SURF SUPPLY

Wave Energy Converter for Marine Vessels and Isolated Communities

FINAL DESIGN REVIEW

Prepared for: U.S. Department of Energy Marine Energy Collegiate Competition

Project Members

Gage Howard	gwhoward@calpoly.edu	Mechanical Engineering
Charlie Camilli	ccamilli@calpoly.edu	Mechanical Engineering
Leo Kirshenbaum	lkirshen@calpoly.edu	Mechanical Engineering
Owen Pyle	opyle@calpoly.edu	Mechanical Engineering
Jonathan Ma	jma56@calpoly.edu	Electrical Engineering
Emigdio Islas	emislas@calpoly.edu	Electrical Engineering
Joseph Bonafede	jbonafed@calpoly.edu	Electrical Engineering
Lou Lou Twietmeyer	ltwietme@calpoly.edu	Business Management
Daniel Thompson	dthomp35@calpoly.edu	Business Management
Tyler Pitts	tmpitts@calpoly.edu	Business Management
Michael Clark	mclark28@calpoly.edu	Business Management

Sponsors

Dr. Peter Schuster	pschuste@calpoly.edu	Mechanical Engineering
Dr. Vladimir Prodanov	vprodano@calpoly.edu	Electrical Engineering
Barry Lieberman	balieber@calpoly.edu	Business Management

Mechanical Engineering Department
Electrical Engineering Department
Orfalea College of Business

California Polytechnic State University, San Luis Obispo

16 May 2023

Statement of Disclaimer

Since this project is a result of a class assignment, it has been graded and accepted as fulfillment of the course requirements. Acceptance does not imply technical accuracy or reliability. Any use of information in this report is done at the risk of the user. These risks may include catastrophic failure of the device or infringement of patent or copyright laws. California Polytechnic State University at San Luis Obispo and its staff cannot be held liable for any use or misuse of the project.

Abstract

California Polytechnic State University's 2023 Marine Energy Collegiate Competition team, Surf Supply, has developed a floating dock that transduces wave energy into electricity. The following report aligns with MECC requirements, and our design changes since CDR are present in the User Manual in Appendix F. Our primary market research of the Blue Economy identified electric marine vessel charging and isolated communities as early adopters that could benefit most from the first generation of our wave energy converter (WEC). Surf Supply's design concept provides a reliable, affordable, and renewable energy source that reduces dependency on conventional fossil fuels, allowing blue economy industries to have increased energy independence.

Our design uses a winch mechanism to generate rotational mechanical power from swells, that, when coupled with a generator, produces electricity. The electrical energy is stored in an on-board battery, so power can be supplied to end users on demand. A key advantage of Surf Supply's WEC is its small, modular design, which allows for operation in low-energy sea states and ease of scalability. Further, the design maximizes use of commercial, off-the-shelf parts, minimizing the costs associated with custom manufacturing. Through our participation in the Build and Test challenge, we were able to test the mechanical and electrical system designs and identify areas for improvement. With continued development, a commercial-ready product promises to increase Surf Supply's early adopter market share, eventually expanding into adjacent markets such as desalination. We feel confident that Surf Supply's wave energy concept could prove to be competitive in the market and experience sustained growth as the demand for clean, independent energy rises.

Table of Contents

List of Figures

List of Tables

1 Business Plan

The following section provides a summary of Surf Supply's market analysis and financial and operating plans.

1.1 Concept Overview

It is widely accepted that the emission of greenhouse gases poses a significant danger to biodiversity and human civilization. Furthermore, with fossil fuel reserves expected to become scarce by the end of the century, the demand for renewable and reliable energy access is increasing beyond our current supply. The ocean represents a significant, untapped source of renewable energy; as part of the U.S. Department of Energy's Marine Energy Collegiate Competition, Surf Supply has set out to create a WEC device that supplies cost-effective power to isolated coastal communities.

After conducting market research, we developed a rapidly deployable point absorber. The device's power take-off system is housed on a surface float, which is anchored to the sea floor via a winch. The vertical heave of a swell causes the winch to unspool and spin a drivetrain. We use an AC generator to transduce the energy from the mechanical domain into the electrical domain, where it is stored in an onboard battery bank.

The electrical output of our WEC can be used to power a variety of Blue Economy markets, such as desalination, offshore charging, and isolated community microgrids. Specifically, we plan to target electric fishing vessels and eco resorts as early adopters, with remote coastal communities representing the subsequent early majority.

We expect near-shore installations to be capable of modular deployment within a 24-hour period; this allows Surf Supply to meet the specific implementation needs of our end users. Our device would be distributed through a tiered recurring revenue model to ensure ease of installation, long-term maintenance of the device, and continued research and development of the technology to increase scale and improve performance.

1.2 Relevant Stakeholders

Government agencies: The project will require safety approval and permitting from government agencies at the local, state, and national levels (e.g., Alaska Dept. of Commerce, Dept. of Public Safety, U.S. Coast Guard). Regulation may also involve governmental bodies that manage natural resources, such as water and marine life, such as the Alaska Dept. of Fish and Game.

Investors: The installed resources necessary for the deployment of Surf Supply require a significant financial investment. Investors providing funding will have a stake in the project's success.

Energy Utilities: We are not planning to generate power at utility-scale production levels; however, end users' use may require a connection to a larger grid depending on their net energy demand, especially during low-energy sea states. A power purchase agreement with a utility or third party served by the grid may be required depending on the application.

Desalination Companies: An early hypothesis for applying wave generation units was to power small, networked desalination units, but we were unable to validate product-market fit during this business plan's development. The initial intrigue stemmed from a previous Cal Poly senior project. If such a market of marine desalination devices were deployed, companies that specialize in desalination technology could be interested if it offers opportunities for them to display their products or services.

Local communities: If our dock is located near a community, the residents and local organizations may be potential stakeholders. They may have concerns about the impact of the project on the environment, scenery, fishing, and recreation. Local communities could also benefit directly from the technology as part of an early majority market.

Environmental organizations: Non-governmental organizations that focus on protecting the environment may be concerned about the potential impacts of our WEC on marine ecosystems.

Shipping and fishing industries: Through secondary research and interviews, we identified the fishing industry as a promising early adoptive market and primary stakeholder. Some sea vessels have already begun the transition towards electric power but are currently limited by range. Strategic placement of WECs could extend how far electric fishing vessels can venture along remote coastlines. Additionally, any maritime industries that operate near our wave generation units would be stakeholders, regardless of whether they have a direct tie to the business.

Maintenance and service providers: Our WEC will require ongoing maintenance and service. Companies that provide these services would have a stake in the success of the project.

1.3 Market Opportunity

Surf Supply has a multi-faceted value proposition. There is substantial value in the low price and limited potential for pollution[1]. In addition, we offer a user-friendly installation that can be accomplished in a single day. The technology's low wave height requirement enables deployment in a wide variety of marine environments, including those close to the shoreline (e.g., sheltered coves and harbors). Our wave generation units can be coupled with electric boat charging units to service the nascent but rapidly growing electric boat fleet.

Further, the modular technology can be scaled to meet the energy needs of customers in remote environments, ranging from a single wave generation unit platform to connected networks that contain dozens or hundreds of wave generation units. Finally, Surf Supply offers value through its versatility with an energy storage unit that can supply electricity on demand. The versatility of a marine microgrid provides a solution for the prolonged remote operations that commercial electric boats and isolated commercial communities require.

Surf Supply has much to offer to the right buyer. The question then becomes *who* that buyer might be and how the company can reach them. To answer that question, this section of our Business Plan summarizes primary and secondary market research undertaken, with the aim of identifying relevant needs in marine and coastal economies. We then use this research to identify two potential early adopter segments that Surf Supply can target for its first sales, and we consider how the company can win over these customers. Later, consideration is given to adjacent markets into which Surf Supply may eventually expand, competitors who are already active in the marine energy space, and a pricing strategy that can help the company capture a share of the market.

1.3.1 Secondary Market Research

Market research began by examining the needs and opportunities related to three topics identified in the *Powering the Blue Economy* report[1]: isolated coastal communities, coastal resilience, and desalination. Our research focused on the needs that Surf Supply might be able to address.

Isolated communities often rely on microgrids powered by diesel generators. This poses a variety of challenges, including transportation logistics, storage, supply chain disruptions, and fuel price volatility. As a result, the energy cost in some coastal microgrids is far higher than the U.S. national average, at times costing more than $1/kWh in Alaska and island territories[1]. Remote eco-resorts face these same conditions, with the additional challenge that reliance on fossil fuel power runs counter to the values of most customers[1]. In all remote microgrid systems, reliability is an important need[1], meaning that there is value in the potential microgrid diversification offered by marine energy technologies. In summary, marine energy has the potential to improve the economics of communities and businesses in remote locations if it can reach a point where it is cheaper than diesel.

In addition to cost challenges, "isolated grids…have less resiliency than areas with neighboring grids and could benefit the most from an independent source of power from the sea" [1]. Diversifying energy and water sources can increase community resilience by reducing the risk of blackouts and water shortages[1].

Coastal desalination markets were also reviewed. Desalination in many forms is energy-intensive and costly. However, there is a belief that wave-powered desalination may be able to reduce these costs by directly pressurizing seawater and eliminating electricity needs. Additionally, integrated energy-water systems could bring great value to coastal locations with unreliable energy or water infrastructure[1].

Our research also identified a need for marine energy sources in low wave-height environments. The California Energy Commission produced a report which noted that "wave energy is estimated to be lower south of Point Conception because the Point and the Channel Islands block swells. To access more energetic waves south of Point Conception, it would be necessary to go farther offshore, which would increase the cost of wave projects"[2]. Marine technologies capable of energy generation in lower-energy wave environments may offer cost-saving advantages.

1.3.2 Primary Market Research - Stakeholder Interviews

Our market research also included direct outreach and interviews with stakeholders with experience in the abovementioned topics. Team members contacted more than six dozen professionals in industries such as energy utilities, microgrids, marine electrification, disaster response and recovery, and ecotourism. Eleven interviews were conducted to assess perspectives on the state of current marine energy and desalination solutions, market needs that are currently unaddressed, and the Surf Supply concept. The data collected during the interviews revealed several key concerns and opportunities.

Stakeholders expressed a wide variety of concerns, many of which related to the untested nature of Surf Supply's technology. These included the potential for detrimental impacts on the marine environment (e.g., litter, brine, noise pollution, or impacts on wildlife behavior), the dock's ability to connect to local power and/or water infrastructure, possible impacts on the boating and fishing industries, and how the technology could be scaled to meet the demands of larger markets. Common stakeholder concerns included dock durability in the harsh ocean environment and the subsequently required maintenance intervals and associated costs.

While these potential issues should not be overlooked, the stakeholder interviews also illuminated opportunities that Surf Supply's technology may be able to cater to. Surf Supply's docks were seen as best suited for small-scale, geographically concentrated uses with relatively low energy demand. Our interviewees suggested that we should explore how the docks could supplement existing energy and water resources and, similarly, if the docks could be part of diversified microgrids. One interviewee mentioned that their company is exploring ways to make microgrids under 1 megawatt more economically viable, and they expressed interest in Surf Supply's technology as a method for achieving that goal.

Unexpectedly, hybrid electric boats also emerged as an opportunity. An interviewee shared that hybrid electric boats can deliver substantial cost savings to commercial fishermen. Another stakeholder with knowledge of this industry shared an example of electric fishing boats, stating that the batteries on these vessels typically last only about 1.5 days before the boat must switch over to diesel generators. When this happens, fishermen not only lose the cost and climate-related benefits of the electric battery but also experience an unpleasant work environment and safety and communication issues caused by excessive noise from the generators. Marine energy technologies that can be towed behind a boat or easily accessed during off-hours have the potential to solve this issue.

1.3.3 Identifying and Securing Early Adopters

As detailed later in the Development and Operations section, our analysis of market opportunities assumes that Surf Supply will initially offer an electric-only minimum viable product (MVP) before moving toward docks that integrate desalination units. With this in mind, two potential early adopter segments emerge.

The first early adopter segment is characterized by geography and economics. Both our primary and secondary research show that Surf Supply has a strong value proposition for microgrids in remote coastal locations with low wave heights and expensive or unreliable energy production options. In these locations, Surf Supply docks can become one of many energy sources that feed into a microgrid. Customers in these locations who may have a particular interest in Surf Supply's technology include eco-resorts, affluent individuals with off-the-grid coastal properties, and small communities. The technology can offer these customer groups an energy source that reduces expenses, increases their resilience to power supply issues, and aligns with sustainability values. In addition, as noted in [1, pp. 91], "Island communities that have limited land availability may specifically provide a competitive advantage for marine energy technologies compared to solar or other renewables." Resorts and properties in island locations may be an especially strong fit for Surf Supply.

A second potential early adopter segment is commercial fishermen operating electric boats. As mentioned above, the status quo of using diesel generators as a backup to electric batteries leaves much to be desired. Surf Supply could be deployed as a multi-dock network within a sheltered cove near fishing grounds, which is where fishermen often stay overnight. By connecting to a Surf Supply dock and charging overnight, the operators of these boats could eliminate or reduce the need to use their diesel generators. Not only would this dramatically increase the quality of work and safety for individuals working on these boats, but it also would give the owner of the boat a competitive advantage by reducing transportation costs and allowing them to position their business as a leader in sustainable practices.

1.3.4 Adjacent Markets

Success with either of these early adopter segments opens opportunities for applications in adjacent markets, with the market segmentation displayed in **Figure 1**.

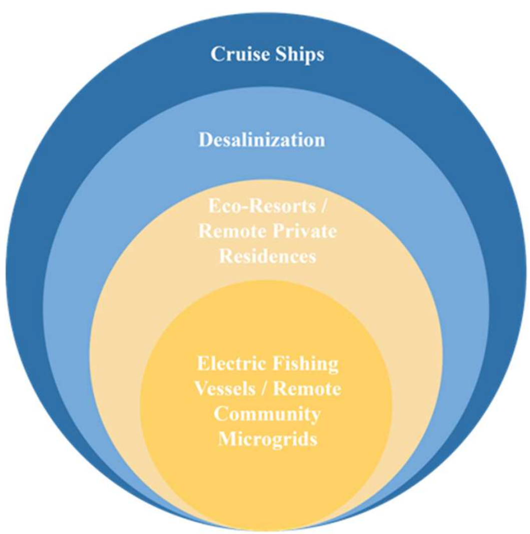


Figure 1. *Market segmentation graphic. Early adoptive and adjacent markets highlighted in yellow and blue, respectively.*

Although we were unable to validate a potential market fit for the desalination component of Surf Supply, it is conceivable that after establishing itself as an electricity utility only, clients may seek opportunities to obtain fresh water to supplement their commercial fishing trip needs. Another potential adjacent market includes cruise ships. Some ships currently use electric shore power provided by ports to power cruise ships while they are at berth preparing for the next round of passengers.

1.3.5 Competitors

Both early adopter hypotheses rest heavily upon Surf Supply's potential to be a better option than the current solution of diesel-powered generators. As mentioned above, reliance on diesel fuel for power generation in remote locations poses numerous challenges, not least of which is the extremely high cost. This means there is great potential for Surf Supply to attract interest from customers who are looking to cut their energy bills - and the ability to do so while also eliminating carbon emissions makes the technology even more competitive.

Compared to other marine energy technologies, Surf Supply occupies a unique niche. The docks can be installed in a single day and are intended to be placed 100 to 200 feet offshore. Additionally, they do not require a grid connection. These features differentiate Surf Supply from competitors and underscore the value propositions identified above. In comparison, competitors such as the OPT PowerBuoy and Columbia Power Technologies StingRAY are much larger and intended for use in deeper waters[3][4]. Eco Wave Power, meanwhile, has developed a design of floaters that attach to pre-existing structures and can produce energy in environments with low wave heights; however, this technology focuses on grid-connected arrays rather than microgrids[5]. In the desalination realm, Resolute Marine's Wave$_2$O system is comparable to Surf Supply in that it is intended to be scalable, but the system is larger and more complex, causing the installation to take multiple days[6]. While Surf Supply will face competition, the docks are unique in their ability to meet the needs of off-the-grid customers with a small, inexpensive, easy-to-install system.

1.3.6 Pricing & Sales

As one interview subject noted, Surf Supply operates in a "blue ocean" industry, meaning that the market is not yet saturated. With customers searching for solutions, Surf Supply will benefit greatly by beating competitors to the market. In this case, pricing should not be focused on profit, but rather on finding a price point that generates sales and allows the company to gain a substantial share of the market.

As discussed further in the Development and Operations Section, Surf Supply intends to employ a tiered recurring revenue model via Power Purchase Agreements and Virtual Power Purchase Agreements. This creates an opportunity to utilize trial pricing with new customers, initially offering a very low price per kWh to attract sales and then increasing prices after the trial period ends and customers gain confidence in the product. This higher price point will still need to be lower than the cost of operating a diesel generator to ensure Surf's Supply competitiveness.

It should be noted that a trial pricing strategy is likely to result in net operating losses during Surf Supply's early years while a large portion of customers are in their trial period. However, trial pricing is in line with the goal of building market share before more competitors enter the space, and investor fundraising can be undertaken to support the company's cash flow during these early years. If successful, this strategy will allow Surf Supply to develop a robust base of recurring revenue that will grow as customers exit the trial period and enter into regular contract terms.

1.4 Development and Operations

Our business model is dependent on the validity of assumptions about our technology. Through development, we intend to use a phased approach to validate concepts with a proof-of-concept unit that advances the technology to technical readiness levels (TRL) 4-6. The next step beyond the MECC contest is to deploy our prototype for TRL 7 validation. Transition through TRL 8 and into 9 occurs after additional fundraising via a seed round. All data collected will drive iteration on the initial prototype satisfactory to a demonstration in an ocean. This location would preferably be in San Luis Obispo County so that university resources can still be leveraged. Ideally, the operating environment demonstration will include multiple docks networked to demonstrate how the solution scales to both greater power and water output levels.

The commercial deployment will initially support the minimum viable product (MVP) electric-only unit. The power-only unit will serve as the MVP as it has fewer moving parts than the water-producing unit. Future co-generation and energy storage units are planned for the road map; however, they will need additional hypothesis validation from the TRL 8 & 9 milestone test units. The MVP units as electric generating units will allow us to understand the range of power levels generated under different conditions. This power generation data will allow us to properly align water production on water producing units by optimally sizing the desalination unit.

Business operations through TRL validation will likely reside in the Cal Poly Center for Innovation and Entrepreneurship, with physical work performed outside of the lab spaces used for the creation of initial prototypes developed for MECC. Initial commercial MVP deployment timing for Series A fundraising can be aligned with the output of that learning. Assuming no significant obstacles to technology scaling present, Series A would look to fund three additional deployments of the MVP along with the initial deployment of the water-producing unit if we were able to validate the need for such a product in an attractive market.

Our business model is not to sell the generation units but to enter into production agreements with host clients. The electric-producing unit will be deployed in either a power purchase agreement (PPA) or a virtual-power purchase agreement (VPPA). The differentiation between PPA and VPPA will align with market targets that either buy directly from a point of common coupling proximate to the electric producing units or sell via transmission agreement with third-party.

Water generation units will operate under a similar volumetric pricing agreement. Quantities of water higher than a single unit will be achieved via networked docks similar to methods demonstrated with the electric generating unit. Electrical conducts connecting dock-to-dock and dock-to-shore would have similar hose tubing analogs in the water generation units. Dock-to-dock units can be derated with progressively narrower conductors and hose tubing to account for less flow at the end of the circuit. Connection points to the customer can be achieved at sea or brought to shore to accommodate different applications of the technology.

Series B funding would occur once local early adoptive customer satisfaction is achieved such that scale can initially be deployed beyond San Luis Obispo County. Market research shows that our units have ideal market conditions in coastal areas where existing wave generation occur; however, the technical differentiation of our solution versus what currently is available in the marketplace allows our unit to be productive in areas with wave heights down to one meter. The two attractive geographies unlocked by our design characteristic include sheltered shorelines and coves such as those found in Southern California, the Pacific North-West, and Coastal Alaska.

This differentiation presents a hypothesis that the areas immediately south of San Luis Obispo County will be our initial target market beyond initial demonstrations and commercial deployments. A March 2008 State of California Energy Commission (CEC) study entitled "Summary of PIER-Funded Wave Energy Research" breaks down the California coastline into ten one-degree latitude cells or "boxes" shown in **Figure 2.**

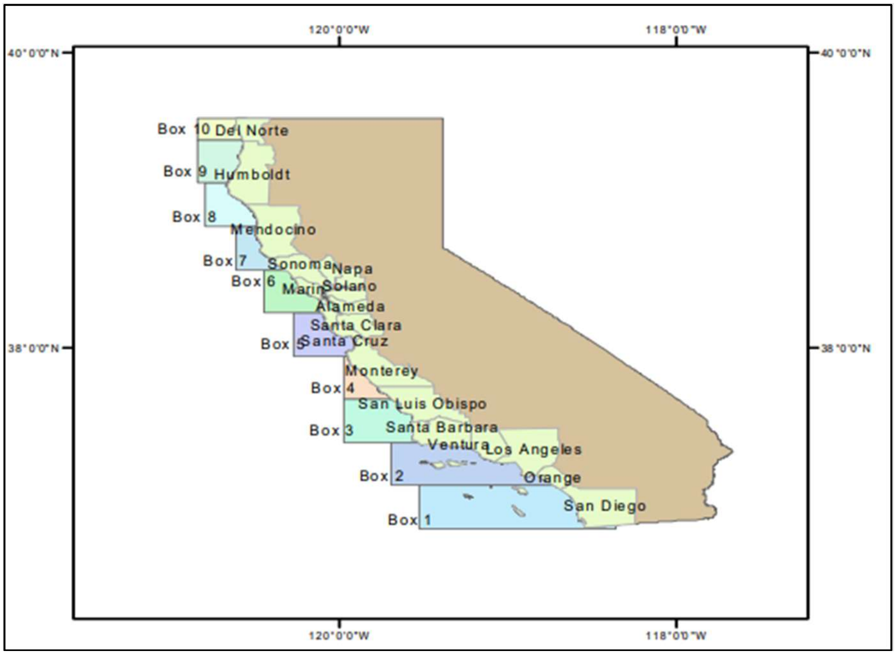


Figure 2. *The 10 latitude boxes used for analysis, sourced from PIER*

In the PIER project, "Wave height, period and average wave energy fluxes (in KW/Meter of wave crest) were calculated" as illustrated in Figure 3. Wave energy is estimated to be lower south of Point Conception because the Point and the Channel Islands block swells. Accordingly, this product differentiation allows us a cost advantage by enabling close-to-shore operations. Although electricity can be conducted easily over longer distances, close-to-shore operations are imperative for successful water export to land.

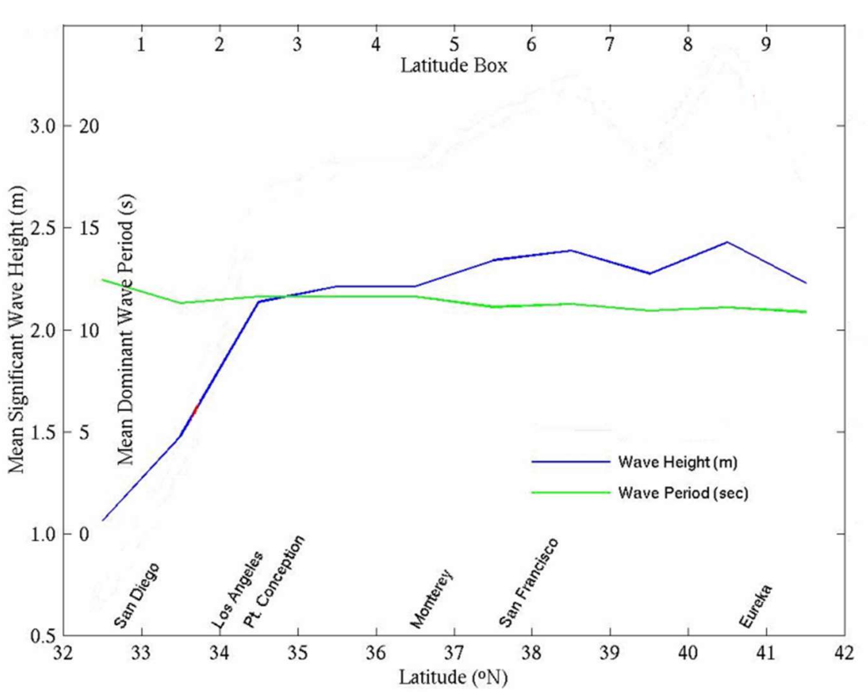


Figure 3. *Relationship between latitude and wave characteristics off the California coastline*

1.5 Financial and Benefits Analysis

We suggest that the seed capital for Surf Supply start at $100,000, growing to $49,100,000 by year 4 as outlined below in **Table 1**. As shown in **Table 2**, Generation 1 of Surf Supply will consist of about 60 units generating 4204.8 kWh of energy, and by Generation 3 consist of 4,640 units generating a total of 14,499.31 kWh.

Table 1. *Venture capital schedule*

Series	Amount	Year
Seed	$100,000	1
A	$4,000,000	2
B	$45,000,000	3
C	$49,100,000	4

Table 2. *Unit economics summary*

Generation #	Units	Production (kWh)
1	60	4,204.8
2	300	8,409.6
3	4,640	14,499.3

We performed a test case to evaluate the projected financial benefit of the dock system from a power perspective only. The following assumptions were made to perform this analysis. The cost of manufacturing and installing the dock is a fixed $13,300. The product is early in development, so this is an order-of-magnitude estimate and is subject to change. The dock was estimated to have a 40% uptime for power generation, which is highlighted in Table 3.

The net present value (NPV) in this case is dependent on the price per kWh because it affects the revenue generated by the dock. The dock generates power which is sold to customers at a certain price per kWh. As the price per kWh increases, the dock generates more revenue, which in turn increases the cumulative income and the cumulative NPV.

For example, in Year 1 the price per kWh is $0.50 and the dock generates $1,752 in yearly income, which results in a cumulative NPV, or Net Present Value, of $1,653 (see **Table 3**). If the price per kWh were to increase to $0.55, as shown in year 3, the dock would generate $1,927 in yearly income, resulting in a higher cumulative NPV of $4,908.

Cumulative income and NPV for Surf Supply will grow steadily. The cumulative income will reach the initial outlay cost of $10,000 around year 5, while the cumulative Net Present Value will do so around year 6, as shown in **Figure 4**.

Figure 5 demonstrates the average cost of dock production will decrease rapidly in response to the number of generators deployed. By year 4, average production costs per dock will decrease from $13,300 to $11,000, and by year 5 with a total of 5,000 docks deployed, this will fall to $5,800 per dock.

Table 3. *Accounting report*

(a) High level 9-row FA accounting statement

Year	Power Price	Yearly Income	Cumulative Income	Cumulative NPV
1	0.50	$1,752	$1,752	$1,653
2	0.525	$1,840	$3,592	$3,290
3	0.55	$1,927	$7,572	$6,734
4	0.575	$2,015	$7,534	$6,504
5	0.6	$2,102	$9,636	$8,075
6	0.625	$2,190	$11,826	$9,619
7	0.65	$2,278	$14,104	$11,134
8	0.675	$2,365	$16,469	$12,618
9	0.7	$2,453	$18,922	$14,069
10	0.725	$2,540	$21,462	$15,488

(b) Key accounting variables

Cost to Produce Dock	$13,300
Initial Price Per KWH	0.5 $/kWh
Power Generation Uptime	40%
Power Price Escalation	5%
Total Gross Income	$21,462
Discount Rate	6.00%
Net Present Value (NPV)	$15,488

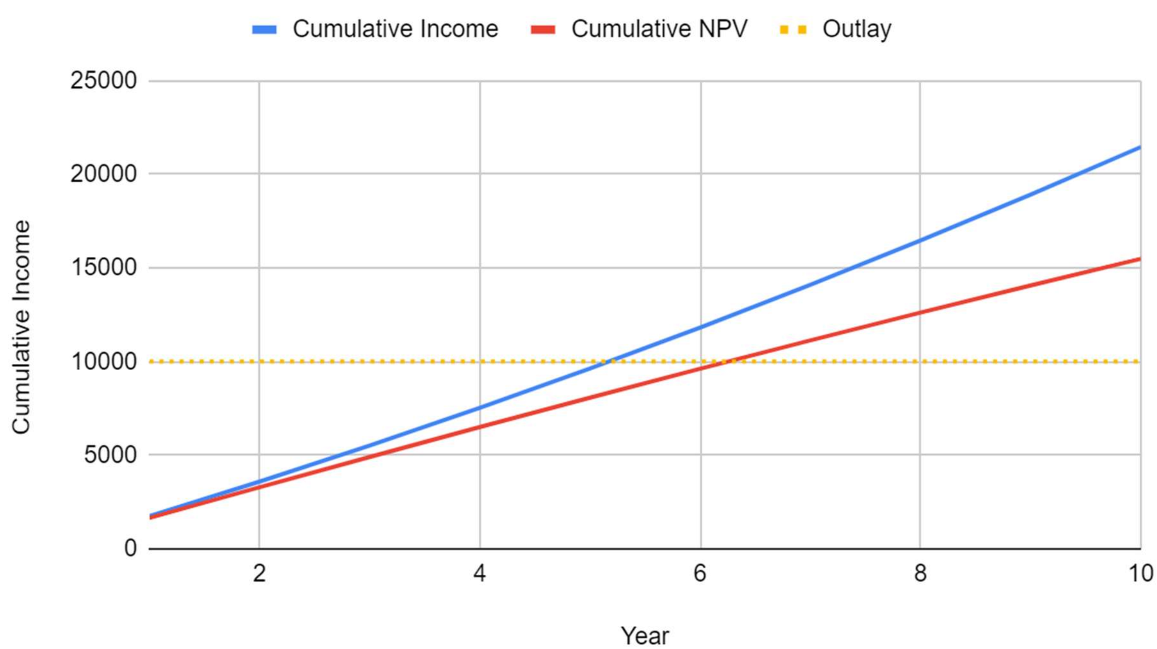


Figure 4. *Projected cumulative income over an initial ten-year period*

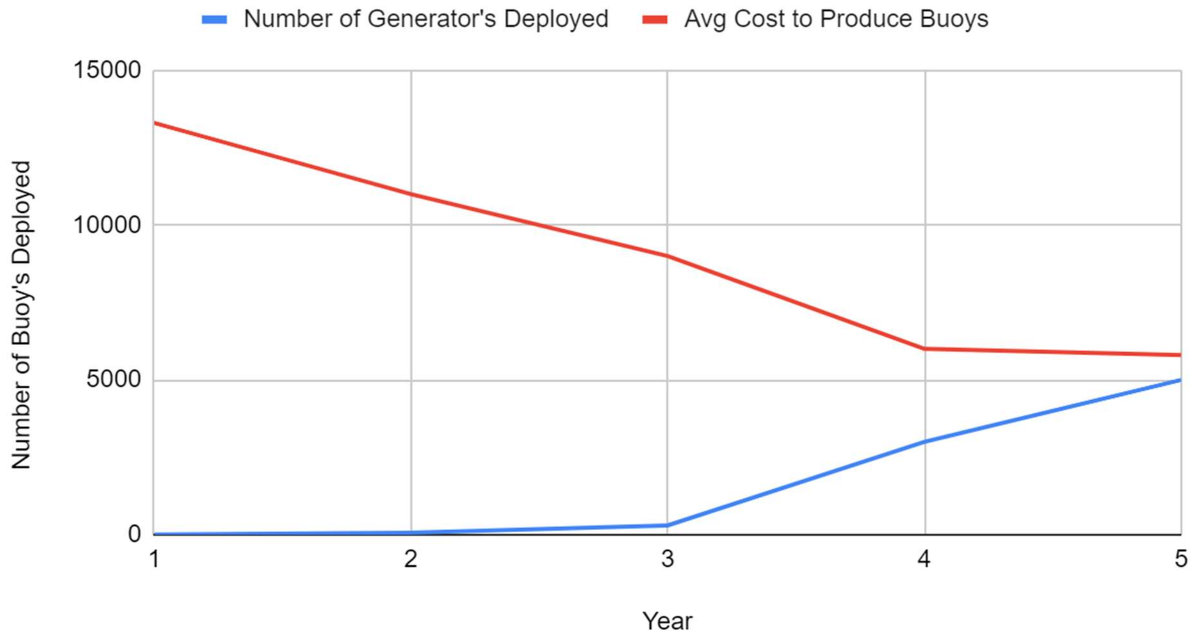


Figure 5. *Predicted device cost and number of units deployed over the first five years of operation*

Table 4. *Summary of unit economics for a $0.50 average price per kilowatt hour, 1 kW peak power, and 40% capacity factor.*

Year	**Number of Generators Deployed**	**Unit Cost** [$]	**Total Expenses** [$]	**Power Capacity** [kW]	**Docks**	**Charging Capability** [200 kWh]	**Charging Capability** [1 MWh]	**Gross Income** [$]
1	1	13,300	13,300	1	1	0	0	1,752
2	60	11,000	660,000	121	25	1	0	108,274
3	300	9,000	2,700,000	721	105	3	1	541,368
4	3,000	6,000	18,000,000	12,721	1,005	26	5	5,413,680
5	5,000	5,800	29,000,000	32,721	1,672	44	9	9,022,800
Net	8,361		50,370,000		2,808			

2 Detailed Technical Design

This section details the design of our WEC dock, describing the design selection, objective and functionality of the mechanical and electrical subsystems. Further, we provide the theoretical analyses we used to verify device durability and performance.

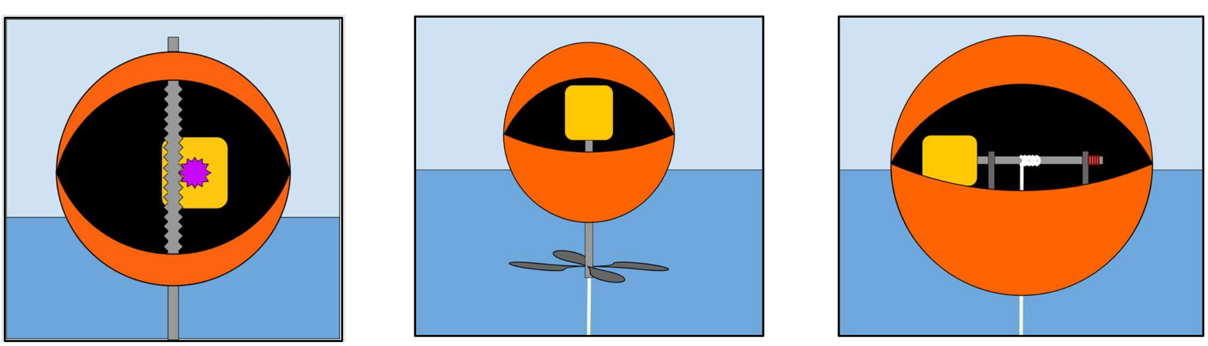
2.1 Design Selection

After a period of research and ideation, our team developed three ways to use vertical motion to create a rotational input for an electrical generator.

First, we explored a lead screw mechanism based on existing point absorbers, such as the OPT PowerBuoy[7]. In this design, a shaft-mounted ball screw moves up and down, spinning a threaded rod. A simplified sketch of our lead screw buoy concept is shown in **Figure 6a.** To maximize efficiency, the components must be tuned to the frequency of incoming waves. We were concerned that our current understanding of mechanical vibrations would be insufficient for a design of any respectable caliber. Further, the costs of designing and manufacturing a customized linear to rotary gearbox would likely be an inefficient use of our budget. Lead screw designs are among the most common in industry, and ultimately, we felt there wasn't much we could bring to the table.

Our second concept investigated a novel turbine idea depicted in **Figure 6b**. As the buoy rises, a turbine is forced upwards, causing it to spin a shaft. A loose cable tethers the assembly to the sea floor so that it does not wander across the sea. Critically, the turbine must be deep enough in the water column that the fluid it travels through is nearly stagnant. If it is too close to the surface, there will be no relative fluid speed because the ambient water will be moving upwards at the same velocity. The turbine point absorber had the opposite problem of the lead screw: there wasn't enough current information to support its credibility. Researchers at the Royal Melbourne Institute of Technology claimed to have generated twice as much power as an equivalent lead-screw design[8]; however, we struggled to match their results using basic hand calculations.

We ultimately decided to move forwards with a winch power take-off system (**Figure 6c**). When a wave is incident, the buoy rises, and the winch unravels, spinning the shaft. Once the wave's peak has passed, a torsion spring returns the system to its initial condition. Only enough energy to rewind the cable is taken away from the wave and stored in the spring's coils. In many ways, the winch design assumes a Goldilocks 'just right' position within our point absorber lineup. The National Renewable Energy Laboratory's wave model analysis tool contains power generation data for a winch-style system; however, the concept is not heavily researched. In this respect, our team was able to balance novelty with feasibility.



(a) **(b)** **(c)**

Figure 6. *Our power take-off concepts, the (a) lead screw, (b) hydraulic turbine, and (c) winch.*

2.2 Design Description

The following section details the component-level design of each specific subsystem, defines relevant variables, and explains design decisions.

2.2.1 Design Objective

Our final design consists of a set of dock floats, structural frame, mechanical drivetrain, and electrical system, with specific consideration for individual risks shown in Appendix A. These subsystems are integrated to mechanically transduce the heave energy of ocean waves into drivetrain rotation, generate electricity, and store the energy for end users (e.g., electric vessel charging, isolated community grid power, and desalination). The overall system design concept is illustrated in **Figure 7**, with the mechanical drivetrain positioned in the center of the floating buoy and the electrical subsystem is housed adjacent in its waterproof enclosure. The design was developed using SolidWorks.

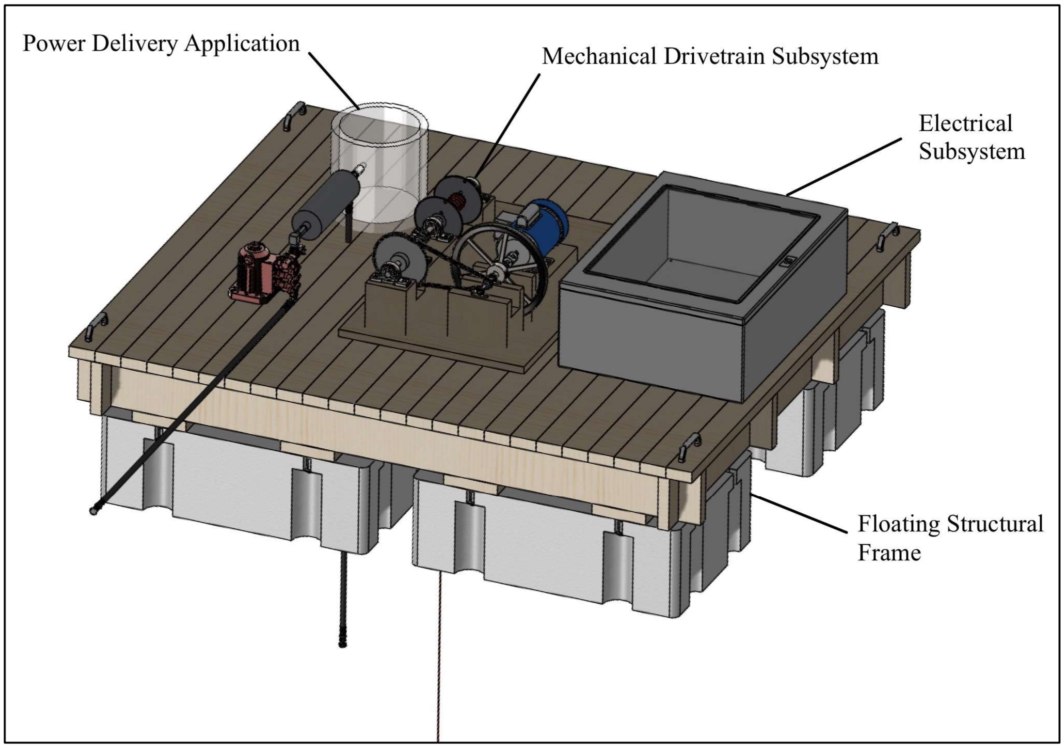


Figure 7. *Isometric view of our overall device model. In this model, surrounding paneling and electronic components are not shown, and the power delivery application chosen is an onboard desalination system consisting of a pump, reverse osmosis membrane, and freshwater storage tank.*

2.2.2 Float Subsystem

The structural frame follows the fundamental design principles of a floating dock. Four foam-filled polyethylene floats provide buoyancy and biaxial stability. The floats are fastened underneath a wood frame and deck. Each float provides 290 lb. of net buoyancy for a total of 1160 lb. - enough to support the weight of the frame (≤ 150 lb.) and the mechanical and electrical subsystems (≤ 200 lb. and 250 lb. respectively), with a safety factor of 1.9[1]. Note that the weight of the wooden frame can

[1] Subsystem weights are discussed in their respective sections.

increase by as much as 40% once it is placed in the ocean due to osmosis. If a higher load capacity is desired for a secondary application, the floats can be upsized at an additional cost without significant changes to the design. The polyethylene casing of the floats is resistant to seawater corrosion and contains ultraviolet inhibitors to prevent damage due to sun exposure. They are fastened to supports on the frame with lag bolts and oversized washers. The frame consists of notched 2x8” beams that are rigidly interlocked and secured with stainless steel joist hangers.

Decking (2x4” planks) is screw-fastened to the frame to provide a base mounting surface for the device subsystems. Additional cut sections of lumber are bolted to the base decking to raise mechanical components to the necessary height for alignment within a 1/32” tolerance. Lift handles and eyebolts in each corner allow for crane-assisted transport and deployment of the dock with the use of a four-point sling. Polyethylene paneling around the deck protects device subsystems from splashing and debris, as well as protecting users and passersby from device hazards. The lumber in the structure is 2.5 CCA pressure treated marine grade, and all fasteners in the structure are stainless steel, which provide superior resistance to rot and corrosion in the marine environment. All told, the floating structural frame is 7 feet long, 6 feet wide, and 3 feet tall when assembled. An isometric view of the assembly is shown below in **Figure 8**.

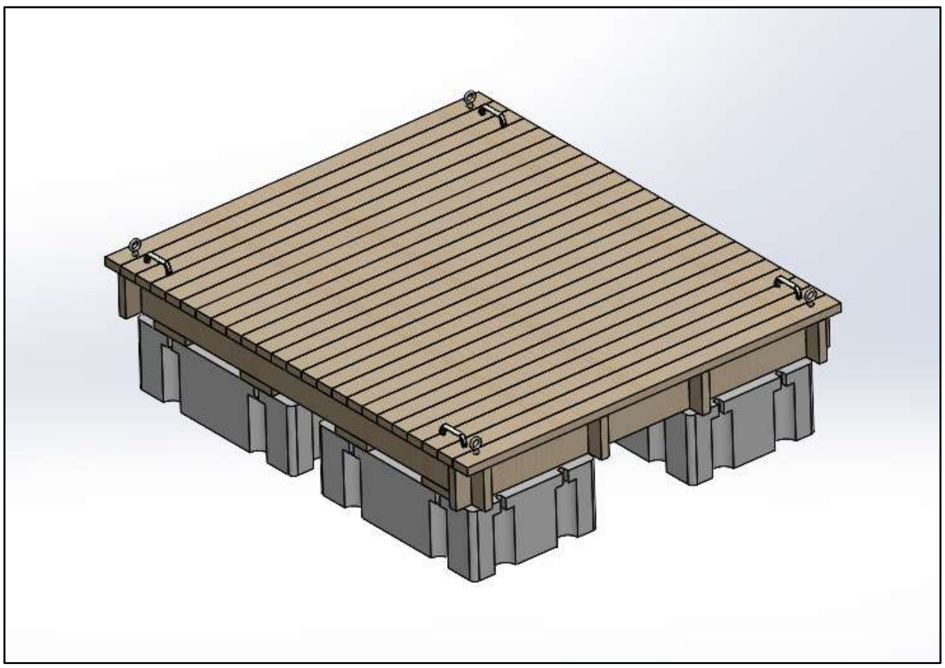


Figure 8. *An isometric view of the base floating structural frame subassembly.*

2.2.3 Mechanical Drivetrain Subsystem

The mechanical drivetrain encompasses all the components required to transmit the heave of waves into usable power, beginning with a winch apparatus and ending with a generator shaft input.

The winch employs a 3/16” polymer fiber cable, one end of which is anchored to the sea floor with an 800-pound mooring weight. The cable is Dyneema SK-78 fiber and has a maximum rated tensile strength of 5,400 lb. The cable rises through the center of our structural frame and is wrapped clockwise around a 6-inch axial section of a 1¼” 316 stainless steel shaft, herein referred to as the “main shaft”. The end of the cable is attached to the main shaft with an adhesive nylon winch grabber. As the a passing wave forces the buoy upwards, the tensile force in the cable, F_i, is transmitted to the spool, imparting a torque, T_i, on the main shaft. The cable unspools, and the main shaft rotates clockwise with angular acceleration, α_i, to a maximum speed, ω_i. The rotation of the main shaft supplies mechanical power, P_i, to the drivetrain.

A secondary winch apparatus uses an effective torsion spring to re-spool the cable slack as the dock moves downward through the trough of the wave. The torsion spring apparatus also maintains tension in the winch cable to accommodate for slack due to changing tides. The 'spring' is a 5/16" EPDM rubber cord that is wrapped counterclockwise around the main shaft. Similarly, we use a nylon winch grabber to fasten one end of the bungee to the shaft. The cord is highly elastic, capable of stretching up to three times its original length. It passes through a series of three pulleys mounted to the deck, as shown in **Figure 9**.

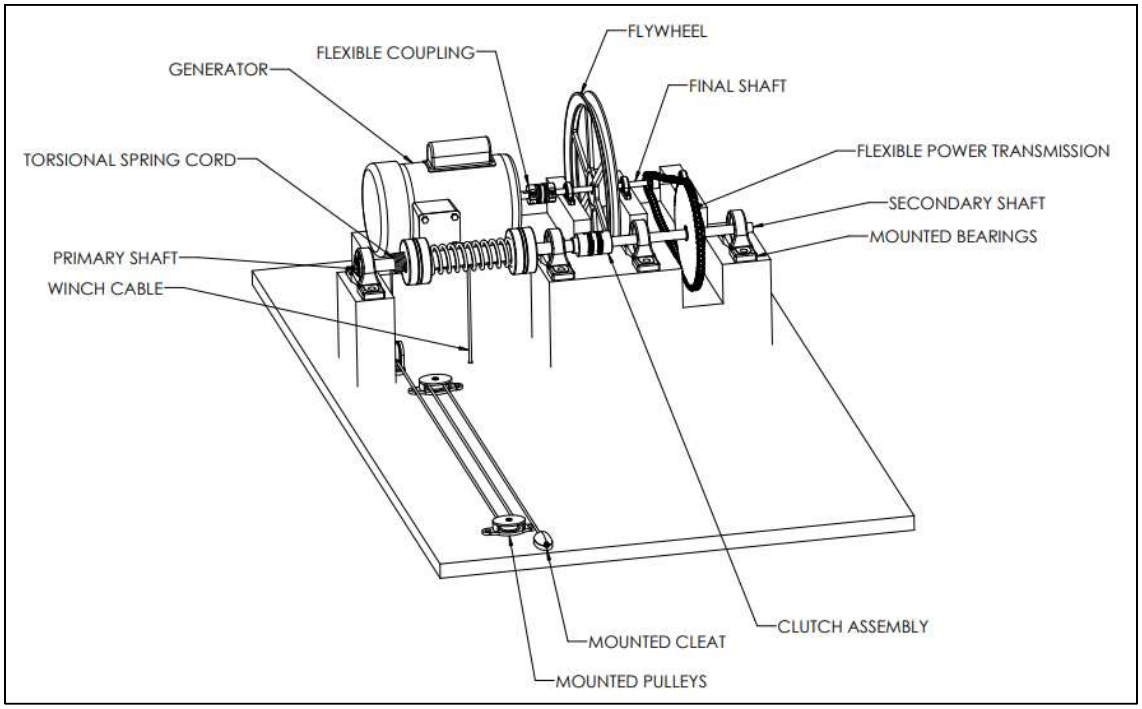


Figure 9. *Isometric view of the mechanical drivetrain system design model from SolidWorks™*

The first pulley is mounted directly below the main shaft and rotates in a plane perpendicular to the deck, turning the cord 90 degrees so it is strung horizontally just above the deck. The other two pulleys rotate in a plane parallel to the deck, doubling the cord back on itself twice to maximize its runout length, l, at 82 in. The end of the cord is tied off to a steel wraparound cleat. During open-water deployment, the cord will be pre-tensioned by sinking the mooring weight with a prescribed amount of winch cable runout, L, equal to the dock deployment depth, d, minus the pretension value, l_p. As the winch cable unspools and rotates the main shaft, the rubber cord is coiled around the main shaft, stretching its length to $l + l_p$. Tensile force in the elastic cord, F_s, ensures that there is sufficient counterclockwise torque, T_s, to respool the winch cable slack at the bottom of the wave trough.

Three ½ inch thick, 5 inch diameter aluminum discs are mounted onto the main shaft to confine the winch cable and the elastic cord. The main shaft is supported by two sealed ball bearings, which are encased in mounted pillow blocks. The bearings have a dynamic radial load capacity of 4,350 lb. 15-7 PH stainless steel retaining rings secure the bearings and aluminum discs at the proper axial position. The retaining rings snap into lathe-turned grooves on the shaft and have a thrust load capacity of 7,460 lb.

A one-way clutch assembly connects the main shaft to a 1" diameter secondary shaft. The clutch assembly is located between the winch and the large sprocket in **Figure 9**, above. The purpose of the clutch is to prevent the main shaft from back-spinning the generator input shaft on the downward heave of the wave. We selected a steel one-way locking needle-roller bearing clutch, which is slip-fit onto the end of the main shaft. The clutch has a maximum torque transmission of 70 ft-lb, or 840 in-lb. A steel clamping coupling connects the outer race of the clutch to the end of the secondary shaft. The coupling has a maximum torque transmission of 2,030 in-lb.

A sprocket-and-chain flexible transmission steps up the speed of the secondary shaft to a final 1" shaft. Single strand ANSI 50 rated chain and sprockets were selected as they are rated to transmit the expected maximum mechanical power of 2.0 kW (2.68 hp) at the expected final shaft operational speed of 500 rpm (see Section 2.3, Performance Analysis) with a safety factor of 1.3. The power ratings of the transmission used are shown below in **Figure 10**.

No. of Teeth Small Spkt.	5/8" Pitch Standard Single Strand Roller Chain No. 50												
	Revolutions per Minute — Small Sprocket												
	25	50	100	200	300	400	500	700	900	1000	1200	1400	1600
	Horsepower Rating												
11	0.24	0.45	0.84	1.56	2.25	2.92	3.57	4.83	6.06	6.66	7.85	8.13	6.65
12	0.26	0.49	0.92	1.72	2.47	3.21	3.92	5.31	6.65	7.31	8.62	9.26	7.58
13	0.29	0.54	1.00	1.87	2.70	3.50	4.27	5.78	7.25	7.97	9.40	10.4	8.55

Figure 10. *Power ratings of ANSI 50 roller chain at varying speeds.*

A 60-tooth sprocket is mounted to the secondary shaft with a key using a keyway that is mill-cut into the shaft and a set screw. A 12-tooth sprocket is mounted to the final shaft in the same fashion. The chain and sprocket flexible transmission has a gear ratio of 5:1, meaning the resulting speed of the final shaft, ω_f , is five times greater than ω_i, and the torque applied to the final shaft, T_f, is five times less than T_i. The chain is self-lubricating and corrosion-resistant. Adjacent to the small sprocket on the final shaft is a 45-pound flywheel. Through-bolts secure the flywheel to flange-mount shaft collars. The added rotational inertia of the flywheel creates a smoother input speed for the generator, limiting the deceleration associated with friction and back torque on the downward heave of the wave. The secondary shaft is supported by two sealed ball bearings, which are encased in mounted pillow blocks. The bearings have a dynamic radial load capacity of 2,800 lb. All bearings, sprockets, and the flywheel assembly are secured at the proper axial position with retaining rings. The chain and sprockets are encased in a sealed plastic chain case for additional protection from debris.

The final shaft connects to the generator input shaft via a flexible shaft coupling, transducing the mechanical energy into the electrical domain. We selected a 3-phase AC generator rated for 1 kW and 120V at 450 rpm. This rotational speed was determined from a Simscape Driveline model on Simulink™, where we modeled each element of the mechanical system for a one-meter wave amplitude and eight-second period (see Section 2.3). The final shaft is supported by three bearings, one at its end and two on either side of the flywheel assembly. The bearings are the same as the ones used for the secondary shaft.

Within the drivetrain system, all mechanical components, including the shaft, bearings, chain, sprockets, clutch, and couplings, are stainless steel for maximum corrosion resistance in the marine environment. The bearings are permanently lubricated and meet IP69K standards for washdown applications. The overall weight of the drivetrain system was estimated at 225 lb from the SolidWorks model, which contained accurate component material assignments and material density information. This estimate included a conservative multiplier of 1.5 on the model weight. Drawings of the drivetrain shafts with exact dimensions can be found in Appendix 1.

2.2.4 Electrical Subsystem

The electrical subsystem encompasses the components that modify and store electrical energy for distribution. The generator spins with the final shaft, inducing an alternating current. This 3-phase AC power is then rectified to make it nearly DC. We use a charge controller to control the DC power stored in the battery and prevent current leakage from the battery to the generator. The battery is also connected to an inverter through the charge controller. This inverter supplies power to the desired output, whether it be a commercial electric boat or for the purposes of a community microgrid. For our testing purposes, we chose to implement a desalination system driven by a pump as the output load. The Midnite Solar charge controller also includes an auxiliary output to control the output of the system. When the battery charge state is too low (15%), the charge controller switches off the output power to allow the batteries to recharge, and it turns the output power back on when the batteries reach a charged state (85% capacity). **Figure 11** illustrates the complete schematic of our electrical subsystem.

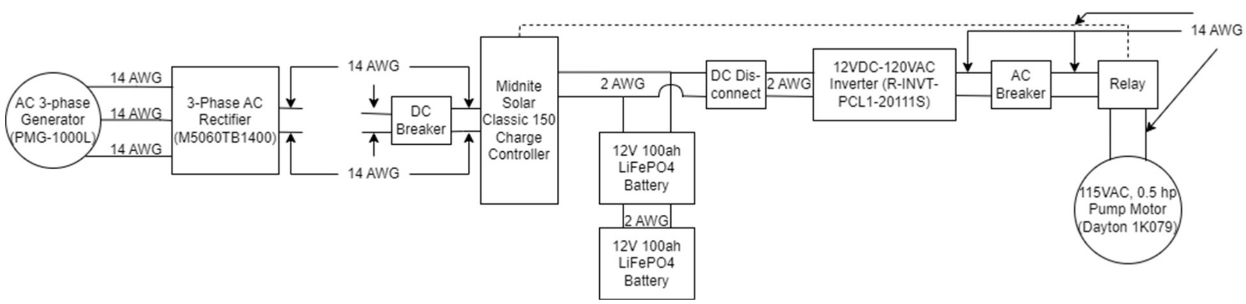


Figure 11. *Electrical subsystem flowchart, including wires, breakers, and disconnects.*

The rectifier is rated for a maximum voltage and amperage of 1400V and 60A, respectively. For reference, the nominal expected values are 120V at 10A. We upsized the rectifier to ensure durability in an extreme sea state. Even if the mechanical system failed to disengage during a large influx of wave energy, our rectifier has a safety factor of 10 for voltage and 5 for current. This should be sufficient to protect our circuitry in a worst-case scenario.

To control how the batteries are charged, we implemented a charge controller which comes with a customizable I-V for max power point tracking (MPPT). A relay switch was needed to regulate the supply of electrical load from the battery to the inverter. To enable this function, we used auxiliary ports that could provide operating voltage. Hence, we chose a solar charge controller with programmable wind-tracking capabilities that imitate the periodic changes in wave behavior.

As mentioned previously, we opted to demonstrate the power delivery capabilities of our design using a desalination system. This decision was made in anticipation of the Build and Test challenge, as we do not expect to have access to an electric fishing vessel. The reverse osmosis membrane was supplied by a former Cal Poly project; however, we still needed to source a pump and motor. The pump was selected based on the mechanical engineering team's concerns about saltwater corrosion, desalination operating pressure (800 psi), and membrane flow rate; reverse osmosis forces fresh water out of a saline solution (i.e., seawater) using a selectively permeable membrane. Using the required pump specifications, we selected a stainless-steel water pump rated at 0.4 hp (approximately 300 W) and 0.5 gal/min flow rate. After choosing the pump, we looked for a 56C face-type motor that could provide the necessary amount of horsepower. We settled on a totally enclosed fan-cooled (TEFC) ½ horsepower single-phase motor with a nominal current of 7.7 A. The current was an important consideration because a higher-rated current would require us to source additional components that adequately compensate for an associated increase in surge current.

We set up the inverter to be a pure sine wave because it is a more reliable power source and is efficient when running large applications such as electrical motors. The selected inverted has a 2 kW nominal value with a power surge rating of up to 6 kW. This window is enough to handle the surge current of an estimated five times the nominal current of 7.7 A. Further, the 2 kW power rating is sufficient to power a motor for our desalination pump.

The batteries are lithium iron phosphate. Compared to alternative batteries of a similar capacity, such as a lead-acid design, $LiFePO^4$ cells have a much longer cycle life (roughly 4000-15000 recharge cycles versus 500–1000 cycles for a lead-acid battery). The $LiFePO^4$ designs can also charge much faster than lead-acid batteries, allowing for more power absorption during high-energy sea states. Unfortunately, the discharge rate was a limiting factor, as commercially available $LiFePO^4$ batteries typically have a max surge discharge current of 200 A. The problem stems from the equivalent DC amperage required by our pump; in our prototype, the pump has a high in-rush current on startup of up to 40 A. This 40 A at 120 VAC translates to roughly 400 A at 12 VDC before the inverter. As such, we chose to use two 12V $LiFePO^4$ batteries in parallel. This increases the maximum available current for pump startup. An added benefit is an increase in total system energy storage capacity, allowing for the pump to run for longer periods of time. It's important to note that the energy demand of an electric fishing vessel is much greater than that of our desalination pump, so the battery storage system would have to be appropriately upsized. If several modular WECs are used in tandem, a large battery storage could be housed on a separate platform so the immense weight/inertia does not inhibit the energy conversion efficiency of our power take-off system.

The relay in our system is located between the inverter and pump motor, allowing us to turn the motor on and off based on the battery charge capacity. There were three criteria for selecting the relay: coil voltage, switching voltage, and current rating. The coil voltage, which is the DC voltage required to turn on the relay, was selected based on the auxiliary output voltage of the Midnite Solar charge controller (which controls the relay). The aux-out port of the Midnite Solar is 12 VDC, which must match the coil voltage. The switching voltage is a rating of the maximum voltage that the relay can control. In our system, the relay is controlling 120 VAC. We chose a relay with a switching voltage of 277 VAC, representing a safety factor of 2.3. The final consideration was the current rating. The nominal working current of the motor is 7.7 A; however, there is an inrush current of up to 40 A. As such, we chose a relay with a current rating of 40A.

The pump motor used in the system represents a load drawing power from the system to show proof of concept that our system would be capable of generating and supplying power to larger industries that would use the power generated from our system such as EV boat charging or microgrids. The system will be able to control the power distributed shown by using the relay to control the pump motor's power draw. By showing our system can power a pump motor for desalination, we show that our system has the potential to power something greater when multiple buoys are put together.

Our data acquisition system consists of a microcontroller, hall-effect current sensors, and a voltage transformer. The microcontroller was chosen due to its low cost and ease of use. Current sensors work as ammeters and produce 200 mV/A at a maximum of 5 V. The voltage transformer scales voltage in a range of 0-240 V to just 0-5 V, which allows the microcontroller to deduce a relative voltage.

Finally, our wiring was chosen based on the ampacity of the gauge wire, which takes into consideration the maximum current safety allowed in the wire. Further, we considered our voltage drop calculations during the selection process. The breakers and disconnects were implemented to isolate the batteries from the rest of the system. This allows the electrical subsystem to shut off when an unexpected surge occurs or maintenance is required. The values of the breakers and the requirements for the disconnects were decided based on the expected currents in the system. When meeting with one of Cal Poly's electricians, we added fault circuit interrupts. This critical safety decision stemmed from the fact that several of our components handled a nominal voltage of 120V.

The overall weight of the electrical system was estimated at 250 lb from summing the individual listed manufacturer weights of selected components.

2.3 Performance Analysis

The following section describes the specifications that ensure our design meets the stakeholder requirements listed in **Table 5**, including justification for how each requirement will be met.

Table 5. *Key Engineering Specifications for Design.*

Engineering Specification	Value	Compliance†
#1 Peak Energy Generation Rate	1 kW	A, T
#2 Energy Storage Capacity	1.2 kWh	S, I
#3 Material Cost: $10,000	$10,000	I
#4 Maximum Wave Height Operating Range	13 ft	T, A
#5 Fatigue Lifespan: 10^6 cycles	10^6 cycles	A
#6 Abuse Case Maximum Stresses: FOS = 3	3	A
#7 Deployment/Installation time: 24 hrs	24 hrs	I
#8 Emergency Shutdown	Pass	T

†Compliance methods: (A) Analysis, (I) Inspection, (S) Similar to Existing, (T) Testing

ˆman-hours (MHRS) = number of people x total time

2.3.1 Load and Stress Analysis

To characterize the loads expected during normal operating conditions and extreme sea states, we utilized NREL's online Small-WEC Analysis tool. Specifically, we identified average power take-off loads, which allowed us to design critical components for ultimate strength and fatigue. We compared NREL's data to our extreme loading case, which assumes the power transmission locks and the entire float is submerged. In this orientation, the upper limit of the buoyant force on the dock, and by extension, the maximum tension in the cable, is achieved. Both situations were analyzed at extreme and average loads. Further, a MATLAB script and Finite Element Analysis (FEA) model were used to ensure our device would not fail in direct loading or fatigue, as shown in Appendix B.

The results showed that for our maximum loading case, the buoy experiences a cable force of 2,955 pounds, with the safety factor for yielding in the primary 1.25" shaft being 0.98. Initially, we calculated a higher safety factor, but a mistake in our analysis was only identified after we placed our purchase orders. Despite the current value being slightly below 1, we decided to move forward with the design due to the low probability that our device will fully submerge during testing. If our float does fully submerge, we understand that the main shaft may fail in bending, but significant water exposure to sensitive electrical and mechanical components will also occur. We recommend that our Cal Poly successors modify the design to ensure the main shaft has a significant safety factor in extreme conditions if they decide to improve and expand upon our design in next year's MECC competition.

Fortunately, the average loading still has a large safety factor, with the maximum stress occurring at the winch cable's point of application. This value is slightly below 10,000 psi, as shown in **Figure 1212.**

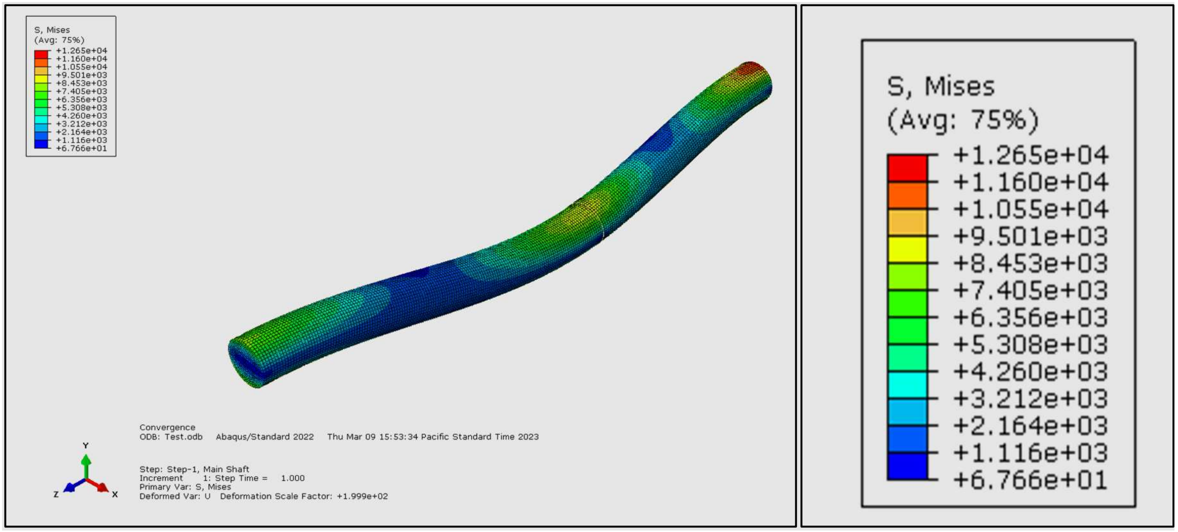


Figure 12. *Screenshot of FEA model (Von Mises Stress for Average Loading on Main Shaft).*
**Note: Exaggerated deflection*

We repeated stress calculations for the final generator shaft and found it had a very large safety factor, indicating the primary shaft would be the first to fail. After testing the maximum load case, we used data from the Small-WEC Analysis tool to determine the fatigue life of our mechanical system[8]. For our nominal expected wave amplitude of 1 meter and period of 8 seconds, we obtained a cable force of 1007 lb. After solving the system by balancing forces and moments, we found our Goodman factor of safety to be 1.4, indicating the main shaft should have infinite life under standard operating conditions, which satisfies specification #6 in **Table 5**.

2.3.2 System Dynamics Model

As mentioned in Section 2.2.3, we used our understanding of system dynamics to determine the expected operating speeds of our mechanical system. Initially, we employed the method of analysis taught in our undergraduate courses. A set of normal trees were drawn with all of the relevant across-type and through-type energy sources and storage elements in our translation and rotational mechanical energy domains (See **Figure 13**). Next, we used our selected wave amplitude and period to develop a time-series relationship between time and the upward velocity of the wave heave, represented as an ideal translational velocity source. The buoyancy effect was modeled as a spring because for a constant cross-sectional area, the buoyant force has a linear relationship with the submersion depth of our buoy. From our normal tree, we used the elemental and constraint equations to generate the system matrices and transfer function. Our undergraduate understanding of energy domains limited our ability to model the characteristics of an AC generator, so we assumed a constant torque load of 20 Nm, which is the rated back torque of our generator. At this point, we wrote a MATLAB script to determine the expected shaft speed for our wave velocity input function, as displayed in Appendix C.

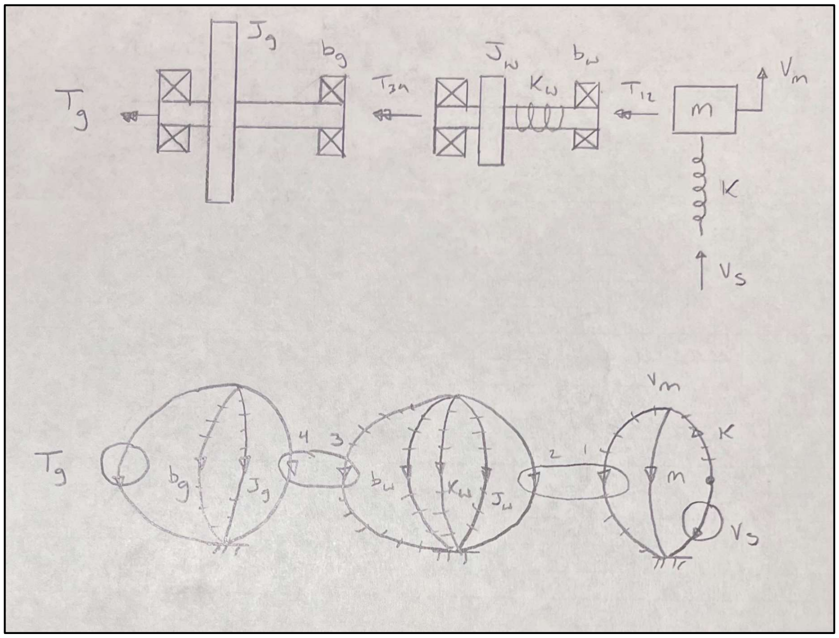


Figure 13. A hand drawing of our system and associated normal tree.

The MATLAB model put us in the ballpark of expected shaft speed, but we were unsure how to write code to account for the unidirectional clutch. We consulted our past professors and learned about Simscape Driveline, which is a MATLAB add-on that allows us to analyze our system pictorially (See **Figure 14**). Simscape allowed us to include a unidirectional clutch and deduce our expected shaft speed of 450 rpm.

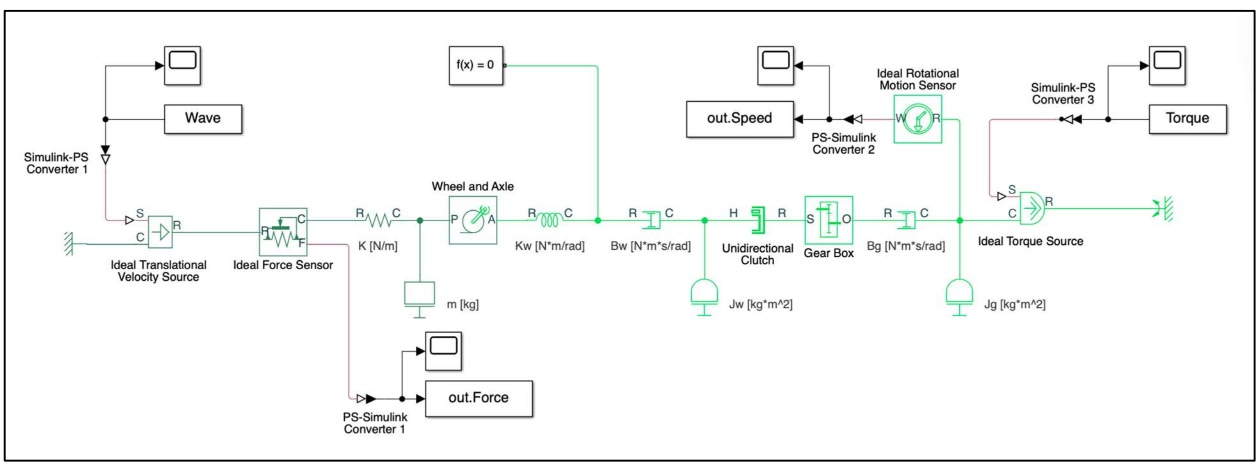


Figure 14. Screenshot of the Simscape Driveline model used to determine rated operating speeds.

2.3.3 Power Analysis

To calculate the expected peak power generation, the flywheel operating speed obtained from the system dynamics model and the maximum expected tension in the winch cable obtained from the MATLAB model was used as a starting point. With F_i equal to 2,955 lb, this results in a T_i equal to 1,847 lb-in on the 1 ¼" diameter main shaft and secondary shaft. With the transmission ratio of 5:1, this results in a T_f of 370 lb-in on the final shaft. With ω_f equal to 450 rpm, the value obtained from the system dynamics model, the resultant power transmitted through the final shaft is 2.0 kW, or 2.7 hp. However, accounting for mechanical and electrical losses, which result in an overall device power-conversion-capture efficiency of 50% or less, the peak expected electrical power generation level is 1.0 kW. The efficiency is mostly due to electrical losses, as the generator is not expected to operate at an electrical to mechanical power conversion efficiency higher than 60%. The mechanical drivetrain is not expected to operate at an efficiency higher than 85% due to frictional losses and the oppositional torque of the torsional spring on the main shaft.

The 120 V generator should provide 1 kW at 500 rpm with 8.33 A. Because of the generator's high voltage, we introduced circuit protection with a circuit breaker and ground fault circuit interrupters. When the rectifier converts the generator's 3-phase AC signal to a DC signal, some losses are introduced, although they are likely negligible because the diodes use a small amount of power.

With our two parallel batteries, we can achieve the 2.4 kWh of energy storage specified in Table 5. The data acquisition will be controlled is powered by an Arduino Uno, which is powered by our 9V battery. The Arduino Uno has a nominal power draw of 3 W, which is largely negligible. The 9V battery has a storage capacity of 500 – 600 mAh, and the Arduino Uno consumes 50 - 60 mA. In the absence of input wave power, the Arduino Uno could continue to run tests for 8 hours.

2.4 Safety, Maintenance, & Repair

We conducted a failure modes and effects analysis (FMEA) to ensure all potential failures were addressed with preventative measures, as well as a Risk Assessment using DesignSafe™ software (see Appendix 2). We individually analyzed the buoy and winch systems to identify failure modes and determined proactive activities and detection plans for each mode of failure. The Seawater, UV exposure, marine life, and intense stresses from the waves are the most significant potential causes of damage to mechanical components. To address the immense forces of the ocean, we have appropriately sized parts to mitigate yielding and fatigue. Due to the saltwater environment, we used corrosion-resistant materials. Although expensive and not required for brief testing periods, we wanted to invest in durable components that future Cal Poly MECC teams could reuse for years to come. This will allow future teams to allocate their budget toward design modification rather than replacing an array of damaged components.

The electrical subsystem is most at risk of failure in a saltwater environment; thus, we have decided to move forwards with a professional-grade waterproof container. We will need to drill holes for wires to pass through and plan to waterproof those entry points with caulk, desiccants, and various other techniques as needed. While this device will undoubtedly require maintenance, we would like to limit the servicing frequency of a consumer-ready design to an annual basis. This would allow us to reduce costs associated with chartering a boat and, possibly, a technical diver.

3 Build and Test Challenge

The following section details how we designed a prototype of the dock, procured parts and materials, manufactured components, and assembled our subsystems to build the wave energy converter. It then delves into the testing process and shares our results, including both our successes and areas for improvement with this prototype.

3.1 Design Process

We began the design process by familiarizing ourselves with the Blue Economy Report. After learning about the different markets for marine energy, we each individually researched topics we were interested in, sharing our top choices with the entire team. As every team member was interested in converting wave energy to electricity, particularly for desalination, we pursued that path, brainstorming potential methods for each necessary function of the device. We spent multiple weeks sharing ideas before using weighted decision matrices to narrow down our design. We created a series of initial mechanism prototypes and CAD models to showcase our design, performing design reviews with peers, faculty, and experts along the way. Then, with our final prototype design ready, we began sourcing parts and finalizing our engineering drawings to prepare for manufacturing. For the built dock prototype, there were several differences from the original design discussed in Section 2.2. Standard fir was used instead of marine grade lumber for the structural frame. Polyethylene paneling for waterproofing was not included in the build as there was not enough time to test the dock in the water, nor was a chain case used. Nickel-plated stainless steel bearings were used which are not IP69K washdown rated. When constructing our prototype, we were more conservative with board placement to save weight than the original design. The machinability of wood allowed us to assemble the dock with real-time feedback for component placement and orientation. For the flywheel, a rubber weight plate was chosen, because we struggled to find an affordable, marine-rated flywheel that satisfied our inertial demand. The flywheel was only 45 lb rather than the 90 lb specified in the original design.

3.2 Fabrication and Assembly

Our prototype featured two mechanical systems that required manufacturing: the buoy platform and the power transmission. As shown in Appendix C, the cost of our project was significant, with most of the power transmission system utilizing off-the-shelf components. However, we purchased custom-bored couplings and machined our flywheel mounting assembly and the transmission shafts from stainless steel stock using a manual mill and lathe. Grooving and turning operations were used on the lathe to create grooves for external retaining rings and clearance to locate the bearings, sprockets, and collars on the shafts. Important milling processes included end milling keyways into the stainless shafts and drilling through holes into the flywheel weight plate as seen in **Figure 15**15. Sourcing flywheels with adequate marine ratings and inertial properties proved difficult, and as a result, we sourced an 18-inch diameter, 45-pound bumper weight plate.

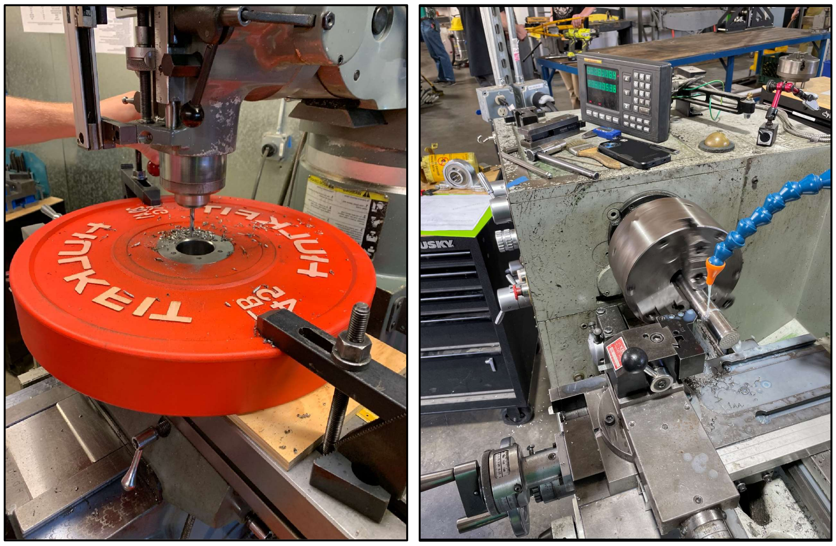


Figure 15. *Machining of flywheel mounting holes (left) on manual mill and primary shaft on lathe (right).*

We elected to construct a platform for the buoy from untreated wood rather than sourcing an existing mooring buoy or lighter, more rigid materials like aluminum or carbon fiber in the interest of cost, safety, time, and ease of manufacturability. The wood frame seen in **Figure 16** was constructed around the dock floats before attaching the decking.

Figure 16. *Initial floating structural frame assembly (assembly was upside down to attach floats).*

The mechanical and electrical assemblies were completed separately before integration with the float subsystem. Center-to-center distance of the sprockets and tensioning of the chain drove the spacing of the power transmission shafts while the placement of the electrical system housing was less critical. Our goal was to distribute weight but minimize the distance that free wires would have to travel. **Figure 17**17 shows the completed build with the electrical and mechanical systems coupled via the generator.

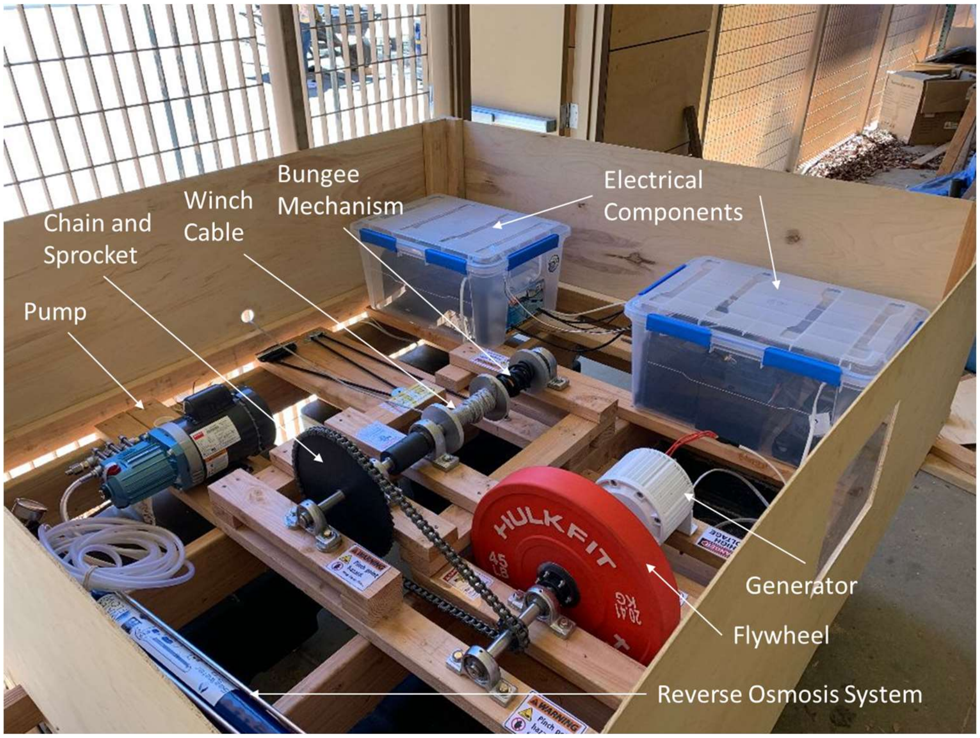


Figure 17. *Surf Supply's fully assembled prototype.*

The electrical assembly's core components are prebuilt parts. The main factors in assembling the system were wiring, housing, and mounting. The wiring was purchased with the components rated currents and sizes in mind. While some components have specific size requirements for the wiring, others do not. Specifically, we calculated the wire size such that it could handle the nominal power at of the system. The wires were cut and measured throughout the manufacturing process to prevent an excess in length which would result in greater loss of power. Additionally, long wires would make it difficult to streamline our set up; a deficit in length could create tension in the wire making the connections easier to fail and the subsystem harder to mount.

The housing of each component we also considered due to the need to for water resistance. The minimum IP rating of the component boxes was determined to be IP66 from the chart in **Figure 1818**. IP66 ensures the components will be sufficiently protected from the effects of the ocean. The generator and motor have their own housing due to their distance from the electrical system and the inverter has its own housing due to its large size, need for maximum ventilation, and safety requirement of distance from the battery. The rest of the components share a housing unit.

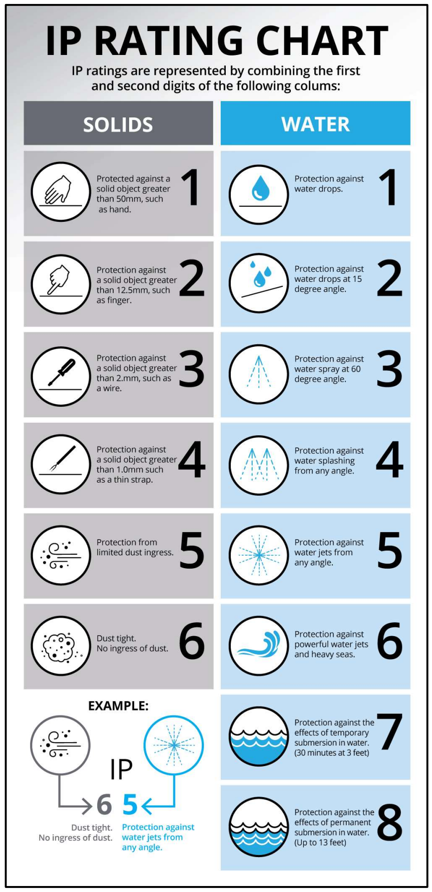


Figure 18. *Ingress protection rating chart*

The components will be mounted to the housing units with a combination of wood, plastic, screws, and adhesives to prevent the components from shifting within the housing unit and prevent exothermic heat from each component affecting the others.

3.3 Testing Methodology

Key testing objectives included the validation of individual components like the charge controller, critical subsystems such as the spring return mechanism, and finally the overall device performance, as shown in Appendix D. Preliminary testing was completed for the mechanical and electrical systems separately before measuring overall device performance and electrical power output with the two systems integrated. These tests verified successful design decisions and highlighted improvements for future prototype iterations and testing.

3.3.1 Preliminary Electrical Testing

The electrical system of our prototype dock was tested in various ways to ensure proper functionality, test system efficiency, and confirm proper safety mechanism operation. We began by performing tests on the individual components to record their characteristics. As we began building the system, we incrementally tested portions of it and took measurements of the power consumption of each device in different modes of operation. This would allow us to calculate the power efficiency of each component as well as all the electrical components in series and calculate the total power efficiency. While testing each section of the design, we included the safety components such as breakers, disconnects and GFCI's to make sure we were protected throughout the whole building and testing process.

We found the power draw of the charge controller by connecting it to a 12VDC power supply and measuring the current drawn. A similar test was conducted for the inverter to find its no load power draw. These measurements were important to find and understand the system's potential losses.

Finding the operating power of the motor will show the potential of powering key market needs through powering a motor for an adjacent market. To get the operating power of the motor used to run the pump, we powered it with a 115 V_{rms}, 60 Hz AC power supply. We also tested the functionality of a controlling relay for the motor by connecting the relay to a 9V DC supply. We took measurements of the operating current as well as the peak inrush current to ensure that the inverter and batteries were able to supply enough power.

The safety system will be enabled to shut off the system. The system should not be charging or discharging from the battery and isolate the electrical components that would harm the other components or people. By turning off the charge controller, the input from the generator is disconnected from the batteries and the switch governing the output power is switched off, effectively turning off the entire system.

The power generation subsystem of our device requires additional testing to form a model of the generator. This would include finding the open circuit voltages produced at various rpm as well as the relationship between torque and current that would give an understanding of the generator's characteristics. These characteristics would be used to form an optimized IV curve of the charge controller's MPPT algorithm to achieve maximum system efficiency. Further testing of the motor with the pump as a mechanical load will be necessary to gain a full understanding of the potential functionality of our system as a power generation and distribution unit.

3.3.2 Preliminary Mechanical Testing

Before integrating device subsystems to test overall performance, we performed a series of preliminary mechanical bench tests, with test procedures shown in Appendix E. For all preliminary and subsequent testing, we ensured safety by constructing a wood testing perimeter around the prototype, protecting users from potential harm caused by device hazards identified during risk assessment, including component failures. A transparent window mounted in the perimeter allowed for visual assessment and laser measurement. Preliminary mechanical testing was performed with the electrical subsystem disconnected by opening the circuit breaker between the generator and the charge controller, so that mechanical drivetrain functionality could be verified independently.

For our first preliminary mechanical test we qualitatively evaluated the winch cable to determine if the line would tangle during respooling and cause any issues with the device. To do this we repeatedly pulled our winch cable a set distance and then released it, observing the winch cable's actions and noting any issues. We performed this test for a variety of winch cable angles and speeds, with the goal being to prove that our cable would not tangle even with unpredictable motion.

The second preliminary test we performed sought to verify the functionality of the torsional spring apparatus and determine the optimal amount of pretension in the elastic cord. The results from this test would allow us to properly select a cable pretension value prior to performance testing so that the dock can achieve the desired wave amplitude operating range while maintaining tension and proper re-spooling of the winch cable. To obtain an optimal pretension value, we manually pulled the end of the winch cable to varying distances using a measuring tape line and then measured the distance the cable would return to, measuring the remaining slack in the cable as a function of displacement amplitude. This would allow us to calculate the minimum pretension value necessary to respool the winch cable as a function of displacement amplitude.

Lastly, we performed a third preliminary test to validate the functionality of the drivetrain mechanism. In this test, we manually pulled the end of the winch cable a set amount using a measuring tape line and measured the resultant rotational speed at the flywheel with a handheld laser tachometer. The winch cable was pulled horizontally through the erected testing perimeter, as pulling the cable vertically beneath the dock for this test was not feasible. The results from this test would allow us to verify that all drivetrain components interface as expected, and that unspooling the winch transmits mechanical power through the drivetrain. It would also allow us to verify that unspooling the winch by a realistic amount results in a flywheel rotational speed within the expected operational range predicted by our system dynamics Simulink model before integrating the electrical subsystem.

3.3.3 Device Performance Task: Land Testing

After preliminary testing on the electrical and mechanical subsystems, we tested overall device performance on land by simulating wave motion with winch cable pulling and measuring generated input power to the battery. We pulled the end of the winch cable horizontally with a car hitch to achieve a cable tension within the expected operational range predicted by our performance analysis and system dynamics Simulink model (~1000 lb). To simulate wave motion, we pulled the winch cable by a discrete amplitude, h, over a measured time period, t_d, followed by an equal time period of leaving the cable static, repeating this sequence 3-5 times in a series for each discrete amplitude tested. The displacement amplitude was measured with a tape measure line and the time period was measured with a stopwatch. The displacement amplitude is equated to wave height, and the total time period, $2t_d$, is equated to the wave period. The end of the cable being pulled relative to the fixed dock simulates the upwards heave of a passing wave. In actual operational deployment, upwards wave motion will move the dock relative to the fixed end of the cable on the sea floor mooring. Leaving the cable static for half of the period simulates the downwards motion of the passing wave, since this allows the flywheel to spin down freely with no further torque input. In actual operational deployment, during downwards wave motion the clutch assembly prevents counterclockwise torque transmission to the flywheel as the torsional spring apparatus respools the winch, and so the flywheel spins down freely with no torque input. The simulated "waves" were applied in a range of 3 feet to 9 feet and 6.5 seconds to 14.5 seconds to replicate realistic sea states along the California coast, as seen in Figure 3. The dock was subjected to a total of 16 unique combinations of amplitude and period. The resultant peak flywheel rotational speed, ω_f, for each "wave" was measured with a handheld laser tachometer and averaged over each series. The resultant peak current, I, and voltage, V, output from the charge controller to the battery for each series of "waves" was recorded from the charge controller sensor data. The current and voltage were used to calculate the peak electrical power input, P_b, to the battery for each series of "waves".

3.3.4 Device Performance Task: Open Water Testing

The purpose of our prototype build and land testing was to get the dock ready for open water performance testing. Our team quickly decided on open water testing as the ideal methodology for the device performance testing task due to the lack of a nearby facility possessing a wave testing tank. Beginning in December 2022, our team was in continuous contact with two personnel at Integral Consulting, a facility in the TEAMER network with open water testing support capabilities. We discussed open water testing logistics as we designed our device design and built the prototype. We developed an open water testing plan with Integral, which will not be covered in this report, and applied for TEAMER funding for testing. However, as a new MECC team, due to time constraint, the dock prototype was not yet ready for open water testing as of the submission of this report.

3.4 Testing Analysis

This section analyzes the raw measurements of the testing procedures outlined in the previous section and summarizes the results.

3.4.1 Preliminary Electrical Testing Analysis

Initial testing of the charge controller indicates that it behaved as expected. The charge controller had a power draw of 3W in testing, which is in line with the manufacturer's ideal self-sustaining power draw of 2.8W-4W in the spec sheet of the manufacturer. The inverter measured a power consumption of 40W with no load, which was slightly higher than the manufacturer's stated no load power consumption of 20W. The power loss between the charge controller and inverter is 43W.

Powering a motor with a common grid electrical socket that supplies a $115V_{rms}$ at 60Hz allowed us to measure the current draw of the motor. The motor was found to draw 7.9A with no load, greater than the expected manufacturer's specification of 7.7A. The peak in-rush current or start up current was measured to be 65A for a less than a cycle of the AC supply, greater than the expected in-rush current of 40A. These factors indicate a greater loss of power than expected. This would result in a need to resize a circuit breaker; however, this will not affect the overall validity of our design of a power generation and supply unit. The batteries and inverter could supply a 65A current meaning our system could handle this load.

The electrical system shut down successfully with no current measured through the system once the charge controller was shut off. The placed breakers also prevented any current in the circuit indicating the successful functionality of the emergency shut off system.

Further testing of the generator would give a wholistic understanding of the potential power supply of the system. A theoretical power curve can be decided for the charge controller; however, a tuned curve can only be found with further testing.

3.4.2 Preliminary Mechanical Testing Analysis

The results of the second preliminary mechanical test for verifying the torsional spring apparatus functionality are shown below in Figure 19 and indicate flaws in the elastic cord. The cord was never able to fully respool the winch cable to its original position for any displacement, and a clear cutoff in operating range is observed for displacements greater than 35 inches where the winch cable was unable to return within 25% of its displaced distance. From observation, this can likely be attributed to high friction the bungee cord material experienced with itself and extreme pinching where it wrapped around the main shaft. This test indicated that the torsional spring would need to be redesigned with a different material. The current design would allow for slack to build up in the winch cable over time, preventing continuous power transmission.

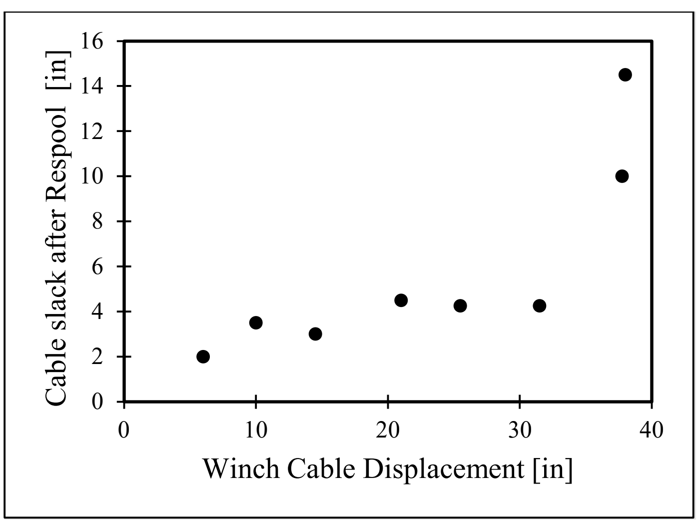


Figure 19. *Winch cable displacement and return to equilibrium test results.*

3.4.3 Device Performance Land Testing Analysis

The device performance land testing successfully validated our prototype’s functionality, as our team was able to measure significant electrical power generation caused by simulated wave motion. The collected data is shown below in **Table 6** and **Figure 2020**. 9

Table 6. *Device performance land test data.*

Winch Cable Displacement, h **[ft] ± 0.5**	Displacement Period, $2t_d$ **[s] ± 0.1**	Average Displacement Period **[s] ± 0.1**	Peak flywheel speed, ω_f **[rpm] ± 0.05%**	Peak Current, I **[A] ± 0.1**	Peak Voltage, V **[V] ± 0.1**	Peak Power, P_b **[W]**
3	7.9	11.7	150	7.6	13.1	99.6
3	10.5		157			
3	16		155			
3	14.6		147			
3	9.3		144			
5	10.5	12.1	161	8.9	13.1	116.6
5	14.5		151			
5	11.7		181			
5	11.6		148			
7	10.1	10.5	142	6.6	13.1	86.5
7	11.4		149			
7	9.8		156			
7	10.6		150			
9	8.1	7.8	175	8.8	13.1	115.3
9	6.5		160			
9	8.9		145			

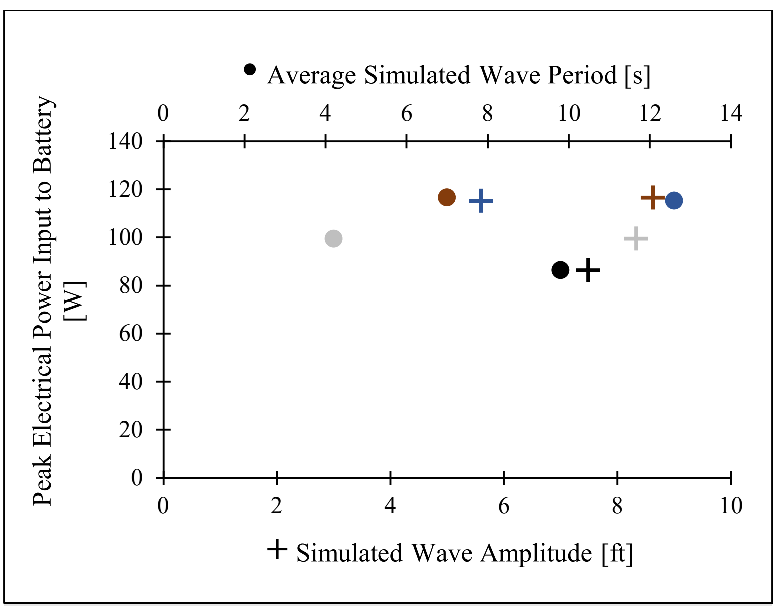


Figure 20. *Device performance land test results. Pairs of wave amplitude and period data are colored the same.*

The voltage input to the battery from the charge controller was relatively constant because the charge controller keeps the batteries at a specific voltage while supplying current to charge them. **Figure 20.** Device performance land test results. Pairs of wave amplitude and period data are colored the same. shows that the highest resultant peak power occurred for a pairing of relatively large wave amplitude (9 feet) and short average wave period (7.8 seconds). However, the peak power was surprisingly consistent across range of the tested conditions, showing no trend with a standard deviation of only 12.4 W. Real operating deployment in the ocean may not exhibit this consistency as we would expect a stronger positive correlation between wave height and peak power generation. It is also worth noting that the flywheel rotational speed, which is speed of the generator input shaft, never exceeded 181 rpm, only 40.2% of the expected operating speed of 450 rpm obtained from the system dynamics model. The largest peak power generation rate was 116.6 W, only 11.6% of the theoretical expected peak generation rate of 1 kW. These discrepancies are most likely due to the mechanical and electrical losses, respectively, characterized in Section 2.2.

3.5 Lessons Learned and Future Testing

Over the course of this design project, we have learned many crucial lessons that we plan to utilize on future projects. One of the main takeaways is the importance of designing for manufacturability. As we are not manufacturing engineers, we were not familiar with the tooling we had available and the restrictions of the on-campus machine shops. Due to being inexperienced with our shops, we planned specific manufacturing processes that were not feasible on campus. Simple fabrication steps had to be reworked due to the machine shops not having the proper tooling. These mistakes considerably lengthened the manufacturing process and made us realize the importance of checking with manufacturers to ensure the planned processes can be completed before finalizing a manufacturing plan.

While testing our device, we also realized the need for a clear testing plan, with tight time constraints forcing us to adapt to land testing. Although using a vehicle's tow hitch to simulate the force from a wave worked to stimulate our system, it was difficult to maintain a steady input force and period, and the only way to stop the drivetrain was to brake with the car and then wait for the flywheel to slow down naturally. This revealed the need for a mechanical apparatus capable of disengaging the coupling between our primary and secondary shaft, protecting the rest of the system when the buoy experiences rough swell that may create erratic motion in the main shaft. Testing also demonstrated the ineffectiveness of the torsional spring, with the cord not being capable of fully rewinding the winch cable. This appeared to be due to friction between the cord and itself or the pulleys, restricting it from stretching the correct amount. In the future we will replace this component with a fabric-coated version that has less frictional resistance and single-wrap the bungee onto the shaft to prevent unnecessary friction.

Finally, we learned that open-water testing is a time and cost intensive process, with it being vital to plan early to ensure testing can be completed. With the significant amount of design work we had to complete, testing was not at the forefront of our workload until later in the project timeline. Although we explored multiple avenues for testing our prototype in the ocean, we ultimately ran out of time and funds to pursue such an endeavor. We recommend that future Cal Poly teams begin planning for testing as early as possible, applying to TEAMER early and reserving a significant portion of the budget in case they are not accepted, with a complete user manual detailing our recommendations listed in Appendix F. In the end, despite our excitement at the potential of seeing our device operate in the ocean, we adapted and modified our test plan to be land-based, manually pulling on the winch cable to simulate ocean swell.

4 Conclusion

To meet the Marine Energy Collegiate Competition's challenge of developing a marine energy application for a blue economy market, we developed a winch-based point absorber dock capable of providing power and freshwater to isolated communities and electric boats. We also built and tested a prototype device. Although we were unable to perform open water testing on the prototype, and the torsional spring apparatus requires improvement, we successfully proved that our device could produce power through the winch system in numerous operational conditions. As a school, Cal Poly will continue to iterate on this design for future competitions, improving the efficiency, durability, and testing of the device.

References

[1] A. LiVecchi et al., "Powering the Blue Economy: Exploring Opportunities for Marine Renewable Energy in Maritime Markets," U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Washington, D.C., USA, 2019.

[2] "Summary of PIER Funded Wave Energy Research," California Energy Commission, PIER Program, Sacramento, CA, USA, 2007.

[3] "PB3 PowerBuoy." Ocean Power Technologies. https://oceanpowertechnologies.com/platform/opt-pb3-powerbuoy (accessed March 8, 2023).

[4] The Ocean Exchange. " 10 - StingRAY Wave Power by Columbia Power Technolgoies: USA (VA) - 2016 Ocean Exchange Finalist." YouTube. https://www.youtube.com/watch?v=JOUjtlu9g9k (accessed March 6, 2023).

[5] "Changing the World One Wave at a Time." Eco Wave Power. https://www.Ecowavepower.com (accessed March 7, 2023).

[6] "Technology." Resolute Energy. https://www.resolutemarine.com/technology (accessed March 7, 2023).

[7] Boundarycreative.co.uk, "Ocean Engineering & Design," *Ocean Power Technologies*. [Online]. Available: https://oceanpowertechnologies.com/expertise/ocean-engineering-design/. [Accessed: 23-Apr-2023].

[8] "Small WEC: Visualize." Small WEC | Visualize, https://apps.openei.org/swec/visual?devices=%5B%7B%22name%22%3A%22single_body_absorber%22%2C%22scale%22%3A0%7D%5D&viz_type=heat_map¶m_one=average_PTO_heave_force&view=2D.

[9] "Clean energy tech extracts power from ocean waves." Royal Melbourne Institute of Technology, https://www.rmit.edu.au/news/all-news/2021/aug/wave-energy-technology. (Published: 18 August 18, 2021).

Appendices

Appendix A: Risk Assessment

WEC Device 2/22/2023

Risk Level Report

Application: WEC Device
Description:
Product Identifier:
Assessment Type: Detailed
Limits:
Sources:
Risk Scoring System: ANSI B11.0 Two Factor

Analyst Name(s):
Company:
Facility Location:

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

Final Assessment Severity Probability	Risk Level	Item Id	User / Task	Hazard / Failure Mode	Risk Reduction Methods /Control System	Initial Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
Moderate		1-1-1	maintenance technician set-up or changeover	mechanical : crushing dropping device over person during install or removal	Properly rated lift points on device	Moderate Remote	Negligible	Implemented
Serious		1-1-2	maintenance technician set-up or changeover	mechanical : cutting / severing touching chain or sprocket at high RPM	Warning stickers on high RPM components	Serious Remote	Low	Implemented
Serious		1-1-3	maintenance technician set-up or changeover	mechanical : drawing-in / trapping / entanglement appendages getting caught in winch cable, elastic cord pulleys, or sprockets, as well as entanglement in anchor line	Warning stickers on entrapment-prone components	Serious Unlikely	Medium	Implemented
Moderate		1-1-4	maintenance technician set-up or changeover	mechanical : pinch point appendages getting caught in winch port	Warning stickers on pinch points	Moderate Unlikely	Low	Implemented
Minor		1-1-5	maintenance technician set-up or changeover	mechanical : unexpected start rogue wave starts mechanical PTO	Not needed	Minor Likely	Low	
Catastrophic		1-1-6	maintenance technician set-up or changeover	mechanical : break up during operation frame, shaft or cable failure	Device perimeter	Catastrophic Unlikely	Medium	Implemented
Moderate		1-1-7	maintenance technician set-up or changeover	mechanical : machine instability buoy platform flips or moves erratically	Weight distribution and balancing	Moderate Likely	Medium	Implemented
Serious		1-1-8	maintenance technician set-up or changeover	electrical / electronic : energized equipment / live parts live electrical components	Warning stickers on high voltage components	Serious Likely	High	Implemented
Serious		1-1-9	maintenance technician set-up or changeover	electrical / electronic : lack of grounding (earthing or neutral) improper electrical setup or damage to grounding during operation	Proper grounding	Serious Unlikely	Medium	Implemented
Moderate		1-1-10	maintenance technician set-up or changeover	electrical / electronic : water / wet locations device is in ocean	IP67 rated electrical enclosure	Moderate Very Likely	High	Implemented
Minor		1-1-11	maintenance technician set-up or changeover	electrical / electronic : unexpected start up / motion and emergency shutdown fails rogue wave starts mechanical PTO	Not necessary	Minor Likely	Low	
Minor		1-1-12	maintenance technician set-up or changeover	slips / trips / falls : slip wet boat surface during work	Visual check	Minor Likely	Low	
Minor		1-1-13	maintenance technician set-up or changeover	slips / trips / falls : trip trip over cable or shaft	Visual check	Minor Likely	Low	
Minor		1-1-14	maintenance technician set-up or changeover	ergonomics / human factors : lifting / bending / twisting lifting device during install or removal	Crane assisted lifting	Minor Likely	Low	Not Implemented
Minor		1-1-15	maintenance technician set-up or changeover	noise / vibration : noise / sound levels > 80 dBA generator noise	Not necessary	Minor Remote	Negligible	
Serious		1-1-16	maintenance technician set-up or changeover	noise / vibration : equipment damage dropping or impacting device during install or removal	Proper distance from crane assisted lifting	Serious Unlikely	Medium	Not Implemented

Page 1 Privileged and Confidential Information

Page 2 Privileged and Confidential Information

Final Assessment Severity Probability	Risk Level	Item Id	User / Task	Hazard / Failure Mode	Risk Reduction Methods /Control System	Initial Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
Catastrophic		1-1-17	maintenance technician set-up or changeover	noise / vibration : fatigue / material strength frame failure due to high loading	Frame reinforcement	Catastrophic Unlikely	Medium	Not Implemented
Minor		1-1-18	maintenance technician set-up or changeover	environmental / industrial hygiene : hazardous waste brine discharge	Brine containment	Minor Very Likely	Medium	Implemented
Minor		1-1-19	maintenance technician set-up or changeover	fluid / pressure : high pressure pump operating pressure	Proper hosing and pump fastening	Minor Very Likely	Medium	Implemented
Catastrophic		1-1-20	maintenance technician set-up or changeover	fluid / pressure : explosion / implosion R.O. device explosion	Device perimeter	Catastrophic Remote	Low	Implemented
Minor		1-1-21	maintenance technician set-up or changeover	fluid / pressure : surges / sloshing wave surges and sloshing	Device perimeter	Minor Very Likely	Medium	Implemented
Serious		2-1-1	passer by / non-user misuse - physical interaction with device	mechanical : cutting / severing touching chain or sprocket at high RPM	Warning stickers on high RPM components	Serious Remote	Low	Implemented
Serious		2-1-2	passer by / non-user misuse - physical interaction with device	mechanical : drawing-in / trapping / entanglement appendages getting caught in winch cable, elastic cord pulleys, or sprockets, as well as entanglement in anchor line	Warning stickers on entrapment-prone components	Serious Unlikely	Medium	Implemented
Moderate		2-1-3	passer by / non-user misuse - physical interaction with device	mechanical : pinch point appendages getting caught in winch port	Warning stickers on pinch points	Moderate Unlikely	Low	Implemented
Serious		2-1-4	passer by / non-user misuse - physical interaction with device	electrical / electronic : energized equipment / live parts live electrical components	Warning stickers on high voltage components	Serious Likely	High	Implemented

Page 3 Privileged and Confidential Information

Final Assessment Severity Probability	Risk Level	Item Id	User / Task	Hazard / Failure Mode	Risk Reduction Methods /Control System	Initial Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
Serious		2-1-5	passer by / non-user misuse - physical interaction with device	electrical / electronic : lack of grounding (earthing or neutral) improper electrical setup or damage to grounding during operation	Proper grounding during operation	Serious Unlikely	Medium	Implemented
Serious		2-1-6	passer by / non-user misuse - physical interaction with device	electrical / electronic : water / wet locations electrocution by live components due to conduction	Proper insulation of all live electrical components	Serious Unlikely	Medium	Implemented
Moderate		3-1-1	resource end user drink desalinated water	environmental / industrial hygiene : trace metals trace metals in water due to pump rusting or damage	Periodic testing of desalinated water	Moderate Unlikely	Low	Not Implemented
Minor		3-1-2	resource end user drink desalinated water	chemical : reaction to / with irritant chemicals Drinking saltwater	Salinity testing of desalinated water	Minor Likely	Low	Not Implemented

Page 4 Privileged and Confidential Information

Appendix B: Stress Assessment MATLAB Code

Senior Project - Stress Calcs

MECC

1/22/2023

Solve for Cable Load

```
%inputs
rho_sw = 1025; %kg/m^2
g = 9.81; %m/s^2
volume = 1.6; %m^3
mass = 300; %kg

%outputs
Fb_max = rho_sw * g * volume; %N
Weight = mass * g; %N
Fb_equilibrium = Weight; %N
F_cableinitial = Fb_max - Fb_equilibrium; %N
FOS = 1;
F_cablemetric = FOS * F_cableinitial %N
```

```
F_cablemetric = 1.3145e+04
```

```
F_cable = F_cablemetric / 4.448 %lbf
```

```
F_cable = 2.9554e+03
```

```
F_cablewecsim = 1007; %lbf
```

Solve for Forces on Main Winch Shaft

```
%inputs
r_shaft = .625; %in
r_winch = .625; %in
r_af = 12; %in
r_bf = 6; %in
L1 = r_af + r_bf; %in

B_y = F_cable * r_af / L1 %lbf
```

```
B_y = 1.9702e+03
```

```
A_y = F_cable - B_y %lbf
```

```
A_y = 985.1169
```

```
Torque = F_cable * r_winch %Torque in shaft in lb-in
```

```
Torque = 1.8471e+03
```

Solve for Stresses in Main Shaft

1

```
%Torsion
J = (1/32) * pi() * (r_shaft*2)^4;
Torsion = (Torque * r_shaft) / J
```

```
Torsion = 4.8165e+03
```

```
%Bending
M_A = A_y * r_af %lbf*in
```

```
M_A = 1.1821e+04
```

```
M_B = B_y * r_bf %lbf*in
```

```
M_B = 1.1821e+04
```

```
M_max = M_A;
Bending = (4*M_max) / (pi()*(r_shaft^3))
```

```
Bending = 6.1651e+04
```

```
%Shear
V_max = A_y;
Shear = (4*V_max) / (3*pi()*(r_shaft^2))
```

```
Shear = 1.0703e+03
```

```
%Von Mises
Stress_max = sqrt((Bending^2) + (3 * (Torsion^2)))
```

```
Stress_max = 6.2213e+04
```

```
SafetyFactor = 60900 / Stress_max
```

```
SafetyFactor = 0.9789
```

Solve for Stress and Fatigue w/ Avg Loading in Main Shaft

```
B_y = F_cablewecsim * r_af / L1 %lbf
```

B_y = 671.3333

```
A_y = F_cablewecsim - B_y %lbf
```

A_y = 335.6667

```
Torque = F_cablewecsim * r_winch %Torque in shaft in lb-in
```

Torque = 629.3750

```
%Torsion
J = (1/32) * pi() * (r_shaft*2)^4;
Torsion = (Torque * r_shaft) / J
```

Torsion = 1.6412e+03

```
%Bending
```

2

```
M_A = A_y * r_af %lbf*in
```

M_A = 4.0280e+03

```
M_B = B_y * r_bf %lbf*in
```

M_B = 4028

```
M_max = M_A;
Bending = (4*M_max) / (pi()*(r_shaft^3))
```

Bending = 2.1007e+04

```
%Shear
V_max = A_y;
Shear = (4*V_max) / (3*pi()*(r_shaft^2))
```

Shear = 364.7011

```
%Von Mises
Stress_max = sqrt((Bending^2) + (3 * (Torsion^2)))
```

Stress_max = 2.1198e+04

```
SafetyFactor = 60900 / Stress_max
```

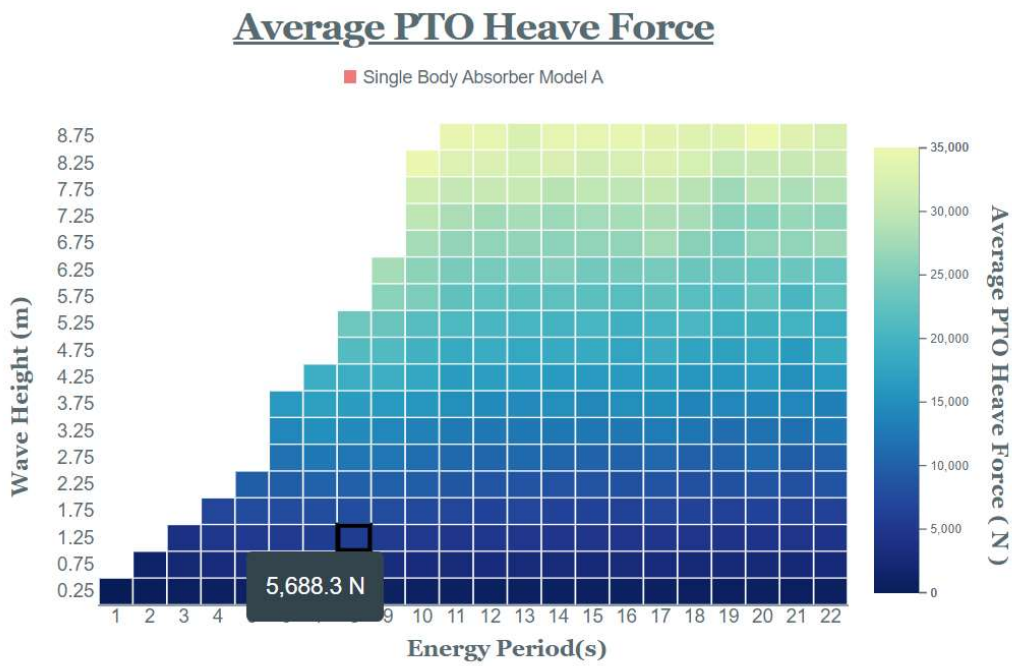
SafetyFactor = 2.8729

```
%Fatigue
Stress_mean = sqrt(3)*Torsion;
Stress_alt = Bending;

%Material Limits
Sut = 60900; %psi
Se = .5*Sut; %psi

%Goodman
n_f = 1 / ((Stress_alt/Se) + (Stress_mean/Sut)) %Need greater than 1 for ultimate life
```

n_f = 1.3577



Average PTO Heave Force
Single Body Absorber Model A
Wave Height (m)
Energy Period(s)
Average PTO Heave Force (N)
5,688.3 N

Appendix C: Budget

Materials Budget for Senior Project

Title of Senior Project:	F53 MECC
Team members:	Charlie Camilli, Gage Howard, Leo Kirshenbaum, Owen Pyle
Designated Team Treasurer:	Owen Pyle
Faculty Advisor:	Peter Schuster
Sponsor:	Marine Energy Collegiate Competition
Quarter and year project began:	Fall 2022
Materials budget given for this project:	$9,000.00

Date purchased	Vendor	Description of items purchased	Quantity	Price per Part	Transaction amount	Shipping + Tax	Total Cost	Submitted By	Purchase Order	How Purchased	Location
01/27/23	Home Depot	Eagle Floats 24 in. x 36 in. x 12 in. Foam Filled Dock Float Drum distributed by Multinautic	4	$ 122.99	$ 491.96	$ -	$ 491.96	CC	SP1	MECC Account	Mustang 60 Locker
01/27/23	Home Depot	Prime-Line Grade 18 to 8 Stainless Steel 3/8 in. x 4 in. External Hex Lag Screws (15-Pack)	2	$28.28	$ 56.56	$ -	$ 56.56	CC	SP1	MECC Account	Mustang 60 Locker
01/27/23	Home Depot	PrimeSource #10 x 2-1/2 in. x Stainless Steel Deck Screw (1 lb.Pack)	1	$ 16.97	$ 16.97	$ -	$ 16.97	CC	SP1	MECC Account	Mustang 60 Locker
02/11/23	Home Depot	Simpson Strong-Tie 2x8 Joist Hangers	8	$ 2.48	$ 19.84	$ -	$ 19.84	CC	SP1	MECC Account	Mustang 60 Locker
01/27/23	Home Depot	Simpson Strong-Tie #9 x 1-1/2 in. 1/4-Hex Drive, Strong-Drive SD Connector Screw (100-Pack)	1	$ 13.98	$ 13.98	$ -	$ 13.98	CC	SP1	MECC Account	Mustang 60 Locker
01/27/23	Amazon	40 Qty 3/8" x 1-1/2" 304 Stainless Steel Fender Washers (BCP565)	1	$ 13.95	$ 13.95	$ -	$ 13.95	CC	SP1	MECC Account	Mustang 60 Locker
01/27/23	McMaster	Spool 6-1/2" Flange Diameter, 8" Wide, 1-7/8" Core OD, 3/4" Core ID	1	$ 11.86	$ 11.86	$ -	$ 11.86			MECC Account	Mustang 60 Locker
01/27/23	Grainger	GRAINGER APPROVED Torsion Spring: 2 in Spring Lg @ Torque, 360 Deflection Angle (Deg.), 4	1	$ 8.74	$ 8.74	$ -	$ 8.74			MECC Account	Mustang 60 Locker
01/27/23	Amazon	Bridgeport Mill Part, Import Milling Machine Clock Spring 1112 Spring Only	1	$ 19.99	$ 19.99	$ -	$ 19.99			MECC Account	Mustang 60 Locker
01/27/23	Home Depot (in person)	2 in. x 4 in. x 8 ft. Lumber WW (Actual: 1.5 in. x 3.5 in. x 96 in.)	21	$ 2.98	$ 62.58	$ 11.75	$ 74.33	CC	SP2	MECC Account	Mustang 60 Locker
01/27/23	Home Depot (in person)	2 in. x 8 in. x 8 ft. Lumber WW (Actual: 1.5 in. x 5.5 in. x 96 in.)	8	$ 7.24	$ 57.92	$ -	$ 57.92	CC	SP2	MECC Account	Mustang 60 Locker
02/07/23	AliExpress	1kw 500 RPM Gearless Permanent Magnet Generator 120V AC AlternatorsUse For Water Turbin	1	$ 360.00	$ 360.00	$ 26.10	$ 386.10	JM	EP1	MECC Account	Mustang 60 Locker
02/07/23	Digikey	M5060TB1400 Rectifier	1	$ 112.20	$ 112.20	$ 15.12	$ 127.32	JM	EP1	MECC Account	Mustang 60 Locker
02/07/23	Amazon	LiTime LiFePO4 Battery 12V 100Ah, Built-in 100A BMS, 4000-15000 Cycles	2	$ 350.00	$ 700.00	$ 50.72	$ 750.72	JM	EP1	MECC Account	Mustang 60 Locker
02/07/23	Amazon	MidNite Solar CLASSIC 150 MPPT Charge Controller, 150 Operating Voltage	1	$ 720.00	$ 720.00	$ 67.16	$ 787.16	JM	EP1	MECC Account	Mustang 60 Locker
02/21/23	ZEMARC	2SF PUMP,5/8" ELEC SS R 0.5/1200	1	$ 1,182.35	$ 1,182.35	$ 150.00	$ 1,332.35	JM	EP2	MECC Account	Mustang 60 Locker
02/22/23	Gainger	DAYTON General Purpose Motor: Totally Enclosed Fan-Cooled, Face/Base Mount, 1/2 HP, 115/	1	$ 350.00	$ 350.00		$ 350.00	JM	EP2	MECC Account	Mustang 60 Locker
02/23/23	Renogy	2000W 12V Pure Sine Wave Inverter Charger w/ LCD Display	1	$ 639.99	$ 639.99	$ 46.40	$ 686.39	JM	EP2	MECC Account	Mustang 60 Locker
02/24/23	Digikey	Relay T9VV1K15-12S	2	$ 7.79	$ 15.58	$ 9.81	$ 25.39	JM	EP2	MECC Account	Mustang 60 Locker
02/25/23	Amazon	Arduino UNO REV3	1	$ 30.00	$ 30.00	$ 0.57	$ 30.57	JM	EP2	MECC Account	Mustang 60 Locker

02/26/23	Amazon	DAOKI 5PCS 20A Range ACS712 Current Sensor Module Detector	1	$ 11.00	$ 11.00	$ 1.00	$ 12.00	JM	EP2	MECC Account	Mustang 60 Locker
02/27/23	Amazon	NOYITO Voltage Transformer Module Active Single Phase Output Voltage Sensor Module	1	$ 6.00	$ 6.00	$ 0.64	$ 6.64	JM	EP2	MECC Account	Mustang 60 Locker
02/25/23	Amazon	Bubba Rope Winch Line Grabber	2	$ 13.45	$ 26.90		$ 26.90	GH		MECC Account	Mustang 60 Locker
02/25/23	Amazon	Dessecant 20 gram 30 packs	1	16.99	16.99		$ 16.99	GH		MECC Account	Mustang 60 Locker
02/25/23	Amazon	Salinity Probe	1	$ 22.00	$ 22.00		$ 22.00	GH		MECC Account	Mustang 60 Locker
02/25/23	Home Depot	1/4 in. x 6 in. Strong-Drive SDS Heavy-Duty Connector Screw (10-Pack)	1	$ 13.38	$ 13.38		$ 13.38	GH		MECC Account	Mustang 60 Locker
02/25/23	McMaster	[6494K16] Mounted Ball Bearing with Nickel-Plated Iron Housing (for 1-1/4" Shaft Diameter)	2	$ 61.83	$ 123.66		$ 123.66			MECC Account	Mustang 60 Locker
02/25/23	McMaster	[91590A137] External Retaining Ring (for 1-1/4" OD, 15-7 PH Stainless Steel)	10	$ 4.27	$ 42.70		$ 42.70			MECC Account	Mustang 60 Locker
02/25/23	McMaster	[3909N25] Clamping Shaft Coupline (for Round Shafts, Step-Down, 1.25 in x 37 mm, 3-34" Long	1	$ 161.95	$ 161.95		$ 161.95			MECC Account	Mustang 60 Locker
02/25/23	McMaster	[6494K14] Mounted Ball Bearing with Nickel-Plated Iron Housing (for 1" Shaft Diameter)	5	$ 39.74	$ 198.70		$ 198.70			MECC Account	Mustang 60 Locker
02/25/23	McMaster	[1553N17] One-Way Locking Needle-Roller Bearing Clutch (Triple Row, for 30 mm Shaft Diamete	1	$ 92.14	$ 92.14		$ 92.14			MECC Account	Mustang 60 Locker
02/25/23	McMaster	[91590A133] External Retaining Ring (for 1" OD, 15-7 PH Stainless Steel) - *Packs of 5 each*	3	$ 10.67	$ 32.01		$ 32.01			MECC Account	Mustang 60 Locker
0/25/23	McMaster	[3937T32] All-Weather EPDM Rubber Cord (5/16" Diameter)	1	$ 19.50	$ 19.50		$ 19.50			MECC Account	Mustang 60 Locker
02/25/23	McMaster	[3073T12] Mounted Pulley for Rope-for Horizontal Pulley (Steel, for 5/16" Diameter, 13/16" Wide)	2	$ 12.67	$ 25.34		$ 25.34			MECC Account	Mustang 60 Locker
02/25/23	McMaster	[3071T1] Mounted Pulley for Rope-for Horizontal Pull (Steel, for 5/16" Diameter, 7/8" Wide)	1	$ 9.56	$ 9.56		$ 9.56			MECC Account	Mustang 60 Locker
02/25/23	McMaster	[33805T841] Wraparound Rope Cleat (for 3/8" Rope Diameter, 316 Stainless Steel, 6" Long, 1-3	1	$ 27.59	$ 27.59		$ 27.59			MECC Account	Mustang 60 Locker
02/25/23	McMaster	[6236K471] Roller Chain Sprocket (for ANSI 50 Chain, 60 Teeth, for 1" Shaft Diameter)	1	$ 107.08	$ 107.08		$ 107.08			MECC Account	Mustang 60 Locker
02/25/23	McMaster	[98870A405] Machine Key (1018-1045 Steel, 1/4" x 1/4", 1-1/4" Long, Oversized	1	$ 12.93	$ 12.93		$ 12.93			MECC Account	Mustang 60 Locker
02/25/23	McMaster	[6280K894] Roller Chain Sprocket (for ANSI 50 Chain, 12 Teeth, for 1" Shaft Diameter)	1	$ 26.65	$ 26.65		$ 26.65			MECC Account	Mustang 60 Locker
02/25/23	McMaster	[9684T4] Flange-Mount Shaft Collar (for 1" Diameter, Black-Oxide 1117 Carbon Steel)	2	$ 72.97	$ 145.94		$ 145.94			MECC Account	Mustang 60 Locker
0/25/23	McMaster	[3014T491] Steel Eyebolt with Shoulder - for Lifting (1/2"-13 Thread Size 1-1/2" Thread Length)	4	$ 5.77	$ 23.08		$ 23.08			MECC Account	Mustang 60 Locker
02/25/23	McMaster	[1661A2] Threaded-Hole Black Plastic Pull Handle (with Brass Insert, Oval Grip, 4-5/8" Center-to	4	$ 5.16	$ 20.64		$ 20.64			MECC Account	Mustang 60 Locker
02/25/23	McMaster	[7210K3] High-Strength Corrosion Resistant Roller Chain (Single Strand, ANSI Number 50, 5/8"	1	$ 66.00	$ 66.00		$ 66.00			MECC Account	Mustang 60 Locker
02/25/23	McMaster	[7210K325] Connecting Link for ANSI Number 50 Single Strand High-Strength Corrosion-Resist	1	$ 2.86	$ 2.86		$ 2.86			MECC Account	Mustang 60 Locker
0/25/23	McMaster	[1610T48] Multipurpose 6061 Aluminum (5" Diameter)	3	$ 15.13	$ 45.39		$ 45.39			MECC Account	Mustang 60 Locker
02/25/23	San Diego Marine Exchange	80 ft Samson Amsteel Blue Dyneema Fiber Rope (3/16")	120	$ 1.11	$ 133.20		$ 133.20	GH		MECC Account	Mustang 60 Locker
02/25/23	Amazon	Flywheel (Hulkfit 45lb Weight Plate)	1	79.99	$ 79.99		$ 79.99	GH		MECC Account	Mustang 60 Locker
02/25/23	Grainger	Hex Bolts for bearings (3/8" - 16 x 3 1/2" Stainless Steel 316, 10 pack)	2	$ 28.91	$ 57.82		$ 57.82	GH		MECC Account	Mustang 60 Locker
02/25/23	Grainger	Top washer for bearings, 3/8" x 1" OD Stainless Steel, 50 pack	1	$ 8.56	$ 8.56		$ 8.56	GH		MECC Account	Mustang 60 Locker

02/25/23	Grainger	Bottom washer for bearings, 3/8" x 2" OD, 50 pack	1	$ 21.56	$ 21.56		$ 21.56	GH		MECC Account	Mustang 60 Locker
02/25/23	Grainger	Lock nuts for bearing bolts, 3/8" Stainless, 50 pack	1	$ 9.11	$ 9.11		$ 9.11	GH		MECC Account	Mustang 60 Locker
02/25/23	Grainger	Hex Bolts for flywheel mounting, 1/4" - 20 x 5 1/2", 10 pack	1	$ 9.35	$ 9.35		$ 9.35	GH		MECC Account	Mustang 60 Locker
02/25/23	Grainger	Washers for flywheel bolts, 1/4" , Stainless steel 18-8, 50 pack	1	$ 2.85	$ 2.85		$ 2.85	GH		MECC Account	Mustang 60 Locker
02/25/23	Grainger	Lock nuts for flywheel bolts, 1/4" - 20, Stainless 316, 50 pack	1	$ 4.60	$ 4.60		$ 4.60	GH		MECC Account	Mustang 60 Locker
02/25/23	Online Metals	1.25" Main Shaft (24" Length)	1	$ 171.50	$ 171.50		$ 171.50	CC	VP1	MECC Account	Mustang 60 Locker
02/25/23	Online Metals	1" Secondary and Flywheel Shaft (36" Length)	1	$ 154.39	$ 154.39		$ 154.39	CC	VP1	MECC Account	Mustang 60 Locker
03/02/23	Home Depot	(By-the-Foot) 2/0 Black Stranded CU SIMpull THHN Wire	12	$ 5.40	$ 64.80	$ 8.00	$ 72.80	JM	EP3	MECC Account	Mustang 60 Locker
03/03/23	Home Depot	15 ft. 14/2 Solid Romex SIMpull CU NM-B W/G Wire	1	$ 21.55	$ 21.55	$ 4.00	$ 25.55	JM	EP3	MECC Account	Mustang 60 Locker
03/04/23	Amazon	T Tocas Hi-AMP T3 Circuit Breaker with Switch Manual Rese, 12V - 48V DC, Waterproof (50A)	1	$ 26.99	$ 26.99	$ 1.00	$ 27.99	JM	EP3	MECC Account	Mustang 60 Locker
03/05/23	Amazon	Square D HOM260 Plug-In Circuit Breaker, 60 Amp, 2-Pole	1	$ 25.90	$ 25.90	$ 1.00	$ 26.90	JM	EP3	MECC Account	Mustang 60 Locker
03/06/23	Amazon	100 Amp DC Circuit Breaker 12-240V 2P Solar Disconnect switches DIN Rail Mount DC MCB	1	$ 17.99	$ 17.99	$ 1.00	$ 18.99	JM	EP3	MECC Account	Mustang 60 Locker
03/07/23	Amazon	Chtaixi DC Disconnect Switch C63, 2 Pole 1000V 63 Amp Isolator, Thermal Magnetic Trip	1	$ 15.98	$ 15.98	$ 1.00	$ 16.98	JM	EP3	MECC Account	Mustang 60 Locker
03/10/23	Harbor Freight	18 In. X 12 In. 1000 Lb. Capacity Hardwood Dolly	4	$ 12.99	$ 51.96	$ 10.49	$ 62.45	GH		MECC Account	Mustang 60 Locker
04/03/23	Amazon	Waterproof Outdoor Junction Box, 24"x16"x9" IP66 Electrical Enclosure	1	$ 119.99	$ 119.99	$ -	$ 119.99	CC		MECC Account	Mustang 60 Locker
04/04/23	McMaster-Carr	Shaft collar 3/4" x 1.25" OD	2	$ 10.46	$ 20.92		$ 20.92	LK		MECC Account	Mustang 60 Locker
04/04/23	McMaster-Carr	Shaft Coupling 1 3/16" x 1" (Generator Coupling)	1	$ 124.74	$ 124.74		$ 124.74	GH		MECC Account	Mustang 60 Locker
04/10/23	McMaster-Carr	18-8 Stainless Steel Hex Head Screw	1	$ 6.07	$ 6.07		$ 6.07	GH		MECC Account	Mustang 60 Locker
04/17/23	McMaster-Carr	[91590A137] External Retaining Ring (for 1-1/4" OD, 15-7 PH Stainless Steel)	3	$ 4.27	$ 12.81	$ 10.19	$ 23.00	CC		MECC Amount	Mustang 60 Locker
04/17/23	McMaster-Carr	[91590A133] External Retaining Ring (for 1" OD, 15-7 PH Stainless Steel) - *Packs of 5 each*	1	$ 10.67	$ 10.67		$ 10.67	CC		MECC Account	Mustang 60 Locker
05/04/23	Staples	Poster Tube	1	$ 6.50	$ 6.50	$ 0.57	$ 7.07	CC	In Person	Charlie's Personal Funds	
05/05/23	Cal Poly Bookstore	CP Hawaiian Shirts for Competition	5	$ 69.71	$ 348.55		$ 348.55	K,OP,GH,JB,	In Person	Personal Funds (need to apply for reimbursement)	
04/19/23	Home Depot	Pulley Mounting Hardware (Thru bolts, washers, and locknuts)	1	$ 30.82	$ 30.82	$ 2.70	$ 33.52	CC	In Person	Charlie's Personal Fund	Mustang 60 Locker
		Total expenses:			$ 7,723.63		$ 8,142.85				
budget:	$ 9,000.00										
actual expenses:	$ 8,142.85										
remaining balance:	$ 857.15										

Appendix D: DVP&R

Test #	Specification	Specification Description	Test Description	Measurements	Acceptance Criteria	Required Facilities/Equipment	Components: Prototype	Components: Parts Needed	Responsibility	TIMING: Start date	TIMING: Finish date	Numerical Results	Notes on Testing
DEV1	#1	Winch Respooling	Spin winch shaft to unspool and respool cable and verify that cable does not tangle	Inspect if cable tangles	Pass/Fail	TECHE Lab	CP	Cable, PVC pipe	Owen	2/9/2023	2/9/2023	Pass, winch successfully respooled at all angles and speeds.	Our preliminary prototype showed that the winch cable would not tangle despite not having guiding grooves.
DEV2	#1	One-Way Clutch Rotation	Rotate the input shaft to clutch bidirectionally to verify output shaft only rotates in one direction	Inspect direction of rotation of clutch output shaft (uni- or bidirectional)	Pass/Fail	Mustang '60	VP	Main transmission shaft, one-way clutch, custom coupling, secondary shaft	Charlie	4/14/2023	4/22/2023	Pass, one-way clutch only transmits torque in one direction.	The one-way clutch successfully transmitted torque in only one direction, allowing the winch to freely respool while not transmitting torque to the sprocket.
DEV3	#4	Bungee System Return Capability	Rotate the main shaft such that the bungee systems coils. Release the bungee sytem tension and allow system to return to equilibrium	Pretension contact knot position (X_i) [in] Contact knot poisiton after release (Xf) [in] Winch cable displacement (D) [in] Winch cable displacement % (%D) [%] Inspect cable wrap	%D = 100%	Mustang '60 Tape measure Cinder block	VP	Bungee cord, pulleys, cable lock (fixed mounting point)	Leo	4/15/2023	4/22/2023	Fail, for displacements greater than 3 feet, there was 10-15 inches of slack in the winch cable.	While the bungee nearly respooled our winch cable fully at small wave amplitudes, it failed to respool the winch as the wave height grew, with excess slack being in the range of 10-15 inches likely due to friction in the bungee. We recommend switching to a bungee cable with a nylon cover to prevent friction.
DEV4	#1	Generator Input Speed and Torque	Subject winch cable to sinusoidal tensile force (displacement of 1-6 ft) and measure input speed to generator	Generator input shaft rpm, Time to Steady State	n > 400 rpm	Mustang 60, Camera, Tape Measure	VP	Full winch subsystem + generator	Gage	4/16/2023	4/22/2023	Fail, reached peak of 175 RPM at wave amplitude of 9 feet. Tested variety of wave amplitudes and all generated around 150 RPM output speed.	Since we were unable to complete open-water testing, we used a Toyota 4-Runner to pull our winch cable, simulating waves. We predict our model is still valid because the lower RPM corresponds to a lower power output, and we believe that in the ocean the forces will be strong enough to achieve RPM>400 and 1kW.

DVP&R - Design Verification Plan (& Report) — Project: F53 MECC; Sponsor: Dr. Schuster; Edit Date: 5/11/2023. DEVELOPMENT TEST PLAN / TEST RESULTS

Appendix E: Test Procedures

Test #1: Winch cable respooling

Test Date: 2/9

Description of Test:

Our advisor at Integral Consulting, Frank Spada, expressed concern that the winch cable would tangle if not mated to a purpose-built drum. During testing, we will be monitoring to see if the cable (a) tangles after 20x repeated cycles and (b) whether this tangling is detrimental to the mobility of the winch apparatus.

Location:

Open-air bay behind Mustang 60 machine shop

Required Materials

- Buoy platform
  - Primary shaft (machined and attached to buoy-mounted bearings)
  - Spring system (bungee cord, pulleys, and attachment points)
- End stop
  - Barred fence
  - Board with cable-sized hole

Testing Protocol

- Preliminary set-up
  - Ensure primary shaft and spring system are assembled and fastened to platform
  - Slide end stop board over cable
  - Tie knot in cable outside of end stop
- Data collection
  - Pull cable three meters, tensioning recoil system
  - Walk cable back to initial position
  - Observe recoiled winch for cross-coiling and entanglement
  - Repeat steps above at different angles (simulates platform drift between anchor points)
  - Repeat steps above at different recoil velocities (slow, expected speed, maximum bungee recoil velocity)
  - Repeat steps above in a random manner, changing angle and speed during a single cycle
- Take down
  - Untie winch cable knot and slide end plate off
  - Return prototype to storage location

Safety Considerations

- Bungee cord tension
  - Do not pull cable beyond 75% of rated bungee cord displacement
  - Wear proper attire (safety glasses, long pants, shoes)
  - Anti-whiplash safeguards (safety pins, ⅛” plywood sides walls, transparent cover)

Side Angle [°]	Recoil Speed	Entanglement		Observations / Comments
		Benign [Pass/Fail]	**Detrimental** [Pass/Fail]	
0	Slow	Pass	Pass	
	Rated	Pass	Pass	
	Max	Pass	Pass	Cable deformed due to extreme loads
5	Slow	Pass	Pass	
	Rated	Pass	Pass	No cable tangling, but winding around center of winch
	Max	Pass	Pass	
10	Slow	Pass	Pass	
	Rated	Pass	Pass	
	Max	Pass	Pass	Same as previous comments, no difference based on angle
Random		Pass	Pass	Cable winding around same spot but not tangling

Test #2: One-Way Clutch Rotation Verification

Test Date: 4/22

Purpose: The purpose of this test is to verify that the one-way clutch allows unidirectional rotation of the secondary shaft for both clockwise and counterclockwise rotation of the input shaft.

Equipment/Components:

One-way clutch assembly:

1) 1.5” primary shaft
2) 1” secondary shaft
3) One-way clutch
4) Custom coupling (OD of clutch to OD of secondary shaft)

Hazards: The primary hazard of this test is pinch points near the mating surfaces of the shafts and clutch and coupling when rotation is introduced.

PPE Requirements:

- Safety Glasses
- Close-Toed Shoes
- Long pants

Facility: Mustang 60
Procedure:

1) Confirm all test participants are wearing proper PPE and safety equipment listed above.
2) Rotate the input shaft (1.5" main shaft) clockwise and observe the rotational direction of output shaft (1" secondary shaft)
3) Rotate input shaft counterclockwise and ensure output shaft does not rotate and is free to rotate in clockwise direction.

Results:
The Clockwise Input Test will pass if:

a) The output shaft rotates clockwise for clockwise input

The Counterclockwise Input Test will pass if:

a) The output shaft does not rotate for counterclockwise input and can still freely rotate clockwise

The system will pass if all input tests pass.

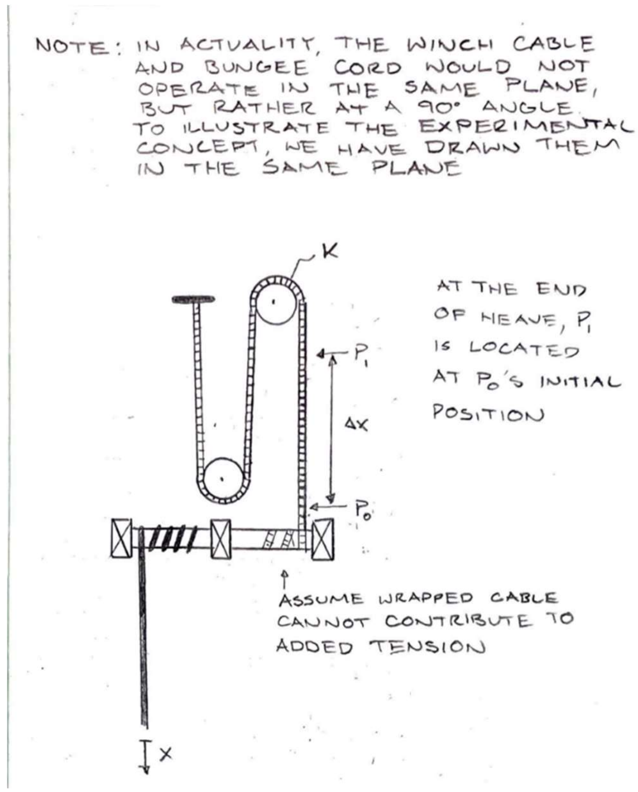
Test Results:

	Output Shaft Rotation	**PASS / FAIL**
Counterclockwise Input Rotation Test	Clockwise / Counterclockwise	PASS / FAIL
Clockwise Input Rotation Test	Clockwise / Counterclockwise	PASS / FAIL

Test #3: Bungee Pre-Tension for Maximum Buoy Displacement

Test Date: 4/22
Purpose: The purpose of this test is to generate a performance curve of cable pretension displacement vs. maximum allowable buoy travel. This will allow us to properly select a cable pretension value prior to open water testing to ensure our device can achieve the desired amount of travel while maintaining tension and proper re-spooling of our winch cable.
Scope: This test procedure applies to the pretension value of the bungee cable and its impact on the maximum distance of winch cable travel we can achieve. By creating a plot of bungee pretension versus winch cable travel we can properly select a pretension value to maximize our buoy travel while ensuring our bungee properly re-spools our winch.
Equipment:

1) Tape measure
2) Cinderblock/Wood Stopping Block



Hazards: One potential hazard of this test is having the bungee cable snap, releasing all the potential energy and potentially injuring an individual near it. To mitigate this we will have a cover over the top of our system, either made of plexiglass, plastic, or plywood, and this cover will prevent the bungee cable or flywheel from breaking free and causing harm. Another hazard is the multitude of pinch points in our power transmission system, which the cover will also protect from.

PPE Requirements:

- Safety Glasses
- Close-Toed Shoes

Facility: Mustang 60

Procedure:

1) Attach winch cable and elastic cord to shaft with winch grabbers (minimum wrap). Tie off elastic cord to cleat with no stretch (verify cord is unstretched with overall length measurement).
2) Place contact point block outside of frame testing perimeter. Place tape measure on ground with zero lined up with outside of contact point block
3) Thread winch cable through contact point block and tie contact knot on outside of block
4) Displace contact knot 6 inches and release
5) Measure new contact knot position to obtain displacement
6) Observe winch cable wrapping. Note any bunching or tangling
7) Repeat steps 4-6 with an additional 6 inches of displacement up to 7 feet of total displacement

Results: Pass Criteria, Fail Criteria, Number of samples to test, Design analysis equations/spreadsheet with uncertainty. Comment on how Uncertainty Analysis will be completed.

Test Results:

Pretension Contact Knot Position [in]	Slack in Winch Cable [in]
6	2
10	3.5
14.5	3
21	4.5
25.5	4.25
31.5	4.25
37.75	10
38	14.5

Test #4: Generator Input Speed based on Wave Height

Test Date: 4/22

Purpose: The purpose of this test is to generate a performance curve of the generator input speed versus the average wave height the buoy experiences.

Scope: This test procedure applies to the maximum speed our final shaft can achieve, demonstrating the input speed our generator will experience at different wave heights. This plot will show us which wave heights are necessary to produce the ideal input speed of 400 RPM to the generator.

Equipment:

1) Tape measure
2) Cinderblock/Wood Stopping Block
3) Tape/Sharpie for marking the shaft
4) Phone Slow-Motion Camera

Hazards: One potential hazard of this test is having the bungee cable snap, releasing all the potential energy and potentially injuring an individual near it. To mitigate this we will have a cover over the top of our system, either made of plexiglass, plastic, or plywood, and this cover will prevent the bungee cable or flywheel from breaking free and causing harm. Another hazard is the multitude of pinch points in our power transmission system, which the cover will also protect from. Also, due to it being potentially dangerous to have an individual get close enough to film the shaft's rotary motion, we will use a phone stand so that no one needs to hold the camera while filming.

PPE Requirements:

- Safety Glasses
- Close-Toed Shoes

Facility: Mustang 60

Procedure:

1) Attach winch cable and elastic cord to shaft with winch grabbers (minimum wrap). Tie off elastic cord to cleat with no stretch (verify cord is unstretched with overall length measurement).
2) Place marking in sharpie on final flywheel shaft in vertical direction, with the other end of the marking on a fixed point on the frame (likely piece of wood).
3) Place contact point block outside of frame testing perimeter. Place tape measure on ground with zero lined up with outside of contact point block.
4) Thread winch cable through contact point block and tie contact knot on outside of block.
5) Displace contact knot to specified value for ideal pretension as determined by previous tests.
6) Place phone camera set to slow motion so that it can record the sharpie marking on the shaft and float, and start recording. Also, start a stopwatch on a separate device when the cable is first pulled.
7) Using the tape measure as a guide, pull the winch cable to a length of 1 foot and then release until the knot returns to its starting position.
8) Repeatedly pull the winch cable to this specific distance until the final shaft appears to reach equilibrium or 10 minutes has passed, whichever comes first.
9) Let the system come to a standstill before reaching into the device to retrieve the phone camera.
10) Record the time it took for the system to reach steady state as seen on the stopwatch.
11) Using the slow-motion feature on the camera, measure the time it takes for 1 revolution while the system is at equilibrium and record this data.
12) Using the time for 1 revolution, convert this value to RPM to find the input speed to the generator.
13) Repeat steps 6-12 for each specified wave height in the table.

Results:

The system will pass if the final rotational speed exceeds 400 RPM after reaching equilibrium. However, due to the time to reach equilibrium likely being large for small wave heights, we will stop testing at 10 minutes and record the final speed at this time. We will test 6 unique wave heights, ranging from 1-6 feet, which is our likely operating range. Also, due to the resolution of a phone camera being the hundredth of a second, this will drive our uncertainty calculations and will carry over into the final rotational speed value.

Test Results:

Winch Cable Displacement, h **[ft] ± 0.5**	Displacement Period, $2t_d$ **[s] ± 0.1**	Average Displacement Period **[s] ± 0.1**	Peak flywheel speed, ω_f **[rpm] ± 0.05%**	Peak Current, I **[A] ± 0.1**	Peak Voltage, V **[V] ± 0.1**	Peak Power, P_b **[W]**
3	7.9		150			
3	10.5		157	7.6	13.1	99.6
3	16	11.7	155			

3	14.6		147			
3	9.3		144			
5	10.5	12.1	161	8.9	13.1	116.6
5	14.5		151			
5	11.7		181			
5	11.6		148			
7	10.1	10.5	142	6.6	13.1	86.5
7	11.4		149			
7	9.8		156			
7	10.6		150			
9	8.1	7.8	175	8.8	13.1	115.3
9	6.5		160			
9	8.9		145			

Appendix F: User Manual

User Manual

1. Message to Next Year's Team

Dear 2023-2024 MECC Team,

Congratulations on being selected as the next generation of senior project students to participate in the Marine Energy Collegiate Competition. We are excited to see where you take this year's design and how you build upon our learnings from our first year in the competition; we certainly learned a lot along our journey and have done our best to set you up for success with the information provided in this user manual. Some of our team members will be returning to campus Fall Quarter of 2023 to wrap up their undergrad and pursue master's degrees. We would love to be a continuing resource for you all and have provided our email addresses in the resources section so that you can reach out to us with questions.

2. Summary of Project 2022-2023

See the SOW, PDR, CDR, MECC Report, MECC Technical Presentation, and FDR.

One thing worth noting here is that we ended up focusing solely on power generation and not including desalination in the MECC submissions and our build & test because the business team was not able to validate a business model for small-scale desalination after they joined the project midway through the year. However, it is still worth pursuing as we have a full-size pump and R.O. membrane that are ready for use, you may just have to get a bit creative with justifying the feasibility from a business perspective (one idea: focus on the humanitarian benefits to remote communities we didn't consider, such as in Africa or Southeast Asia, with potential stakeholders/purchasers being humanitarian aid organizations).

3. Next Steps

1.1.1 4.1.1 Design Changes

The first change you will need to make to the design is to improve or redesign the torsion spring apparatus that recoils the winch to remove slack in the cable during downwards wave motion and changing tides. From our bench testing with the current design, for smaller displacements of less than three feet, the cable was mostly recoiled, but there was up to four inches of cable that was not recoiled and would build up as slack during the oscillating motion of waves. For larger displacements, the slack was much larger. The suspected cause is high friction in the cord causing it to lock, and so the solution may be as simple as using a cord with a more slippery nylon covering. However, the mechanism may need to be altered or redesigned to properly perform its function. We looked into using off the shelf torsion springs (e.g. garage door torsion springs) and clock springs but were unable to find any that are rated for the amount of torque and the amount of travel that is necessary to respool the winch. This is what led us to using the elastic cord and pulley system. We did not write up any analysis for what these ratings need to be, and we recommend that you do so. This issue would need to be solved before water testing or slack would build up in the cable and prevent power from being transmitted continually through the winch. Also, because the generator shaft was metric and the input was English, we had to purchase a custom rigid coupling from McMaster. We recommend trying to source a flexible coupling to better handle deflection of shafts due to more unpredictable loading in an ocean environment.

1.1.2 4.1.2 Waterproofing for Open Water Testing

Due to unexpected delays with part orders, we faced a serious time crunch to manufacture and test and include these results in our MECC report before the deadline. This accelerated timeline combined with challenges planning with open water testing facilities ultimately prevented us from conducting open water testing of our device. Additionally, the design should ideally be fully validated with bench testing on land before moving to open water testing to give the best chance of getting good performance results, considering the amount of time and logistics needed for an open water deployment. The torsion spring apparatus needs to be able to consistently recoil all slack in the cable over the entire desired range of displacement (wave height). Additionally, the charge controller custom input characteristics should be optimized for the expected input from wave motion, which may require some additional analysis and/or bench testing.

Once we knew open water testing would not happen this year, we eliminated adequate waterproofing measures from our prototype build. So, one of your first steps will be to prepare the prototype for an open-water environment. We took special care to source corrosion resistant materials: almost all mechanical drivetrain components are stainless steel. The following is a list of components that will need waterproofing.

a) Electrical Components

The electrical components are housed in waterproof containers but have holes for wiring that need to be properly sealed. Off-the-shelf cable pass-throughs and caulk are probably your best bet.

b) Generator

We purchased an IP66 rated electrical enclosure to house the generator. A hole will need to be drilled in the enclosure for the generator shaft and outfitted with some sort of low-friction waterproof seal.

c) Chain and Sprocket

A chain case to enclose the chain and sprocket will be necessary to protect these power transmission elements from saltwater exposure and prevent leakage of lubrication. This could prove difficult due to the system’s large size and might be best achieved by 3D printing or water jetting custom housing.

d) Overall Device Top and Bottom Covering

Exploring the potential use of a plastic or acrylic cover to protect the device from splashing could be beneficial. Because our decking platform is a lattice, there is nothing preventing water from splashing up through the underside of the device. One idea was to attach a plastic sheet with small holes for water drainage below the decking platform to create a barrier between the water surface and the main device components.

4. Testing Challenges and Advice

Open Water Deployment Challenges

Our device requires the main winch cable to be anchored to the sea floor with enough weight to resist the device buoyancy and wave heave forces. This translates to a 1000-1500 lb. anchor weight and adds to the difficulty of testing our device, as any facilities we utilize must be capable of deploying our ≈700 lb device and recovering an ≈1000 lb anchor from the ocean floor at a depth of 30-50 ft depending on the testing location.

An additional challenge associated with testing our device is achieving appropriate pretension in the winch cable upon deployment. Our best solution was to employ less rope than the ocean water depth and let the falling anchor weight pull the cable taught. Further bench testing with the redesigned winch return mechanism will need to be conducted to determine the optimum pretension distance (ocean depth – winch cable length).

Successfully deploying our device in an open water environment requires careful planning of a wide variety of logistics:

- Device transportation to the testing site
  - We purchased four dollies to manually move the device
  - The Cal Poly ME Department has a trailer that can fit the device
- Contracting a marine vessel
  - If towing device to desired location, needs to have proper towing capacity
  - If hoisting/lifting device, needs proper lifting capacity
    - Adequate buoyancy for when including combined device, anchor, and mooring weights
  - Ability to recover weight from sea floor via a winch/capstan or other mechanism
- Mooring plan
  - In rougher sea states, need mooring to prevent device from drifting and keep winch cable vertically oriented
- Device and Mooring Recovery
  - Need way to recover 1000 lb. anchor weight and any additional mooring weights from sea floor
- Data collection
  - Implementing wireless live data monitoring would be ideal (EE team)
  - Wave buoy capable of measuring independent wave parameters (wave height and period)

TEAMER Testing Support

TEAMER is a DOE organization that can provide fully funded testing support. However, the TEAMER application is intense and requires collaboration with a selected testing facility. We recommend reaching out to someone from a TEAMER facility and immediately, early in the fall and begin working to complete an application for open water testing. We waited way too long into the year, around February-March, before applying to TEAMER and our application was denied. There are several steps in the process after submitting the initial application that we were not aware of, including a requirement to complete a detailed test plan which needs to be reviewed, acquire necessary permitting, and a NEPA analysis. It's unlikely that we would have been ready for open water testing with successful bench testing and waterproofing this year, but we started the process with this ambition anyways, and since these will be your main goals it will be much more feasible.

We identified Integral Consulting based in Santa Cruz, CA, as a testing provider in the TEAMER network that could help us conduct open water testing. We met with Frank Spada, a project scientist, and Samuel McWilliams, a consultant, on many occasions starting in November 2022 to coordinate testing logistics before having to bail on this plan when our TEAMER application was denied because we lacked funding. We recommend that you pick up where we left off with Frank and Sam as they were very knowledgeable, helpful, and enthusiastic about the project. Integral is an ideal organization for open water testing support since marine energy device testing is within their expertise. A principal engineer at Integral, Craig Jones, was actually one of the three technical presentation judges at the 2023 competition. Key resources they can provide include a wave buoy to measure wave height and period, connections to charter marine vessels, and general expertise for deploying, mooring, and recovering a device. We discussed several options for an open water testing plan with them – in order of increasing simplicity: open-ocean deployment in Monterey, deployment in the San Francisco Bay, deployment in a local protected area with a boat ramp (Morro Bay, San Luis Obispo Bay) and deployment in a nearby lake (and having the boat drive in circles around the device to simulate waves). With Integral, we began to develop the logistics for deploying and retrieving the device (transporting it, loading/unloading it to/from a boat with a crane/davit, dropping/recovering the center weight) as well as mooring (two-point mooring system in addition to the center weight with two additional buoys and weights, as well as additional line). However, these logistics were not finalized, so this is what you will have to continue to develop with Frank and Sam. See the **Useful Resources and Documents** section for instructions on where to find this information.

Cal Poly Pier

After testing with Integral Consulting was no longer viable, we explored the possibility of deploying our device from the Cal Poly Pier. We met with Tom Moylan (Pier Facility Manager) and Jason Felton (Pier Technician) who expressed reservations about testing our device near the pier given our lack of bench testing and plan for deploying and recovering the center and mooring weights. The pier has a crane capable of lifting our device but it can only lower objects to the water level and so it would be insufficient for deploying and retrieving the center and mooring weights without a clever rigging strategy. Additionally, if the device was deployed just off the pier using this crane, it would need to be very secure in its position with sufficient spacing from the pier. At the base of the pier, there are some large mooring weights and other mooring equipment that would be ideal for the team to use for testing regardless of whether the testing took place off the pier. The weights would need to be lifted by a vehicle-mounted davit from the adjacent road to transport for deployment. Using the pier for open water testing is certainly a possibility and there is an advantage to working within the resources of the school, but there are important logistical issues that would need to be solved.

Port San Luis Harbor Department (PSLHD)

Through the Cal Poly Pier, we were connected to the PSLHD as a potential resource for providing the equipment and boating support that we would need. We had multiple conversations with Chris Munson at the PSLHD. The PSLHD does have a large boat with a davit that would be capable of deploying the device, as well as a truck with a mounted davit that can pick up the Cal Poly Pier's mooring weights from their open storage area at the base of the pier. They suggested using the anchor field in the San Luis Obispo Bay (a zone where boats can freely drop anchor and stay for a period of time) or the rentable moorings that are in place throughout the Bay (also meant for boats). They also suggested that we may not need to use a two-point mooring strategy and may be able to rely solely on the center weight of the winch to secure the device if it was deployed in the anchor field for a short period of time (several hours) on an adequately calm day.

Recommended Strategy

The ideal testing strategy, based on our conversations throughout the year, would be a combination of the above resources. The team would deploy in the San Luis Obispo Bay during a calm day with waves of roughly 3-4 feet and an 8-10 second period, use the PSLHD's vessel(s) and vehicle(s) for transportation and deployment, use the Cal Poly Pier's mooring equipment (with any additional necessary riggings purchased with project funding), and contract Frank Spada of Integral Consulting with TEAMER funding to travel down for testing support and provision of a wave data collection buoy. A two week window for testing would be planned well in advance with a specific day being selected as the forecast develops. The team would meet with Frank the day beforehand to go over the plan and organize all materials and the deployment process would start early the next morning.

5. Contacts

We have compiled a list of useful contacts that includes the 2022-23 team members and industry connections for facilitating open water testing.

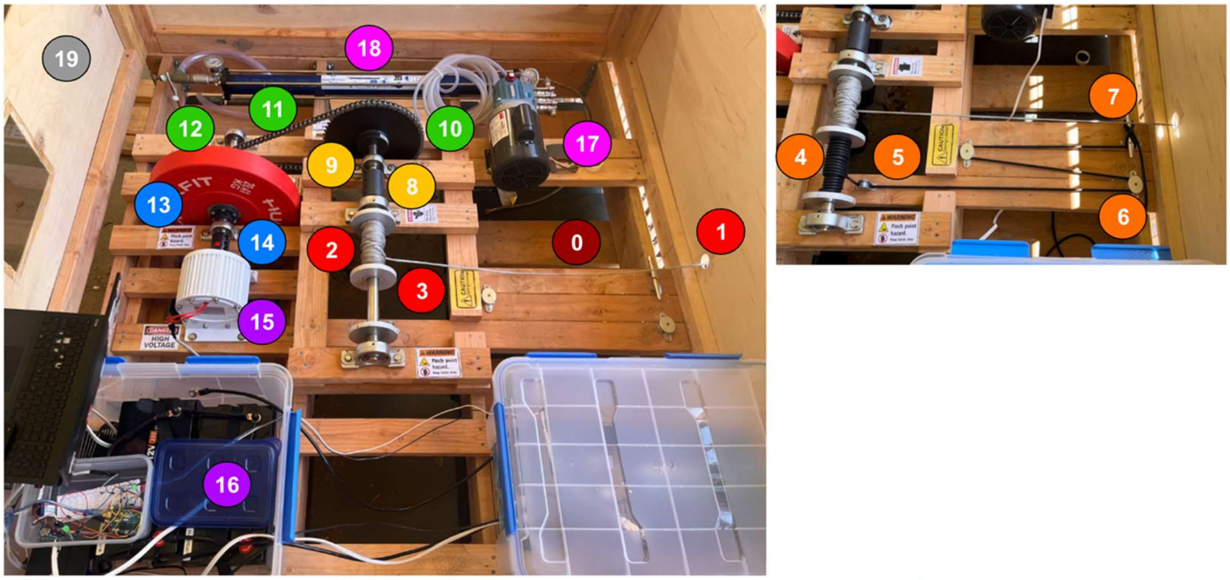
Name	Affiliation	Email
Owen Pyle	ME Student	opyle@calpoly.edu
Charlie Camilli	ME Student	ccamilli@calpoly.edu charliecamilli@gmail.com
Gage Howard	ME Student	Gage777@comcast.net
Leo Kirshenbaum	ME Student	lkirshen@calpoly.edu wolflayo@gmail.com

Frank Spada	Integral Consulting	fspada@integral-corp.com
Samuel McWilliams	Integral Consulting	smcwilliams@integral-corp.com
Tom Moylan	Cal Poly Pier	tmoylan@calpoly.edu
Jason Felton	Cal Poly Pier	jfelton@calpoly.edu
Chris Munson	Port San Luis Harbor District	chrism@portsanluis.com
Joseph Bonafede	EE Student	jbonafed@calpoly.edu
Jonathan Ma	EE Student	Jma56@calpoly.edu
Emigdio Islas	EE Student	emislas@calpoly.edu
Lou Lou Twietmeyer	Business Student	ltwietme@calpoly.edu

6. Useful Resources and Documents

- Small WEC Analysis Tool: shows force/power outputs based on various wave conditions for different types of WECs
    - https://apps.openei.org/swec/
- MECC Google Drive: provides examples of past presentations, posters, and reports from previous years for reference
    - https://drive.google.com/drive/folders/1wgQ8-KEg-Y9MXyY-qkM39mDIloWIw959
- TEAMER Testing Application: found in Teams under General -> Test -> TEAMER application

7. Component Overview and Learnings from Testing



The **Dock Frame** provides the structural foundation which all other components are mated to. The dock floats were fastened to the frame with lag bolts and washers – the washers were double-stacked to prevent them from yielding during tightening. The 2x8 structural planks interlocked; we cut slots into the ends. Unfortunately, the slots were slightly too narrow, and when we hammered the interlocking sides together, some of the regions between the slots and end of the planks sheared off. Additionally, when installing the Simpson strong ties, we were unable to get the boards to be fully flush, so there are some gaps which may affect the structural integrity of the design. After testing, we noticed some concerning cracks starting to propagate throughout the wood on certain sections of the frame. All in all, the wood frame could do with a good redesign – consider using extruded aluminum stock (we were able to source some scrap beams and have stored them under the dock in Mustang 60).

The **Cable Port** was a last-minute addition to allow for dry-land testing. In an ocean environment, the winch cable would descend vertically to the sea floor; however, on land we had to settle for the cable to exiting the assembly horizontally. The cable passes through the port hole and Mustang 60 fence and attaches to the trailer hitch on the back of a car. We were able to hand pull the cable to test the mechanical system, but once the generator was plugged into the electrical subassembly, the added load torque required us to use a car (a Toyota 4Runner that was designed to have a trailer hitch) to apply a large enough tensile load. We tried to simulate different sea states by altering the displacement and average velocity of the car during testing; however, completing this task with any degree of precision proved difficult. We recommend ideating a better way to simulate wave behavior on land, either with or without the use of a car. Our mechanical and structural system (bearings, deck frame) were designed for the loading conditions when the winch cable exits the device vertically (e.g., to the sea floor). We did not observe any warnings that failure would occur with the cable pulling on the winch spool horizontally; however, it is something to keep in mind if you plan on running high-tensile force testing in this orientation. This horizontal cable configuration seemed to be a be a better alternative to securing the dock on its side or designing a vertically-oriented pulley system beneath the winch spool to redirect the direction of the cable after having it initially descend vertically.

The **Winch Spool** coils and uncoils the cable, converting its linear translation into rotational motion. The cable was secured to the shaft using an adhesive Bubba Rope winch grabber. The cable was coiled numerous times to ensure the winch grabber was snugly fastened and we would not run out of cable during testing. Initially, we wrapped the cable very precisely to minimize chaotic overlapping; however, during respool, the rewrapping was not as pretty. Consider redesigning the winch drum so that the respool is more ordered. When selecting our winch cable material, we only considered tensile strength, and did not give any thought about how it would behave in compression. We failed to recognize that although lines cannot act in compression, the outer layer of cable wrapping applied compressive normal forces on the inner layers, because the inner wrappings prevented the outer layers from moving translationally in the direction of the applied tensile force. Consider using a different cable material. Metals would act better in compression but are subject to corrosion in a salt water environment and, according to Eric Pulse (senior shop tech at Mustang 60) are more dangerous in high-tensile force applications because of their tendency to aggressively whiplash in a failure scenario.

The aluminum **End Plates** served to confine the winch drum and bungee wrappings. They were located axially on the main shaft using retaining rings (the rings slotted into grooves on the shaft that were machined with a manual lathe). We purchased the aluminum plates off the shelf and machined the inner diameter with a manual lathe. Unfortunately, we did not get around to properly securing the end plates to the main shaft. They can move freely in the angular direction with respect to the main shaft, even though they are secured axially and radially. This is not ideal, as all shaft components should either remain stationary (e.g., bearings) or move with the shaft (e.g., sprockets). This semi-slip condition is considered bad practice in machine design and should be resolved (e.g., glue the end plates to the main shaft or install a keyway).

The **Bungee Spool** serves as an effective torsion spring; the bungee cord is wrapped in the opposite direction to the main winch, so that it stretches as the main winch unwraps. The idea being that after a wave has passed, the stored potential energy causes the main winch to recoil. As with the main winch drum, we used a Bubba Rope winch grabber to fasten the bungee to the shaft. As explained in our FDR report, this 'torsion spring' proved unsuccessful. We needed several wraps of bungee cord to secure the winch grabber to the main shaft, but similar to the main shaft, the tensile spring loading of the unwrapped bungee caused the outer layer of wrapping to bury itself into the inner layers. This effectively 'braked' the torsion spring, in the same way that a rock climbing belay device 'brakes' climbing rope and did not allow the main shaft to spin backwards and relieve the potential energy stored in the bungee cord.

The **Vertical Pulley** redirects the bungee in the horizontal direction so that it can be oriented in the horizontal plane. It worked as intended - no further comments.

The **Horizontal Pulleys** were intended to increase the allowable travel of the bungee in a confined space. During testing, we observed that the bungee cord would get caught in these pulleys, either due to cable getting pinched or the rotational resistance of the pulley bearing. The section of cord between the vertical pulley and the first horizontal pulley (A) would stretch while the section between the two horizontal pulleys (B) and between the second horizontal pulley and cleat (C) would remain immobile. Once there was sufficient tension in section A, section B would slip and start moving until the tension in section A was somewhat relieved. This would repeat until there was enough tension in section B to cause section C to start stretching. As such, the resistive torque of our effective torsion spring was non-linear. A further consequence was that the horizontal pulley resistance acted in both directions, meaning that sections B and C would hold tension even after we stopped pulling on the winch cable; their stored potential energy could not be used to backspin the main shaft and recoil the winch.

The **Cleat** served as a tie off point for the far end of the bungee cord. It functioned as intended.

The custom rigid **Shaft Coupling** connects the 1.25” main shaft and 1” intermediate shaft. The bores of the coupling mate with the outer diameter of the one-way clutch and (due to a miscalculation when ordering the coupling) the outer diameter of shaft collars mounted to a turned-down section of the 1.25” main shaft. The turned-down main shaft and incorporation of the shaft collars are changes to the overall design since the completion of our CDR. We were forced to purchase a custom-dimensioned coupling because we sourced a metric one-way clutch. Ideally this would be a flexible clutch, but McMaster only offers rigid custom couplings. The one-way clutch allows the flywheel and generator to rotate freely while the winch cable respools. Take care when handling the one-way clutch during assembly and disassembly, as the individual needle rollers are fragile and can come loose.

We sourced two different specifications of **Bearings**, two copies for the 1.25” main shaft and five for the 1” intermediate and final shafts. The main shaft and intermediate shaft must be colinear for the rigid shaft coupling to function properly. Because of the different diameters and associated bearing specifications, we used washers as spacers to raise the smaller bearings on the intermediate shaft. To ensure the bearings would not rip out of the wood under high loads, we incorporated through-bolts with washers and lock nuts on the underside. Note that this assembly task was rather involved, and required the use of power drivers, socket wrenches, and box wrenches. After drilling pilot holes to the correct bolt diameter, we used the power driver to drive the through bolts into the wood. Then, on the underside, we used a socket wrench to thread on the lock nut as far as it would go before bottoming out the hex bit. We then switched to tightening the lock nuts with the hand-held box wrench, using the socket wrench on top of the bolt head to prevent it from unthreading and achieve maximum tightness. Finally, we used Allen wrenches to tighten the clamping screw on top of the bearings. Based on observation, the bearings functioned as intended with no pressing improvements needed.

The **Large Sprocket** is the high-torque, low speed side of our flexible transmission. It was attached to the shaft using a key and keyway. The keys were store-bought based on the size of the keyway in the large sprocket. We then machined keyways into our stainless steel shafts using the manual mill, taking care to ensure precision in keyway width and depth. Additionally, we used an end mill to face off a small flat plane on the surface of the intermediate shaft; this allowed the sprocket’s clamping screw to mate properly with the shaft.

The **Small Sprocket** is the low-torque, high speed side of our flexible transmission. It was fastened to the shaft using the same process as the large sprocket. During assembly, we tried to ensure that the two sprockets were coplanar, so that the chain did not have to twist or bend out of plane. To minimize vibrations during testing, ensure that the clamping screw on both sprockets is adequately tightened.

The **Chain** connects the two sprockets. During assembly, we positioned the final shaft as close to the center of the dock frame as possible without the flywheel interfering with a structural beam. From there, the lateral position of the intermediate and main shaft was determined based on the chain length we purchased (this chain length was calculated based on the ideal theoretical spacing between the two sprocket diameters, using principles learned from ME 329). As such, the main shaft was not positioned perfectly over the center of the dock frame and was biased in the direction of the flywheel. The roller chain was pre-lubricated and the two ends attached with a connecting link. The connecting link proved difficult to install; we accidentally caused yielding in the side-mounted metal clip when trying to install it with pliers. Fortunately, we had a spare and took greater care the second time around. Overall, the transmission system worked rather well. We did observe some vibrations in the chain, possibly because the two sprockets were not perfectly coplanar, or maybe because there were too few teeth on the small sprocket. Future testing should employ the use of a protective cover to ensure that nothing gets caught in the chain during operation – including fingers!

We have reached the crown jewel of our distinguished wave energy converter: the **Flywheel**. This immaculate piece of machinery has humble origins as an Olympic bumper plate. Most off-the shelf flywheels are intended to smooth out the rotational speed of a shaft in high-frequency applications, such as in a car, where the linear motion of pistons does not translate perfectly to continuous rotational motion. Finding a marine-rated purpose-built flywheel that had sufficient energy storage to power a 20 Nm load torque (electrical generator) on the downward heave of the wave (> 4s) proved exceedingly difficult and expensive. And from that challenge came the call to action for our knight in shining red rubber. I wish we took pictures of the faces of all of the shop techs in Mustang 60 who observed us machining this 45-lb behemoth for the purpose of a flywheel – their concerns were well-warranted, as purpose-built flywheels are religiously balanced to ensure minimum vibrations at high speeds (this contributes to the high cost). Nevertheless, we felt confident that we could adequately balance this bumper plate flywheel using sticky-weights purchased at Harbor Freight. We took great care to drill the through-holes for the face mounted shaft collars at equidistant radii around the center of the flywheel. When the day of testing finally arrived, we tentatively spun up the flywheel to observe its behavior. To our surprise, the system appeared stable, even at our rated speed of 500 rpm – without any balancing required! Of course, we did not perform any quantitative testing to measure cyclical vibration forces in the bearings; thus, we recommend you exercise caution when conducting your testing and do not try to exceed 500 rpm. Consider undergoing the balancing process – something we ran out of time to do.

The flexible **Generator Coupling** functioned similarly to the shaft coupling; however, there was no need for custom dimensions or a one-way clutch. It connected the generator shaft input to the final shaft. We do not have any pressing recommendations for this component.

The **Generator** input shaft needed to be colinear with the final shaft. Rather than repeat the washer spacing process used for the bearings, we elected to plane down the wood to the correct height. Even though this reduced the structural integrity of the wooden plank to some degree, we felt confident this approach was valid because the expected loading was minimal. The same method of through bolts with lock nuts was employed during fastening.

The mechanical team is not prepared to detail the assembly and key takeaways of the electrical system; however, we can comment on the **Electrical Housing**. These marine rated plastic boxes were secured to the dock frame using small screws at the bottom. Further, we drilled holes for the wires to pass through. As such, their waterproofing ability is currently compromised.

Consider ways to seal off the wires and their holes. Further, you may want to consider waterproofing the bottom of the boxes where we screwed into the wood.

Testing was completed very close to the MECC report deadline. Unfortunately, we were unable to test the **Pump** and **Osmosis Membrane** subsystems because we were missing a key pump component and did not have time to acquire it (at the inlet, there is a main return bypass valve which drained all of the water before it entered the pump). Ultimately, after our business team invalidated desalination as a potential market, our team put the pump and reverse osmosis membrane on the back burner. Consider researching more about pump set up and operation (lubrication oil, etc).