Marine Energy Collegiate Competition 2025

Business Plan, Technical Design, & Build and Test Report

Northern Arizona University

Northern Arizona University
Mechanical Engineering

---Undergraduate Students---
Aiden Lee: Team Lead, Logistics Manager
Asher Aspili: Financial Manager & Test Engineer
Elijah Woolridge: Mechanical Engineering Assistant
Haakon Pedersen: Electrical Lead Designer
Justin Patterson: Energy Engineering Assistant
Patrick Grosse: Manufacturing Engineer & CAD Engineer
Taseen Chowdhury: Programing Lead

--- Faculty ---
Carson Pete: Mechanical Engineering Advisor
Connor Gaudette: Graduate Teaching Assistant
David Willy: Capstone Section Professor
Jim Clark: Capstone Section Professor

Contact: Carson.Pete@nau.edu

Word Count: 8790

Executive summary

The WATTERJacks team at Northern Arizona University developed a new wave-powered energy system for the 2025 Marine Energy Collegiate Competition (MECC). Their interdisciplinary, student-led project addresses an urgent and daunting challenge in naval defense, environmental monitoring, and oceanographic exploration: how to supply stable and sustainable electrical power to underwater systems within remote, high-pressure, and inaccessibly situated marine environments. Their device is a semi-autonomous, modular energy harvesting system that transforms the vertical motion of waves into electricity. Their system is designed for long-term, off-grid subsea deployment and minimizes reliance on conventional power sources such as diesel generators, throwaway batteries, and undersea cabling.

The system's focal point is a yo-yo-shaped surface buoy that converts the kinetic energy of wave-stimulated vertical motion into one-way rotation. This mechanical movement powers a geared generator to provide electricity to power storage in lithium-ion battery modules housed within pressure-resistant enclosures. The unit is configured for modularity for adaptable power setups on a scalable basis, based on mission duration and power requirements. The product is purpose-built for ocean use, with corrosion-resistant elements, sealed electronics, and thermal management systems designed to preserve operating efficiency in variable ocean conditions. Focus was also given to stealth and low-profile operations to facilitate covert missions, particularly in defense-oriented situations where device detectability needs to be minimized.

The WATTERJacks identified four principal marketplace applications for their system: 1) powering underwater communication nodes for military and surveillance missions; 2) powering autonomous underwater vehicles (AUVs) and sensor networks; 3) powering oceanographic monitoring for climate and ecological research; and 4) powering persistent, remote environmental sensing platforms. Industry and government stakeholders, such as Kenautics, the Naval Research Laboratory, and the Salt River Project, in interviews and technical discussions, validated these use cases and helped shape some of the primary design features. Stakeholder input emphasized reliability, modularity, field serviceability, and surface-tether-free and power-supply-cable-free aspects as essential design features.

Economic modeling demonstrated that the system would be a cost-saving option compared to conventional power delivery methods. A complete deployment is projected to achieve break-even in around five years, driven by reductions in logistical support needs, fuel transport costs, and maintenance cycles. The system is beautiful for long-duration deployments when periodic servicing is not possible. Technical validation of the concept included simulation modeling with real NOAA buoy wave data, subsystem testing on bench-top generator configurations, and system-level tests in university laboratory environments. While full open-ocean tests were not within the competition timeline, scaled-test results closely mirrored expected performance criteria, reinforcing confidence that the design scales and is robust.

The team's prototype was able to capture wave motion energy, store it in modular batteries, and operate reliably in simulated marine environments. The device had significant functional specifications, including one-way gear engagement, high-energy storage efficiency, and watertight electronics integration. Subsystem integration proved low power losses and high consistencies on multiple test runs. The consistency facilitates future system efficiency improvements, especially in the gearbox and power electronics.

In the future, the WATTERJacks team will continue to optimize the mechanical efficiency of the geartrain, improve the energy management and battery balancing systems, and upsize the physical structure of the buoy for greater energy capture. Controlled open-water testing will give further insight into the device's performance in real-world conditions, specifically its hydrodynamic performance and energy generation under different sea states. Further cooperation with marine engineers and naval researchers will assist in preparing the system for certification and operational deployment.

Overall, the NAU WATTERJacks team successfully designed and tested an innovative wave energy system tailored for isolated underwater use. Their work supports the strategic goals of increasing marine renewable energy use, improving the sustainability of ocean facilities, and improving national defense, autonomous systems, and climate research capabilities. The project shows the ability of student teams to contribute significantly to real engineering challenges and lay the groundwork for future innovation in the marine energy sector.

1 Business Plan Challenge

1.1 Concept Overview

Our project resolves a significant issue with the naval defense sector: power delivery that is secure, renewable, and long duration for deep-sea communications networks. We're proposing a wave-driven, semi-autonomously maintained energy platform intended to provide a consistent power source to underwater communications nodes without relying on periodic servicing, costly cabling, or surface-based infrastructure that would compromise operations. This technology supports defense activities, scientific discovery, and remote sensing applications where power integrity, operating duration, and stealth are essential.

Our model targets to supply customized renewable energy systems to government, military, and research customers requiring non-stop, independent offshore communications solutions. As it was first promoted for defense, the system can scale up to larger markets such as oceanographic research and commercial offshore communication networks. Sales would be generated from system sales, maintenance and support services contracts, and licensing of the proprietary power take-off (PTO) system of the platform.

Value proposition extends to financial, social, and environmental gains. Financially, the system saves money by reducing the cost of routine, expensive maintenance journeys to remote destinations. Sociably, it adds to national security by enabling covert, ubiquitous communications infrastructure. Environmentally, it replaces fossil-fuel-based systems with clean ocean power, which cuts carbon emissions hugely and lessens ecological footprint compared to conventional diesel generators or surface buoys.

Our 2025 design takes advantage of overall marine energy conversion concepts worked out in earlier years by our university teams. Previous efforts were centered on surface-mounted wave energy converters (WECs) for generalized renewable power generation. Having learned from those designs, this year we moved toward a deep-sea, low-visibility implementation introducing a new PTO system specific for underwater long-term deployment. This paradigm change is grounded on the principles of energy capture efficiency, system lifetime, and military and deep-research stakeholder-specific operational needs.

Based on the competition and prior work, we knew that prior designs were not optimized to the harsher conditions of deep ocean environments where servicing is rare and extreme pressure is the norm. Therefore, we developed a hybrid mechanical-electrical PTO, enhanced modular buoyancy control, and ruggedized system architecture that is capable of long submerged missions. These address directly vulnerabilities in prior work and include user feedback regarding stealth and performance requirements.

Finally, our concept stimulates sea energy of the future through presenting a durable, sustainable power alternative for offshore equipment critical to life. It transports wave energy technology out of typical green power manufacturing into special high-value applications for defense and communication.

1.2 Relevant Stakeholders

Our primary end customer is Kenautics, which is a company dedicated to developing persistent underwater communications networks. Our marine power system is specifically designed to support their mission by providing a dependable, renewable energy source for deep-sea communications nodes, reducing missions to replace batteries and minimizing operational exposure in hostile or remote locations.

Other than Kenautics, we have also found some secondary stakeholders impacting our technology's broader application and societal importance:

- Northern Arizona University (NAU)
- NAU Energy Club
- United States Department of Energy (DOE)

To better understand the requirements and operational constraints of our target users, we conduct organized stakeholder engagement. This involved conducting interviews with industry practitioners, speaking to academic advisors and peers, and reviewing DOE documentation on marine energy system integration, environmental factors, and equitable distribution of technology. Our engagement in doing so was to choose up technical as well as non-technical details to input the system design process, including energy delivery requirements, system modularity, reduction of biofouling, and Levelized Cost of Energy (LCOE) in consideration.

1.2.1 Interview Summaries and Key Findings with Kenautics (Alan Kenny and John Roscoe-Hudson)

Kenautics, San Diego, California, designs high-technology underwater communication systems for divers, vehicles, and subsea engineers. Their current systems are rechargeable batteries that must be replaced periodically, leading to downtime, environmental exposure, and logistical costs. From our discussions, we saw a clear opportunity to marry our wave energy platform to deliver in situ charging, thereby extending maintenance cycles and mission duration.

The key lessons learned from the interview were:

- System Modularity: Designs must be capable of supporting flexible deployment configurations to accommodate different operating environments and device types.

- Prevention of Biofouling and Corrosion: Effective choice of anti-fouling materials and coatings is required to ensure long-term submerged operations without degradation and maintaining efficiency.
- Testing and Validation: Recommendations were progressive validation steps that included starting with benchtop trials, followed by controlled aquatic environment testing, finally ending in full-scale ocean trials.

1.2.2 Interview Summaries and Key Findings with Salt River Project (Tom Acker)

Salt River Project, an Arizona-based giant utility company committed to procuring 100% renewable energy by 2035, was highlighted by Tom Acker on the pivotal role that energy storage systems play in the integration of renewables, particularly in hybridized storage methods well-positioned to manage variable renewable energy outputs.

Key takeaways from the interview were:

- Energy Storage Solutions: Aligning storage technologies (e.g., lithium-ion, flow battery, or supercapacitor) to the temporal profile of maritime energy production is essential to system viability.
- Engineering Economics: Financial modeling insights highlighted reducing the system's LCOE to be competitive with traditional and new renewable solutions.
- Financial Viability Models: Equity-to-debt ratios were discussed and how early-stage technology startups can model project economics to obtain financing and partners.

1.2.3 Interview Summaries and Key Findings with Naval Research Laboratory (Cheryl Blain)

Cheryl Blain, with the Naval Research Laboratory in Virginia, gave insight into numerical modeling of deep ocean and coastal dynamics and underwater system design for unmanned vehicles like the Manta Ray AUV. Her observations gave insights into top design drivers for missioning in extreme depth environments with limited access.

Among the top findings from the interview were:

- Durability and Stealth: System design must reduce hydrodynamic drag, suppress acoustic signatures, and resist corrosion fatigue and pressure-induced material degradation.
- Simulation and Iterative Testing: Python, MATLAB, and Fortran simulation software must be used to model full ocean systems before prototyping, validating performance under a range of environmental conditions.
- Lifecycle Engineering: Autonomous systems must be designed for minimum-touch maintenance cycles, balancing deploy ability and durability to support long-duration missions without external servicing.

1.3 Market Opportunity

The global underwater communications market is expected to experience phenomenal growth by 2030, driven in large part by increasing demand from military, scientific research, and offshore industrial uses (full source citation to follow). In the face of these promising market opportunities, there is a vital technology gap: the lack of reliable, long-endurance, and renewable power supply systems for underwater communication systems.

Most underwater communication systems today employ two principal power solutions: battery systems and shore-cabled systems. Battery systems must be replaced or recovered at regular intervals, which incurs high maintenance costs, logistical complexity, and operational downtime. Shore-cabled systems, while reliable, are geographically confined to coastal environments and require massive infrastructure investments, rendering them unsuitable for application in deep-sea operations.

Our system directly addresses this fundamental market shortage by offering a renewable-energy-powered, semi-autonomous energy platform that facilitates long-endurance underwater communications with no need for routine maintenance or surface infrastructure. Our innovation offers a scalable, sustainable solution that is comparable to the expected trajectory of growth for the global undersea communication market.

We have identified three primary market sectors where our technology possesses distinctive advantages: naval and defense communications, sonar and video imaging networks, and hybrid diver-ROV/AUV systems. For naval and defense applications, the need for secure, persistent, and stealth-capable underwater communications is critical. Our system provides the resilience and autonomy necessary for such applications. For sonar and video imaging networks, which facilitate underwater mapping, surveillance, and environmental monitoring, our technology supports uninterrupted continuous operation. Finally, hybrid diver-ROV/AUV systems benefit from decentralized energy access, with longer mission capability and reduced operational risk.

Through direct engagement with stakeholders such as Kenautics, Salt River Project (SRP), and the Naval Research Laboratory (NRL), we validated these market needs and confirmed the operational, financial, and environmental priorities our system addresses. Stakeholder feedback emphasized minimizing operational downtime, maximizing stealth and autonomy, and facilitating renewable energy transitions.

Our pricing strategy first seeks lifecycle cost parity with conventional battery systems. By leveraging significantly lower maintenance costs, with servicing intervals estimated at one to two years, and by minimizing retrieval missions, our system offers a compelling economic case. Further, anticipated government incentives for the decarbonization of defense technologies are expected to boost return on investment (ROI) for early adopters. Financial models factor in both current and pending tax credits and grants for stimulating the adoption of clean technologies in priority sectors.

Competition in this market includes conventional battery suppliers, shore-cabled communications systems, and emerging subsea renewable projects. Conventional battery systems are faced with inherent limitations in operational life and maintenance logistics. Shore-cabled systems have geographical limitations and are subject to surface-threat vulnerability. Emerging subsea renewable projects are generally challenged by high system complexity and cost feasibility concerns. Whereas our platform offers a low-profile, autonomous, and scalable solution purpose-built for deep-sea communication networks, with stakeholder validation and system-level lifecycle optimization.

By creating an addressable market gap with a validated, stakeholder-driven solution, our marine energy system can meet growing needs in underwater communication markets while advancing sustainability, operational efficiency, and mission autonomy.

1.4 Development and Operations

Our system deployment and concept development strategy reflect a prudent balancing of the demands of engineering practicality, environmental responsibility, and regulatory accountability.

The system is manufactured using corrosion-resistant materials specifically designed to be durable in extended underwater conditions. Modularity facilitates easier fabrication and field assembly, with simple deployment in different marine environments. The anchor methods were selected to cause minimal seabed disturbance, and the design, consequently, should be to ecological conservation specifications. All these choices are incorporated into the initial models as shown under the technical design section.

We plan to leverage strategic partnerships—such as with Kenautics—to integrate advanced communications systems with our marine power platform (Kenautics, 2025). Such partnerships enhance functionality, reduce development risk, and improve scalability. Major manufacturing and deployment stage risks include delayed procurement of materials, component degradation in marine conditions, and logistical challenges specific to sites. We recommend overcoming such risks through phased prototyping, use of standard components, and early-stage coordination with stakeholders.

Significant technical issues include the supply of reliable data transmission in distant ocean regions and operability in bad weather and sea conditions. Social, regulatory, and environmental concerns are being proactively tackled by maintaining regular contact with maritime and environmental authorities to ensure compliance with marine protection policies. At the social level, this system facilitates renewable energy job creation development and can improve energy access for remote ocean operations.

Autonomy is afforded great importance by the operations and maintenance plan to limit the need for frequent human oversight. Automatic checks and embedded diagnostics make maintenance plans flexible and less demanding than their predecessors. Our marine energy system compares favorably with cable-dependent or diesel-powered systems in having lower operating expenses and logistic needs over its lifetime.

1.5 Financial and Benefits Analysis

Based on a cost analysis, each unit has an estimated production cost of approximately $12,077. This cost-effective solution of device costing around $676 dollars in manufacturing, significantly undercuts existing technologies, offering substantial savings compared to battery-powered or cabled systems. The expense covers hardware procurement (assumed deployment 15 devices × $676 each) and a one-time boat deployment/docking charge of $975 ($800 docking and a 7-mile 25per gallon deployment). Annual operating expenses total $960 for the entire fleet—$80 in maintenance work per device plus 12 labor-hours of leak-inspection and routine servicing. With a conservative discount rate of 7 %, these costs establish the baseline against which project cash flows are assessed. Our detailed financial model accounts for materials, manufacturing, assembly, and deployment logistics, as well as minimal operational and maintenance expenses.

On the income side due to information protected by a Non-Disclosure Agreements with our potential end user, the team assumed that each buoy generates $1,000 in service revenue by supporting ten days of autonomous-vehicle (AUV) operations at $100 per day, yielding a fleet-level inflow of $15,000 per year. After deducting annual Operations and Maintenance, net cash inflow is $2,923 per year, allowing the project to recover its initial investment in roughly five years. The discounted cash-flow analysis results in an NPV of -$86—effectively breakeven at the chosen 7 % hurdle—and an internal rate of return of ≈ 7 %, confirming that the venture meets, but does not materially exceed, the target cost of capital. These figures suggest the pilot is financially viable in its current scope, yet any upside in utilization days, day-rate pricing, or O&M efficiencies would materially improve the project's economic attractiveness.

Operational and Maintenance (O&M) considerations include costs for periodic autonomous drone inspections, minor repairs, boat logistics, and minimal electrical maintenance per device. These cost factors are significantly lower compared to conventional alternatives, creating an attractive return on investment for stakeholders.

Economically, the low initial capital expenditure combined with minimal O&M costs ensures a rapid payback period, typically within one operational year. Additionally, utilizing renewable marine energy aligns with broader government and military sustainability goals, positioning the technology for potential governmental incentives and grants.

Table 1: Expenses and Initial Cost

Description (Expenses)	Amount
Product Cost Device (Manufacturing)	$676
Maintenance Cost	$80.00
Number of Units (Deployed)	15
Maintenance Hr/Yr	12
Deployment Cost	$975.00
Annual Maintenance Cost	$960.00
Total Production Cost	$12,077

Table 2: Expected Revenues Based on End User

Description (Revenue/Income)	Amount
Device Assembly Units	15
Product Use Cost	$100.00
Days of Deployment	10
Total Revenue	$1,000.00
Total Revenue Per Unit Per Year	15000

Table 3: Cash Flow and Net Present Value Analysis

Years	CF	NPV
0	($12,077)	($12,077)

1	$2,923	($8,733.76)
2	$2,923	($6,347.68)
3	$2,923	($4,117.70)
4	$2,923	($2,033.61)
5	$2,923	($85.86)
NPV		($85.86)
IRR		7%

In conclusion, our marine-powered underwater communication energy system offers strategic, economic, and environmental benefits, ideally suited for deployment in sensitive naval and research applications. It addresses current market gaps with superior reliability, cost efficiency, and environmental sustainability, securing a competitive position within the rapidly expanding underwater communications market.

2 Technical Design Challenge

2.1 Introduction and Background

Marine power forms one of the most substantial green innovation prospects in the Blue Economy. Driven by ocean conditions as a clean and sustainable source of power, the sector can provide renewable power options for distant offshore operations where standard power grids could be unviable or out of reach. Through the translation of mechanical power from ocean waves, researchers can create devices capable of powering sea industries, underwater exploration, and national security operations with minimal disruptions to the marine environment.

The 2025 Marine Energy Collegiate Competition (MECC) invites student groups to develop energy systems powered by marine energy at least 51% with solar or wind resources as backup for hybrid devices. Technical feasibility, affordability, and environmental consciousness are encouraged throughout the competition to develop a device that can potentially operate under extreme and volatile ocean conditions.

Our team, WATTERJacks, created a wave-powered charging station for underwater navigation and reconnaissance systems. These systems, including sensors, navigation, and automated underwater vehicles (AUVs), become more vital to offshore operations, defense, and marine science. Presently, these devices function with battery replacement or surfacing to recharge, which prevents deployment time and increases operation costs. Our approach is a light, modular power system that harnesses wave motion to generate electricity so that rechargeable in-situ underwater systems can sustain themselves for extended periods.

Our design incorporated technical research, stakeholder involvement, simulation modeling, and prototyping. Deriving from real-world practical engineering needs, we created a vertically actuated buoy system—like a yo-yo system—converting wave-induced vertical motion to rotational energy. This is stored in onboard batteries and relayed to underwater devices through a docking interface. Simplicity of durability, scalability, and integration were fundamental tenets while developing the system.

2.2 Market Evaluation and End User Research

Our target industry is independent subsea electronics such as AUVs, data relays, water sensors, and navigation systems that require reliable off-grid power sources. This equipment is crucial in long-term ocean monitoring, open ocean exploration, and defense operations. Among the major issues with such sectors is having devices to utilize for battery replacement, which reveals the cost of missions and risk, especially where it is situated in distant or hostile terrain.

To validate our direction of design, we interviewed industry and academic experts. Through expert interviews, we obtained information on actual problems and design problems of energy systems run in marine environments.

Kenautics, a manufacturer of underwater navigation and communication devices, became our biggest end user. Their gear is used by the military and later in development, research diving equipment. As per Kenautics management - Alan Kenny and John Roscoe-Hudson, in actuality - the current operations are afflicted with a low battery life for the extended time necessary for divers to use their flagship product, which requires frequent retrievals to halt missions and reduce efficiency in operations. Based on these needs, we have developed a recharging system compatible with their systems.

Kenautics made significant contributions in the areas of environmental resilience, mechanical assembly, and deployment of operations. They demanded the use of resilient, modular parts that can function without human intervention for extended periods. They offered techniques to resist water leaking at higher water pressure through coatings, material choice and pressure/vacuum testing, and they emphasized the advantage of scalable test protocols to maximize performance before field deployment.

We also interviewed Tom Acker of the Arizona Salt River Project (SRP), who shared with us information regarding energy storage and power management. His experience in renewable integration and energy economics helped us determine the feasibility of onboard lithium-ion storage to buffer power variability with varying wave conditions. His comments guided our energy buffering strategy and system resilience.

Cheryl Blain of the Naval Research Laboratory (NRL) gave her experience with numerical modeling and operations in deep-sea environments. She recommended modeling subsurface salinity, pressure conditions, and density gradients to enhance our electrical and mechanical subsystems. Her comments again emphasized the importance of simulation-based testing before tank and field testing and brought our attention toward modular redundancy.

2.3 Design Objectives and Concept Overview

Our project aim is to design a marine power system that captures and stores energy from wave motion to automatically charge modular batteries underwater. The system must be robust, compact, and adaptable to meet different deployment conditions, from shallow coastal waters to deep-sea platforms.

The system must be efficient across different sea states and easy to scale or reconfigure based on the user's need.

Our design, pictured in Figure 1, is a buoy shaft drum that bobs at the end of an underwater tether. When waves passing by make it go up and down, mechanical motion is created in the tether (see Figure 3). This is converted to rotation by a center shaft driving a planetary set of gears (see Figure 2). One-way clutches supply smooth, one-way motion regardless of the direction waves approach. It is the ideal setup for driving a generator that produces direct current (DC) electricity. An internal assembly can be seen in Figure 2.

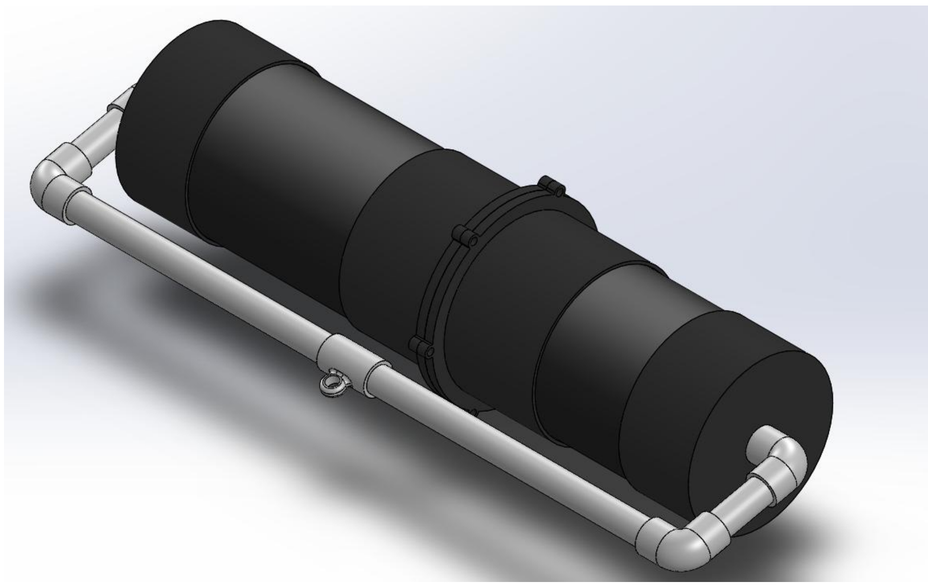

Figure 1: CAD Illustration of Yo-Yo-Type Horizontal Buoy Design

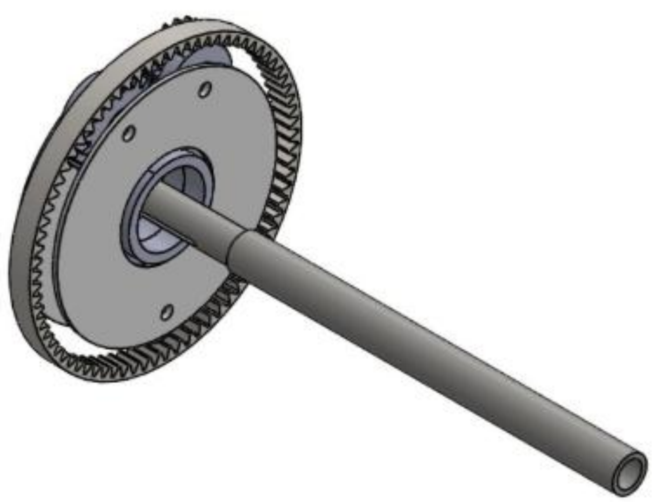

Figure 2: CAD Render of Internal Gear Assembly

Wave motion power is stored in modular lithium-ion battery packs that are connected to the buoy. An energy management system based on a microcontroller regulates charge cycles, temperature, and voltage to ensure battery safety and optimal energy transfer. Future iterations will include a docking station that is compatible with Kenautics' gear and possible other submersible systems. The interface uses magnetic or keyed connectors for secure underwater power transfer and includes diagnostics for monitoring system performance.

One of the primary benefits of the design is that it is extremely modular. The size and configuration of the buoy, tether, and gearbox can vary in various applications without alteration to the mechanism itself. This capability accommodates well to deployment under nearly any conditions, augmenting the overall flexibility of the device for use in research and commercial applications.

2.4 Legacy Design Review

This is our institution's first year of competing in the Marine Energy Collegiate Competition, so our design process was constructed without an existing predecessor institutional model to adapt or build from. Instead of a legacy model, our group researched more recent designs such as CorPower Ocean’s rack and pinion styled marine energy machines that capture wave motion and convert it into mechanical power. These devices, although satisfactory functionally, were marred by numerous issues like mechanical over-complexity, friction losses, and difficulty in sealing and waterproofing. These problems prompted us to look for a simpler, more durable design exploiting rotational energy harvesting with a smaller number of moving components. Our design is centered on modularity, ruggedness, and maintainability as per stakeholder feedback and the marine environment's limitations.

To combat these problems, we developed a yo-yo-style horizontal system. In this configuration, mechanical motion is simpler, with more efficient and smoother energy transmission. Central drum design also allows for easier installation of internal hardware in a watertight enclosure. With fewer hardware components and a linear motion path, the new system is stronger and simpler to maintain.

We also parametrically re-modeled our CAD files to expedite design iterations. It is now possible to make quick modifications to dimensions, tolerances, or component fit, enabling us to respond to stakeholder comments effectively. The enclosure design was modified to ensure IP68 compliance for underwater deployment, including seal interfaces and shock-absorbing mounts to ensure internal components are shielded from damage during long-term exposure.

2.5 System Design Description

The system consists of four integrated subsystems: surface buoy, mechanical conversion chamber, electrical storage module, and tether straightener.

The buoy consists of composite pours material to provide positive buoyancy. It is constructed to produce maximum vertical displacement and minimum hydrodynamic drag to provide repeatable motion under various wave conditions. The buoy is secured to the tether by a reinforced eyelet and swivel assembly to prevent tangling and wear.

Figure 3: Small Scale Buoy & Tether Design

The tie is supplied to the mechanical convertor device—a drum secured in a sealed housing with a planetary gear set. The gearing adds speed of rotation at the cost of torque so that the drive can be effective for the axial flux generator. The one-way bearings ensure stabilization of motion and offer direction consistency.

DC power is conditioned by a charge controller and fed to a lithium-ion battery bank. Batteries are available in thermally controlled, replaceable modules, vibration- and moisture-resistant. State-of-charge, temperature, and energy flow are monitored by onboard diagnostics fault or anomaly detection systems.

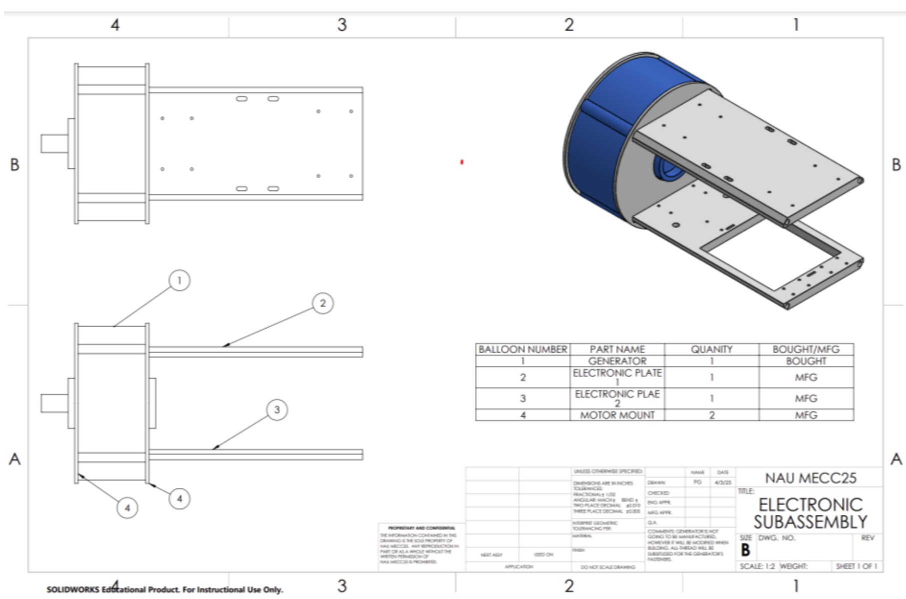

Figure 4: Internal energy storage and management layout

In future iterations, the docking interface will be created to dock underwater equipment in passive or active guidance mode. It has physical locking guides, water-sealing connectors, and wireless communication as an optional method of data transfer. The configuration provides AUVs or diver-assisted systems with automatic recharging capability, ensuring mission continuity without manual recovery.

2.6 Performance and Efficiency Analysis

To evaluate the potential of the device to produce power, a performance simulation was conducted with historical wave records from NOAA buoys from the Pacific and Gulf coasts. MATLAB routines were used to process the time-series wave period and height data to allow the estimation of energy in vertical displacement under different season conditions, as shown in Figure 5. Potential energy was next translated to mechanical input energy in the buoy interface and applied to simulate rotational output on the generator shaft.

We approximated subsystem efficiencies for both conversion processes. Generator efficiency, load, and thermal effects was approximately 85% during normal operating conditions. Battery storage and conversion efficiency, controller overhead and battery heat losses, provided another 80% round-trip efficiency. Overall system efficiency from wave energy to useful electrical output was estimated to be approximately 68%.

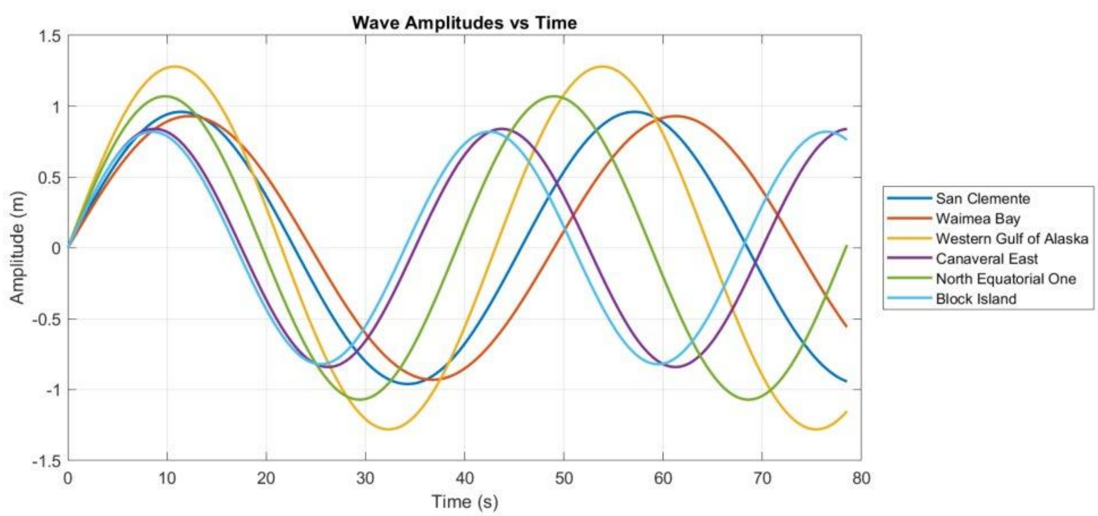

Figure 5: Theoretical Ocean conditions graph for different wave conditions

The simulated system delivers 4.8 kWh/day at sea states of medium (Amplitude ~1.0m, T ~6s), sufficient to charge an array of small underwater sensors or one large AUV per day. We also explored the feasibility of smoothing power using a capacitor bank, but onboard battery capacity for storage equals expected loads.

2.7 Mechanical Loading and Safety Analysis

For operational risk, safety multipliers of 2.5 to 3.0 were applied to critical mechanical elements. Electronic control system failsafe shutdown program triggered by internally unacceptable high temperature, overvoltage, or shock sensing. During emergency conditions, the system can shut down power generation and dump the load within 2 seconds, according to MECC competition standards. All Failure Mode and Effects Analysis (FMEA) and mitigations can be seen in Table 4 below.

Table 4: FMEA Table

Part and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Potential Causes and Mechanisms of Failure	RPN	Recommended Action
Gear Box: Mech Power	Stress/Fatigue	Does not produce enough mechanical power	Gear characteristics are not integrated well with resource mechanics, gets wet	40	Gear Analysis
Shaft: Mech Power	Stress/Fatigue	Does not produce enough mechanical power	Shaft material/selection is weak	40	Shaft Analysis
Casing: Component Protection	Stress	Snaps and internals get wet	Material selection	100	Check ipx rating and material
Generator: Power Generation	Electric Short	No power generation	Too much power generated/gets wet	40	casing and power gen analysis
MicroController: Power Generation	Electric Short	Can't control the device (power on or off)	too much current/ gets wet	80	casing and power gen analysis
ChargeController: System Control	Electric Short	No power regulation	too much current/ gets wet	60	casing and power gen analysis
SemiConductors: Power Regulation	Electric Short	Electrical flow isn't regulated through the system	too much current/ gets wet	60	casing and power gen analysis

2.8 Engineering Drawings and Diagram

A full set of engineering drawings was created to aid prototyping and final production. Provided with the SolidWorks files are dimensioned part drawings, tolerance stacks, and assembly instructions for each of the major subsystems. The drawings are crafted carefully for easy production using additive and subtractive manufacturing techniques and are supplied carefully for gasket placement, PCB mounting, and cable runs (see Figure 6 for final drawing).

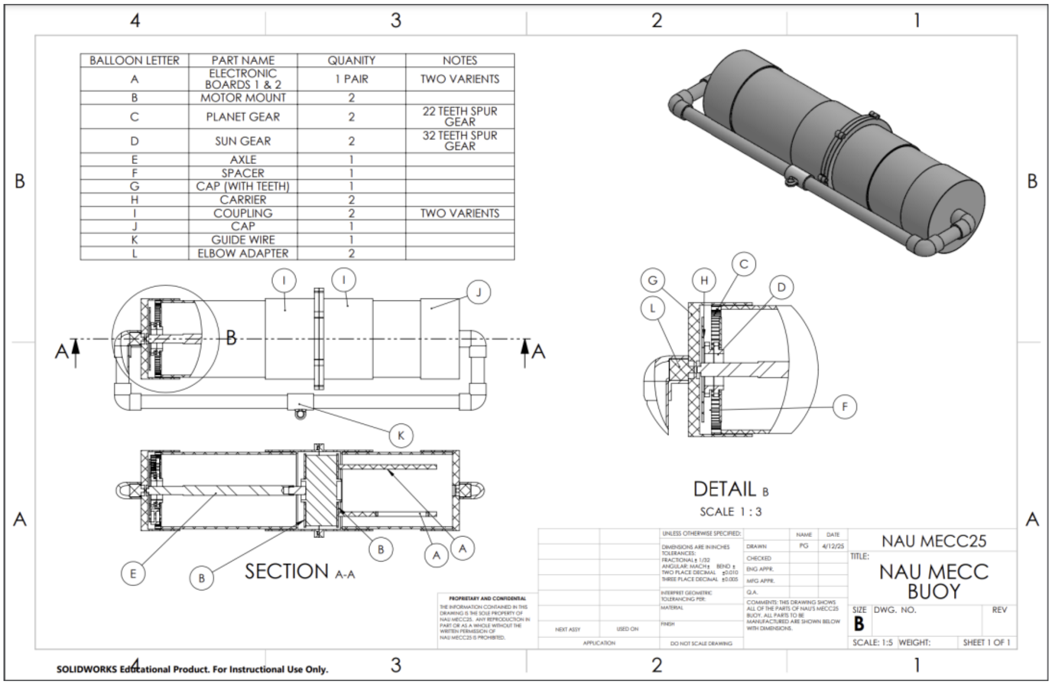

Figure 6: Final CAD Drawing of Entire Assembly

Table 5: Prototype Device Bill of Materials with Suppliers and Unit Cost Estimates

NAU MECC25 BOM (Updated 4/12/25)					
Electrical components			Mechanical Components		
Description	Quanity	Total Cost	Description	Quanity	Total Cost
12V Generator	1	$185.00	Bearings (10 pack)	2	$ 14.00
Microcontroller	2	$20.00	One Way Bearing	2	$ 12.60
Battery	1	$19.12	One Way Bearing Large	2	$ 30.00
Semiconductor	1	$39.62	O-rings(small Diameter)	1	$ 8.66
Digital Display	1	$4.90	Bearings Large	2	$ 14.00
Display Module	1	$7.78	Nuts (for all thread)(100 pack)	1	$ 2.33
Charge Controller	1	$25.99	Shaft	1	$ 28.63
DC Power Sensor	1	$9.95	All thread 12in	4	$ 5.60
AC Voltage Sensor	1	$7.30	O-rings (large Diameter)	1	$ 26.23
Accelorometer	1	$12.95	3D Printed parts	18	$ 60.00
Temperature Sensor	2	$14.95	PVC pipe (24")	2	$ 6.32
Mini Breadboard White Breadboard	1	$6.00	PVC elbow	4	$ 3.16
Misc hardware (1 pack)	1	$19.49	ABS pipe (6" diameter)	1	$ 8.97
			ABS glue	1	$ 7.87
			Machine Tap (M16-2.0)	1	$ 14.04
			ABS Spool	4	$20.00
			Caulking Sealant	1	$15.00
	sub total	$373.05		**sub total**	$ 277.41
				Final Total	$650.46

The CAD files contain an exploded view of all the internal and external components and associated fasteners and fittings. These design files will be utilized in future production at the university's prototyping lab.

2.9 Design Justification Against Market Needs

Both Kenautics, our direct end-user, and user feedback from our institution impacted our technical decisions to remain within industry needs. The company needed field serviceability, reliability, and compatibility with their modular equipment. Our design provides these by using a self-contained system that will operate without needed operator interaction for weeks, internal diagnostics, and modular external access ports.

Having the average power output gives sufficient charging capabilities with Kenautics' diver navigation system. Our energy supply system provides interrupted power supply capabilities even under conditions of low-energy waves. Being compact and light in weight facilitates transportation and use by two-man dive teams or small ROVs.

In addition, system modularity allows the system to be utilized within other industries, i.e., seafloor observatories, underwater mining sensors, and offshore aquaculture. That is what gives it greater commercial appeal within various industries.

2.10 Conclusion and Future Work

Our wave-powered charging system is a reliable, sustainable means of powering underwater equipment in remote oceanic regions. It meets stakeholder demands in modularity, long lifespan, and efficient operation, yet is scalable and affordable to the point of being universally applicable.

Future development goals include the production of a larger scale prototype with a greater gear ratio, water testing tank, and performance data acquisition under various conditions. Further integration with Kenautics devices will be sought and contacts with other interested users such as NOAA and NRL will be established. Future development includes generator architecture optimization, higher gear ratio to produce more energy in poorer conditions, and expansion of energy management system capability for multi-load operation.

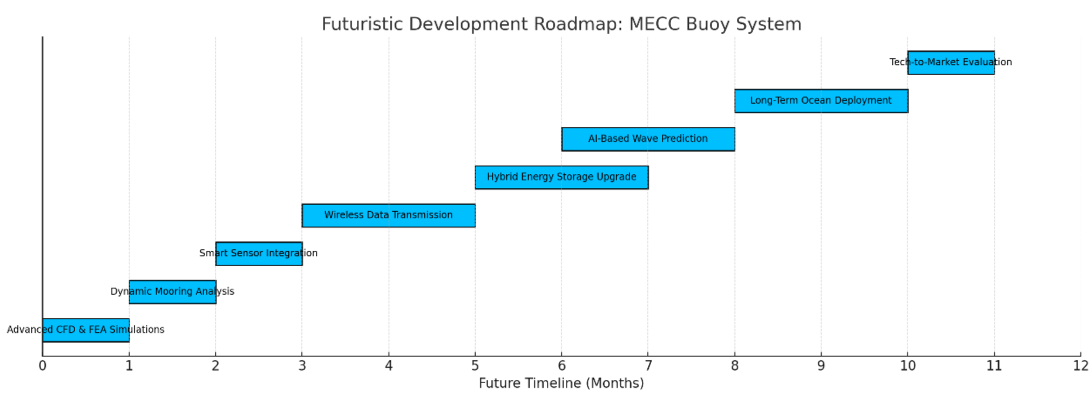

Figure 7: Development Roadmap and Future Work Schedule

From a longer-term perspective, the vision of the system is the wide-scale deployment of autonomous recharging pods as a part of a completely integrated marine power network providing low-maintenance continuous operation for the most severe subsea environments

3 Build and Test Challenge

3.1 Introduction and Objective

The prototype that we created is part of a larger system intended to take advantage of energy from oceanic waves. It serves mainly to provide constant power to subsea communication systems that cannot be reached by power lines or periodic battery replacement. We also use prototypes to test how effectively important parts - namely the energy conversion system, rotation-based power generation under dynamic conditions, and buoyancy - operate in modeled conditions that mimic real ocean waves.

Our original plan was to test the device inside a towing tank facility at Arizona State University and that is exactly what we had planned. However, in mid-January we heard that this tank would not be available when it was originally scheduled and so we collectively decided that we would independently test each component of the system. By analyzing individual components individually, we could still collect meaningful data and ensure that all of it would work together within the complete system.

Since we did not have an elite wave tank to work with, we improvised using lab facilities and equipment on campus, mostly in the College of Engineering. By accommodating what we did manage to do into the context of the tests we designed, we were still able to produce useful results by which to learn how the prototype would behave. The purpose and outcome of each test are listed in Table 6.

Table 6: Testing Objectives

Test Name	Range	Risks	Mitigations	CR#/ER#
Internal Air Pressure	1.5 atm, 2 hrs	Leaks	Sealant	ER1, CR1, CR4, CR6
Hydrophobic	No Leaks	Leaks	Same as Pressure Test	ER1, CR1, CR4, CR6
Electronics	Within limits	Corrosion, Overload	Grease, Thick Wiring	ER2, ER8
Environmental Monitoring	Stable Readings	None	N/A	CR4
Neutral Buoyancy	Positive/near-neutral	Sinking	Increase Volume	ER1, ER6,
Counterweight Adjustment	Optimized Rotation	Imbalance	Adjust Weight	ER6
Charge Time	Varied Charge Times	Inefficiency	Analyze Data	ER2, ER3, ER4

3.2 Design Process

To reach our ultimate design, we performed an iterative engineering design cycle. We first created three alternate concepts individually from each member in our team. We then as a group explained and discussed each of those ideas among ourselves. We then narrowed down the strongest ideas to critique using a decision matrix according to our customer requirements (Figure 8). This matrix helped us to compare all designs based on performance, manufacturability, cost, and how well it would fit our test limitations. Most surprisingly, the most rated design was also the one that we were most excited about because it was a whole new concept that we had not seen in our initial study.

Decision Matrix

Applications Scale 1-10

Key information	Spinning Ball w/ Under Turbine	Bobber	Time Puller	Resivour	Attenuator	Up Down Rocker	Lever mech	Spinning rod
Safe to users	3	2	6	7	8	9	7	8
Presentation type	7	7	7	4	4	6	7	8
Under budget	5	5	7	7	6	8	6	7
Non-hazardous to Marine Life	4	8	8	8	4	8	4	7
Aesthetically appealing to public	6	10	9	1	4	4	7	7
Works in different climates	7	9	9	5	7	8	7	7
Ease of manufacturing	3	7	7	3	8	8	8	8
Easily integrable into the power grid	8	8	8	10	8	9	9	8
Resistant to nature (seawater/weather/etc.)(IP rating >57)	7	6	7	6	4	7	6	8
Duration of use during 24 hour period	10	10	10	5	10	7	7	8
Possible efficiency	7	6	7	5	6	4	6	7
Testable in a lab/tank(ease of testing)	3	4	6	5	8	7	6	8
Compatible in multiple environments	4	5	8	6	6	7	7	7
Use of marine energy <51%	10	10	10	10	10	10	10	10
Safety/ability to shut off remotely	5	4	9	8	5	9	7	6
TOTAL	59.3	67.3	78.7	60.0	65.3	74.0	69.3	76.0

Figure 8: Decision Matrix

After settling on the best idea, we then set to work on how we could turn it into an operational prototype. We went through several iterations, testing out different methods of getting the rotational generator to run effectively through the motion of waves. Our biggest breakthrough was finding out how to convert motion in two directions into one output direction by means of a sprag bearing system (Figure 9). This gear configuration was the core of our energy generation system.

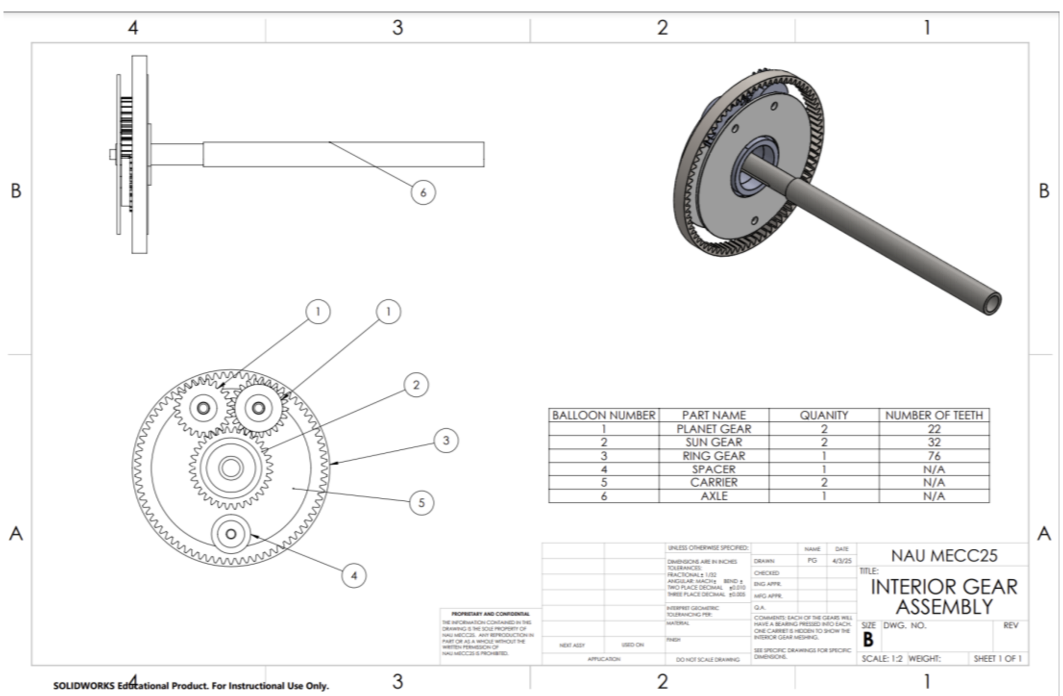

Figure 9: Internal Gearing Assembly

Once the gearing mechanism was done, we then focused on maximizing the inner composition of the device. In our last design, the generator was located at the system's center of mass, while the electrical and mechanical subsystems were on opposite sides. Besides stabilizing the buoyancy of the device, this also provided a reasonable separation of labor for the mechanical and electrical teams. By splitting the two subsystems, we enabled concurrent construction and testing processes to occur, which enhanced efficiency and minimized interdependencies. This purposeful system-level structuring was critical in enabling us to maintain project momentum as well as to attain design cohesion.

In this system, the electrical engineering team created and implemented a complete power management architecture to convert and regulate energy from the mechanical input. A mechanical force applied to the Power Take-Off (PTO) unit drives a three-phase generator, which generates alternating current. This AC power is fed to a three-phase rectifier, where the power is converted to direct current (DC). The DC power is then sent through a DC-Link, which provides intermediate energy storage and smoothing. Following the DC-Link, the converter stage regulates voltage and manages power distribution to the load and a battery system, which serves as a backup power supply and for load balancing. A microcontroller is integrated into the system for monitoring essential parameters, including DC current, DC voltage, and load voltage. It enables system diagnostics and control logic for efficient operation. The end-of-powertrain load circuit contains a resistive element and active components to simulate real-world energy consumption. The setup offers continuous and stable power supply for remote or autonomous applications, suggesting efficient coordination between power electronics, embedded systems, and energy storage. See Figure 10 for the detailed electrical system layout of the buoy.

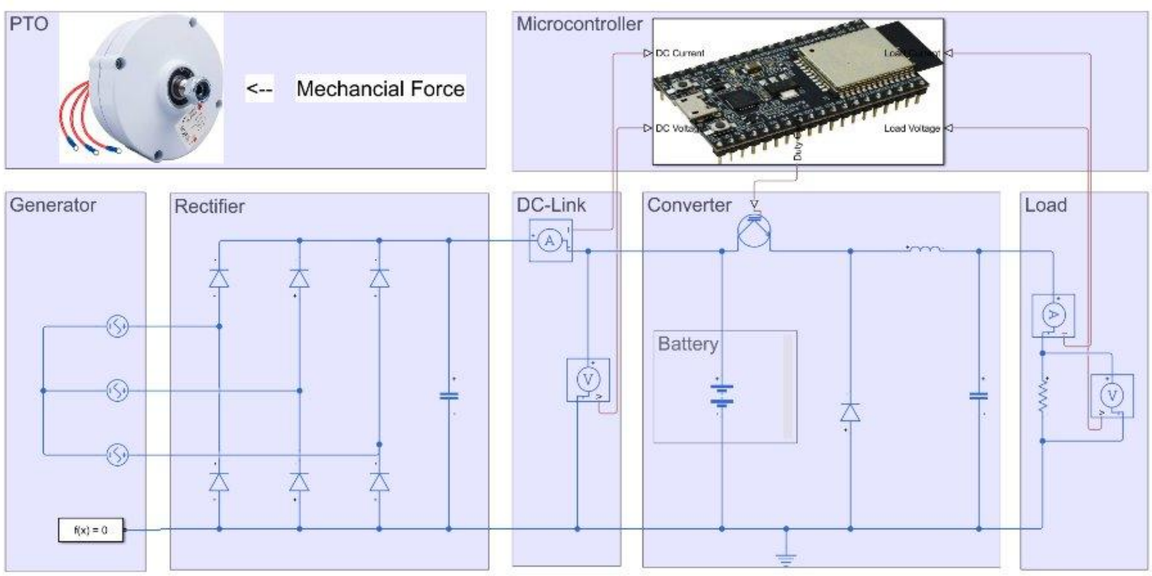

Figure 10: Simulink model of wave energy converter system electrical circuit.

3.3 Prototype Fabrication

To create our prototype, we primarily used 3D printing to print most subsystem components. We made multiple iterations to create tolerance until all the printed pieces fitted together perfectly and functioned as needed. In addition to additive manufacturing, we used traditional machining processes to machine the axle. This entailed lathe and milling work to ensure the precise dimensions required for proper fit and function. The other parts, such as the ABS tubing and the electrical components, were purchased as off-the-shelf items so that assembly could be kept to a minimum and one device's cost remained low overall, as illustrated in Figure 11.

NAU MECC25 BOM (Updated 4/12/25)					
Electrical components			Mechanical Components		
Description	Quanity	Total Cost	Description	Quanity	Total Cost
12V Generator	1	$185.00	Bearings (10 pack)	2	$ 14.00
Microcontroller	2	$20.00	One Way Bearing	2	$ 12.60
Battery	1	$19.12	One Way Bearing Large	2	$ 30.00
Semiconductor	1	$39.62	O-rings(small Diameter)	1	$ 8.66
Digital Display	1	$4.90	Bearings Large	2	$ 14.00
Display Module	1	$7.78	Nuts (for all thread)(100 pack)	1	$ 2.33
Charge Controller	1	$25.99	Shaft	1	$ 28.63
DC Power Sensor	1	$9.95	All thread 12in	4	$ 5.60
AC Voltage Sensor	1	$7.30	O-rings (large Diameter)	1	$ 26.23
Accelorometer	1	$12.95	3D Printed parts	18	$ 60.00
Temperature Sensor	2	$14.95	PVC pipe (24")	2	$ 6.32
Mini Breadboard White Breadboard	1	$6.00	PVC elbow	4	$ 3.16
Misc hardware (1 pack)	1	$19.49	ABS pipe (6" diameter)	1	$ 8.97
			ABS glue	1	$ 7.87
			Machine Tap (M16-2.0)	1	$ 14.04
			ABS Spool	4	$20.00
			Caulking Sealant	1	$15.00
	sub total	$373.05		**sub total**	$ 277.41
				Final Total	$650.46

Figure 11: Bill Of Materials

Our fabrication timeline was based on a Gantt chart prepared at the project planning phase. This timeline allowed us to track progress and set concrete deadlines for each building milestone. The gear system was the first stage of fabrication that had to be aligned and checked for tolerance. Following this confirmation, we proceeded with printing the end caps and fabrication of the electrical part enclosure. A prototype of the 3D-printed gearing is shown in Figure 12. After we completed the dimensions of the outer casing to meet buoyancy requirements, we completed machining the axle and began system-level assembly.

One of the primary issues that we encountered in fabrication was the mounting configuration of the generator. Initially, the gearing mechanism was spinning along with the outer casing, which was the opposite of what we wanted to be stationary while the driveshaft spun. To meet this, we changed out the original all thread rod that connected the generator to the electrical mounting plates for longer ones. This issue occurred as when modeling the design, it wasn't originally considered that one part of the gear assembly had to be fixed relative to the generator.

We also introduced supporting bearings surrounding the generator and increasing the coupling to allow for free rotation of the outer shell without transferring motion to the generator body. This new design provided efficient energy transfer and maximized the mechanical performance of the system.

Visual recording of significant steps of fabrication operations, component testing, and the final assembly stage is shown through Figures 12–16.

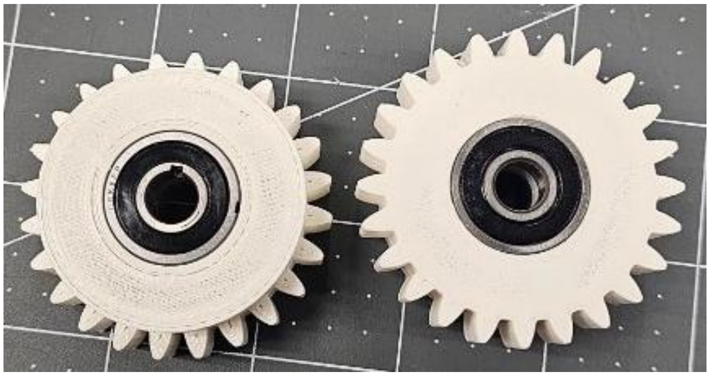

Figure 12: 3D Printed Components

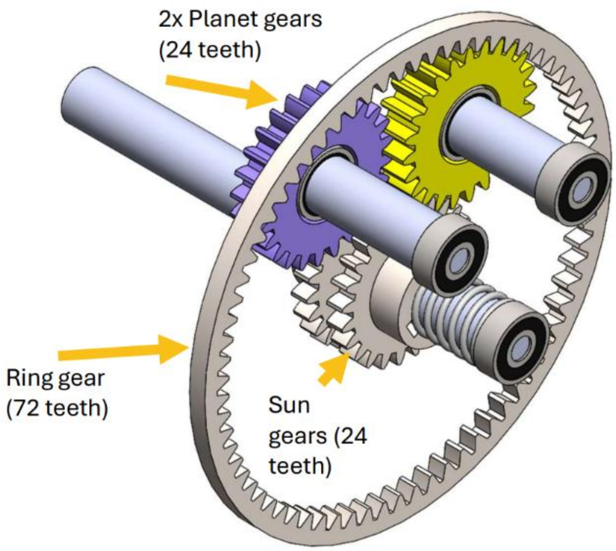

Figure 13: Initial Gear Protypes

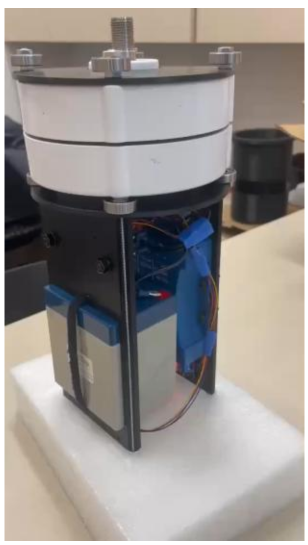

Figure 14: Generator Assembly

Figure 15: Endoskeleton Assembly

Figure 16: Complete Assembly

3.4 Test Setup and Instrumentation

At the beginning of the project, the NAU MECC25 team was initially granted access to a water tank facility through a collaborating professor at Arizona State University. However, the facility was still under construction during the early stages of the competition, and its estimated completion date did not align with our test schedule. To maintain project momentum and meet critical build and validation deadlines, the team improvised by conducting subsystem-level testing through available university equipment in the region.

Three primary testing categories were pursued:

- Hydrophobicity and pressure sealing verification
- Electronic Verification & Environmental Monitoring
- Buoyancy tests and maximum allowable tether weight determination
- Rotational energy harvesting and charge time analysis

Each of the tests was conducted with realistic setups to most accurately simulate realistic conditions with the limited environment.

3.4.1 Hydrophobicity and Pressure Testing

For testing water resistance and airtightness, the group utilized the spa of the university as an in-house controlled testing facility. This gave them the opportunity for submerged testing of the device's enclosures and seals with static pressure of water so that nothing inside them would get wet during operation.

3.4.2 Electronic Verification & Environmental Monitoring

Electronics were tested by being fully assembled in a dry test bench environment. The generator was driven with an external DC motor, which produces power at or above the rated speed. During operation the power measurements and battery status can be monitored live. After shutdown, environmental data can be collected from microcontroller with USB.

3.4.3 Buoyancy and Tether Weight Capacity Testing

Indoor buoyancy testing was also performed in the spa to measure the maximum permissible combined mass of the buoy, anchor, counterweight, and tethering line while still maintaining positive buoyancy. Incremental mass was loaded onto a mockup tether system, and the buoy was submerged to test floatation limits. This testing provided critical constraints for the final system design, which is that the device must remain surface-floating while generating sufficient mooring force for operational stability.

3.4.4 Charge Time and Energy Output Testing

To determine energy generation performance, the team designed an in-house benchtop system that included a handheld digital tachometer, a torque adapter, and mobile devices as data loggers. The measured rotational speed and torque values were then evaluated using a MATLAB-based code to approximate energy output in simulated wave conditions. This allowed for performance validation and deployability assessment at various candidate locations as well as seeing if there is any future changes in the design.

3.5 Experimental Methods

This section outlines the structured procedures used to validate the waterproofing, buoyancy, and energy generation performance of the prototype system. Each experimental method was designed to simulate realistic marine conditions while ensuring reproducibility, consistency, and safety throughout testing.

3.5.1 Hydrophobicity and Leak Testing

To assess the waterproof integrity of the buoy’s housing, a hydrophobicity test was conducted in a controlled aquatic environment. The two halves of the buoy were separated from each other and submerged to a depth of approximately one meter with the opening facing the spa flooring. The exterior was observed for air bubbles, which would indicate leakage through seals or surface imperfections. If leakage was detected, the buoy was removed from the water, fully dried, and a hydrophobic coating was applied to the contact surfaces. The process was repeated iteratively until no air bubbles were observed, confirming that the enclosure was water-tight and suitable for deployment under shallow water pressure conditions.

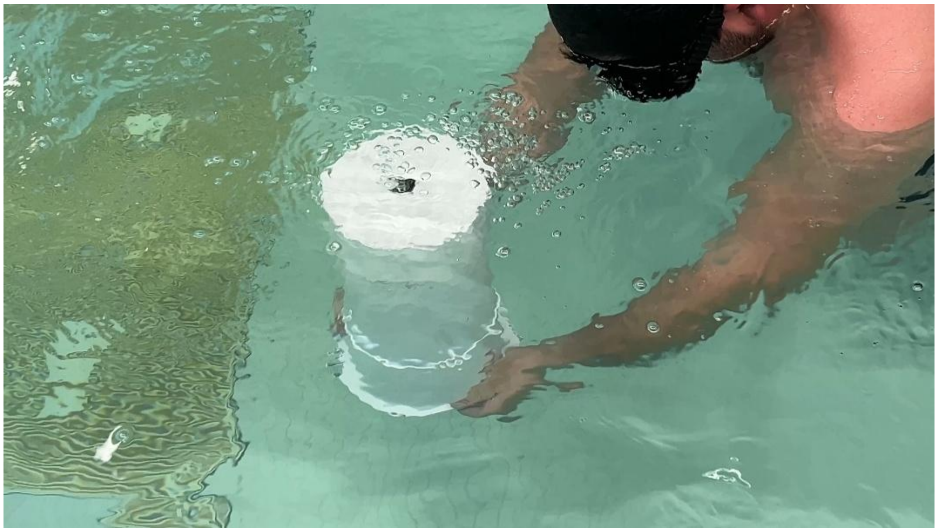

Figure 17: Leak Testing

3.5.2 Electronic Verification & Environmental Monitoring

The electronic testing proved successful at a generator speed range of 450 rpm to 1200 rpm. Voltage was generated and rectified, with amplitude proportional to the speed. The battery charges at or above 12 V output and can fully charge in ~40 minutes. The environmental data was read off and showed stable internal pressure, temperature and humidity.

3.5.3 Buoyancy and Counterweight Analysis

Buoyancy testing was performed to determine if the volume of the buoy would maintain positive buoyancy with the combined mass of internal components. The secondary test was to calculate the maximum weight that the anchoring hardware, and counterweights could be if the scale model was to be put in any body of water. First, the total weight of internal electronics, mechanical assemblies, and a safety margin was measured using a digital scale. Equivalent test masses were prepared, and the buoy was sealed and placed in water to evaluate whether it maintained surface flotation (Figure 18). If the buoy failed to remain buoyant, modifications were made—such as increasing the device’s volume or adding buoyant materials—until a configuration was achieved that allowed the system to stay afloat. This test provided an upper limit for the total tethered weight permissible during deployment to ensure operational stability without compromising buoyancy.

Figure 18: Buoyancy Testing

3.5.4 Charge Time and Energy Generation Estimation

To assess the energy generation capabilities of the system, the minimum RPM required to initiate battery charging from the generator was determined through benchtop testing. A custom test rig consisted of a torque adapter, handheld digital tachometer, a hand drill and a mobile data acquisition tool (Figure x10). Once the threshold RPM was identified, additional trials were conducted to observe charge duration at that RPM and above. In tandem with physical testing, a MATLAB-based computational model was developed to simulate energy output under varying ocean conditions. This script uses wave amplitude and period data sourced from NOAA buoys to calculate wave arc lengths, rotational displacement at the buoy's outer diameter, and the resulting generator RPM through the system's gear ratio. The output is a theoretical watt-hour estimate for several deployment scenarios based on real-world wave patterns. The full MATLAB script and methodology are included in Appendix C for reference.

Figure 19: Charge Time Setup

3.6 Data Analysis and Results

Upon the completion of four principal experimental tests, all acquired data were evaluated with MATLAB and validated using computational and visual analysis methods.

Visual inspection was utilized to test hydrophobicity and pressure integrity. Lack of or appearance of bubbles during submergence was taken as the key sign of leakage. The test was declared successful when there was no appearance of bubbles, proving the water-tight closure of the enclosure in static condition. Results from the load and buoyancy tests were also visually verified. The buoy was submerged in a water tank with simulated internal mass and tether weights. Positive buoyancy was confirmed if the device buoyed up with no portion being beneath the waterline, demonstrating sufficient displacement for the anticipated deployment load.

Supplemental quantitative findings were obtained with charge time and energy output tests. Using a hand-held tachometer with torque adapter, we recorded RPM, torque (Nm), and generator output (W) measurements at various velocities. These are summarized in Table 7 (to be included below), and it shows the measured values taken at various conditions of operation.

Table 7: Charge Time Experimental Data

Volts(V)	Current(A)	Watts(W)	RPM		Torque(N)
12.47	0.02	0.25	857		2.786

Based on these measurements, a MATLAB script was developed to extrapolate power generation at different ocean conditions from wave data procured from NOAA's National Data Buoy Center. The script calculated wave arc lengths, rotations at the outer diameter, resulting internal RPM after reduction, and theoretical watt-hour output (see Appendix C for script). These six locations with the best optimum wave conditions were used as case studies, and the computed energy output at each site is presented in Table 8.

Table 8: Power Produced at Six Different Environments

Buoy ID	Station Name	Region	Water Body	Power Generated (Whr)
46239	Point Sur, CA	Central California	Pacific Ocean	49.920
51201	Waimea Bay	Hawaiian Islands	Pacific Ocean	47.760
46001	Western Gulf of Alaska	Gulf of Alaska	Pacific Ocean	53.100
41010	Canaveral East	Southeast U.S.	Atlantic Ocean	49.350
41040	North Equatorial One	Tropical Atlantic	Atlantic Ocean	51.460
44097	Block Island	Min-Atlantic	Atlantic Ocean	49.560

An illustrative summary of the theoretical power output at all six sites is presented in Figure X3.6, graphically presenting predicted energy output as a function of wave period and amplitude.

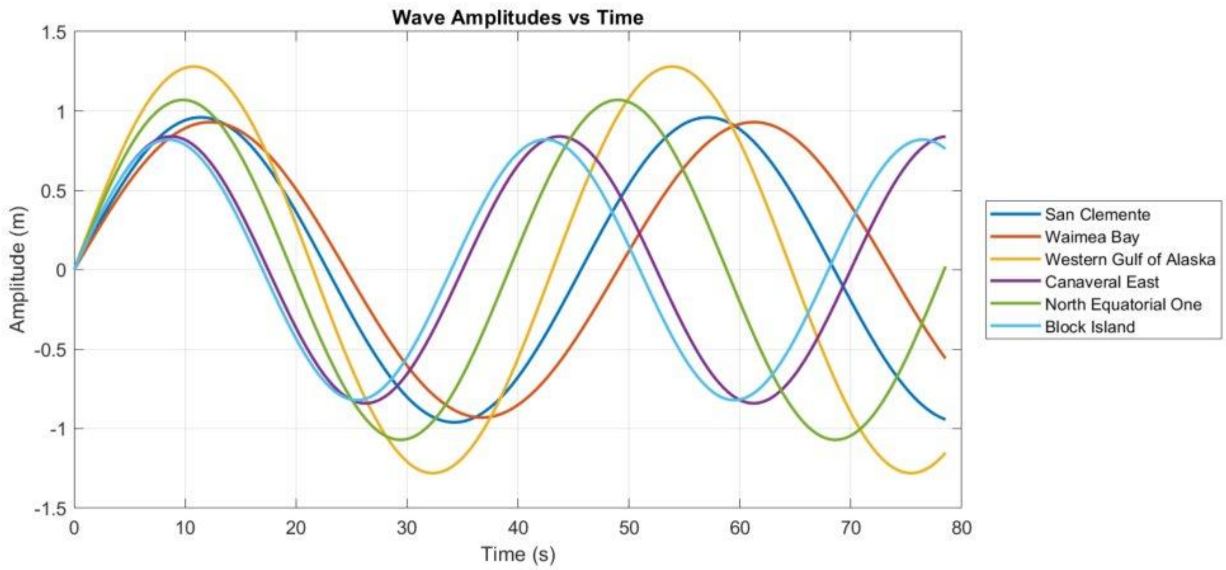

Figure 20: Wave Amplitude of Six Different Environments

These efficiency curves are used to show the performance envelope of the device under various sea states.

From the perspective of performance metrics, the prototype demonstrated the ability to generate mechanical torque consistently at low RPMs, and the gear system successfully transferred bidirectional wave motion to unidirectional shaft rotation. The generator began producing useful power once above the threshold RPM, and conversion efficiency increased with proportionally higher wave energies. These results validate expectations established through early-stage design modeling and bench-scale prototyping.

While the data had strong indications of the abilities of the system, it is pertinent that the results were generated in ideal laboratory conditions. Such practical considerations as turbulence, wave irregularity, and mechanical losses due to extended wear were not built into this testing session. Therefore, an uncertainty analysis was performed to provide allowance for limits of precision and repeatability. Uncertainty in measurement was primarily a function of torque reading tolerances, minor RPM variations during testing, and assumptions made in the MATLAB energy model. While results were consistent within repeated trials in controlled environments, environmental testing would be required to fully guarantee long-term repeatability.

Despite these shortcomings, the results convincingly support the feasibility of the prototype's energy harvesting concept. The actual and simulated performances closely align with initial projections, affirming the promise of the design for small-scale marine power harvesting.

3.7 Lessons Learned

The experience of being involved in the Marine Energy Collegiate Competition gave our team excellent learning experience to apply theoretical principles in actual engineering practice, and it gave us several important insights into design methodology, prototyping, and testing processes.

3.7.1 What Worked Well

The iterative design and testing approach employed throughout the project worked well. In particular, the modular approach used on the gearbox allowed for incremental, focused improvements with less fabrication time and expensive rework avoidance. Additionally, the structured cycle of feedback integrated into our capstone course - through weekly progress reports and design reviews—allowed for constant opportunities for improvement. This allowed us to identify problems early, report difficulties accurately, and remain sensitive in our process. Our idea generation and brainstorming process were also strengths because they enabled the team to generate a large range of design possibilities prior to coming to a final decision.

3.7.2 Problems and Challenges Faced

Despite the project creating a functioning prototype, some issues were experienced while fabricating and testing the same. The principal problem was that rigorous quantitative tests were not made at an early stage of the decision-making process. The early selection of the design might have been enhanced with a more powerful decision matrix derived from analytical modeling, particularly in determining theoretical power output and an ideal gear ratio. Moreover, the construction of the full-scale shell at the initial stages of the project limited our ability to alter internal parts easily, which required time-consuming alterations. Material selection and some methods of waterproofing also required surprise reworking once performance limits were found in the tests.

3.7.3 Influence of Feedback and Past Work

The team design process was guided not only by peer and advisor feedback, but also by learnings based on past MECC competition reports and the literature on marine energy that is available. For instance, past capstone reports stressed the importance of compromising mechanical reliability with power output, which led to our emphasis on modularity and durability. Feedback from faculty mentors assisted us in determining key oversights in load balance and buoyancy during initial testing, resulting in specific design revisions. The group-based format of the capstone course also motivated knowledge sharing and reflective analysis that directly enhanced our problem-solving approach.

3.7.4 Opportunities for Improvement

In the future, there are several areas for improvement that have been determined. Future prototype releases could utilize more extensive application of numerical modeling tools at earlier stages to simulate energy yield and mechanically optimize parameters like gear ratio. A higher gear ratio could significantly enhance generator RPM and efficiency of energy harvesting. Enhance the generator and battery to be suitable for higher rotational speeds to improve system optimization further. In addition, a more formalized testing procedure with quantified performance metrics would make it easier to validate and increase general data reliability. Prioritizing smaller, faster iterations on all the subsystems- rather than driving full-scale production too aggressively -would also increase design amenability further and reduce integration issues.

All in all, this project offered invaluable first-hand experience in systems engineering, and helped to reinforce the importance of continuous feedback, analytic rigor, and adaptive thinking in successful prototype development.

3.8 Conclusions and Next Steps

The finished prototype is a key achievement in the design and development of a subsea-optimized wave energy conversion system. The device was able to meet the basic performance requirement established at the project's inception—demonstrating the ability to extract power from wave-induced motion. Success was also achieved with the design and integration of the bidirectional-to-unidirectional gearbox, a mechanically advanced subsystem that was a major challenge and required multiple iterations to create.

Despite these accomplishments, the prototype had some design limitations that inform future design improvements. One of them was mechanical interference between the gearbox assembly and the internal shell structure. This was primarily a result of relative motion between the buoy and the unanchored gear carrier. In future designs, direct anchoring of the gear carrier to the electrical subassembly is expected to eliminate this interference and improve mechanical reliability. In addition, the then-existing prototype had a small physical size limit, restricting how much energy it could store, in addition to the power at which it could release it. As sufficient proof of principle, nevertheless, additional scaling up of the system for increasing the size of the counterweight and energy storage system mass would be needed.

These findings hold far-reaching implications for systems development on large scales. The overall architecture of the prototype, its energy harvesting method, and its mechanical power take-off system remain highly favorable for scaling to larger platforms. With increasing size and weight, the system could potentially supply the long-term power requirements of underwater communication systems, environmental monitoring stations, or autonomous underwater vehicles (AUVs) that periodically need to be refilled.

In the future, some subsequent actions are planned to bring the prototype nearer to practical implementation. First, the internal structural interface needs to be reengineered to eliminate gear binding and increase mechanical life during extended operation. Second, comprehensive dynamic modeling and simulation must be conducted in order to maximize gear ratios and predict energy output for various wave conditions. The generator and battery subsystems must also be upgraded to accommodate a scaled-up buoy's higher rotational velocities and power requirements. Extended open-water testing will be necessary to validate the system's operational performance, structural integrity, and energy delivery capacity in real-world marine environments. Finally, later prototypes must be fitted with underwater sensors or communications hardware to evaluate the system's viability as a standalone power source for remote marine applications.

Overall, the project not only yielded an operating prototype but established a good technical foundation for further development. The group is pleased with what was achieved and believes the potential is high for this concept to develop into a field-ready, effective marine energy product with some more tweaking and targeted testing.

References

[1] A. O. Pecher and J. P. Kofoed, Handbook of Ocean Wave Energy. Cham: Springer International Publishing, 2017, pp 203-219.

[2] W. G. Nickels, J. M. McHugh, and S. M. McHugh, "Chapter 13 Marketing: Helping Buyers Buy," in Understanding Business, 12th ed, New York, NY: McGraw-Hill Education, 2019, pp. 326–351.

[3] A. Barua and M. Salauddin Rasel, "Advances and challenges in ocean wave energy harvesting," Sustainable Energy Technologies and Assessments, vol. 61, p. 103599, Jan. 2024. doi: 10.1016/j.seta.2023.103599

[4] M. S. Lagoun, A. Benalia, and M. E. Benbouzid, "Ocean Wave Converters: State of the art and current status," 2010 IEEE International Energy Conference, vol. 2, pp. 636–641, Dec. 2010. doi:10.1109/energycon.2010.5771758

[5] G. Reikard, P. Pinson, and J.-R. Bidlot, "Forecasting Ocean Wave Energy: The ECMWF WAVE model and time series methods," Ocean Engineering, vol. 38, no. 10, pp. 1089–1099, Jul. 2011. doi: 10.1016/j.oceaneng.2011.04.009

[6] D. Giancoli, "Physics for scientists & engineers, 5th Edition," Physics for Scientists and Engineers with Modern Physics, https://www.pearson.com/en-us/subject-catalog/p/physics-for-scientists--engineers/P200000007024/9780137488179 (accessed Nov. 27, 2024).

[7] "IEEE SA - AIEE standards - electrical measuring instruments," IEEE Standards Association, https://standards.ieee.org/ieee/33/6408/ (accessed Sep. 16, 2024).

[8] "Energy efficiency and renewable energy sources — Common international terminology," ISO, https://www.iso.org/obp/ui/#iso:std:iso-iec:13273:-1:ed-1:v1:en (accessed Sep. 16, 2024).

[9] E. Hultman and D. Salar, "A robotized 6-DOF dry test rig for wave power," *Sustainable Energy Technologies and Assessments*, vol. 59, p. 103393, Oct. 2023. doi:10.1016/j.seta.2023.103393

[10] J. Lin, W. Peng, J. Jiang, and L. Wang, "Cost-effectively laboratory experimental techniques for performance assessment of scale-down wave energy converters," *Ocean Engineering*, vol. 297, p. 117061, Apr. 2024. doi:10.1016/j.oceaneng.2024.117061

[11] Michael Borg, et al. "Offshore Floating Vertical Axis Wind Turbines, Dynamics Modelling State of the Art. Part III: Hydrodynamics and Coupled Modelling Approaches." Renewable and Sustainable Energy Reviews, Pergamon, 24 Nov. 2014, www.sciencedirect.com/science/article/pii/S1364032114009253

[12] M. Nachtane, M. Tarfaoui, D. Saifaoui, A. El Moumen, O.H. Hassoon, H. Benyahia, "Evaluation of Durability of Composite Materials Applied to Renewable Marine Energy: Case of Ducted Tidal Turbine" in Energy Reports, 2018.[Online]. Available: DOI: 10.1016/j.egyr.2018.01.002

[13] L. Rodrigues. " Wave Power Conversion Systems for Electrical Energy Production." Repqj.com. Accessed Sept. 15th, 2024. [Online]. Available: https://repqj.com/index.php/repqj/article/view/1826/380-leao.pdf

[14] C. F. Kutscher, J. B. Milford and F. Kreith, "Ocean, Hydropower, and Geothermal Energy Converstion," Principles of Sustainable Energy Systems, 3rd ed. FL, USA: CRC Press, 2019, ch. 13, sec. 13.3.

[15] C. F. Kutscher, J. B. Milford and F. Kreith, "Ocean, Hydropower, and Geothermal Energy Converstion," Principles of Sustainable Energy Systems, 3rd ed. FL, USA: CRC Press, 2019, ch. 13, sec. 13.2.

[16] Dimopoulos, George G., et al. "A General-Purpose Process Modelling Framework for Marine Energy Systems." Energy Conversion and Management, Pergamon, 2 June 2014, www.sciencedirect.com/science/article/abs/pii/S0196890414003501.

[17] E. Oberg, F D. Jones, H. L. Horton, and H.H. Ryffel, " Internal Gearing" in Machinery's Handbook, 29th ed., NY, NY, USA: Industrial Press, 2012, ch. 12, sec 3, pp. 2169-2171.

[18] Griffiths, John, et al. "Guidelines for Health and Safety in the Marine Energy Industry." Tethys-Engineering.Pnnl, British Wind Energy Association, 2008, tethys-engineering.pnnl.gov/sites/default/files/publications/EMEC-2008-Health-Safety.pdf.

[20] M. E. McCormick, Ocean Wave Energy Conversion. Courier Corporation, 2013.

[21] "Wave-Coast Interactions | manoa.hawaii.edu/ExploringOurFluidEarth." [Online]. Available: https://manoa.hawaii.edu/exploringourfluidearth/physical/coastal-interactions/wave-coast-interactions

[22] "The Engineering Handbook - Buoyancy." [Online]. Available: https://enghandbook.com/naval-architecture/buoyancy/

[23] A. Muetze and J. G. Vining, "Ocean Wave Energy Conversion - A Survey," in Conference Record of the 2006 IEEE Industry Applications Conference Forty-First IAS Annual Meeting, Oct. 2006, pp. 1410–1417. doi: 10.1109/IAS.2006.256715.

[24] J. Wu, L. Qin, N. Chen, C. Qian, and S. Zheng, "Investigation on a spring-integrated mechanical power take-off system for wave energy conversion purpose," Energy, vol. 245, p. 123318, Apr. 2022, doi: 10.1016/j.energy.2022.123318.

[25] "Marine Energy Atlas." [Online]. Available: https://maps.nrel.gov/marine-energy-atlas

[26] "Wave Energy Converters." [Online]. Available: https://theliquidgrid.com/marine-clean-tech-briefs/wave-energy-converters/

[27] N. O. and A. A. US Department of Commerce, "National Data Buoy Center." Available: https://www.ndbc.noaa.gov/

[28] E. Oberg, "Fasteners," in Machinery's Handbook, 29th, Twenty-Ninth edition., South Norwalk, Connecticut: Industrial Press, 2012, pp. 1521–1537.

[29] E. Oberg, Machinery's Handbook, 29th, Twenty-Ninth edition., South Norwalk, Connecticut: Industrial Press, 2012, pp. 2211–2239.

[30] E. Oberg, “O-RINGS,” in Machinery’s Handbook, 29th, Twenty-Ninth edition., South Norwalk, Connecticut: Industrial Press, 2012, pp. 2587–2592.

[31] “Mechanism for Converting Two-Way to One-Way Rotation 6b - YouTube,” YouTube. [Online]. Available: https://www.youtube.com/watch?v=etlnSt0XqRE

APPENDICES

Appendix A: Business Challenge

Appendix B: Technical Design Challenge

Appendix C: Build & Test Challenge

Matlab Code for Location and Energy output

```
Clear
clc
format short

%buoy ID number from ndbc.noaa.gov site
buoyID = input(['what buoy would you like the information from? use this site
to find the buoy'...
    ' https://www.ndbc.noaa.gov/data/realtime2/ '],'s');
url = sprintf('https://www.ndbc.noaa.gov/data/realtime2/%s.txt', buoyID);

%File name for the Excel spreadsheet
outputFile = sprintf('%s.xlsx', buoyID);

%Download and process data
try
    opts = weboptions('Timeout', 20); %cancels code if takes loger than 20
seconds
    data = webread(url, opts);

    %Parse data using textscan, skipping header lines
    rawData = textscan(data, '%f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f
%f %f %f', 'HeaderLines', 2, 'TreatAsEmpty', 'MM');

    %Check lengths of all columns and find the minimum valid length
    columnLengths = cellfun(@length, rawData);
    minLength = min(columnLengths);  %Find minimum length across columns

    %Ensure all columns are the same length by trimming to minLength
    for k = 1:length(rawData)
        if length(rawData{k}) > minLength
            rawData{k} = rawData{k}(1:minLength);  %Trim each column to the
minimum length
        end
    end
```

```
    %Convert to a data matrix after trimming
    dataMatrix = cell2mat(rawData);

    %Create a excel sheet with column names
    buoyDataTable = array2table(dataMatrix, 'VariableNames', ...
                            {'YY','MM','DD','hh','mm', ...
                             'WDIR','WSPD','GST', ...
                             'WVHT','DPD','APD', ...
                             'MWD','PRES','ATMP','WTMP', ...
                             'DEWP','VIS','PTDY', 'TIDE'});
    %Write the table to an Excel file
    writetable(buoyDataTable, outputFile);

    %Display success message if successful
    fprintf('Data has been successfully saved to %s\n', outputFile);

    % Calculate and print the average needed values, ignoring empty cells
    avgWVHT = mean(buoyDataTable.WVHT, 'omitnan'); %average wave height
    avgADP = mean(buoyDataTable.APD, 'omitnan'); %average wave period
    ampWVHT = avgWVHT/2; %average wave amplitude
    avgWSPD = mean(buoyDataTable.WSPD, 'omitnan'); %average wind speed
    avgWDIR = mean(buoyDataTable.WDIR, 'omitnan'); %average wind direction

    fprintf('Average wave amplitude for buoy %s: %.2f meters\n', buoyID,
ampWVHT);
    fprintf('Average wave period for buoy %s: %.2f seconds\n', buoyID, avgADP);
    fprintf('Average wind speed at buoy %s: %.2f knots\n', buoyID, avgWSPD);
    fprintf('Average wind direction at buoy %s: %.2f degrees from North\n',
buoyID, avgWDIR);

 catch ME
    fprintf('Data retrieval failed for buoy %s\n', buoyID); %reads error if
failed
    disp(ME.message); %displays error reason
 end
```

Energy & RPM calculation

```
 C = .52; %m circumference of buoy
 x = avgADP*2*pi; %length to get 1 whole period
 LenghtofWave = integral(@(x) sqrt(1 + ((2 * pi * ampWVHT / avgADP).^2 .* cos(2
* pi * x / avgADP).^2)), 0, avgADP);
 RPP=(LenghtofWave/C); %rotations per period (of buoy)
 periodpermin=(60/avgADP); %number of periods per min
 RPM_OD= periodpermin*RPP %RPM in one period for outer diameter
```

```
RPM_ID = RPM_OD*3 %RPM in one period for ID (gear ratio for prototype is 1:3)
```

Verifying if buoy works at that location

```
if RPM_ID <= 400
   fprintf('The buoy will not work at %s', buoyID);
   WattPerMin = .019*RPM_ID*(2*pi)/60
    WattPerHour = WattPerMin*60
    kWattPerDay=WattPerHour*24/1000
else
    fprintf('The buoy will work at %s', buoyID);
    WattPerMin = .019*RPM_ID*(2*pi)/60
    WattPerHour = WattPerMin*60
    kWattPerDay=WattPerHour*24/1000
end
```