POWERING the BLUE ECONOMY™

2024 Marine Energy Collegiate Competition Report
Michigan Technological University

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Michigan Tech

Strategic Education through Naval Systems Experiences
SENSE

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1.0 Executive Summary

The 2024 Marine Energy Collegiate Competition marks SENSE's third consecutive effort of participation. In 2022, the team constructed a prototype oscillating water column with the intent of integrating it with shore protective measures - such as breakwalls - local to the Keweenaw Peninsula. In 2023, the team switched gears on the power source, choosing to construct an oscillating surge flap, however the blue economy focus remained: protecting America's shores. The 2024 competition marked the beginning of an entirely new initiative for the SENSE MECC team; The aim stated in our application was to design a system that exceeded both previous efforts in versatility and accessibility, while incorporating a much stronger argument of environmental compliance into our project. Achieving these benchmarks took months of ideation before any official design, fabrication, or successful simulations were complete. Several stakeholder and community outreach interviews were conducted with a variety of interdisciplinary professionals, with the hopes of gaining insight, productive criticism, and above all, collaborative inspiration to produce a project both new and innovative in today's Blue Economy, while also reinforced by years of previous professional efforts with the same goals.

To achieve system versatility, we aimed to design a WEC that was not necessarily limited by environmental wave conditions, nor by operational depth or location. Thus, taking inspiration from Reference Model 3, we elected to design and build a two-body heaving point absorber. Applying this to a feasible maritime market, the aim of our point absorber is to produce power for integrated underwater AUV charging docks, with an initial target market location of the Great Lakes. Our market analysis, substantiated by several renewable energy grants, military mobilization efforts in the Great Lakes region, and a particular NOAA initiative to have the Great Lakes mapped in high density resolution by 2030, inspired us to proceed with this Powering the Blue Economy (PBE) application and integrate it into our technical system design. The team was able to build a functional prototype of the wave energy generator, and it was performance-tested in the MTU Wave Tank facility in April. The full-scale model was simulated in WECsim, and the results were cross-referenced against a theoretical feasibility analysis to determine the system's capability of meeting the overall power requirements. The following three reports lay out the team's entire business plan, the development and specifications of the technical system, and the overall narration and results of the prototype assembly and performance tests.

Business Plan Challenge Report

Business Team

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Word Count: 5,627

2.0 Business Plan Challenge

2.1 Concept Overview

The maritime market - coined in competition as the Blue Economy Application - that the team elected to address is the current inefficiency regarding autonomous water vehicle missions, as explained in Section 1.0. Specifically, our solution focuses primarily on underwater autonomous vehicles (AUVs), however if future MECC teams elect to expand on this particular system, modularity could potentially be increased and include surface water vehicles. Currently, AUV missions are somewhat handicapped by the nature of the environment in which they operate - they are battery-powered, and missions are limited by their inability to obtain a recharge without a home recall or a monitoring ship. The solution conceived by our team (and in development in various national laboratories) is the concept of offshore charging stations that obtain their power from wave energy. There are various sustainable benefits of this system; chiefly, the AUVs obtain their charge via renewable energy. Additionally, AUVs are commonly used for information acquisition that is generally in servitude of the public; for instance, water quality monitoring, invasive species identification, aquatic life population mapping and a greater general understanding of our freshwater lakes and oceans is all information that is made publicly available and is used for purposes to enhance the way we interface with the world in which we live. Coupling this model with the benefits to national security that covert charging operations would encourage and how they may extend military mission life, the value model is logically justified.

2.1.1 Concept Overview: Economic Benefit

The wave energy technology chosen to power this system considered various economic factors, such as ease of deployment and retrievability, maintenance, and operational versatility - thus the two-body heaving point absorber inspired by Reference Model 3 was chosen to be the team's power source. Point absorbers are easier to deploy and retrieve than competing wave energy designs, and the nature of their design allows them to achieve functionality regardless of the direction of wave propagation. With the AUV industry rapidly growing, (see Figure 1) deploying point absorbers capable of powering AUVs within the Great Lakes is a sensible and feasible capture for a stake in the market. Moreover, AUV charging stations offer a low-cost alternative to AUV retrieval missions, which are labor and resource-intensive. With a charging infrastructure in place, the cost of conducting AUV missions will decrease, thus driving demand and incentivizing stakeholders to enter the AUV market and utilize our point absorber-powered stations.

2.1.2 Concept Overview: Environmental Benefit

Currently, AUV retrieval missions require combustion-driven boats to venture and collect the AUVs, or anchor nearby for frequent recharges. This drives fuel consumption and consistently releases byproduct into the water and atmosphere. By mitigating the requirement for manned retrieval missions, there will be less boating activity in the AUV industry, resulting in cleaner missions. Furthermore, the AUVs will obtain their charge through renewable energy directly from the source of where their missions are conducted, allowing a consistent and clean power source to perpetuate missions. The system will minimize the disruptive nature of AUV charging and maximize the potential of understanding the Great Lakes' natural resources, while additionally propelling a more detailed and informative monitoring of water quality and general lake conditions, allowing for us as a people to be more reactive to any concerns that arise regarding the safety of humans, aquatic life, and vegetation.

2.1.3 Concept Overview: Social Benefit

Financial incentives aside, AUV missions have numerous social benefits. AUVs can be utilized for research purposes such as mapping and species tracking, which increases our understanding of the areas they operate in and we interface with in a multitude of other ways. The Great Lakes are the largest freshwater source in the world, and we have yet to fully understand their impact on us and our impact on them. By enhancing AUV mission capabilities, we propel this research into new and sustainable territory. Finally, a proven AUV charging infrastructure will decrease AUV costs and thus lower the barriers of entry into the AUV research field. This will increase market diversification and enable new stakeholders to participate in Great Lakes discovery and missions.

2.2 Stakeholder/End-User Outreach Effort

Dr. Timothy Havens - Great Lakes Research Center | Michigan Technological University

There is a healthy demand among academic and government institutions to advance the AUV industry. For instance, the Great Lakes Research Center at Michigan Technological University is an active participant in AUV exploration in Lake Superior - use examples include high-resolution cameras to locate shipwrecks, reading fish tag data to track invasive species, and conducting image/water sampling. These initiatives, along with the general increasing demand for AUV missions in the Great Lakes, were substantiated by our first stakeholder interview with **Dr. Timothy Havens, the director of the Great Lakes Research Center**. One of the most resonating messages from this interview was his response when asked about the demand for offshore AUV charging and data offload technology, where he indicated that there is not a current demand, but there inevitably will be. He solidified that AUV's presence will increase across the marine exploration industry, the Great Lakes included. We spoke about retaining autonomy while increasing efficiency, and how this concept could be scaled to not just AUVs, but autonomous surface water vehicles as well. A few of Dr. Havens' concerns included how the technology interfaces with ice formation, the undersea dynamics associated with surface wave propagation and how our team would address them in our design, and our operational depth - all concerns that pointed us in the direction of being as comprehensive as possible with our business model and technical delivery.

Rob Downs - National Oceanic and Atmospheric Administration

Additionally, the National Oceanic and Atmospheric Administration (NOAA) has outlined initiatives to map the entire Great Lakes in high-density resolution and will require AUVs to do so. Our team was able to conduct a second stakeholder interview with **Rob Downs, the Chief of Hydrographic Systems and Technology in the Coast Survey Development Laboratory at NOAA**. He expanded on various NOAA missions that utilize AUVs for nearly every capability the market currently offers - these missions occurring in several oceanic and lake environments across the continental United States. He believed that NOAA would benefit from offshore charging technology, especially in deepwater locations. We were able to briefly also speak on Lakebed 2030, where he explained it as the initiative to have the Great Lakes completely mapped in high-density resolution by the year 2030 - less than 15% are currently mapped at this resolution. Offshore charging stations would undoubtedly steamline this achievement.

Dr. Andy Gish - Naval Academy

The United States Navy also depends on AUVs for security purposes, such as surveillance and locating underwater explosives. While the Navy does not extensively use AUVs in the Great Lakes, they are an ideal location for military AUV testing due to their size and geographic security. In November, we took the time to interview **Dr. Andy Gish. Dr. Gish was an officer in the Navy for 33 years and now serves as a Professor of Ocean Engineering at the Naval Academy.** Dr. Gish believes that as the need for energy and power supplies increases so will the need for AUVs and projects significant growth within the next 20-50 years. Dr. Gish believes that AUVs are limited by mission length and vehicle communication. While Dr. Gish sees the deployment of AUV charging stations as a challenge, he also thinks that if they can become more cost-effective than support ships they will become viable in the marketplace. To do this, Dr. Gish thinks that an AUV charging station needs to be as standardized as possible so that it is compatible with a range of AUVs. Dr. Gish knows that the potential of wave energy is highly location-dependent and while high output is proven in parts of the ocean, it has yet to be in the Great Lakes, making proof of concept feasibility one of our team's most significant focuses. Overall, Dr. Gish informed us that for an AUV charging station to become economically viable it must be cost-effective, versatile, and capable of utilizing Great Lakes wave energy to power itself and charge the AUVs that dock at its station.

2.3 Market Opportunity

2.3.1 Problem Definition and Market Assessment

As of 2023, the Global AUV market is valued to be $1.84 Billion in 2023 and is projected to grow to 6.81 billion by 2031 (Fortune Business Insights). Given their numerous capabilities, the industry has seen a significant push in both the private and public sectors to invest and deploy AUVs for various purposes. As outlined in the technical report, AUVs are dependent on their battery power. This limits the mission duration for an AUV, handicapping their ability to go on extensive missions and travel to remote locations. Moreover, when AUVs approach the end of their battery life, significant time is wasted on recall to HQ or their mission ship - some even requiring retrieval missions. These missions are both costly and time-consuming, requiring AUV owners to spend extensive amounts of resources to ensure safe and successful retrieval. With permanent charging stations, AUVs become capable of longer missions and their need for manual retrieval is significantly reduced. It would also reduce the need for mission ships to oversee AUV missions. By extension, AUV charging stations increase the potential usage of AUVs, allowing them to serve a greater purpose while simultaneously decreasing costs and resource usage for AUV owners. This will further incentivize potential stakeholders to invest in AUVs and decrease barriers to entry for the AUV industry. Overall, AUV charging stations have the potential to revolutionize the AUV industry.

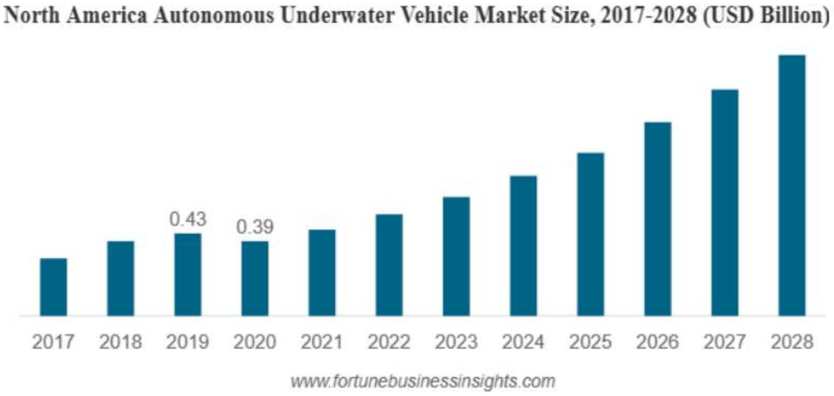

Figure 1 - AUV Market Forecast Through 2028. *Fortune Business Insights.*

2.3.2 Market Forecast

Considering our proximity and ties to the Great Lakes, our team wanted to focus on a clean energy initiative that could directly benefit the area we live in. The Great Lakes are often overlooked as a location for AUV missions. However, there is a growing local demand for AUVs within the region, as less than 15% of the Great Lakes have been mapped at a high density resolution, as mentioned earlier (NOAA). A thorough map of the Great Lakes would help assess their aquatic health and track key erosion and climate change trends which would help with coastal development and economic planning efforts, which is the primary intent of the National Oceanic and Atmospheric Administration's Lakebed 2030 Initiative. Similarly, the US Geological Survey has conducted multiple AUV missions in the Great Lakes to research and improve fishery assessments and map lakebed habitats. Research institutions such as the Great Lakes Research Center (GLRC) have conducted and plan to further expand their AUV initiatives within the Great Lakes, as reinforced by Dr. Tim Havens (see section 2.1). Additionally, the Great Lakes offer a unique opportunity for the U.S. Military, offering greater levels of security to conduct AUV military testing than open oceanic environments. On this note, Michigan Governor Gretchen Whitmer recently issued grants to accelerate maritime and mobility innovations within the Great Lakes region (Achtenburg, Michigan Business). Overall there is a pressing demand to utilize AUVs to improve maritime missions and an increasing demand to conduct these missions within the Great Lakes, indicating a relatively stable market that is in its growth phase and an immense opportunity to capitalize on.

2.3.3 Competition Analysis

The market of autonomous offshore AUV charging is still in the early development stages. Thus, the market is undersaturated, primed for innovation, and laden with opportunity. Certain AUV charging stations have already been designed, built, and tested. For example, Teledyne has made headway with a unique technology designed to prolong AUV missions offshore using electrodialysis charging technology (Offshore Journal 2018). The Monterey Bay Aquarium Institute has also tested models of underwater charging stations that feature a cone-capture system and inductive charging system, however, this technology is not yet commercial (Dhanak and Xiros 2016). Thus, we do not necessarily view our business model through the lens of competing with market adversaries; instead, this is a technical system that would seek to be as collaborative as possible with relevant research institutions and testing facilities, such that the development of this technology is expedited through efforts that include as many disciplinary considerations and contributions as possible. Additionally, this system is not necessarily a product for an everyday customer - it is a highly technical system that would serve the general public through defense, surveillance, and environmental monitoring applications - all activities governed and executed by public institutions.

2.4 Ownership Structure

One of the primary considerations of any business model is the ownership structure of product delivery. We examined three different ownership models for our overall technical system. The first option in consideration was a **Customer Ownership Model** (Table 1), in which the theoretical purchaser would, upon purchase, assume complete technical system ownership. This would include the wave energy generator array, the anchor, and the charging dock (these are the components that comprise our technical design, and are expanded in Section 3.0). Additionally, the customer would assume the responsibility of obtaining state conveyances for placing technology on the lakebed. While this would allow us to maintain a consistent price and give the customer full autonomy over system access, there are a variety of major concerns such as how to address maintenance and warranties. Additionally, this model would rely on us selling each charging station, limiting our access to new customers and our ability to maximize the charging station's capacity. Thus, we elected to abandon the customer ownership model.

Table 1 - Customer Ownership

Customer Purchases and Assumes Complete Ownership of System	
Pros	**Cons**
● System purchases would be made on a customer-by-customer basis, which would allow us to reflect a very consistent and itemized price. ● This model allows the customer to assume complete domain over the	● Purchase contracts would likely require us to routinely perform operational maintenance, as well as winter removals and spring deployments. ● This model creates a less predictable income pattern, which raises questions

device, and would eliminate risk of conflicts between different users. ● On our end, it gives the primary customers a higher influence over our business model and serves as a marketing strategy to user competitors or collaborators.	for the sustainability of our business model. ● This business model would also require the issuance of warranties, which become increasingly ambiguous as to how they would be enforced. ● Does not allow for varied customer volume.

The second option considered was what we repeatedly called the **Open Access Model** (Table 2). This model functions such that customers can charge their devices when desired, and would pay per usage. This model maximizes the accessibility of our device as anyone with a compatible AUV can access the charging station when it is available. Moreover, customers will receive a fair and consistent payment-to-usage rate. However, it presents high levels of risk for us as we are dependent on high levels of activity to achieve healthy revenue levels. Additionally, if anyone has access, it is made impossible to vet untrained users. Overall, there is too much variability in this model to pursue it with confidence.

Table 2 - Open Access Model

Open Access Model - Customers Pay for Individual Charges	
Pros	**Cons**
1. Customers are ensured their payments are accurately reflected, as they are being charged a consistent, per unit power supplied, monetary rate. 2. Customers are not worried about meeting a usage quota to cover their financial books. Anything that "worries" a customer is a barrier to transactions and a profit reduction. 3. This is the most accessibility-friendly model, as it encourages virtually any customer to enjoy its capabilities.	1. Has the potential to lead for long gaps in usage, or for multiple customers wanting to dock at the same time. 2. There is a difficulty on the supplier end to cover ownership costs and depreciation if there is a low traffic volume. 3. If the device is too accessible, there is a risk of customers that are unfamiliar with the technology attempting to charge their AUVs against general procedure. This raises the risk of customer-caused system damages.

The third and final structure ideated was a **Subscription Based Usage Mode**l (Table 3). In this model, we would retain full ownership of the system. Any qualified user who has paid a tag fee is granted access to the station. This model does present a similar degree of risk including the potential inability to acquire subscribers and the overutilization of a charging station once a customer gets unlimited access during their subscription period. On the other hand, the Subscription Model allows us to best allocate customers to our charging stations so that traffic levels remain constant and controlled. Additionally, this allows us to vet unqualified customers and provide training to those looking to acquire a subscription. Once a customer purchases a subscription, they can use the charging station at will, allowing them to easily plan AUV missions. From our end, we will receive a guaranteed source of revenue throughout a customer's subscription period. Retaining system ownership gives us the flexibility to conduct maintenance and safety initiatives when required.

Table 3 - Time Ownership Model

Subscription Based Usage	
Pros	**Cons**
1. Rates are consistent and transparent across the customer domain. 2. Gives customer liberty to use at will and allows for more effective mission planning. 3. We keep overall system ownership, warranty, and insurance on our end, eliminating numerous potential customer conflicts. 4. Allows us to vet unqualified potential users, provide training, and keep track of all customers. 5. Guarantees income over subscription-period.	1. Customers may be hesitant to subscribe, as they may not be confident in how much they'd use it. 2. Any system failures/downs may prompt customers to demand subscription refund - quality assurance over an entire subscription period may prove challenging. 3. May hurt margins with unlimited domain over subscription period (i.e. more customer volume than anticipated).

2.5 Development and Operations

2.5.1 Deployment Plan

Deployment of the system would follow a carefully outlined procedure, which would start with customer identification. Based on the end-user outreach, there are a variety of interested users including government, military, university, and potentially even private prospects. System deployment should truly be examined through two different, but equally important, lenses: The business rollout and the technical system deployment.

2.5.2 Business Deployment

Based on an end-user outreach, of which the chief findings are outlined in Section 2.0 of this business report, we identify several starting points for customer identification. Our business model is centered around the idea of optimizing Great Lakes exploration, monitoring, and surveillance for qualified entities. However, there are a variety of issues that arise when exploring the idea of the customer assuming complete ownership of the technical system. Thus, we concluded that the most effective deployment and ownership procedure would be subscription-based for qualified entities. This means interested customers would undergo procedural training and be vetted through a qualification program that examines their professional reliability, their AUV specifications, and their overall control capabilities when utilizing our technology. When they are deemed both qualified and trained, a subscription-based system would be employed in which they assume liberty to use, at will, over the course of the designated subscription period. Any period of use would include notification to the owner (in our case, our business), which would then be relayed to all other potential users in the area to prevent customer docking clashes. This procedure was selected after brainstorming a variety of different system ownership structures, identifying the strengths and weaknesses associated with each, and arriving at an optimal final solution. The details of this entire selection process are outlined above in Section 2.4.

2.5.3 Technical System Deployment

Being that we retain full system ownership after product release, all system manufacturing, as well as physical deployment and retrieval efforts, would be self-performed (this is not to say certain engineering components would necessarily not be outsourced). Thus, locations would be selected based on optimum system performance, logistical feasibility, and human/technological safety in-house. The overall system outlined in the Technical Design Final Report, including the wave energy generators, the power transfer system, the anchor, and the charging station, would be carefully assembled in on-land facilities. Based on the system's physical configuration, namely the fact that the only system component that reaches the lakebed is the anchor, there would be no need for any sort of underwater construction or human labor for deployment - a leveraged advantage compared to various other marine energy technological deployments, especially when considering annual retrieval and maintenance procedures.

The required equipment involved in physical deployment would be a crane ship capable of hoisting and deploying loads between 3-5 tons. Various crane ships commonly used for offshore operations can be rated for loads up to 80 tons, thus system payload is not an issue. The entire system would already be moored together, and the WEC would be deployed first and allowed to free float in the designated area. The crane would then deploy the anchor to the lakebed, simultaneously deploying the calibrated docking station to sit in the water column. When the anchor has been deployed and is sitting on the lakebed, the system is effectively deployed.

2.5.4 Risk Management

Risk: Storm Survival

Average wind speeds in Lake Superior range from 10 mph to 17 mph (BeachWeather), however these values increase significantly during storm events, namely return period storms of 5, 10, and 25 years. Winds of this magnitude create dangerous surface waves over Lake Superior that could be capable of causing damage to the WEC, as well as interfering with AUVs attempting to dock in the station.

Measure: Multiple technical solutions relate to this - the first being a sink-safety-command that could be potentially incorporated into the design as a ballast configuration, such as the concept illustrated in a study performed by Ryan Coe, Jennifer van Rij, Yi-Hsiang Yu, and Alan McCall titled "Extreme Load Computational Fluid Dynamics Analysis and Verification for a Multibody Wave Energy Converter, 2019". In environmental conditions where waves are deemed a threat to the device's integrity, a ballast system incorporated into the WEC could potentially be commanded to sink to a safe level in the water column, and return when conditions subside. Additionally, to avoid the conflict of waves causing motion that interferes with the docking process, each docking station would be designed such that it would sit at a level in the water column where it is double the maximum wavelength equivalent in vertical depth from the water's surface. Airy's Wave Theory suggests that this specific design parameter will prevent any surface propagation from causing any unwanted motion to the charging station, regardless of conditions.

Risk: Cybersecurity

If this technology were to be deployed for any surveillance or defense information purposes, it is logical to assume it to be a potential target for enemy intelligence. Additionally, the onboard computers are at risk of hacking and autonomous deactivation - which would render the technology useless, potentially stranding AUVs that are worth hundreds of thousands of dollars.

Measure: This could be addressed by implementing necessary cybersecurity measures into the onboard computer that controls the charging station. Such cybersecurity measures may include a form of blockchain technology, which doubly acts as a measure to prevent users who are not subscribed from attempting to dock. This is economically efficient in the sense that the method used for cybersecurity also acts as network security.

Risk: Shipping Interference

Problem: Specifically in the Great Lakes, shipping lanes are a major logistical concern when choosing a location. Any interference with predetermined shipping lanes would be a) illegal and b) very costly should any damage to the ship and/or technology occur.

Measure: First, the technology's location will be determined such that shipping interference will never be a concern, and will be designed in such a way that the WECs themselves are limited to a specific radius of float travel via the mooring method we eventually choose. Additionally, all WECs would be marked with the appropriate Coast Guard marking insignia (flags, posts, standardized colors) so that any other maritime traveler, such as fishermen or recreational boaters are aware of the technology's location.

Risk: Illegal Land Usage

Problem: For any structure that touches the lakebed of the Great Lakes, permission must be obtained from the rightful owner or it is considered maritime trespassing.

Measure: For any new deployment, the location chosen will be permitted through the US Army Corps of Engineers and the Michigan Department of Environment, Great Lakes, and Energy (EGLE). It will be determined as to who the rightful landowner is in the given area, and generally this will be the State of

Michigan. Thus, a conveyance will be legally obtained for that specific land, allowing the technology to exist and operate legally.

2.5.5 Technical Barriers

One of the chief technical barriers with any wave energy application is how power will be maintained in calm sea-states. This would be addressed by incorporating marine-grade batteries into either the WEC or the charging dock (likely the WEC, due to the fact that the charging dock must be positively buoyant and thus weight should be minimized as much as possible). Therefore, situations of low-energy wave action where the WEC is not capable of meeting the power requirements would require the batteries to charge the AUV instead. The system batteries would be recharged in the intermittent periods when no AUV is actually parked at the dock. This entire system could be autonomously controlled, allowing a remote user or the computer itself to determine the setting of the WEC at any given time. This also relates to various other technical barriers. For instance, the control system could also theoretically control output to maintain a consistent charging rate, regardless of conditions. It could also be a reactive system to violent weather, and initiate emergency shut-off commands or survival commands.

The system will also require annual maintenance in the winter months when it will be retrieved, and potentially unforeseen maintenance if any components should break during operation. It is important that the float is designed with a rigid polymer and the shaft with aluminum to mitigate this to the maximum extent possible. However, operational maintenance is inevitable. The system was designed to be retrievable and deployable with only a crane ship. Theoretically, no individual should ever have to enter the water during these processes. Thus, no maintenance would ever need to be executed in the water.

2.5.6 Social Barriers

Problem: Foreign structures can often have a bad rap when entering the Great Lakes, as they interfere with its natural state. This often leads to a backlash among those who use the bodies of water for recreational purposes. Additionally, the Great Lakes are frequently used for trade and there are well-established shipping routes. Interference with those routes will lead to immense criticism from shipping companies and potentially have legal consequences, as outlined in the risk management plan.

Solution: First, we must select locations that interfere with personal property and shipping routes as little as possible. This way we will experience the least amount of potential backlash from other users. However, if we do interfere with property or routes we need to mitigate the presence of charging stations such as limiting the sound and space it takes up. One way we can do this is by lowering the point absorber and charging station below the surface of the water when it is not in use. This will keep the device out of sight of potential onlookers and out of the way of shipping activity. Additionally, as outlined in the risk management plan, each system would require markings and flags in consistency with Coast Guard requirements to notify any maritime traveler of the system’s presence.

Problem: When introducing a new energy-powered device, the technical capabilities are often met with

confusion and skepticism from outside stakeholders. Failure to address the concerns and meet the standards of these stakeholders will prevent the device from generating the momentum required for it to become viable in the market space.
Solution: Technical demonstrations provide an effective way to showcase our device's abilities. When courting potential customers we will ensure that we provide a wave tank demonstration so they are aware of our device's potential and limitations. This will provide them with the transparency needed to confidently form an opinion about our device and give us a greater ability to win them over as both investors and supporters.

Problem: When deploying a large piece of technology into the environment it is crucial to ensure that the device is environmentally compliant. Following and adhering to the proper permits for a device in the Great Lakes is essential.

Solution: With the deployment of a device such as this there are several required permits, primarily under Part 325 under the Natural Resources and Environmental Protection Act. The device would use a lubricant that is designated by the EPA as an Environmentally Acceptable Lubricant (EAL). Based on toxicity, biodegradability, and bioaccumulation metrics. See Section 2.5.7 for a greater explanation of environmental compliance.

2.5.7 Environmental Compliance

One of the chief shortcomings of last year's project was the MECC Team's failure to address environmental compliance in their deployment, which was a series of surge converters to be deployed in nearshore Gulf of Mexico coastlines. We have decided this year to not only make environmental consciousness a concern, but rather full environmental compliance for our concept. Being that this involves both state and federal regulations, we reached out to both the Michigan Department of Environment, Great Lakes, and Energy (EGLE) which oversees all state compliance and the United States Army Corps of Engineers (USACE) which oversees all federal compliance.

Our first conversation was with Ryan McCone, the Upper Peninsula District Supervisor for EGLE's Water Resources Division. We spoke in great detail about our team's concept, and he was able to provide us with examples of various permits we would likely need to acquire for an actual deployment based on our project description. These state permits include a Part 325, also known as a Submerged Wetlands permit, a Part 303, which would pertain to offshore construction, a Part 323, which addresses an offshore device/structure's effect on the coastline, and a Part 353, which addresses the drilling aspect of construction on the lakebed. All of these permits are dependent on whether our docking station would exist on the lake bed or in the water column. With our current technical system, the only component that touches the lakebed is the anchor. Therefore, drilling is not a concern and no subsurface contaminants or discharges would be released by deployment. He was also able to provide a more general array of areas to address, like fish habitat irritation, spawning areas, land conveyance with the state, how the operation would affect water quality, and analysis of geotechnical substance release if any drilling occurred. We concluded the interview by discussing the state's push for renewables, which he reinforced as strong and increasing across various sectors of renewable energy.

Our second conversation was with Kerrie Kuhne, an environmental engineer for the United States Army Corps of Engineers. Like Ryan, we spoke in detail about our team's concept before discussing the environmental impacts of the project. Kerrie explained the difference between EGLE's laws and USACE's laws, the latter covering all federal aspects of compliance. The only specific permit she mentioned was a part 404, also known as a discharge permit. While our design would need to be approved by both regulators, it is unlikely that this project would require a discharge permit. If anything, the only associated discharge would be the accidental release of the device's lubricant, which our team plans to address by including an environmentally friendly, biodegradable lubricant. She also recommended we address the logistic aspect of our location(s), to make sure they do not interfere with shipping lanes. Additionally, she informed us of the Coast Guard ordinances that would require a specific marking flag with an indicative color.

2.6 Financial Benefits and Analysis

2.6.1 Financial Potential

Within Michigan, there is a growing desire to finance clean energy projects. Currently, Michigan is second to only California in funding renewable energy projects, having secured nearly 1.3 billion dollars in funding (EGLE). Also, Michigan is the top Midwest state for clean energy jobs (MI Healthy Climate Plan Report). With significant statewide interest in clean energy initiatives, our project has the potential to tap into a growing source of funding. Governor Gretchen Whitmer has given out numerous grants to accelerate mobility innovations in the Great Lakes (MEDC). Encouragingly, when we interviewed stakeholders from the Great Lakes Research Center and the US Navy, they expressed interest in an AUV charging model and are highly open to utilizing it once complet*e.* Overall, the amount of effort and interest dedicated to funding similar initiatives suggests there is ample opportunity to secure funding.

2.6.2 Ancillary Benefits

One significant benefit of deploying and maintaining an AUV charging device in the Great Lakes is job creation. The build and deployment stage of the project will require the work of engineers, project managers, construction laborers, and a boat crew. These positions will provide temporary employment in the Great Lakes region. Additionally, we will need to have an on-call maintenance crew when repairs are needed. This will provide a long-term source of income for the maintenance crew. Furthermore, the project laborers will gain valuable experience when building and deploying the charging stations enhancing their technical expertise.

Another benefit of our AUV charging station is that it decreases the barrier of entry for new AUV missions. AUV users will not need to spend as much time developing their retrieval strategies and devoting resources to retrieval missions. This will decrease the expertise and costs required to conduct an AUV mission. Additionally, a charging infrastructure will increase the mission potential for AUVs. With increased mission duration and removing the need for manned retrieval, AUVs can spend more time exploring and traveling further depths and distances than once required. Finally, decreasing AUV retrieval missions will in return decrease the safety risk retrieval missions pose to laborers and the environmental impact caused by fuel usage and noise pollution.

One final benefit is the positive impact our AUV charging station will have on the Great Lakes. With our network in place, the Great Lakes will have advanced AUV mission capabilities, increasing the amount of research done in the area. This will allow us to gain a better understanding of the Great Lakes. Moreover, advanced mission capabilities will incentivize more people to conduct AUV research which will increase the economic potential of the Great Lakes.

2.6.3 Capital and Financing

After talking to Lisa Thomas from EGLE, we identified numerous funding opportunities. Our initial plan is to work with the Michigan Economic Development Corporation to secure preliminary funding avenues. These include their First Capital Funds that enable technology companies to have the resources required to enter the commercialization stage of the project (MEDC). Additionally, we will partner with the Business Accelerator Fund and Emerging Technology Fund which provide other means for financing R&D and commercialization initiatives (MEDC). Another unique opportunity lies with the COS-C3 program through Centropolis. The COS-C3 program offers funding via grants and investments. They provide expert instruction and include access to the Michigan Match Assistance Pilot Program which offers cost-sharing opportunities and customer demonstrations. This will provide us with guidance and access to expert resources which will further advance our WEC development. Next, the COS-C3 program has private investors who have previously financed projects such as Whirlpool and Wells Fargo. Finally, the MTEC SmartZone is a valuable resource close to Michigan Tech's campus. SmartZone aims to mentor startups and accelerate business growth (MTEC SmartZone**)**. Overall, we will use a combination of the financing and mentorship resources available to us to maximize our growth potential.

2.6.4 Long-Term Objectives

Once we have successfully constructed and deployed our marine-powered AUV charging station we aim to build on our momentum to achieve higher levels of efficiency, customer satisfaction, and profitability. We have identified multiple objectives to achieve continuous improvement.

1) Increase the number of deployments
Our first aim in our charging network is to ensure quality and reliability. However, a strong network also needs accessibility. With the addition of new AUV charging stations in the Great Lakes, customers will have more range to work with for their missions, thus increasing their mission flexibility and capability. Moreover, deploying additional models will allow us to expand our customer base while ensuring access to the charging stations. Additionally, each build deployment results in an increase in economics of scale and a decrease in the learning curve. This will increase our efficiency with our ability to release charging

stations and lower our costs per output. Overall, this positive feedback loop will allow for rapid expansion of our charging infrastructure.

2) Expand into new markets

Due to our geographic location and the untapped potential of the source, the Great Lakes are an excellent place to start our project. However, the Great Lakes only see a fraction of the activity present along the coast of the Pacific and Atlantic Oceans. Once we have proven our capabilities and earned a healthy market share in the Great Lakes we will look to increase our presence in oceanic environments. With deployments in the Atlantic and Pacific Ocean, we will have access to new customers, allowing us to rapidly expand our customer base and growth potential. Moreover, the Atlantic and Pacific Oceans are locations where we can further legitimize our technical capabilities and prove that we have a universal solution for AUV charging.

Technical Design Challenge Report

Technical Design Team

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Word Count: 1,868

3.0 Technical Design Challenge

3.1 System Overview

Figure 2 is a 3D rendering of our team's overall technical schematic. The design underwent various iterations as concerning design questions surfaced, generally related to system survival and versatility in varying operational locations.

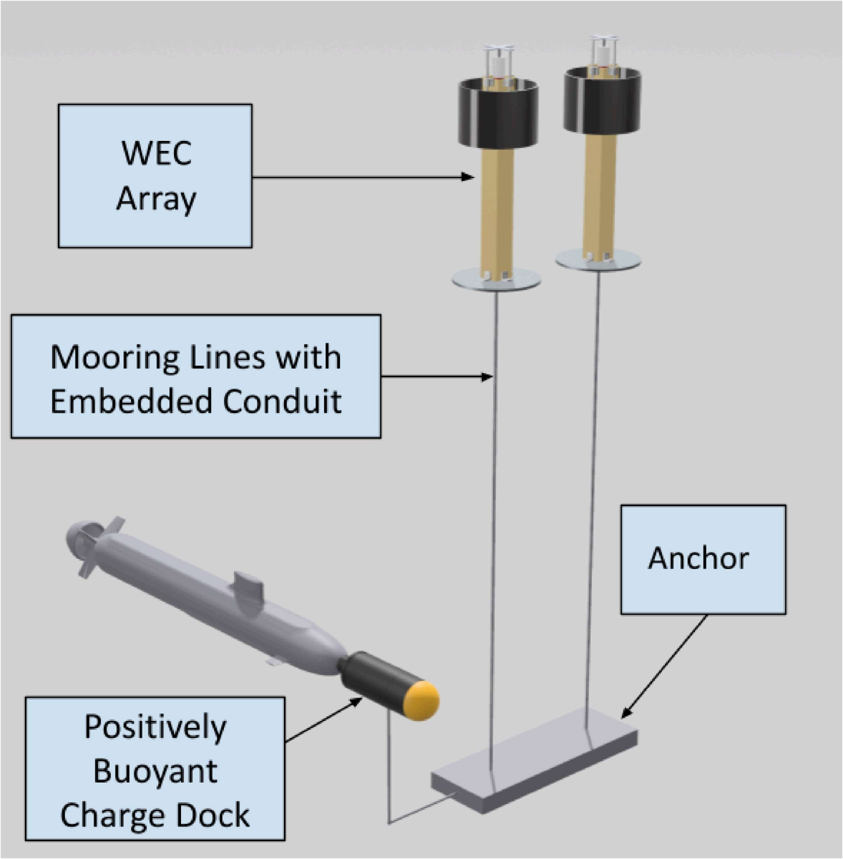


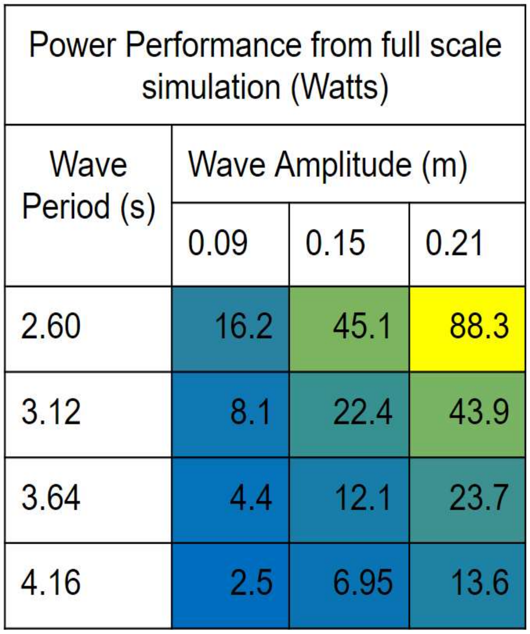
Figure 2 - System Rendering

In this schematic design, the WEC system of point absorbers would operate at the water's surface, replicating the prototype concept. It would be moored only from the bottom by mooring lines that contain embedded electrical conduit and span the design depth length to a lakebed anchor. This mooring design eliminates the requirement of any sort of underwater construction and secondly, the act of actually penetrating the lakebed - upon penetrating the lakebed, various other permits are required that would otherwise not be necessary. The anchor is designed to house the electrical conduit and guide it to a separate line, transmitting power back "up" vertically to a charging dock that is equipped with positively buoyant design additions, such that it hovers in the water column. The logic behind this design, as opposed to previous designs, is that the system is not necessarily constrained by the depth ratings of the charging stations or the AUVs receiving power. Each system can be individually designed such that the charging docks and AUVs remain within safe operational depths, while the system is rigidly moored to the lakebed in depths that potentially greatly exceed the technology's ratings.

3.2 WECsim Results and System Validation

Being that the full-scale model is a 4x scale of the prototype, the geometry of the buoy, spar, and plate were accordingly scaled, as well as the testing plan (amplitudes and frequencies) and input into WECsim to simulate the full-scale model's conceptual performance. Simulink was used to generate the model which simulates the actuation force of the power takeoff (see Figure 3). Table 4 illustrates the overall power performance based on both the simulated actuation force and the relative displacement between the spar and the buoy.

Table 4 - WECSim Power Performance



Power Performance from full scale simulation (Watts)			
Wave Period (s)	Wave Amplitude (m)		
	0.09	0.15	0.21
2.60	16.2	45.1	88.3
3.12	8.1	22.4	43.9
3.64	4.4	12.1	23.7
4.16	2.5	6.95	13.6

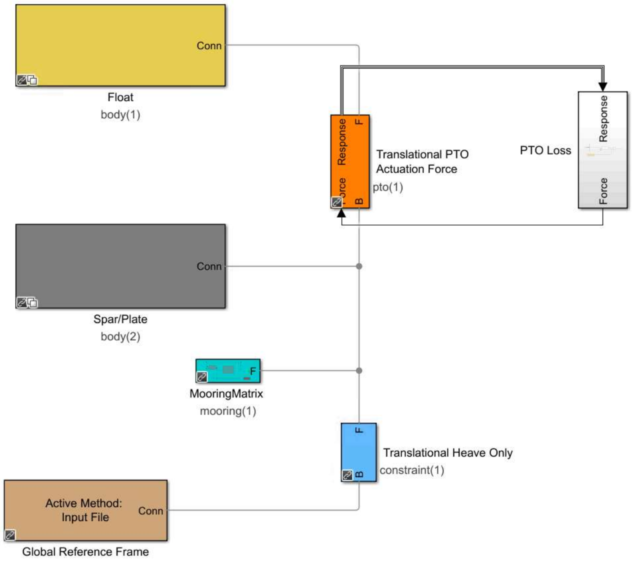


Figure 3 - Simulink Model

Based on the simulation results, the WEC geometry and power takeoff method are capable of making voltages exceeding 80W based on real-time wave data from Lake Superior, but also perform relatively unimpressively in conditions involving smaller waves and lower frequencies. Thus, charging AUVs with wave energy, based on the simulation results, is promising, if conditions permit. IVER3s contain batteries with associated storages of 800 Wh, thus, in an ideal scenario, a WEC making 80W of power could hypothetically charge an IVER3 in approximately ten hours.

To account for conditions insufficient to meet an AUV's power requirement, either the dock or the WEC would likely require a power storage capability in which batteries charge the AUV.

3.3 Full-Scale Model Design

The CAD was scaled up by 4 times to illustrate the full-scale model's performance. It was scaled such that the simulation would imitate what the implemented model could expect to experience and how it would reactively perform. The WECSim data can be used to ascertain the force values to be input into the CAD model's load analysis. From this, we can use the data to simulate the stresses imposed on the design itself.

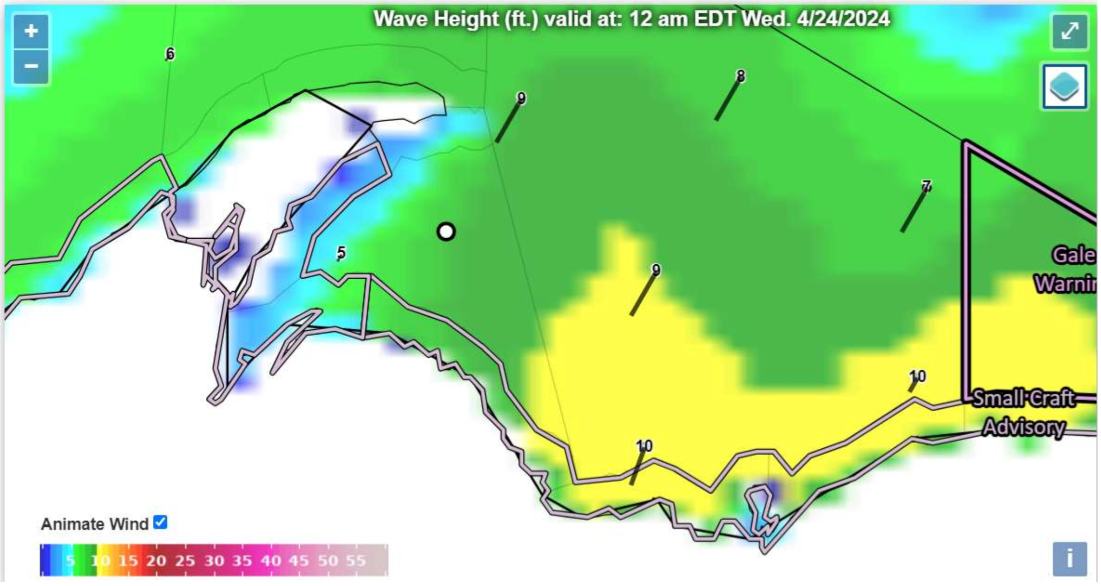


Figure 4 - Great Lakes Portal Interface | Wind Map

The Great Lakes Portal Forecast allows the user to pick any location in the Great Lakes, so we picked the spot where we were thinking of implementing the point absorber, which is expanded in the Build and Test challenge report. The waves and gusts are most active during the day, achieving a maximum value of 27 kt (31 mph) and a minimum of 14 kt (16 mph). We divided by the time to get acceleration and multiplied this result by the mass of the point absorber. This allowed us to obtain a force value of 710 N. A simulation was used for the maximum force on the float to simulate the stress. To simulate this, Simcenter 3D was used to set a mesh element. The auto mesh was used for simplicity purposes. A distributed load was added to the buoy and shaft. A fixed constraint was added to the buoy where the buoy will move up and down. The simulation experienced some errors but the team was able to calculate the force for the simulation and assure the device's structural performance. The Simcenter model used is depicted in Figure 5.

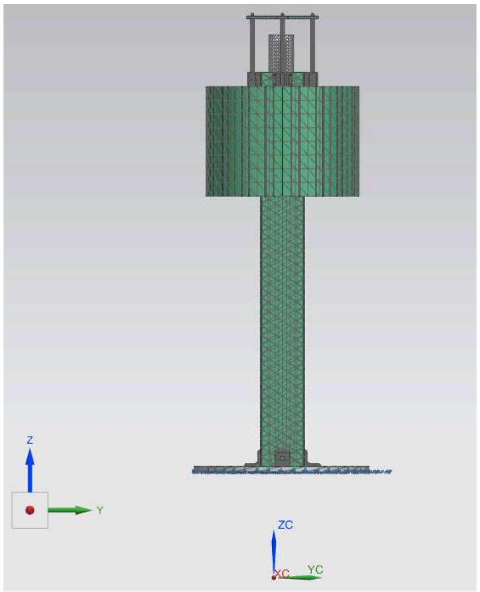


Figure 5 - Simcenter Model

3.4 Autonomous AUV Charging with Wave Energy

The proposed charging schematic would require a highly complex design to ensure the AUV's safety and the effectiveness of the charging itself. To better understand the IVER3, the team met with Dr. Chris Pinnow. He explained that while the GLRC's IVER does not have inductive charging capabilities, the Navy has employed AUVs that do. There are three computers inside the AUV, and one of them includes location and tracking capabilities that could hypothetically locate a charging dock and self-navigate.

A few underwater charging docks have been designed and tested. Many of them feature a "cone-capture" design, which is what our design would conceptually seek to replicate. Our unique design feature in this system would be the addition of a suitable amount of buoyant material, such as foam, that would allow the station to float in the water column and remain moored by the anchor. As expanded earlier, this particular design feature is included in an attempt to eliminate depth ratings as a location constraint for our overall system.

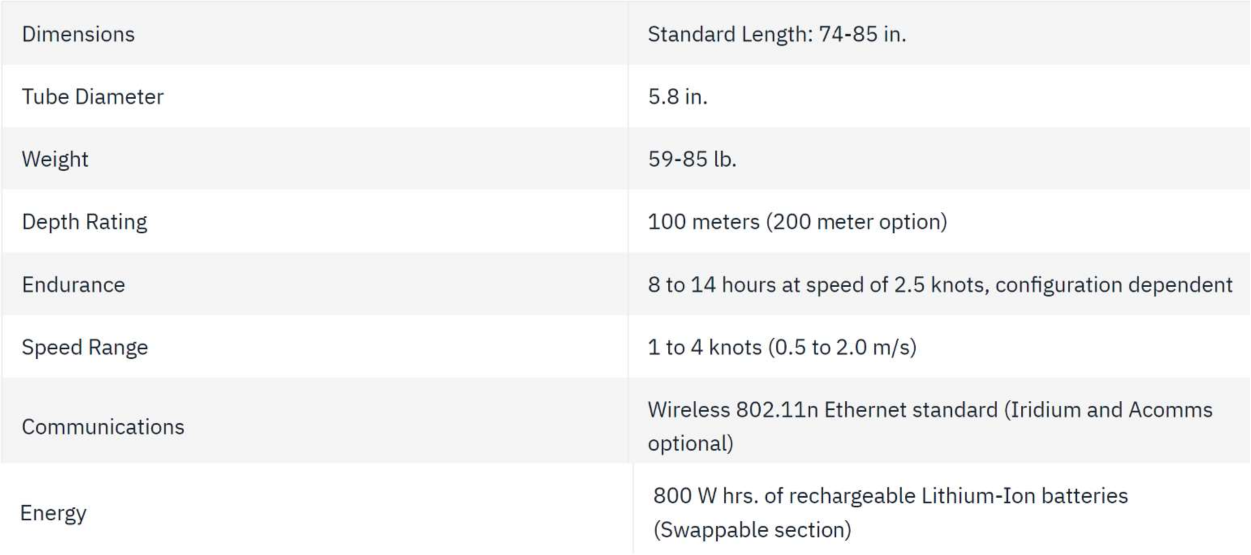
To reiterate our business model - our mission is to deploy point absorbers into the Great Lakes in conjunction with offshore docking stations for AUVs that would be designed with the specific intent to provide autonomous battery charging and potentially, data offload services, drawing the necessary power from the aforementioned point absorber.

Autonomous underwater vehicles (abbreviated AUV) are unmanned, untethered, autonomously controlled vehicles that operate underwater. They are used for their various sensor capabilities that include bathymetric surveying, water quality monitoring, undersea surveillance, as well as other maritime mission-based operations and defense applications. They generally range in length from 1.5

meters to 6 meters, and resemble a torpedo in shape for optimal hydrodynamic performance [Virginia Institute of Technology]. They are controlled by an onboard computer and are battery-powered. Most small-size AUVs undergo missions that last between 5 and 20 hours. This being their designation, AUV missions are often limited by both their associated battery lives and their data storage capacities, missions often involving wasted recall time for recharge or offload, or wasted man-hours and money for retrieval missions. These conclusions, substantiated by multiple stakeholder interviews and market research, are what led our team to decide this to be the market opportunity to pursue.

For our purposes, we have identified the Iver3 Standard AUV, a product of L3Harris Technologies, to be our reference model for the scope of this project. The Iver3 is a popular AUV for maritime missions, routinely utilized for hydrographic and swathe mapping, water quality monitoring, search, and surveillance (Gish, Driscol, and Coe 2019). These capabilities make the Iver3 a suitable reference model for missions in the Great Lakes, and by extension for our work. The official specifications on L3Harris's website are listed in Table 5. The standard Iver3 has a maximum depth rating of 100m, however, there is a 200m option, making that the upper constraint for this analysis.

Table 5 - IVER3 Specifications



Dimensions	Standard Length: 74-85 in.
Tube Diameter	5.8 in.
Weight	59-85 lb.
Depth Rating	100 meters (200 meter option)
Endurance	8 to 14 hours at speed of 2.5 knots, configuration dependent
Speed Range	1 to 4 knots (0.5 to 2.0 m/s)
Communications	Wireless 802.11n Ethernet standard (Iridium and Acomms optional)
Energy	800 W hrs. of rechargeable Lithium-Ion batteries (Swappable section)

After validating the business model using WECsim, as outlined in Section 3.3, a more theoretical analysis was conducted based on Linear Wave Theory and taking analytical structural reference from Andy Gish and Ryan Coe's "Charging AUVs with Wave Energy: A feasibility study."

Based on wave data obtained from Lake Superior, we assumed our reference wave height (H) to be 0.75 meters and our average period (T) to be 3.5 seconds. Equation 1 outputs average wave power density (J) in kW/m, measuring the available power per meter width of a surface wave along a wave crest, and is an industry-accepted formula used for location optimization for wave energy devices, where rho represents water density and g represents acceleration due to gravity (9.81 m/s^2).

Equation 1

$$J = (\rho g^2 H^2 T)/(64000\pi)$$

This value was then used in Equation 3, which uses three coefficients of efficiency, as well as a characteristic dimension (B) which is used to characterize the geometry of the WEC and is a function of the maximum horizontal cross-sectional area of the WEC (A) and can be found using Equation 2, essentially representing the radius of the buoy for a point absorber. When all other efficiency measurements are assumed for this point in our project, the characteristic dimension becomes the optimization factor. As referenced in Table 5, the Iver3 has a battery storage capacity of 800Wh. Assuming the Iver3 to be on missions for 8 hours, and to justify the feasibility of our business model, we concluded the WEC should be optimized to charge the AUV in no more than 10 hours based on theoretical calculations. Oceans generally offer more favorable wave conditions and studies have proven the feasibility of charging an Iver3 in less than 10 hours with offshore technology, but given Lake Superior's current available data and the progress in our research, 10 hours was designated the design charge time. We assumed generator efficiency (ɑ) and electrical efficiency (ε) based on the evidence presented in Gish and Coe (2019) as 0.75 and 0.8, respectively. The wave-capture efficiency metric (ɳ) is expressed as a percentage and is a function of characteristic dimension. Given the available wave power density, and optimizing our WEC based on this equation to meet a power capability of 80W based on our design charge time, our characteristic dimension came to 1.75 meters, outputting a cross-sectional area of approximately 2.4 square meters. This is in close alignment with the WECsim model, which is a 4x scale of the prototype design. The prototype design's characteristic dimension is 0.4 meters. Thus, the scaled dimension of our model is 1.6 meters. There is an expected degree of difference between the theoretical analysis and the actual CAD model, and in this instance, it was a difference of 15 centimeters in buoy radius. However, each WEC would likely be designed according to the wave conditions of its particular operating location, thus any radial difference between the two analyses that is within reason was acceptable in our eyes. Any power generated by the WEC while the AUV is missioning could theoretically charge a marine-grade battery, either located inside the WEC or the dock. As outlined in Gish and Coe (2019), the AUV has an additional power requirement to keep its non-propulsion systems active while it is docked, and the dock battery could also theoretically fill this role.

Equation 2

$$B = (4A/\Pi)^{0.5}$$

Equation 3

$$P = JB\eta\epsilon\alpha$$

If all listed assumptions are met and certain conditions maintained as ideal, a WEC is designed according to these calculations to indicate that a point absorber located in deepwater Lake Superior in conditions outlined on the WISPortal, where all of our wave data was retrieved, could theoretically recharge an IVER in approximately ten hours. It is important to note that in real-time operation, wave conditions are in constant fluctuation and there is no single height or period value to truly represent the WEC's performance, thus the simulation was used comparatively alongside this analysis. Additionally, the assumed electrical and linear generator efficiencies are not guaranteed to be achieved by our specific system. However, both the Linear Wave Theory analysis and the WECSim model simulation indicate that Lake Superior is a feasible location for charging AUVs offshore with wave energy if designed accordingly.

Build and Test Challenge Report

Build and Test Team

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4.0 Build and Test Challenge

Though we ended the Fall 2023 semester with a working CAD, the model underwent multiple significant design changes. Figure 6 illustrates the prototype CAD as of December 11 and how it evolved into the CAD model that governed fabrication and assembly.

The CAD was drafted on Siemens NX design software. While the team aimed to have the prototype initially tested for functionality in mid-March, various difficulties arose that eventually caused an overall testing delay of nearly a month, as the WEC was not tested in the MTU Wave Tank facility until April 19th. However, the testing process was completed and provided promising feedback. The system preparation, test objectives, and test methods are outlined in Section 4.3, and the results are reported in Section 4.4.

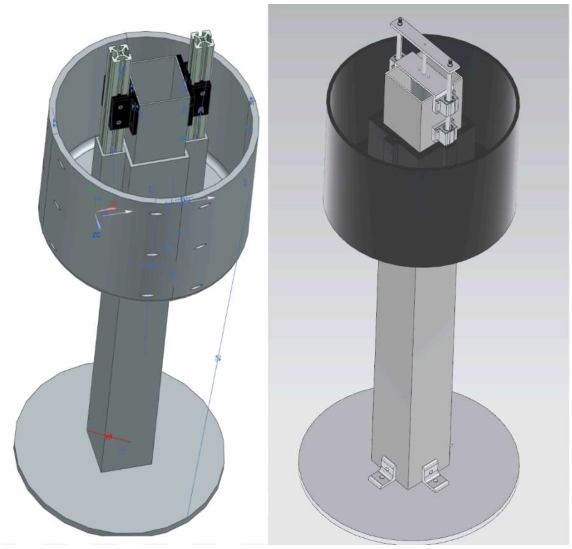


Figure 6 - Prototype CAD as of 12/11/23 (left) and 4/4/24 (right)

4.1 Prototype Design and Development

After multiple weeks of brainstorming and discussion in the fall, the team decision was to design, build, and test a two-body heaving point absorber. The first design iteration had a 14” diameter buoy and 16” diameter plate with 2 pieces of 80/20 acting as rods with linear slides that would allow the spar to move up and down. But after examining the specifications of roughness, friction, and weight-to-size ratio, this was not an acceptable linear guide, as it was extremely heavy and there was a significant amount of friction that would likely be applied to the 80/20 from the sliders as shown in Figure 6. Additionally, the buoy in the first iteration was to be printed in quarters or 4 equal sections as the 3D printers that we had access to couldn’t print over 10” wide.

The second design iteration substituted linear rods and linear bearings to replace the 80/20 guide system. Initially, the dimensions of the linear rods and linear bearings were to be 1/4" in diameter and 9" in length. However, concerns regarding the linear rods shifting either vertically or horizontally caused us to switch to linear rods with threaded ends to be able to screw directly into the buoy and have a much lower chance of shifting while in place. However, due to the manufacturer's sizings the rod diameter had to be increased to 3/8". Due to this, the buoy had to be redesigned for the added diameter and the different center of rod distances to the edge of the bearing face. With the extra distance required for the bearings, we opted to construct the buoy in one piece to increase the rigidity and strength of the buoy. The area where the heat nut had to be inserted had to be increased due to the new loads and stresses that would be applied. The buoy originally had a thickness of 1/8" on the outside and the bottom but was increased to 1/2" on the bottom and 1/4" on the sides for concerns with water tightness and extra added rigidity. The buoy also had an increased infill % for increased internal strength and water resistance. The engineering drawing of the buoy is depicted in Figure 7.

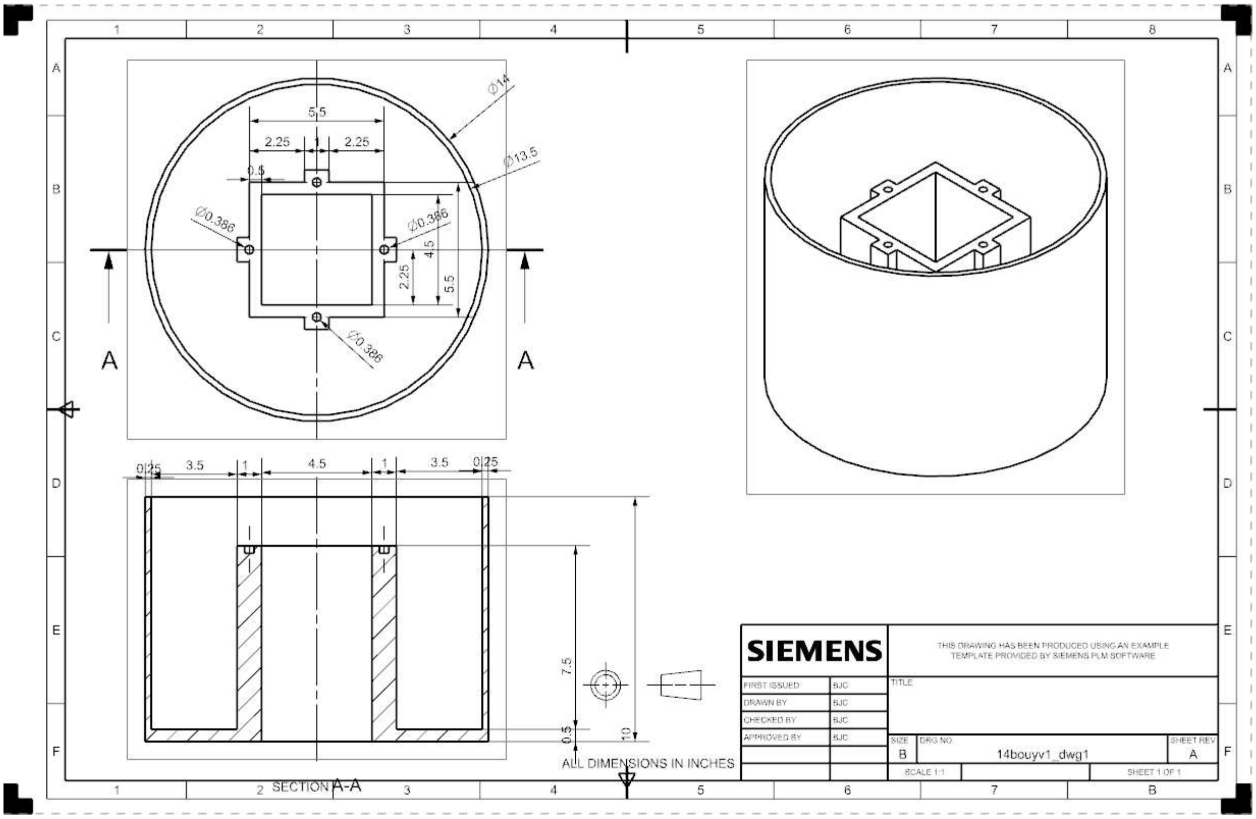


Figure 7 - Prototype Buoy Drawing

The selected power take-off was a linear DC voice coil motor produced by Monticont. This was decided for various advantageous reasons, including its linear nature, as well as the ability to potentially control the voice coil in future MECC work. The motor has maximum continuous power of 40 watts, a maximum stroke of 2.75'', and a resistance of 6 ohms.

4.2 Assembly Narration

The assembly process comprised two separate teams and initiatives: Mechanical and Data Acquisition.

4.2.1 Mechanical Assembly

Once all mounting components had been machined, device assembly began in the lab. The team decided to work bottom-up, in order to have a stable spar for all construction activities involving the buoy. Thus, fixing the spar to the drag plate was the initial task. The center of the drag plate was found via arc alignment, and the spar was mounted on-center thereafter. Due to the initial misalignment of the spar's through holes, we were forced to use our backup spar and be more attentive to bolt alignment to achieve a flush set. The seal was initially created using Blue HRV and allowed a 24-hour cure. A bead of marine-grade caulking was then applied around the brackets after a small leak was examined during the first seal test and was also allowed to cure for 24 hours. Finally, a coat of Flex-Seal was applied.

The next step involved testing the alignment of the buoy and the linear bearings. The motor mount and associated bearings were installed onto the spar, and the linear guide rods were threaded into the heat-sink fasteners in the buoy. There were no issues with system alignment at this stage. However, the self-alignment feature of the bearings allowed the buoy a concerning freedom to "rock" upon any introduction to a side load. This was addressed later in the assembly.

The system was then subjected to a buoyancy test in the wave tank facility, without any motor components installed. It was here our team realized a design error we had made regarding overall system buoyancy. Initially, our WEC was designed with a fiberglass spar, which has a density of approximately 2.4 g/cc. This was a major factor in the hand calculations from Archimede's Principle used to determine the exact length of the spar that was to be submerged below the water line. However, upon assessing the dangers of cutting fiberglass, the team elected to purchase a composite spar instead. However, the composite being significantly lighter than the former, the system was far too buoyant in its initial test. This was solved by adding water ballast to the spar's interior until it reached stability and optimal buoyancy. Figure 8 illustrates the initial buoyancy test before and after ballast was added. Note that in the pre-ballast image, a hand was required to maintain WEC stability due to the unexpected buoyancy. Ballast allowed the spar to float at design depth and self-stabilize. The idea of using density conversions to determine a concrete quantity suitable for permanent weight was assessed, however, due to the lack of modularity associated with this solution, it was discarded. However, using water ballast was equally concerning. The WEC was expected to experience high degrees of tilt and twist during testing, and having a loose ballast capable of interfering with the voice coil motor proved dangerous to the device's integrity, thus we eventually elected to use copper-coated iron Crosman BBs as the ballast method, given they are non-invasive into other design components and are easily adjustable should weight need to be added or subtracted in the field.

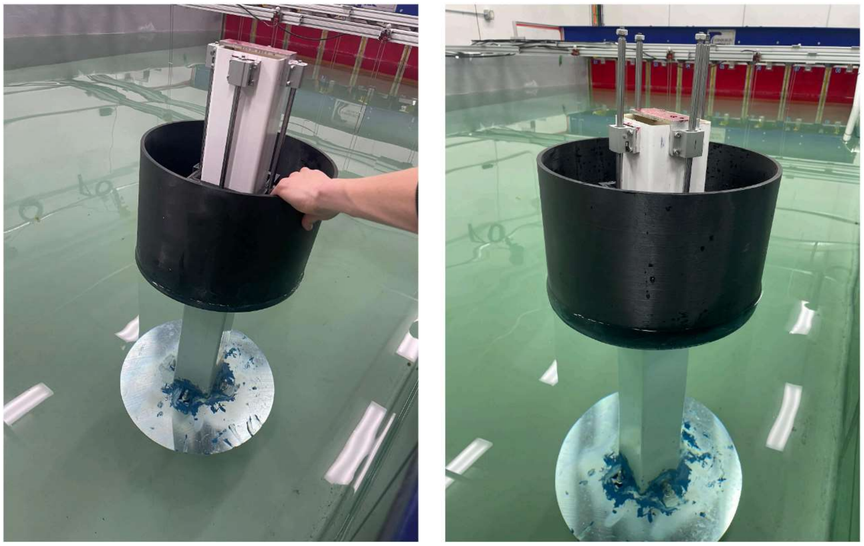


Figure 8 - WEC Before Ballast (left) and After Ballast (right)

After realizing the concerning lean incurred by the buoy caused by the self-alignment aspect of the linear bearings, the linear guide system design was altered by instead stacking two bearings apiece on two opposite sides of the spar, in contrast to each side of the square spar having its respective bearing. The spacing between the two bearings had to be redesigned with careful tolerances, namely to ensure the voice coil would achieve its 2.75” maximum stroke without separating itself during a full system heave. The illustrations used to determine the new alignment are illustrated in Figure 5, the left figure illustrating a cross-sectional system view of the voice coil at full upward heave, and the right illustrating the same view but at full downward heave. Both analyses concluded that the vertical bearing spacing should be 1.675”, and the ballast should be added accordingly to accomplish a relative buoyancy that allows a free stroke of 1.375” in both the upward and downward direction before any acting wave force. These illustrations also allowed our team to ascertain the necessary additions to the guide rods to achieve the optimal full stroke without shocking the system at every heave stop, namely using ⅜” shaft collars, rubber grommets, rubber washers, and steel washers.

Once the design change had been implemented, we were able to fully install the voice coil. According to the CAD and the adjusted drawings above, the system was designed such that at a full upward and a full downward heave, it would achieve the coil’s specified maximum stroke length of 2.75”. Upon installing the motor, we were only achieving approximately a 2.65” stroke, just short of our target. After some investigation, we realized this was likely because the rubber grommets and washers did not compress as significantly as expected when designing the guide system. Thus, the system self-limited in a manner more strict than expected. The team discussed removing some of the rubber on the shafts, however, this could not be done in a way that would prevent the heaves from sending a concerning vibrational shock throughout the system, putting its integrity at risk - therefore we accepted that our maximum stroke would fall 0.1” short of the motor’s full capability. This inevitably would limit our power output, however, in future work, this is a potential design adjustment. Figure 9 illustrates the fully assembled WEC.

Figure 9 - Fully Assembled WEC Prototype

4.2.2 Data Acquisition Circuit

In order to collect the voltage and power being produced from the buoy we designed a DAQ (Data Acquisition) box (Figure 7) containing a small circuit to facilitate the safe gathering of voltage data. One factor that had to be considered was the ability to change the resistance easily while testing the buoy, as well as keeping the circuit away from outside factors such as water.

A DAQ circuit was built with a modular slide resistor, and the resistor was set at 6 Ohms, to match that of the voice coil and maximize power output. The circuit ran from the voice coil leads through a BNC cable, through the resistor, and eventually connected into dspace, where the voltage data was archived over a timestep. A housing, eventually named the "MECC DAQ Box" held the resistor. In addition to measuring voltage output from the voice coil, we also measured the relative displacement using Qualysis Motion Tracking cameras. Figure 10 illustrates the resistor and an aesthetic image of the MECC DAQ Box running cable to the WEC.

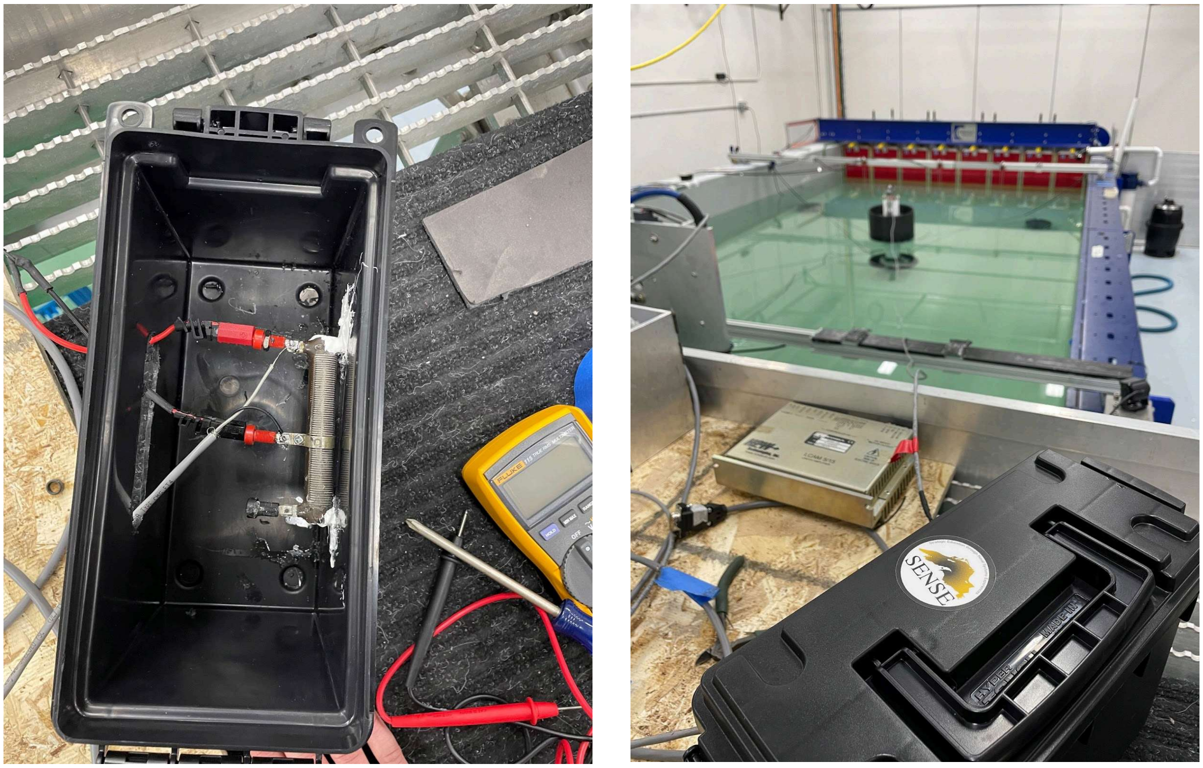


Figure 10 - DAQ Setup

4.3 Facility Preparation and Test Methods

The WEC was tested in MEEM (Mechanical Engineering, Engineering Mechanics Building) S001 on April 19th using the wave tank designed and manufactured by Edinburgh Designs, beginning around 13:00 and concluding around 18:30.

4.3.1 Facility Calibration

Facility preparation in S001 is a highly integrated process that demands several hours of calibration before any actual testing. This calibration was performed primarily by Dr. Gordon Parker and Tania, though the DAQ team was involved in observing and learning the process. The facility has several available inputs and outputs that can be utilized in synchronization to assess a specific design’s hydrodynamic performance, however, to achieve said synchronization, calibration must be done carefully and sometimes requires multiple iterations. For this specific project, we utilized three different methods of measurement:

- Wave gauges: Three gauges were utilized to measure the elevation of the waves. These gauges were positioned approximately 1.5 meters from the paddles, spaced in a line parallel to the crest of propagating waves.
- Qualisys Motion Tracking: This camera system was used to measure the displacement and velocity of the spar and the float. The cameras were used to track markers that were velcroed onto the spar and buoy.
- Voice Coil: To measure the voltage being pushed by the WEC, the DAQ circuit outlined in Section 4.2.2 was used to connect the voice coil to dspace and obtain voltage readings.

4.3.2 Mooring

Following a meeting with Dr. Parker, our team designed a strategy for the mooring system, opting to integrate four connection points onto the buoy. To achieve this, we acted on the construction of two sturdy concrete buckets using Quikrete, each weighing 20 lbs. Within each bucket, we embedded an eye bolt, facilitating effortless tie-off procedures. Placing these concrete buckets strategically on the floor of the wave tank provided us with the flexibility to maneuver them as needed and ensured adjustments during testing phases. Subsequently, we affixed two ropes at the base of the spar, anchoring them securely to the concrete buckets. Utilizing a practical clamp design similar to the square U-bolt commonly observed on boat trailers, we attached two additional ropes halfway up the spar. One end of one rope was firmly tied to the blue wall, while the other rope was secured to the cement wall using wood clamps. By employing this four-rope configuration, as illustrated in Figure 12, we crafted a triangular support structure, hopefully assuring the buoy's stability throughout the testing process. As an added safety precaution during the initial testing phase, we stationed a team member close to the ropes, ensuring prompt intervention if necessary. Figure 13 depicts the WEC moored in the tank.

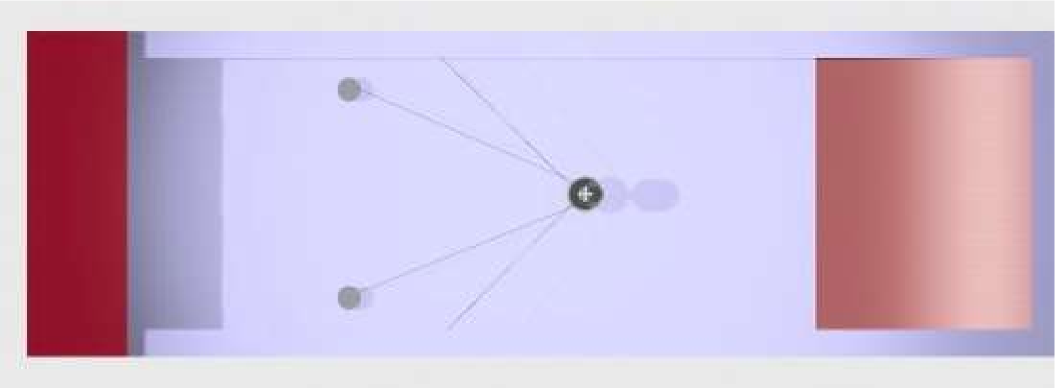


Figure 12 - Mooring Rendering

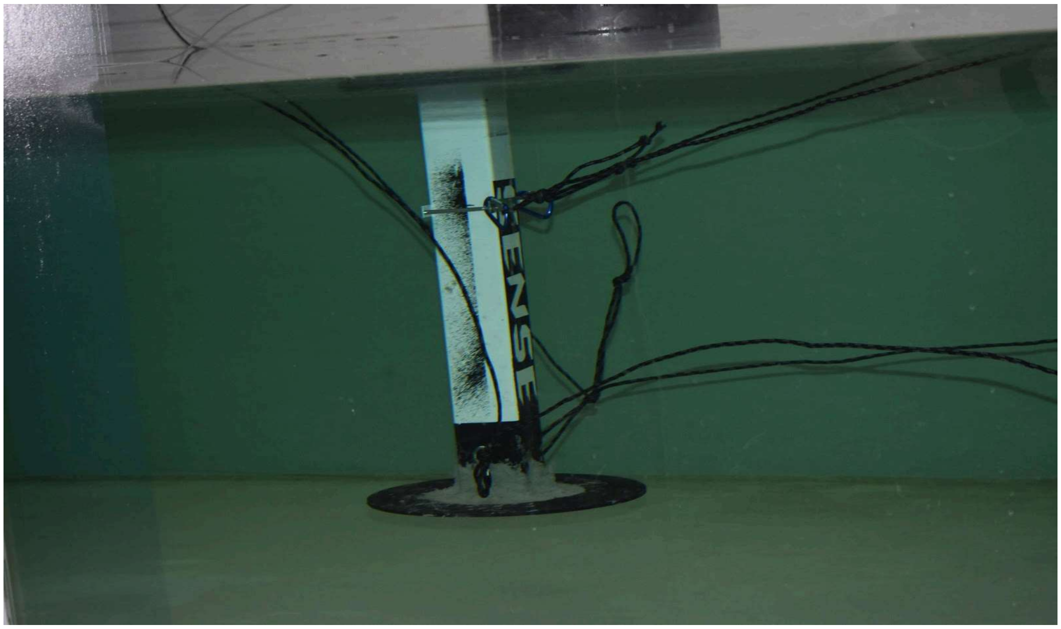


Figure 13 - Moored WEC

4.3.3 Testing Plan and Methods

To develop a testing plan that was representative of the full-scale model's expected environment, we consulted the WISPortal - an online resource managed by the Coastal and Hydraulics Laboratory that archives a wide array of wave data including periods, heights, velocities, etc - to ascertain both an appropriate location for the technical system and to obtain its associated relevant data. For a
variety of reasons, including

promising wave data, and location feasibility, the data from Station ST95501 was used. A screenshot from the WISPortal is shown in Figure 14 which outlines the approximate location. The station is located approximately 40 miles due south of Manitou Island, which is right at the tip of the Keweenaw Peninsula and floats in approximately 100m depth of water. We felt this location was most representative of the ideal locations for this technology to exist - that being depths not overly extreme, a significant enough distance offshore to justify usage, and promising wave data for energy production. All of the relevant environmental and lithologic information was obtained from the Environmental Atlas of the Great Lakes, produced by the Government of Canada and the US EPA.

Figure 14 - Approximate Location of Station ST95501. *Taken from WISPortal.*

A spreadsheet was created to sort all of the WISPortal data. An individual sheet was dedicated to each month's relevant data, and the average wave height and period of each month were obtained and graphed on Figure 15. Each of these averages was adjusted by a factor of four on the Froude Scale, to adjust for the fact that our prototype is ¼ scale of the conceptual full-scale model, thus wave heights were divided by four, and periods were divided by root four. Periods were then converted to frequencies and wave heights converted to input amplitudes, generating an official testing matrix which is illustrated in Table 1.

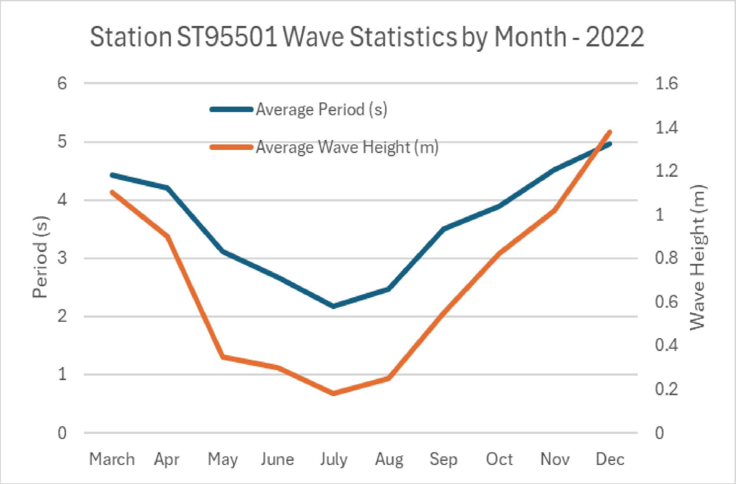
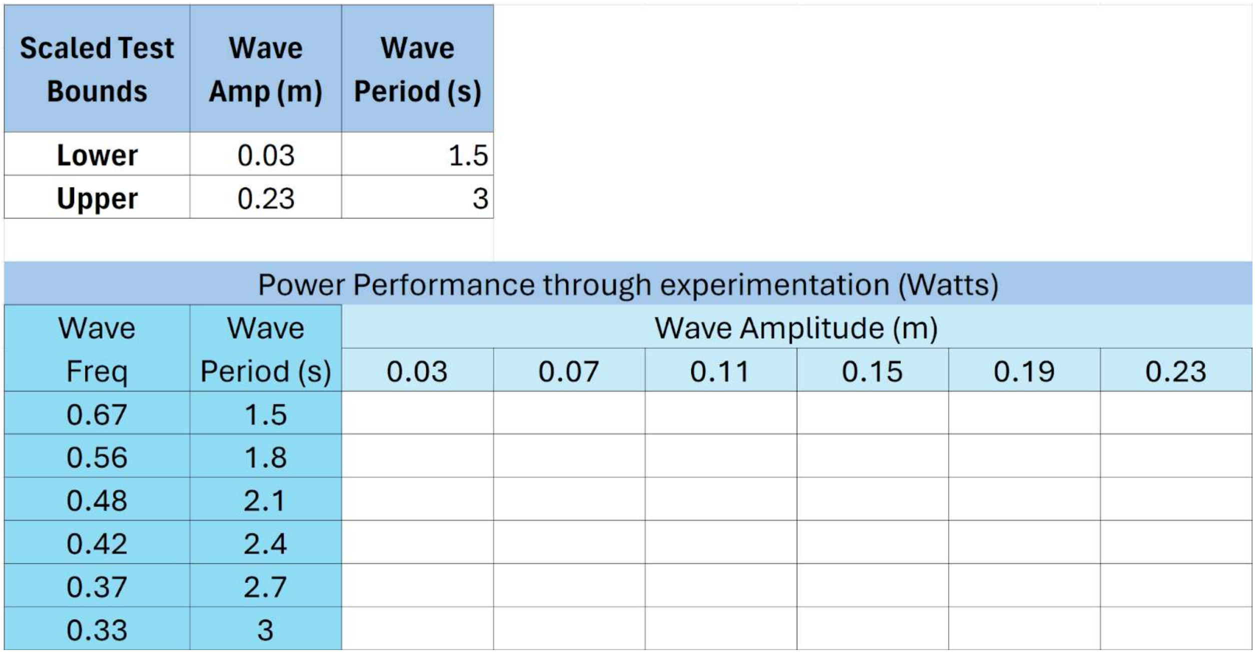


Figure 15 - Average Wave Heights and Periods (2022)

Table 6 - Official Preliminary Test Plan



Scaled Test Bounds	Wave Amp (m)	Wave Period (s)
Lower	0.03	1.5
Upper	0.23	3

Power Performance through experimentation (Watts)							
Wave Freq	Wave Period (s)	Wave Amplitude (m)					
		0.03	0.07	0.11	0.15	0.19	0.23
0.67	1.5						
0.56	1.8						
0.48	2.1						
0.42	2.4						
0.37	2.7						
0.33	3						

Once the WEC was moored as described in Section 4.3.2, the testing plan was put into place. However, once testing had begun, a few field observations were immediately identified, which are expanded in Section 2.4, Experimental Results. Namely, the test amplitude of 0.07m achieved a consistent maximum stroke of the voice coil at upper-echelon frequencies. Additionally, the higher frequencies caused a great degree of tilt at this specific amplitude. The buoy never submerged; however, it got concerningly close multiple times. The testing plan was then modified to eliminate testing amplitudes greater than 0.07m, and a new testing amplitude of 0.05m was added. Due to lower frequencies resulting in a far less impressive stroke, the lowest frequency (0.33) was also eliminated as it would have generated very little power with our prototype, and we were time-constrained. Thus, the final results outlined in Section 2.4 present a 3x4 performance matrix of amplitudes between 0.03m and 0.07m and frequencies between 0.33 and 0.67 waves per second, which is deviated from the procedure outlined in Table 1. The conclusions regarding these modifications, as well as those regarding the rest of the obtained performance results, are outlined in Section 2.4.

4.4 Experimental Results

The following experimental results are sorted into two categories: Power Performance and Hydrodynamic Performance.

4.4.1 Power Performance Analysis

As explained above, one of the primary measures of data acquired during testing was the voltage being pushed by the voice coil. Being that the resistor was set to six ohms and we were receiving voltage into dspace, we were able to calculate the power being generated using the equation P = V^2/R, and generate Figure 11. Figure 12 illustrates the total amount of energy generated. Both Figures 11 and 12 were generated from Test 9, where the period was 1.5s and the amplitude was 0.05m.

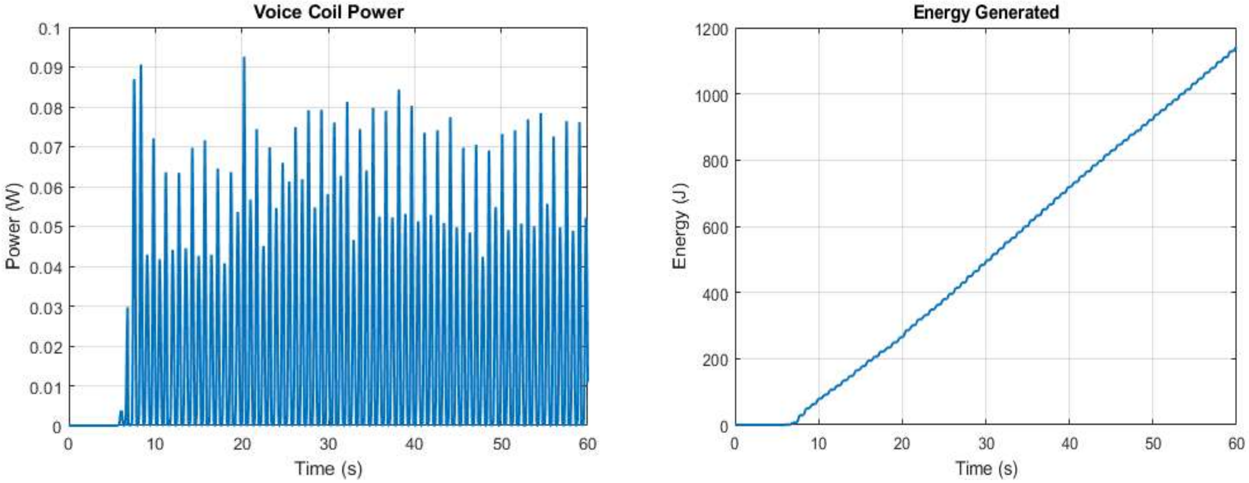


Figure 16 - Voltage Output (left) and Total Energy Generation (right). *Test 9.*

As mentioned above, Figure 9 illustrates only the power and energy generated from Test 9, the total test consisted of nine different performance iterations. The performance matrix below (Table 7) illustrates the results of these tests.

Table 7 - Prototype Power Performance Analysis

Power Performance through experimentation (mWatt)			
Wave Period (s)	Wave Amplitude (m)		
	0.03	0.05	0.07
1.5	8.04	21.2	42.87
1.8	2.9	12.14	25.75
2.1	0.84	4.8	8.02
2.4	0.06	1.84	5.53

What can be ascertained from Table 7 is that the voice coil achieved the best performance at the highest amplitude and highest frequency, which was expected. However, being that the amplitude generating the largest amount of power is an amplitude that exceeds in length the stroke of the voice coil, the system was effectively limited by the length of the motor - and the motor utilized in the WEC harbored the longest stroke length of all of the available options. This limiting factor is expanded in Section 4.4.2.

4.4.2 Hydrodynamic Performance Analysis

In addition to measuring voltage output from the voice coil, we also used Qualysis Motion Tracking to determine the WEC's hydrodynamic behavior while subjected to wave action. Markers were placed on the buoy and the spar and recognized by the camera system. Being that Qualysis was synchronized with dspace and the wave gauges, the displacement data was associated with the same time-step and tank input as each respective voltage reading. Figure 17 (top) illustrates the displacement of each body with respect to each other as a function of time, while Figure 17 (bottom) illustrates the system's overall relative displacement as a function of time, thus representing the voice coil's stroke. Similar to the results illustrated in Figure 16, Figure 17 is associated with Test 9. As can be seen, the spar displaced vertically more so than the buoy. While we still achieved consistent motor stroke, this was not the design objective. It is important to note that point absorbers are designed to be moored from the bottom, however, and this was impossible in the MTU Wave Tank given our design dimensions and the tank's geometry.

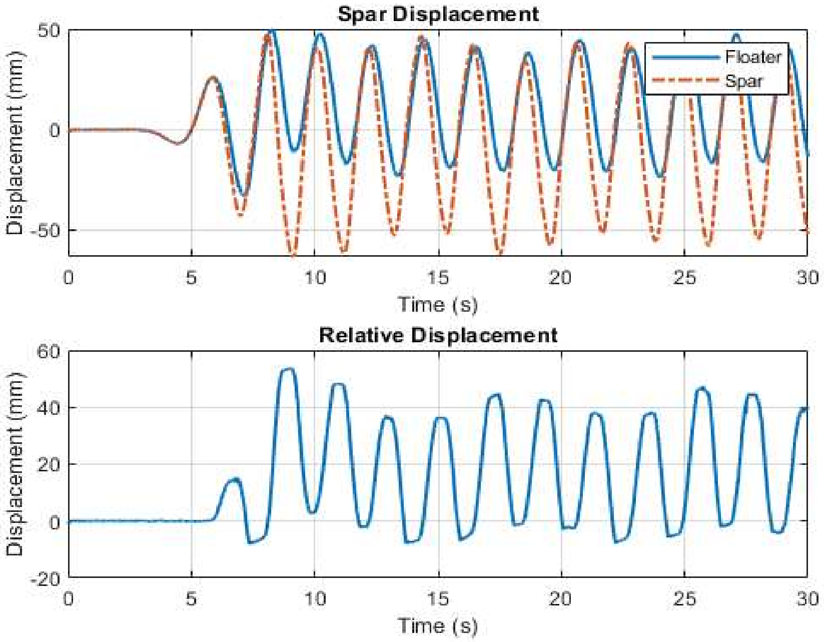


Figure 17 - Hydrodynamic Performance Results. *Test 9.*

It can also be seen that the relative displacement of the voice coil nears 60 mm, equating to around 2.25" whereas the maximum prototype stroke was around 2.65". Thus, in test 9 we did not achieve a full stroke, but came close. At or near a full heave, the voice coil would stiffen as the moment arm on the heave rod increased. This is likely the root cause of not achieving a full heave despite the system's hydrodynamic displacement exceeding the stroke length. This is an additional design adjustment to be addressed in future MECC work.

5.0 Conclusion and Future Work

In all, the 2024 MECC project at MTU presented obstacles at nearly every step of the project, however each individual fulfilled various roles to see the project through effectively. Many of these roles were outside the domain of the team member’s technical expertise, thus the project not only challenged us in our current education, but forced each team member to broaden their skillset beyond what their curriculum instructs. The business plan aimed to be as holistic as possible, identifying local end users, varied market demand in multiple sectors, a system ownership structure most realistic for today’s market, financing opportunities, and full logistical, legal, and environmental compliance. The technical system aimed to be versatile and accessible, while meeting the power requirements of charging AUVs offshore in the Great Lakes, integrating technical capability with the financial capability in the business plan. The prototype underwent several fabrication challenges, namely relating to waterproofing, alignment, and relative buoyancy, as well as designing a capable DAQ circuit to allow us to read the voltage being pushed by the voice coil motor.

The project was a challenging but satisfying and rewarding experience. As a team, we learned several lessons along the way that are not necessarily technical in nature. Inter-team communication is absolutely critical. Assuming two team members interpret a given issue the same way will only prolong the issue - instead, each understanding must be fully communicated before moving forward. Additionally, we learned it is critical to ask each other for help. Many of us, as engineers, feel bad burdening others with the request for assistance. However, the resonating theme of our entire project this year was most definitely consistent collaboration. Seeing the team grow from just a group of students to a functional project unit was clear evidence that through effective communication and goal-driven collaboration, the most stressful and daunting challenges are often the most fun, where the most memories are made, and where team members really begin to develop trust and reliance on each other.

In the future, the MECC team aims to learn to control the voice coil, expanding on our current technical design and increasing the WEC’s versatility, survivability, and overall performance while simultaneously strengthening the feasibility of the overall technical system power delivery and hydrodynamic performance.

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