 3: Battery Pack Functionality

1. The objective of this experiment was to ensure even charging and discharging of the individual batteries within the packs. This is necessary to promote stable lives of the individual cells and to prevent overheating of individual cells.

2. The experiment consisted of using a Multimeter to check voltages

3. The experiment consists of doing a precheck on each cell to ensure charge, checking each cell's voltage after spot welding the extension electrodes into place, and a final check of the voltage of the pack after the cells had been joined to the central electrodes.

4. Expected results are of the batteries to be charged fully and remain so throughout the spot welding process

Test 4: BMS and Test Bench Compatibility

1. This test's objective was to ensure that there would be no issues when connecting the test bench to the BMS and the overall functionality and durability of both systems as well as data collection of how long it will take for the batteries to fully charge.

2. The experiment consisted of the following:

    a. Battery Management System
        i. Batteries
        ii. Voltage Sensors
        iii. Power Resistors
        iv. Relays
        v. Arduino UNO
    b. Test Bench
        i. BJT Transistors
        ii. Linear Voltage Regulators
        iii. Digital Potentiometers

        - iv. Arduino UNO
    - c. Other
        - i. Power Supplies
        - ii. Multimeter
        - iii. Jumper Wires
        - iv. Wago Connectors
        - v. Timer

3. The test bench will be connected into the BMS through a designated relay channel for the charger to charge the batteries. The system will continuously run and we will keep track of time and progress points. In tracking over minute intervals, we can determine the rate the batteries are charging with the variable input from the test bench by recording the increases in voltages.

4. The expected results are that the batteries would need around six hours to fully charge from 0V.

4.3.2 Results of Performance Testing and Analysis

Test 1: Analog to Digital Potentiometers

1. Successful conversion of Testbench from Analog to Digital potentiometers was performed.. Analog potentiometers and digital potentiometers were able to change output and alter LED luminosity.

2. Analog potentiometers allowed voltage control with manual turn of the potentiometer knob. Clockwise turn reduces resistance and allows more voltage output. Counter clockwise turn increases resistance, which resulted in lower voltage output. Implementation of digital potentiometer should perform exactly the same, but with automatic control.

3. Successful conversion of digital potentiometers, the Testbench behaved in the expected manner. Higher wiper value meant more resistance which resulted in lower voltage output. Lower wiper value performed vise-versa.

4. No corrective actions were needed.

Test 2: Relays

1. When the batteries needed charging, the red LED would turn on. If Battery 1 needed discharging, the blue LED would turn on. If Battery 2 needed discharging, the green LED would turn on. Otherwise, no LEDS would turn on.

2. The results were exactly as expected.

3. The test results imply that the program accurately controls each individual relay and according to the logic of the program as in doing the correct action dependent on the voltage reading.

4. No corrective actions were needed besides implementing the testing program into the main program for the BMS.

Test 3: Battery Pack Functionality

1. The results were 3.9 V of the individual cells before and after spot welding to extend the electrodes. After joining the extended electrodes the voltage remained at 3.9 V.

2. These results matched what was expected

3. The test results indicate that the batteries were successfully joined to the Nickel strips to extend their electrodes and join them into packs without damaging the cells.

4. No corrective actions necessary.

Test 4: BMS and Test Bench

1. The results illustrated that within one minute intervals, the battery would charge for 46% of the time and not charge for the rest. Additionally, the BMS was able to withstand the variable voltage with no issues.

2. The results were roughly what was expected. By finding the charging rate, it can be calculated that the time to charge the batteries from 0V would be 6.54 hours.

3. We realized that the batteries would charge for the percentage of time stated above was due to the minimum amperage requirement in order to charge our batteries, further implicating that only the higher voltages in the variable power supply from the test bench actually charged the battery.

4. No corrective actions were needed.

Each test case yielded positive results, affirming the efficacy of the BMS and its constituent components. The successful conversion of potentiometers, accurate relay control, and seamless integration with the Test Bench underscored the team's meticulous design and implementation efforts.

4.3.3 Lessons Learned and Future Improvements

Moving forward, opportunities for enhancement were identified, spanning across all project facets. Improvements to the Test Bench involved utilizing integrated circuits (ICs) to reduce voltage drop and transitioning to a printed circuit board (PCB) design for enhanced current regulation. Similarly, optimizations to the BMS circuitry and software were proposed to address voltage sensor performance and prioritize cell discharging. Additionally, upgrades to battery packs were suggested, including the exploration of saltwater batteries for environmental sustainability and integration with the ME buoy generation system to fulfill competition objectives and provide renewable energy solutions to coastal regions.

5. Conclusion and Future Directions

5.1 Suggestions for Future Research and Development

MEH-1 Recommendations:
Several improvements can be made to enhance the efficiency and effectiveness of the current design. Firstly, in terms of buoy design, transitioning to more traditional shapes like a donut or tear drop could enhance durability and stability above the waterline. Consideration should also be given to enveloping the current design in a traditional ring buoy to improve stability during wave motion. Material selection, specifically closed-cell polyurethane for its buoyancy and UV protection, should be reevaluated to prioritize durability in oceanic environments.

The collaborative effort of three separate teams throughout the design process exemplified real-world engineering scenarios. Confidence in the approach taken for calculations assures the device's functionality amidst varying wave conditions.

MEH-2 Recommendations:
Our project has successfully demonstrated the feasibility of converting mechanical wave energy into electrical energy via direct mechanical drive. However, our testing phase has revealed areas for improvement, particularly in generator efficiency and mechanical integration.

One key recommendation is the development of an alternate mechanical system, such as a sprocket mechanism and flywheel apparatus, to maintain optimal generator rotation speed, thereby enhancing system efficiency. Moreover, optimizing the gearbox mechanism and selecting the appropriate generators are essential steps to maximize performance.

MEH-3 Recommendations:
The team's recommendations focus on cautious consideration regarding the chosen design's cost and efficiency for further development. Communication challenges among the teams highlight the need for clearer boundaries and deadlines.

5.2 Acknowledgements

ME Team Acknowledgements:
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Business Team Acknowledgements:

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5.3 Conclusion

In conclusion, our direct mechanical drive wave energy generator and onboard battery storage device represents a significant step forward in renewable energy innovation. With its potential to revolutionize data buoy markets along the Pacific coast, our project underscores the importance of sustainable energy solutions in mitigating climate change. We extend our deepest gratitude to all contributors and supporters whose invaluable contributions made this project possible. Together, we have laid the foundation for a brighter, more sustainable future.

6. List of References

Business Plan

[1] Ocean Motion Tech Blog. (2023, November 29). Data buoys. Medium. <https://medium.com/ocean-motion-tech-blog/ical3-data-buoys-1c1a0c5590d7>

[2] Ocean Motion Tech Blog. (2023, November 29). Navigating the depths of data: The future of oceanographic analysis (No. 12). Medium. <https://medium.com/ocean-motion-tech-blog/12-navigating-the-depths-of-data-the-future-of-oceanographic-analysis-baeb647059dc>

[3] California Legislature. (2023, October 9). Bill text - SB-605 wave and tidal energy. Leginfo.legislature.ca.gov. <https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=202320240SB605>

[4] Clark, A., Halas, J., Merrill, D., & Halas, J. (1988). Mooring buoy planning guide poly rope buoy weight eye bolt. <https://www.coris.noaa.gov/activities/resourceCD/resources/mooring_buoy_g.pdf>

[5] U.S. Department of Energy. (2022, January 25). DOE announces $25 million for cutting-edge wave energy research. Energy.gov. <https://www.energy.gov/articles/doe-announces-25-million-cutting-edge-wave-energy-research>

[6] Gallagher US. (n.d.). Energy insurance and expert energy consultants. Gallagher US. Retrieved May 7, 2024, from <https://www.ajg.com/us/industries/energy-insurance-and-consulting/>

[7] LiVecchi, A., Copping, A., Jenne, S., Gorton, A., Preus, R., Gill, G., Robichaud, R., Green, R., Geerlofs, S., Gore, S., Hume, D., McShane, W., Schmaus, C., & Spence, H. (n.d.). Powering the blue economy: Exploring opportunities for marine renewable energy in various maritime areas. United States. <https://doi.org/10.2172/1525367>

[8] Gravity Marine. (n.d.). Marine research services & consulting. Gravity Marine. Retrieved May 7, 2024, from <https://gravitymarine.com/?source=post_page-----1c1a0c5590d7-------------------------------->

[9] McLeod, I., & Ringwood, J. V. (2022). Powering data buoys using wave energy: A review of possibilities. Journal of Ocean Engineering and Marine Energy, 8(3), 417–432. <https://doi.org/10.1007/s40722-022-00240-3>

[10] U.S. Coast Guard. (n.d.). Prevention Division private aids. Pacific Area. <https://www.pacificarea.uscg.mil/Our-Organization/District-11/Prevention-Division/PatonOne/>

[11] Roarty, H., Cook, T., Hazard, L., & George, D. (2019, May 14). The global high frequency radar network. Frontiers in Marine Science. <https://www.frontiersin.org/articles/10.3389/fmars.2019.00164/full?source=post_page-----f48776aefa57--------------------------------->

[12] Scripps Institution of Oceanography. (2019, June 23). Status, opportunities and challenges of wave energy conversion for Scripps users. Scripps.ucsd.edu. <https://scripps.ucsd.edu/events/status-opportunities-and-challenges-wave-energy-conversion-scripps-users>

[13] National Institutes of Health. (n.d.). Understanding SBIR and STTR. Seed.nih.gov. <https://seed.nih.gov/small-business-funding/small-business-program-basics/understanding-sbir-sttr>

[14] U.S. National Data Buoy Center. (2018). National Data Buoy Center. Noaa.gov. <https://www.ndbc.noaa.gov/>

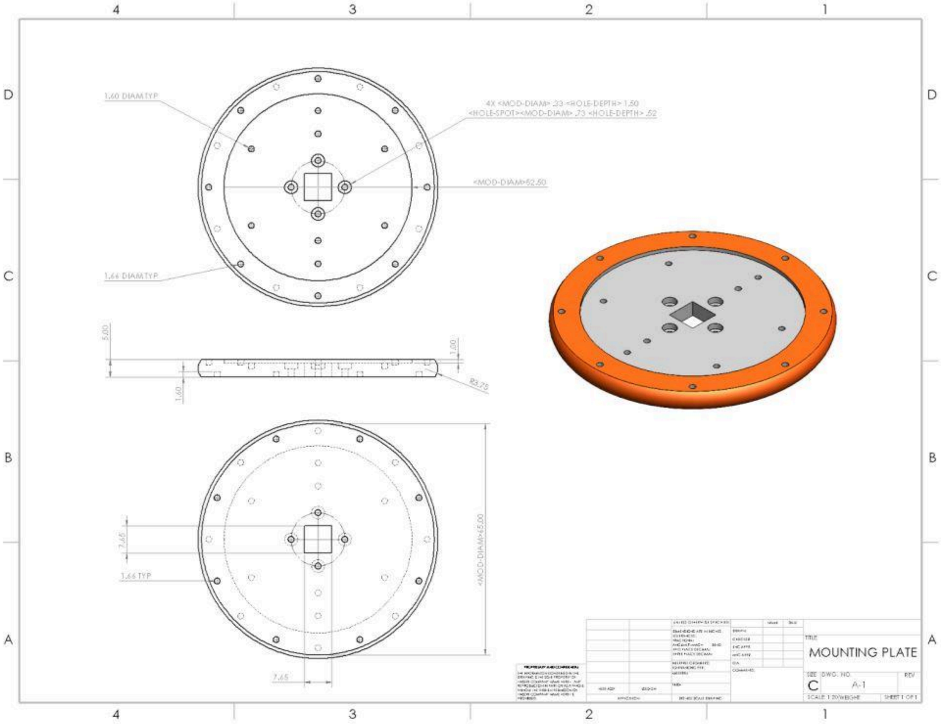
[15] U.S. Department of Commerce, National Oceanic and Atmospheric Administration. (n.d.). NDBC station page. National Data Buoy Center. <https://www.ndbc.noaa.gov/station_page.php?station=ljac1>

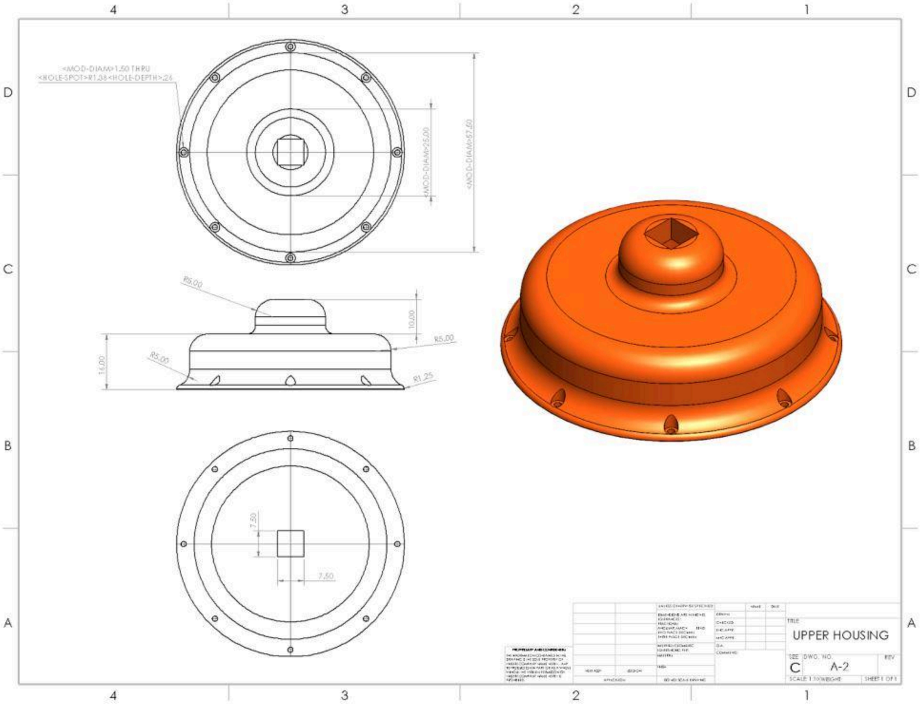
Technical Design

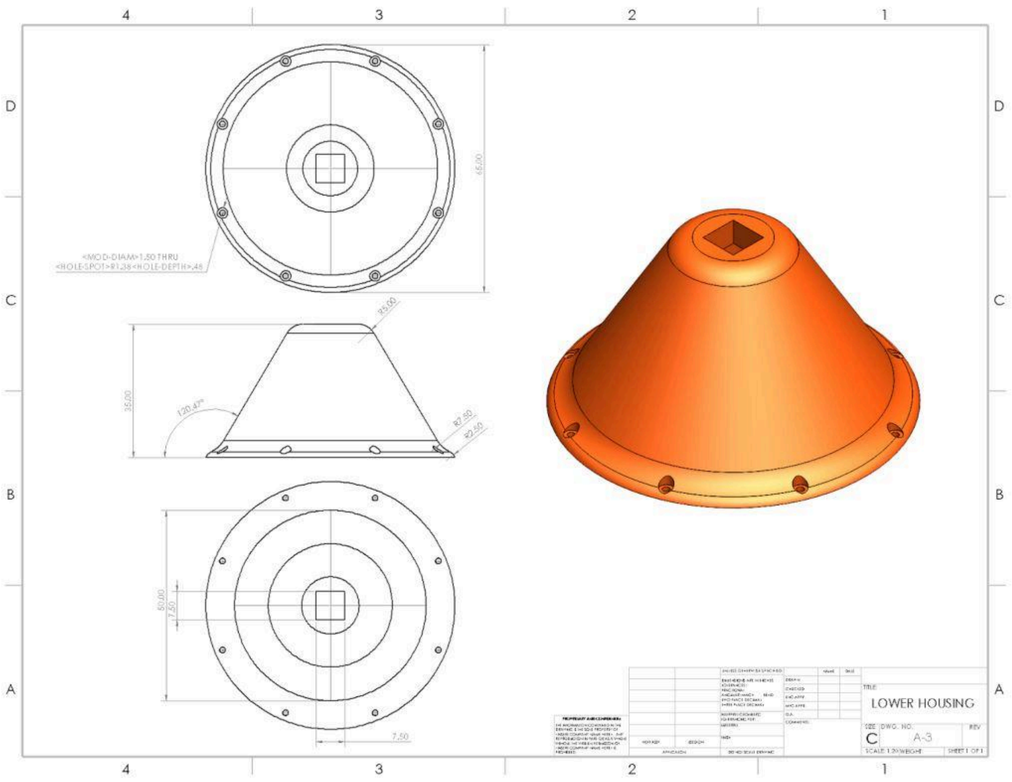
[1] Lavaa, Anaa. “What is wave energy: A Complete Guide.” Linquip Technews (2023) What Is Wave Energy? Different Types & Working Principles | Linquip
[2] Vedantu. “Facts about Wave Energy.” Vedantu (2023) Facts About Wave Energy - Benefits, Advantage, and Disadvantage (vedantu.com)
[3] “DOE-Funded Study Pinpoints Potential that Lies Within the Waves.” Energy.gov DOE-Funded Study Pinpoints Potential that Lies Within the Waves | Department of Energy
[4] Uihlein, Andreas and Magagna, Davide. “Wave and Tidal Current Energy - A Review of the Current State of Research Beyond Technology.” Science Direct. Vol. 58 (2016): pp. 1070-1081. Wave and tidal current energy – A review of the current state of research beyond technology - ScienceDirect
[5] “Wave Energy”. The Liquid Grid. https://theliquidgrid.com/marine-clean-technology/wave-energy-converters/
[6] “Types of WECs”. Near Shore Wave Energy Conversion Devices (WEC). Texas A&M University. https://waveenergyconversiontamu15.weebly.com/
[7] “About Us.” (n.d.). Welcome to Foam Factory, <https://www.foambymail.com/about-us.html> (Dec. 12, 2023).
[8] “About.” (2023). Fiberglass Shop Supplier and Composite Materials Distributor, <https://plasticmaterials.net/about-pmi/> (Dec. 12, 2023).
[9] “Your Industrial Metal Supply in inland empire.” (n.d.). Inland Empire Metal Supply| Metal Supplier in Riverside, CA, <https://www.industrialmetalsupply.com/locations/riverside-metal#1> (Dec. 12, 2023).
[10] https://americanmadechallenges.org/challenges/marine-energy-collegiate-competition/docs/Marine-Energy-Collegiate-Competition-Rules.pdf
[11] Penabla, Markel and Ringwood, John. “A Review of Wave-to-Wire Models for Wave Energy Converters.” Energies Vol. 9 No. 506 (2016). DOI 10.3390/en9070506
[12] Doell, Cheryl. “5 Complications for Tidal and Wave Energy Devices.” last modified August 11, 2017, accessed October 10, 2023, https://pmiind.com/category/tidal-and-wave-energy/
[13] Qiao, Haider, Yan, Ning, and Binbin Li. “Review of Wave Energy Converter and Design of Mooring System.” Sustainability Vol. 12, No. 8251 (2020). DOI 10.3390/su12198251
[14] Neill Simon, and Hashemi Reza. Fundamentals of Ocean Renewable Energy Generating Electricity from the Sea. Academic Press, 2018.
[15] “Introduction to CFD with flow simulation,” SOLIDWORKS, https://www.solidworks.com/media/introduction-cfd-flow-simulation (accessed Jan. 18, 2024).
[16] B. Zhang et al., “Atomically Dispersed Dual‐Site Cathode with a Record High Sulfur Mass Loading for High‐Performance Room‐Temperature Sodium–Sulfur Batteries,” Advanced Materials, vol. 35, no. 1, p. 2206828,Nov. 2022, doi: https://doi.org/10.1002/adma.202206828.
[17] C. Elton, “Sea salt batteries could be a cheap, green alternative to lithium,” euronews, Dec. 13, 2022. https://www.euronews.com/green/2022/12/13/significant-breakthrough-this-new-sea-salt-battery-has-4-times-the-capacity-of-lithium
[18] Diy Electronic. “DIY Lab Bench Power Supply: 1-30V 0-10A Variable Power Supply Adjustable Voltage and Current.” Diy Electronic, Blogger, 15 June 2022,

www.diyelectronic.in/2022/05/diy-lab-bench-power-supply-1-30v-0-10a.html.
[19] “Guide for Relay Module with Arduino,” Random Nerd Tutorials, Jan. 15, 2019. https://randomnerdtutorials.com/guide-for-relay-module-with-arduino/
[20] “How to measure voltage of multiple batteries connected in string/array in series or parallel combination with microcontrollers,” Engineers Garage. https://www.engineersgarage.com/series-combination-of-batteries-voltage-monitor/
[21] H. Tian et al., “Stable, high-performance, dendrite-free, seawater-based aqueous batteries,” Nature Communications, vol. 12, no. 1, p. 237, Jan. 2021, doi: https://doi.org/10.1038/s41467-020-20334-6.
[22] “Interfacing Voltage Sensor with Arduino,” Last Minute Engineers, May 27, 2023. https://lastminuteengineers.com/voltage-sensor-arduino-tutorial/ (accessed Mar. 20, 2024).
[23] R. Wells, “UCF-Developed Seawater Battery is Safer for People and Environment | University of Central Florida News,” University of Central Florida News | UCF Today, Feb. 04, 2021. https://www.ucf.edu/news/ucf-developed-seawater-battery-is-safer-for-people-and-environment/
[24] S. Arnold, L. Wang, and V. Presser, “Dual‐Use of Seawater Batteries for Energy Storage and Water Desalination,” Small, vol. 18, no. 43, p. 2107913, Aug. 2022, doi:https://doi.org/10.1002/smll.202107913.
[25] “SmartGauge Electronics - Interconnecting multiple batteries to form one larger bank,” www.smartgauge.co.uk,Apr. 03, 2009. http://www.smartgauge.co.uk/batt_con.html (accessed Mar. 19, 2024).
[26] S. Pittaway, “Stuart Pittaway - YouTube,” www.youtube.com, Mar. 04, 2024. https://www.youtube.com/@StuartPittaway (accessed Mar. 20, 2024).
[27] Staff, LME Editorial. “Interfacing Voltage Sensor with Arduino.” Last Minute Engineers, Last MinuteEngineers, 27 May 2023, lastminuteengineers.com/voltage-sensor-arduino-tutorial/.
[28] “Test of Samsung INR18650-25R 2500mAh (Green),” Lygte-info.dk, 2024. https://lygte-info.dk/review/batteries2012/Samsung%20INR18650-25R%202500mAh%20%28Green%29%20UK.html#:~:text=Charging%20time%3A%20 Standard%20 charge%20%3A%20180 min (accessed Mar. 20, 2024).
[29] W. Connor, “Simple DIY Arduino BMS for eBike Battery: Part 4,” www.youtube.com. https://www.youtube.com/watch?v=QpdiBOrYQvs (accessed Mar. 20, 2024).
[30] Z. Yildiz, “ZAFER YILDIZ - YouTube,” www.youtube.com, Mar. 06, 2024. https://www.youtube.com/@ZAFERYILDIZ52 (accessed Mar. 20, 2024).

7. Appendix: Engineering Main Part Drawings



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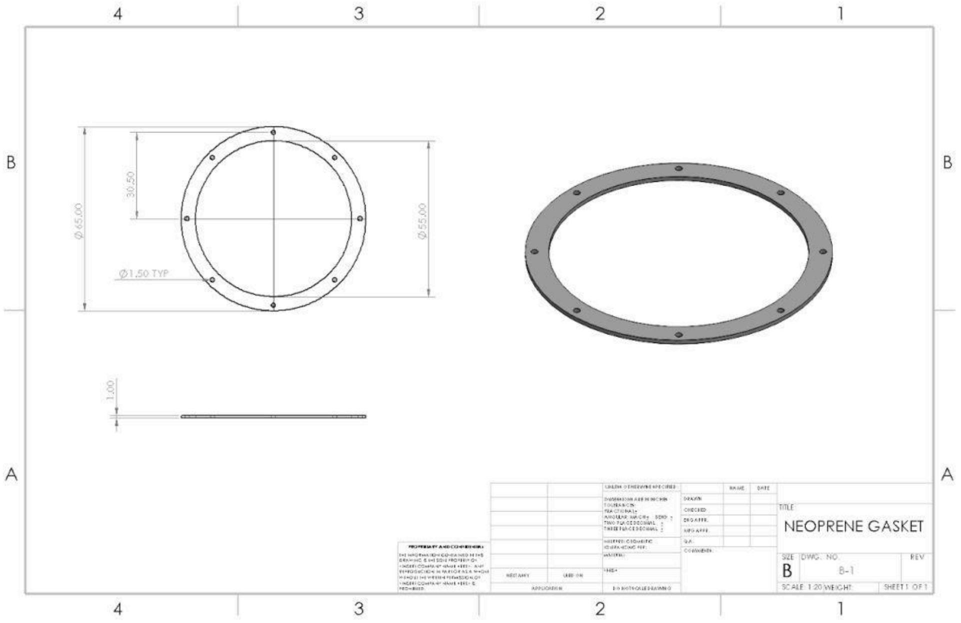
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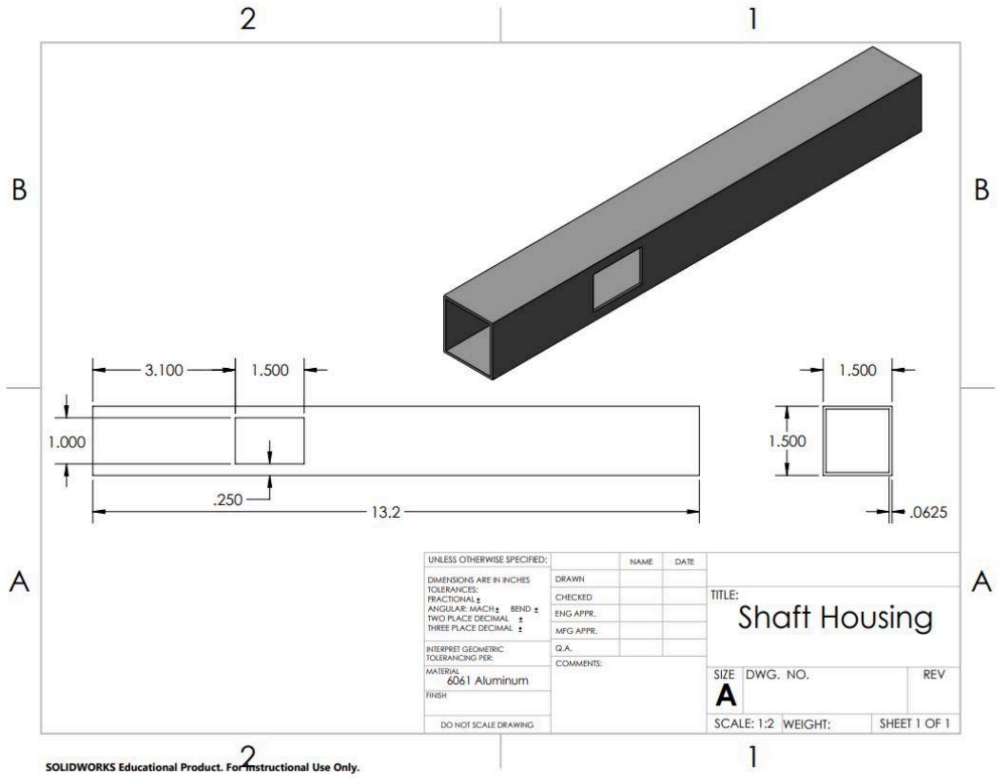
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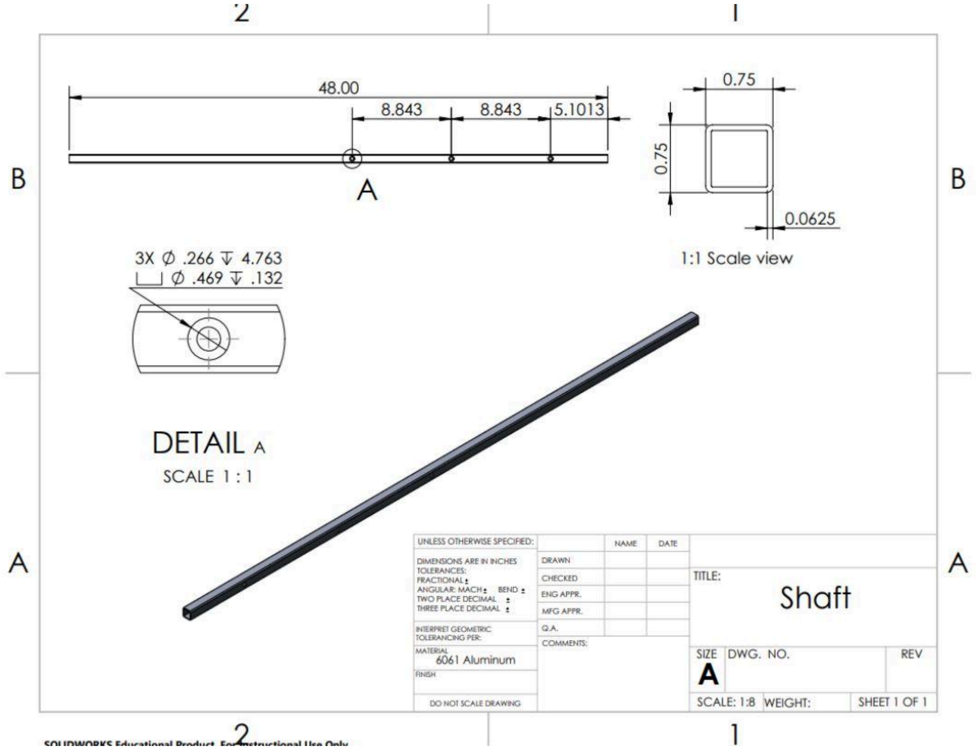
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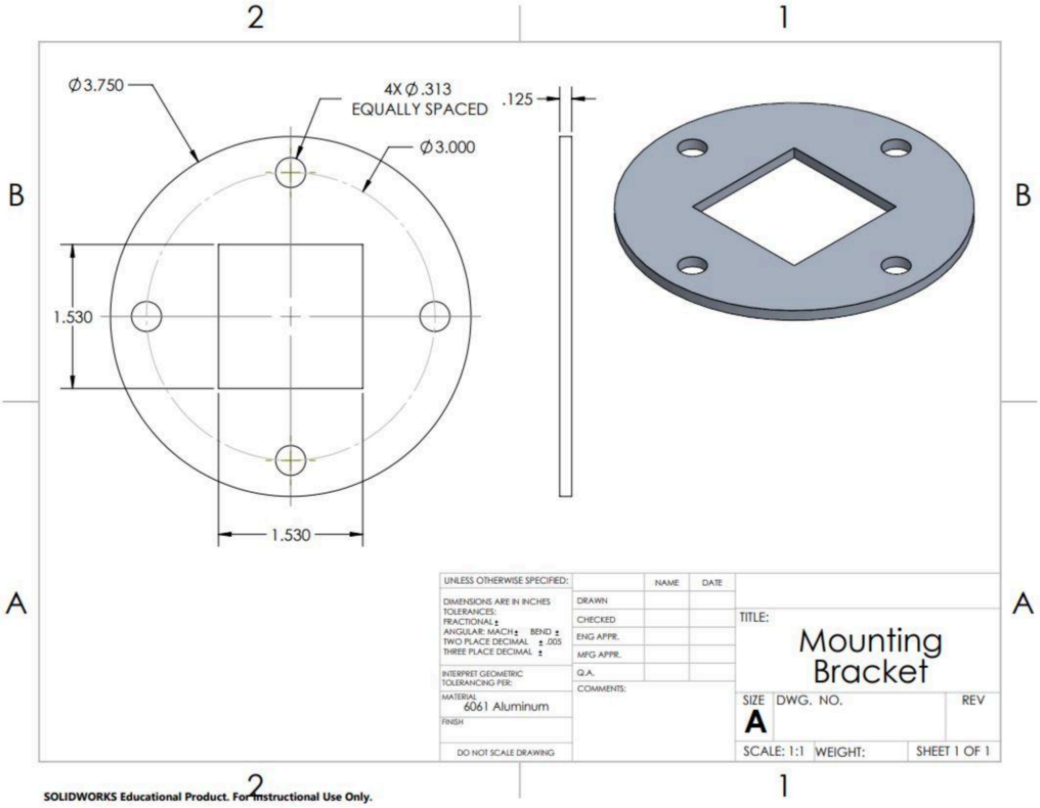
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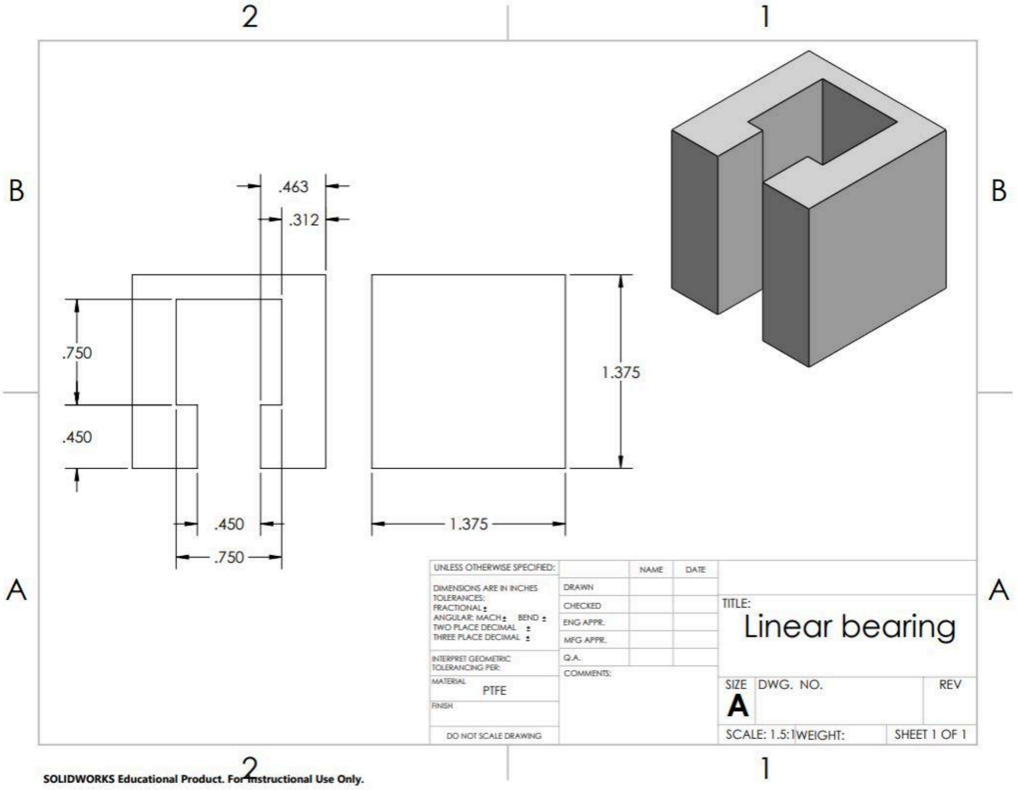
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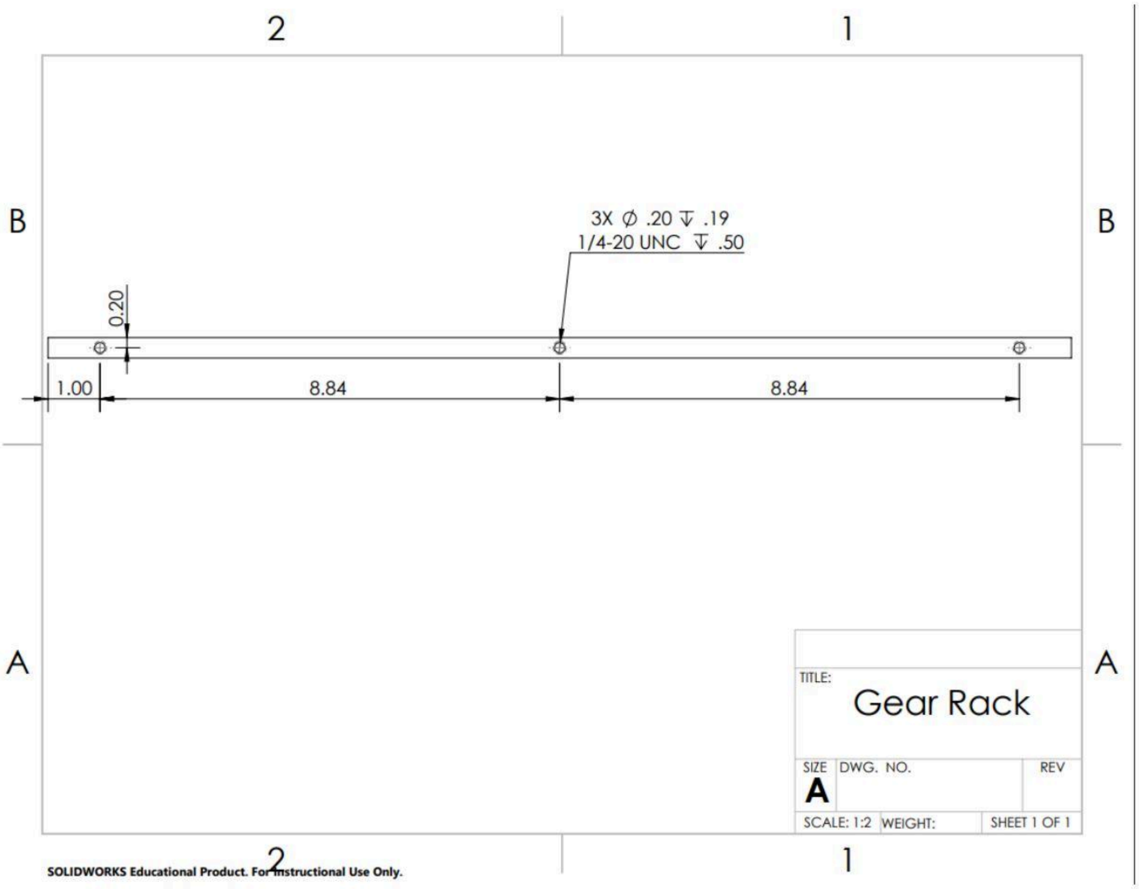
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