# Final Report: Business Plan, Technical Design, Build & Test

2024 Marine Energy Collegiate Competition

**California Polytechnic State University, San Luis Obispo**

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## Executive Summary

PolyWave Energy is the second team from California Polytechnic University at San Luis Obispo to compete in the Marine Energy Collegiate Competition. PolyWave Energy consists of Mechanical Engineering, Electrical Engineering, and Business Administration students who have worked together from September 2023 to May 2024 on designing, building, and testing a marine power device to serve a selected market.

In response to the escalating concerns surrounding carbon emissions, climate change, and the depletion of fossil fuels, California Polytechnic State University's Polywave Energy team has developed a sustainable and reliable energy source for Autonomous Underwater Vehicle (AUV) charging. Through extensive research of the AUV market and stakeholder interviews, our team found that companies within the oil and gas industry would benefit most from our charging device.

We are strategically positioning PolyWave Energy to cater to the specific needs of the target market while still identifying opportunities for expansion into adjacent market sectors. Our device's competitive edge lies in its scalability and the fact that it is easily deployable, which effectively navigates the limitations of traditional moored Wave Energy Converters. We also offer a cost-effective, environmentally friendly alternative to current AUV charging methods on the market. PolyWave Energy is poised to navigate the complexities of product development and operations by focusing on rigorous testing and proactive risk management. Additionally, our financial projections help validate the company's viability, providing a visible pathway to profitability by combining sales revenue and recurring maintenance contract revenue. PolyWave Energy aims to establish itself as a leader in renewable energy solutions, leveraging the distinct features of our device to drive a positive environmental impact and ensure sustainable long-term growth.

The device is a rack and pinion wave energy converter. Featuring a floating portion in the water to capture the vertical motion of the waves, the device efficiently converts this motion into rotational energy. The rotational energy spins a generator, which stores electricity in a battery for reliable, around-the-clock AUV charging. The rotational and electrical systems will be mounted above the water on a fixed platform, and the relative motion between the floating portion and the fixed structure is used to create electricity.

In our project, we built a scaled down model of our device, scaled to meet the constraints of our testing setup. We tested our model on land, using wave data from the Gulf of Mexico, our target location for the device. Our team underwent extensive analysis to select and design components, ensuring that the device would be durable, safe, and effective in producing electricity. Numerous prototypes and iterations brought us to the final specifications of our device, for which our team procured the parts, fabricated, and assembled them. The device was tested under six conditions and successfully generated power in all conditions. The device functioned as expected, showing promise for future marine power generation and implementation in charging of AUVs.

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# 1. Business Plan

## 1.1. Concept Overview

For years, the ocean has provided a foundation for economic activity at both local and global scales as a source of food, energy, recreation, and trade. The rise of the blue economy represents a global shift toward sustainable energy solutions in response to increasing concerns about carbon emissions and the threat of climate change. The PolyWave Energy team has developed a wave energy converter that offers a clean and efficient way for oil and gas companies to charge autonomous underwater vehicles.

AUVs are unmanned underwater vehicles without a tether or line to a surface ship. The current battery capacity of AUVs limits the duration of their missions to 24-48 hours (about 2 days) and many AUVs must return to the ocean's surface to be manually charged by a team of people using diesel generators. Underwater charging of AUVs with our device would eliminate the need for AUVs to return to the surface as frequently, reduce human risk, increase mission duration, and reduce carbon emissions.

After conducting comprehensive market research, our team decided to target oil and gas companies who are currently using AUVs. These companies employ AUVs to enhance operational efficiency and safety for underwater inspections, welding, remote sensing, and oil spill prevention at offshore oil rigs. AUVs play a crucial role in reducing environmental risks and providing valuable data in offshore operations. Additionally, offshore oil rigs are facing intense pressure from the public to decrease their carbon footprint. Attaching our sustainable charging device would improve their public image by reducing their reliance on diesel generators to charge the AUVs. This demonstrates to the public that oil and gas companies are taking steps to reduce their carbon footprint.

Our technology can be mounted to oil rigs, piers, and other stationary offshore infrastructure. To power our device, a buoy bobs up and down with the waves and is attached to a rack and pinion mechanism to convert the linear motion of waves to rotational motion. In our transmission system, the rotational motion is filtered to single-direction rotation by the usage of a one-way clutch, and a gearbox that increases the speed of a generator. The electricity will be stored in a battery to make it readily available for AUVs. To minimize exposure to the extreme marine environment and provide ease of maintenance, the rack, pinion, and transmission system will all be stored above water in a waterproof enclosure.

Our business model plan is to sell the device directly to offshore oil rig companies, along with an annually renewed maintenance contract. This will be further discussed in detail in the development and operations section of the report.

PolyWave Energy's wave energy converter creates significant value for our customers by generating clean, predictable electricity, reducing reliance on fossil fuels, and contributing to a more sustainable energy future. Since we will not be mooring our device to the bottom of the ocean, we can drastically decrease the price of installation by attaching it to the oil rig. The system is also easily scalable to meet different energy needs, allowing for countless applications across many industries. Our converter can be used to charge AUVs in a cleaner and more efficient way, advancing an already rapidly growing market.

## 1.1. Relevant Stakeholders

**Government Agencies:** The project will require safety approval and permitting from government agencies at the local, state, and national levels. For example, the Federal Energy Commission holds regulatory authority over the interstate transmission of electricity, including marine energy projects. The Commission would ensure that our project aligns with federal regulations and receives the necessary permits and approvals for installation. Additionally, the Bureau of Ocean Energy Management (BOEM) manages the development of the nation's offshore energy resources in an environmentally and economically responsible way. In partnering with the BOEM, we could ensure that our project receives the correct leases, easements, and rights of way.

**Environmental Organizations:** Non-governmental environmental organizations could provide us insight into how our marine energy device decreases the carbon footprint of offshore energy operations and positively impacts the ocean. Ocean-focused organizations like The Ocean Conservancy, Surfrider Foundation, and Oceana would be valuable as well.

**Investors:** Installing, deploying, and maintaining our marine energy device will require significant financial investment. Investors in the project will have a significant stake in the project's success. Some sources of investment to consider include Shell Ventures, EIT InnoEnergy, Katapult Ocean, and the Office of Clean Energy Demonstrations.

**Oil & Gas Companies:** As future customers of our marine energy devices and key participants in the offshore energy industry, oil and gas companies are crucial to PolyWave Energy's long-term success. Because they will be interacting with our device firsthand, the oil and gas companies that we partner with will be able to provide us with important feedback on our device's functionality, key insights into the oil and gas industry, and guide us through regulatory and policy implications.

**AUV Companies:** Other AUV companies would be stakeholders in our project as this system could become a product add-on to their existing solutions.

**Stakeholder Outreach & Engagement:** Throughout our project, we interviewed several different stakeholders in the oil and gas, renewable energy, and autonomous underwater vehicle industries. These interviews allowed us to investigate previous wave energy conversion inventions, explore diverse funding sources, understand the significance of financials, and network within the marine energy, oil, and gas industries. Most importantly, our interviews with these industry professionals gave us important insights into stakeholder requirements, customer needs, and the industry environment. Our outreach to stakeholders is further discussed in the primary market research section below.

## 1.2. Market Opportunity

The AUV market is a newer and rapidly growing market. It is projected to be worth $6.4 billion by 2030 and has a compound annual growth rate (CAGR) of 22.4% (Global AUV Market). With such strong projections, there are endless opportunities for PolyWave Energy to build momentum in this market.

Primary drivers of the market's growth are the increasing capital expenditures of offshore oil and gas companies, the increasing need for ocean data and mapping, and rising defense spending worldwide. As fossil fuels become increasingly difficult to locate, oil and gas companies invest more in exploration and production activities such as drilling in deeper waters and more remote locations. Consequently, they are spending more money on these endeavors and are increasingly relying on AUVs over manual expeditions.

A significant market gap exists due to the higher operational and charging costs of AUVs. However, our device offers a solution by providing a continuous supply of renewable energy. Offshore oil rigs currently rely on diesel generators or grid power (if available) to supply them which electricity, which is extremely expensive. Our device offers a cost-efficient alternative by providing constant access to energy even in remote locations. One of the primary selling points of our device is the reduction of long-term costs, as outsourcing energy offshore is extremely expensive.

The simple installation and the maintenance contract ensure that offshore oil rigs will never have to worry about the upkeep of the PolyWave system and can be assured that part replacement, maintenance, and device issues would be taken care of by our team. While other solutions exist on the market, none provide the same level of cost-efficiency and ease of installation and maintenance as PolyWave Energy's energy converter.

### 1.2.1. Secondary Market Research

Our market research started with a comprehensive review of the *Powering the Blue Economy* report, which highlighted various needs and opportunities within the Blue Economy. Through this review, we identified a significant gap in the AUV charging market. Deeper research on autonomous underwater vehicles led us to identify which specific areas were lacking in this market.

As a newer market, our team found there was much to be uncovered regarding AUVs and had to dive deep into researching to find substantial information. AUVs, unmanned vehicles used for various purposes, are currently charged through fossil fuels which produce carbon emissions and are very costly. This creates charging limitations for the AUVs, resulting in a short battery life. PolyWave Energy's device offers a promising solution to this challenge by providing an endless supply of energy and significantly reducing long-term costs.

A big market driver that we found through our research was the rise of defense spending in countries around the world. Governments are prioritizing the enhancement of maritime security and defense capabilities, with a particular focus on AUVs (Growth Market Reports). As the need to modernize underwater inspection, security, and exploration continues to grow, the number of AUVs being developed and used worldwide is increasing. AUVs are emerging at the forefront of new technological advancements, making them a key component of f

The offshore oil and gas industry has also accelerated the growth of AUVs through the increase in capital expenditures and investments (AUV Markets). Despite the high expenses associated with using AUVs, the oil and gas industry continues to utilize them for offshore operations. Offshore oil rigs benefit greatly from AUVs, with the primary limitation being charging capabilities.

Through our secondary research, the PolyWave Energy team identified multiple gaps and opportunities within the AUV market that can be addressed through marine energy solutions. By understanding the challenges within this market and the driving forces behind AUV adoption, PolyWave Energy created an innovative solution to close these market gaps and adapt to the evolving needs of the industry.

### 1.2.2. Primary Market Research

Our primary market research involved direct outreach and interviews with six industry professionals. The interviewees included CEOs, product developers, researchers, managers, and consultants at ocean technology startups, Advanced Navigation, the UW Applied Physics Laboratory, Beltra Energy Corporation, Vandenberg Space Force Base, and the Pacific Northwest National Laboratory. These interviews allowed us to investigate previous wave energy conversion inventions, explore diverse funding sources, gain insight into the current state of the marine energy and AUV industries, understand market gaps, and network within the marine energy, oil and gas industries. From those interviews, we were able to take away two primary insights, outlined in the following paragraphs.

Stakeholders provided valuable insights into the technological development process and how to optimize our marine energy device to ensure it is as efficient and effective as possible. Chris Malzone, Senior Account Manager at Advanced Navigation, highlighted that designing wave energy devices that are optimized for specific wave characteristics is crucial for maximizing output and ensuring efficiency. He also suggested that we research other successful commercial devices within the marine energy market to uncover what aspects of their business and design contribute to their success, and what factors contribute to their challenges. Advanced Navigation focuses on using AI (Artificial Intelligence) robotics and navigation technologies, Malzone emphasized that using AI software for simulations can significantly reduce costs and increase efficiency in the technology development process.

Interviewees also emphasized the importance of stakeholder engagement and communication, both internal (within the team) and external (with stakeholders, and the SLO (San Luis Obispo) community). As PolyWave Energy's wave energy device contributes to global efforts to mitigate climate change, it will have an impact on the public. Therefore, stakeholder engagement and community involvement are essential to our project's success.

Jose Beltran, CEO of Beltra Energy Corp, emphasized the importance of networking within the marine energy industry to secure investor funding. According to Beltran, building strong relationships with investors, industry experts, and potential partners is essential for successfully raising capital for marine energy projects.

Curtis Anderson, an Environmental Engineer for the Pacific Northwest National Laboratory noted the complexity of the marine energy industry, especially marine energy devices. The ability to communicate the technicalities of the device as well as our vision and mission statement in a way that the public would clearly understand would be incredibly valuable.

### 1.2.3. Early Adopters

PolyWave Energy has chosen to focus on offshore drilling rigs used by oil and gas companies as the early adopters of our marine energy device. Due to its extensive history of pioneering technological advancements in subsea exploration and investing in the research, development, and deployment of underwater operations, the oil and gas industry is at the forefront of autonomous subsea technology. Several companies within the oil and gas industry are already using AUVs for underwater inspections, oil spill prevention, and the maintenance of infrastructure. However, these AUVs are currently being charged using diesel and gas generators which are expensive and harmful to the environment. By using PolyWave Energy's charging device, oil and gas companies would have access to a consistent, clean energy source, could extend AUV mission duration, and could save substantial amounts of money in the long run. Additionally, by attaching our device to their offshore rigs, oil and gas companies can demonstrate their commitment to environmental responsibility, addressing increasing public pressure to implement more sustainable operations. PolyWave's charging device offers oil and gas companies a practical and clean solution to their AUV charging needs, making them ideal early adopters of our technology.

### 1.2.4. Market Segmentation

While the end goal of PolyWave Energy is to eventually access the entire AUV charging market, as a new startup, we must start with a small portion of that market: the offshore oil and gas industry. In the United States, there are currently thousands of active offshore oil rigs, mostly located off the coasts of Louisiana, Texas, California, and Alaska. In our research, we found that the Gulf of Mexico is the primary source of offshore oil and gas for the United States. This information helped us narrow down the region we would target for preliminary customers. The Gulf of Mexico has 2,366 active offshore oil rigs (Oil Infrastructure in the Gulf of Mexico). This quantity can be visually demonstrated through the image in Figure 1. This number offers many opportunities for success in placing our product on these rigs.

Currently, there are approximately 1,300 AUVs operating in the Gulf of Mexico, with an average of 50 new units being built annually (Market Prospects for AUVs). On average, each offshore oil rig utilizes one to two AUVs for operations, maintenance, inspection, etc. Given the substantial use of AUVs by offshore oil rigs, our objective is to secure 10% of the offshore oil rigs currently in use in the Gulf of Mexico within the first five years of operation. If this proves to be successful, we will continue expanding into the offshore oil rig market. Figure 2 below illustrates how we broke down the AUV charging market, starting with the overall market, then focusing on AUVs within offshore oil and gas sector, narrowing down to the Gulf of Mexico region, and finally, targeting 10% of the oil rigs in the Gulf of Mexico.

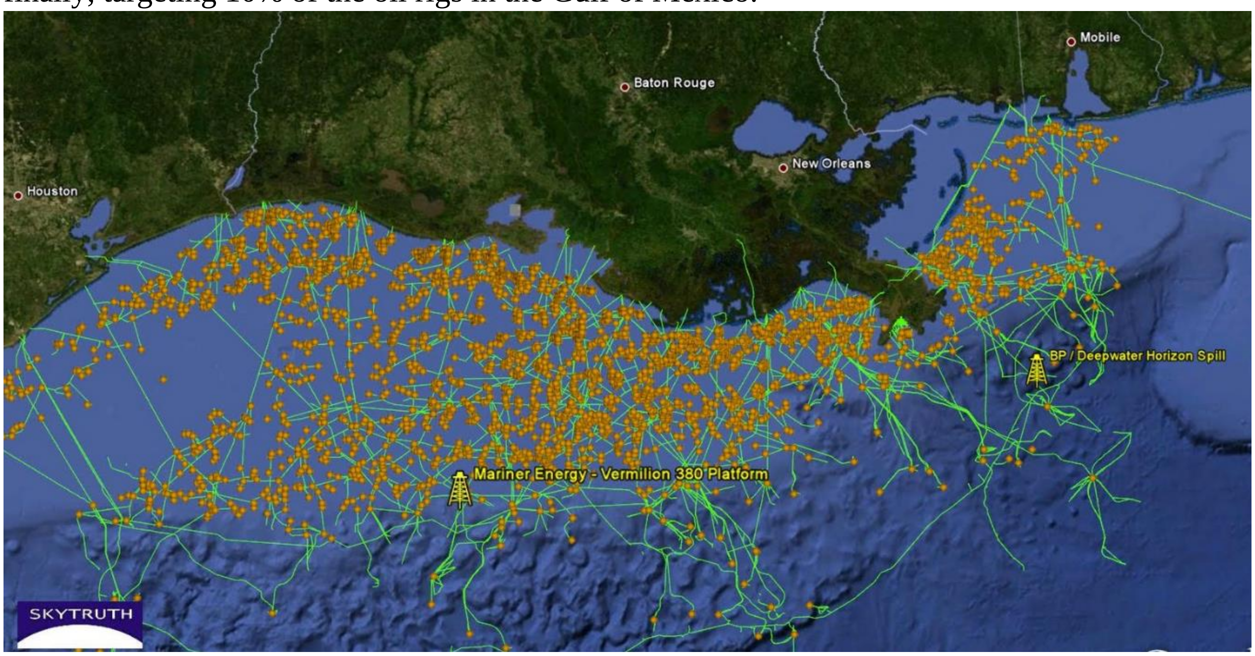


**Figure 1**: Map of the offshore oil rigs in the Gulf of Mexico (orange dots equate to rigs).


**Figure 2**: Demonstration of how we segmented the market for entry.

### 1.2.5. Adjacent Markets

Securing success with our early adopters in the oil and gas industry is crucial for PolyWave energy to expand into adjacent markets successfully. While the use of fossil fuels will remain prevalent for the foreseeable future, the number of offshore platforms will start to decline as renewable energy becomes more widespread. Because of this, one potential adjacent market would be providing power to decommissioned oil and gas platforms, including the AUVs being used at these locations. Currently, these decommissioned structures are being repurposed for marine monitoring, energy and environmental research, scientific education and training, and more (Creating Alternate Uses for Offshore Oil and Gas Platforms). Additionally, the platforms can also serve as infrastructure for offshore renewable energy and offshore aquaculture operations. PolyWave Energy is positioned well to make a smooth transition into this market due to the structural similarities between our devices and the platforms they will be attached to.

Once PolyWave Energy has established itself as a reputable and mature company, another potential adjacent market would be charging AUVs being used by the military. Similar to AUVs being used by oil and gas companies, PolyWave's product can replace the gas and diesel generators currently being used to charge military AUVs and provide a more efficient and reliable energy source. Obtaining an energy contract with the Department of Defense could prove to be very lucrative for PolyWave Energy. The military is a significant consumer of energy, requiring power and fuel for vehicles, aircraft, ships, and to power its vast network of bases and facilities around the world (U.S. Department of Defense). This presents an opportunity for PolyWave Energy to expand out of just AUV charging and provide power and electricity for the various other military vehicles and infrastructure.

### 1.2.6. Competitors

The current primary charging method for AUVs is through gas and diesel generators. For PolyWave Energy to capture our early adopter market of oil and gas companies, we must offer a better solution than the current one. Relying on gas and diesel generators on offshore oil rigs can be expensive and environmentally damaging, presenting an opportunity for PolyWave Energy to attract customers looking for a consistent source of renewable energy.

Most wave energy converters on the market require extensive and costly installation due to the requirement of mooring the device to the bottom of the ocean. For example, Ocean Power Technologies' (OTP) PB3 PowerBuoy functions as a point absorber whose design is required to be attached to the ocean floor (PB3 PowerBuoy).

CorPower Ocean is another competitor with a device that requires mooring. Their product is used for large-scale energy generation, enough to power hundreds of thousands of homes. Unlike PolyWave Energy, this business model requires CorPower's WECs to be connected to a power grid (CorPower Ocean). PolyWave Energy's device requires a significantly simpler installation process by attaching directly to any stable ocean structure without the need for grid connection.

Similarly, Eco Wave Power's wave energy converter can be attached to any structure located in the ocean similar to PolyWave Energy's product. However, Eco Waves' device is used to generate power to the grid dissimilar to PolyWave Energy (Eco Wave Power).

Apart from the wave energy industry, Chevron would also be a large competitor for PolyWave Energy. Many AUVs are currently being charged with diesel generators using diesel that is manufactured by oil and gas companies such as Chevron. These companies can buy diesel straight from their own refineries, allowing them to purchase it at a highly discounted price.

However, by using diesel, companies incur recurring costs in transporting the diesel onto the offshore rig each time the supply runs out. PolyWave Energy eliminates this cost and harnesses a source of energy that will never run out. Furthermore, PolyWave Energy also allows these companies to claim clean energy use, which is an important public relations benefit.

## 1.3. Development and Operations

Throughout the course of PolyWave Energy's development, our team has been using Technology Readiness Level (TRL) phases as a means to validate our assumptions and approach.

When developing a new technology, TRL is an essential tool to use for validating proof of concept. TRL levels 1-3 are focused on research and developing a basic proof of concept. Then it moves into TRL levels 4-6, which are centered around testing and prototype verification.

PolyWave Energy is currently ranked at TRL 6. We have conducted thorough research, validated proof of concept, and successfully tested our prototype. The next step for PolyWave Energy is to transition into TRL 7; deploying the prototype in an operational environment. Within our 5-year business model, we plan to achieve TRL 7 in year 2 by installing the device onto offshore oil rigs for operational prototype testing. TRL 8 and 9 will follow once we start selling the WEC for revenue in a commercial environment. Ideally, we will start producing and selling a small amount of product in year 3, and that will be profitable enough to continue with development and operations.

The initial scaled prototype testing in year 2 will provide valuable insight into adjustments needed for both the device and our business model. Since we will be installing the product onto active offshore oil rigs, we will be able to collect data on how much energy and electricity our wave energy converter is producing in comparison to the needs of the AUV charging. While the current device only provides energy to the already installed charging ports, future development could include integrating charing ports into PolyWave Energy's system. The initial phases of operations will help validate our hypothesis and assumptions regarding the scaled version's ability to produce a high amount of power and energy. From there, we will continue to iterate and make refinements based on the data and feedback gathered during testing.

PolyWave Energy business operations will be conducted out of Cal Poly's Center for Entrepreneurship and Innovation. With the variety of resources and professional guidance there, our team is confident in our ability to continue developing the minimum viable product (MVP) and start looking for funding. All manufacturing of the product will be done in an industrial warehouse near the initial deployment regions.

Following our business model, we will be selling the WEC directly to the oil and gas companies with offshore oil rigs using AUVs. Along with selling the product, we will enter into a maintenance contract with these companies as a form of recurring revenue. Through the maintenance contract, PolyWave Energy will provide all services regarding upkeep and repairs of the device. This way, the companies will have full ownership of the device, without having the pains of maintaining the product. This allows our business to stay competitive within the market among other wave energy companies. The device will be sold at a set price, with only the maintenance contract having a fluctuating price; the more devices purchased, the higher the maintenance contract fee will be.

As with any technical project, there are certain risks involved that may impact the overall success of the project. Therefore, we must take the time to consider these risks and respond proactively to mitigate their impact on our project's success. Perhaps the most pressing risk is the environment we will be deploying our marine energy device to. Extreme conditions at sea, including weather, the salt from the ocean, and strong ocean currents could significantly impact our device's performance. In our design process, we have taken measures to ensure that our charging device will be able to withstand the intense environment at the offshore oil rig. We plan on implementing a survival mode in the device, so when ocean conditions get too harsh, there will be a control system that shuts the WEC off and stops it from moving until conditions improve. We also plan to prevent corrosion by making parts out of stainless steel. The design of our device makes it so no part of it sits directly in the water, which also helps prevent corrosion and makes it easier to deploy and maintain.

In addition to the extreme physical environment, the market environment is also highly technical and competitive, making it difficult to enter. To stand out from our competitors, we must effectively communicate our device's reliability, cost-effectiveness, and environmental benefits. Additionally, the technicality of our device may pose a risk to the market's acceptance of our device. To counteract this, we must be able to clearly and effectively communicate our device's capabilities to the target market.

PolyWave Energy must also be wary of technical barriers to implementation. These include regulatory and environmental barriers, specifically regarding the permitting process and adherence to existing policies. Obtaining the necessary permits for deploying the device in offshore environments can be a lengthy and complex process. Additionally, to publicly claim environmental benefits, environmental regulation agencies may require us to complete a comprehensive environmental impact assessment. Our team must be able to verify that our charging device does not negatively impact the surrounding marine environment. This includes noise, light pollution, and habitat disturbance.

Compared to land-based renewable energy systems, the maintenance and operations for our marine energy device involve unique challenges and considerations due to the extreme environmental conditions, high levels of technical specialization, and intense competition within the marine energy industry. Our device will require more preparation concerning protection against harsh weather conditions, saltwater exposure, and strong ocean currents. This involves the use of corrosion-resistant materials, regular maintenance, and specialized marine expertise.

## 1.4. Financial and Benefits Analysis

After building a detailed 5-year financial model, which is pictured in Appendix 1, our team was able to forecast the expected revenue, operating expenses, and the required capital needed by the business. We aim to get an initial seed investment of $1,200,000 to cover the expenses of year 1. Then a series A round of $1,600,000 to cover the expenses of years 2 and 3 as pictured in Table 1 below.

**Table 1**: Venture Capital Schedule

| Series | Amount | Year |
|---|---|---|
| Seed | $1,200,000 | 1 |
| A | $1,600,000 | 2 |

When creating the 5-year financial model, there were many factors we considered when calculating revenue and costs. To determine the cost of goods sold (COGS), we first had to understand what the variable costs of materials, installation, shipping, and maintenance would be. For materials, we took the total cost of our prototype and scaled it up by 3 times, which is the number we found we had to scale the device for commercial sales in the Gulf of Mexico. Installation, shipping, and maintenance required deeper research where we used information on the Pelamis wave energy converter as a guide for our cost determination. The Pelamis is 26 times larger than our scaled device, so we took the costs of installation, shipping, and maintenance of the Pelamis and scaled it down 26 times to calculate our variable costs.

To calculate fixed costs, we considered salaries and operating expenses. These numbers were found from detailed research into the various operating expenses of a WEC business and what kind of employees we would need for the first 5 years of business. Since these are fixed expenses, we assumed they would stay static for the first 5 years of operations, however, we understand that as PolyWave Energy expands, these numbers may increase as we hire new employees and take in more operating expenses.

In the first few years, we plan on steadily scaling the business. In year 1, PolyWave Energy will be producing a scaled prototype that is not for sale and will not be tested on an operational oil rig. In year 2, we will produce 3 real units that will not be sold but will be tested on active oil rigs with AUVs. We will then increase production to 30 units for sale in year 3. We will increase production to 60 units in year 4 and 120 units in year 5. This tactic will allow our business to properly adjust in the beginning while still working towards making a profit.

Our business will have 2 sources of revenue: new sales revenue and recurring revenue. New sales revenue will come directly from selling the WEC to oil and gas companies at a price of $72,596.42. This price was created through the variable costs of producing one unit with a markup of 50%. The recurring revenue will come from the annual maintenance contracts we sign with the oil and gas companies. As discussed in earlier sections, the maintenance contract price will be based on a per unit basis and will vary depending on the quantity of devices purchased and labor. If one unit is purchased, the annual maintenance contract fee will be $12,828.

Overall, with our assumed business model, we will be breaking even by year 4, which shows great promise for PolyWave Energy. The benefits of having two forms of revenue will allow for flexibility in profit and losses. If our assumptions are successfully validated, with the investments we will be receiving in addition to the profits being generated, PolyWave Energy will be able to expand into the market quickly and have a leading renewable energy product.

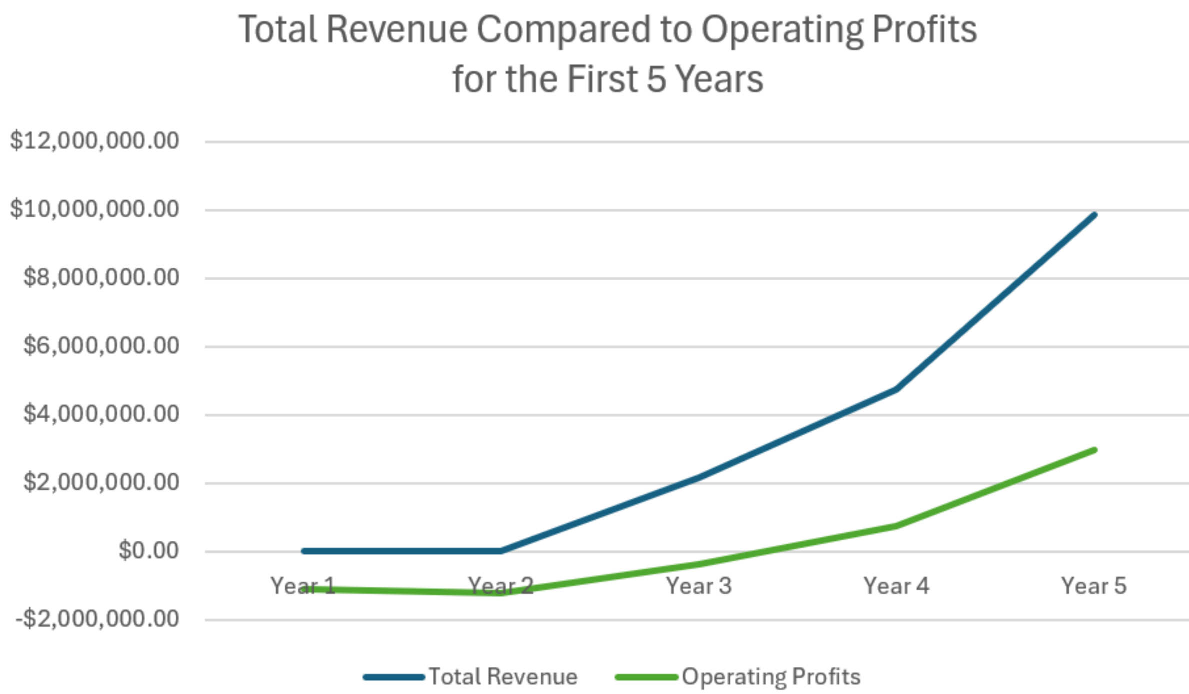


**Figure 3**: Graph depicting total revenue and total operating profits for the first 5 years of business.

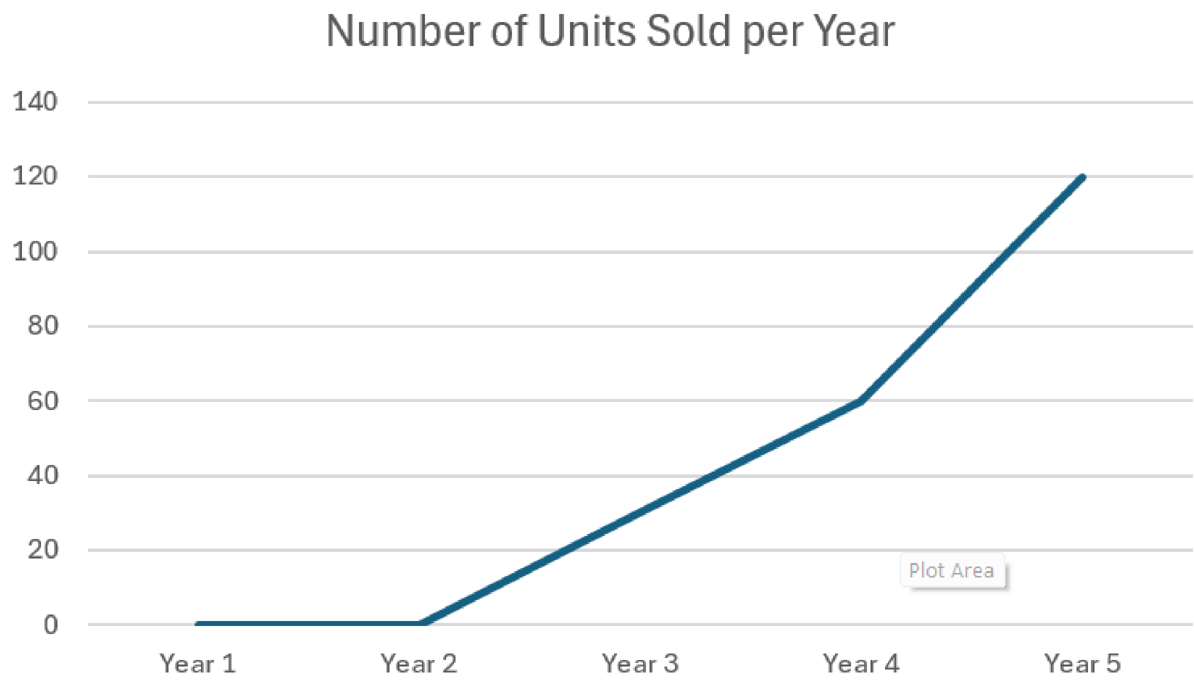


**Figure 4**: Graph depicting the number of units sold per year, which differs from the number of units produced

## 2. Technical Design

The following sections describe the design of the scaled prototype of PolyWave Energy's concept for a wave energy converter that uses a rack and pinion to harness the vertical heave of waves. The design of PolyWave Energy's WEC was developed using research on end user needs, environmental considerations, and testing constraints, all of which are detailed in the Design Objective section below.

### 2.1. Design Objective

One of the main goals of the engineering team this year was to ensure that our WEC was designed and built at a testable scale. The prior year's competing team, Surf Supply, built a winch-based floating dock at full-scale and had planned to test it in open water since they were not able to access a wave tank for testing. Surf Supply was ultimately unable to test the device extensively due to its weight, size, and difficulty to install in open water.

Like last year's team, we were not able to secure access to a wave tank, so we initially designed our device with the plan to test it at the Cal Poly Pier. We met with the Cal Poly Pier manager, Tom Moylan, and were encouraged and inspired by the opportunity to test there and compare our device's performance to a simulation using real-life wave data collected at the pier. To utilize this local, real-time data, we worked with Cal Poly professor Dr. Stefan Talke, who is conducting research on ocean wave data using a wave sensor developed by his research team.

In January, we learned that open water resting was not allowed per competition rules, so we decided to pursue bench testing and narrow our scope to studying the effectiveness of using a rack and pinion mechanism for a WEC design. For this reason, we identified the risks associated with installation in a marine environment and considered mitigation strategies. We narrowed our scope to exclude weatherproofing from our design.

Based on the end users identified by the business team, AUV charging stations located on offshore oil rigs, the engineering team developed a pier mounted wave energy converter that harnesses the upward heave energy of waves as linear mechanical energy, which is converted to rotational mechanical energy using a rack-and-pinion, and further converted to electricity using an electrical generator.

### 2.1.1. AUV Requirements

To ensure that the energy produced by the WEC is easily accessible to the end users, it is imperative that the device is in close proximity to the AUV charging stations. For this reason, a pier-mounted device would satisfy the needs of oil rig AUV charging stations by allowing the WEC to be attached to the oil rigs themselves. Additionally, securing the device to an existing platform at the surface of the water, rather than anchoring at a large depth, makes the installation less costly and the device easier to maintain.

To understand the power that our device needs to produce, we researched AUVs and their charging needs. According to a report by the Department of Energy in Powering the Blue Economy, AUVs are limited from their battery charge capacity and data storage. Our device will allow for AUV missions to be extended by providing them with electricity to charge their batteries at sea. The length of an average AUV mission is often around 24-48 hours, usually limited by the amount of time a AUV battery lasts. Small AUVs have a battery capacity of only a few kWh, and larger ones have about 10 kWh capacities. The amount of energy needed for mission recharges varies on the mission and amount of AUVs deployed but can range from 66 kWh to 2.2 MWh.

Charging stations would need to be able to store at least 66 kWh of electricity in batteries so that an AUVs fleet can charge continuously when needed. When scaled up, our device should also be able to generate this 66 kWh over 24 hours, so that when the AUV batteries run out, there will be storage of the amount of energy needed. This means a 2.75 kW capacity would be required, likely by using multiple batteries in the scaled-up design. The generator for a full-scale system should be specified for this amount of power, as well as the torque and speed that the mechanical system will deliver.

### 2.1.2. Environmental Considerations

Another major consideration for our team was the environmental impact of our device. Beyond the economic benefits, a major motivator for using wave energy is to protect the environment. The most impactful way that our device will protect the environment is by producing carbon-free electricity, but there are also potential environmental impacts that we have worked to mitigate. We researched these potential environmental impacts, and according to PNNL, Ocean Energy Council, and Tethys, prevalent concerns include harm to nearby animals, disruption of animal migration patterns, underwater noise that could affect wildlife communication, noise in general, and emissions of electromagnetic fields.

Since our design functions primarily above the water, and the only part in direct contact with the ocean waves would be the buoy, the risk of animal entanglement with our device is reduced. Our research showed that buoys, like the one on our device, are not conclusively shown to cause harm to marine animals. Since our device can be mounted on pre-existing platforms, new major infrastructure is needed, which will limit the amount that we need to build in the ocean and cut down on permitting challenges that new large infrastructure WECs experience. The platform that we would mount the device on would have been previously approved, and there would likely have been research on the environmental impact of the pre-existing platform.

Another benefit of having the device mounted above the ocean is that there will be no noise created underwater, and since the generator is above the water, there will be no emissions of electromagnetic fields underwater that could affect wildlife. Even though our device will be above water, we aimed to minimize noise pollution in designing our device and specified that it would operate at a max of 75 dB, which is below the harmful threshold for sea life.

The largest concern environmentally associated with our design would be leakage of lubrication used for the pinion and rack meshing. Lubrication was not used in our testing setup, and flow of lubricant and disposal was not addressed in our scaled model. Due to higher contact stresses that the rack and pinion would experience in actual conditions, lubricating the teeth would help reduce the wear. Oil is generally used for lubrication, and oil leaks in the ocean can harm birds and fish. In further iterations using lubricants, a housing around the rack and pinion with sealed bearings would be used to minimize the risk of oil being released into the ocean.

### 2.1.3. Testing Constraints

Further requirements of our device were mainly governed by the scale and performance capabilities of our testing apparatus. Since we were not able to test in open water or in a wave tank, we designed our own testing apparatus using a linear actuator to trace a sinusoidal path that simulates the vertical heave motion of waves.

To ensure that our device can meet the needs of the users within the starting market identified by the business team, oil rigs in the Gulf of Mexico, we developed simulated waves that reflect the conditions in that region. These waves were created using data from National Oceanic and Atmospheric Administration (NOAA) and Froude scaling principles. The maximum travel of this actuator was 0.7 m, which defined the degree to which the waves needed to be scaled down, and thus the scaling of our WEC prototype. Wave scaling will be further discussed in the Wave Scaling and Characterization section of the Build and Test report.

With the selection of a point absorber that would be mounted on a pre-existing structure such as a pier, along with the business findings to serve the market of AUV charging, we identified a list of engineering specifications to satisfy the needs of our end users and constraints of our testing apparatus that we will use to evaluate our design. Additional specifications relating to the cost of our prototype, its weight, and size were included based on funding available from the competition, as well as requirements for safe operation of the device by our team members. These specifications are displayed in Table 2 below, and the associated assessment of compliances will be detailed in Sections 2.7-2.11 of this report, which discuss our testing methodology and results.

**Table 2**: Engineering Specifications

| Spec No. | Description | Requirement or Target | Tolerance |
|---|---|---|---|
| 1 | Power Output | 100 W | ± 20 W |
| 2 | Weight | 150 lb. | ± 25 lb. |
| 3 | Size | 100 $ft^3$ | ± 25 $ft^3$ |
| 4 | Cost to Manufacture | $10,000 | Max. |
| 5 | Energy Storage | 1.2 kWh<br>(1 battery) | + 1.2 kWh<br>- 0.0 kWh |
| 6 | Efficiency | 35% | ± 5% |
| 7 | Noise Level | 75 dB | Target + 25 dB |
| 8 | Safety - MECC Safety and Tech. Inspection | Pass/fail | - |
| 9 | Operating Cost | 5% of initial cost | Max. |
| 10 | Maintenance Frequency | Quarterly | Max. |
| 11 | Range of Travel | 0.7 m | +0.0 m<br>-0.3 m |

## 2.2. Design Description

The following sections detail our design and its intended functionality. Our design of a wave energy converter consists of 3 main subsystems: the linear mechanical elements, rotational mechanical elements, and electrical elements. These three subsystems combine to make up the full wave energy converter. Additionally, we designed and built a bench-testing setup so that we can assess the performance of our device without access to a wave tank. Figure 5 shows an image of our full assembly, labeled with subsystems and major components.

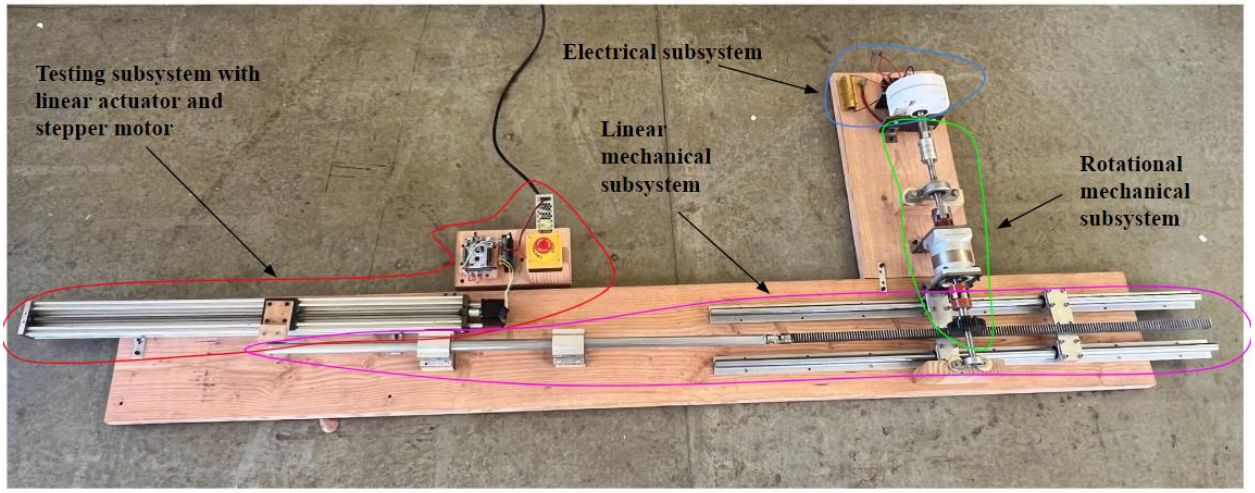


**Figure 5**: Full system assembly.

As a retuning team, we faced the decision at the beginning of the year to move forward with the prior year's design or pursue a new energy conversion mechanism. Due to the large scale of the previous year's design, we would have needed to completely rebuild and redesign the floating dock and winch system at a small scale to allow us to test it. For this reason, we decided to devise a different way of harnessing the vertical heave of the waves and build a scaled prototype. This year's mechanical system is a completely different design than Surf Supply's design, and none of their mechanical parts were used in our device. Figure 6 shows the previous year's design.

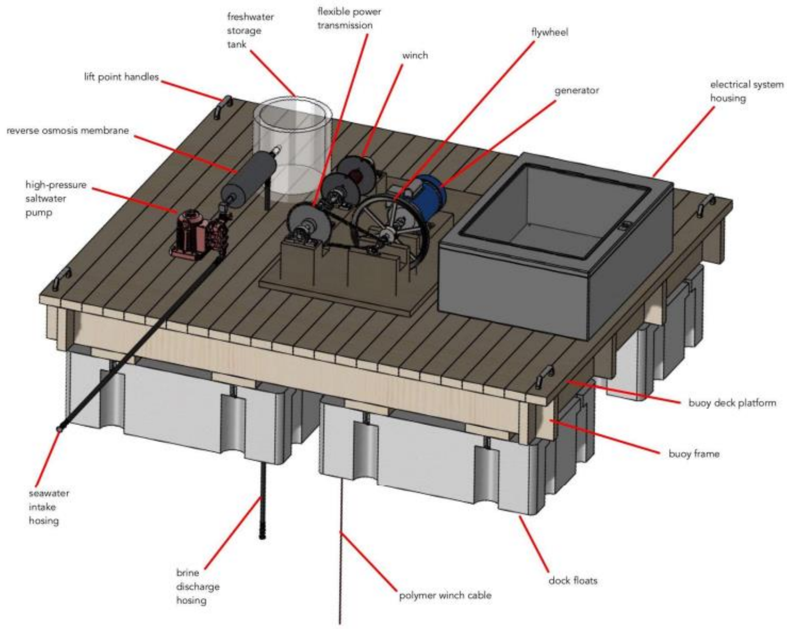


**Figure 6**: 2022-2023 Surf Supply design.

We learned a lot from their design process and research and decided to similarly design a point absorber type WEC. Surf Supply used a winch system with issues with recoiling and produced much friction, damaging the winding material. We replaced the winch system with a rack and pinion. They were also not able to test due to the size of their device, which was full-scale. Our device is scaled down and is therefore testable. In contrast, their transmission system worked very well, so our rotational system uses many of the ideas from their design, such as the one-way bearing and a speed increase. Where Surf Supply used a chain, we used a gearbox to increase the rotational speed. Like Surf Supply, we also opted to keep the rotational and electrical systems above water.

This year's electrical system has a few key differences from the design in 2023. The largest difference is the downscaled generator since it controls the power creation of the system. Its rated power is 12 times lower than before. Since the final goal of the system also changed, a motor is no longer needed to drive the desalinization process meaning the AC to DC converter was dropped altogether. The microcontroller was also altered to a cheaper developmental STM model compared to last year's Arduino board. All the smaller PCB components, such as relays, resistors, and bipolar junction transistors (BJTs), were adjusted for the smaller ratings of the new system.

### 2.2.1. Mechanical Subsystems

The mechanical system comprises a linear and rotational system connected through the rack and pinion, where the linear motion is transmitted to rotational motion. The rotational system's purpose is to provide the torque and speed necessary to power the generator. Our linear subsystem will be connected to the linear actuator in our testing subsystem at the location of the buoy. The linear actuator is designed to operate in the horizontal plane and will simulate a test wave to accelerate the linear system of our WEC. To accommodate the operating requirements of our testing setup, we will be fixing our linear subsystem horizontally rather than its real-world vertical orientation.

This WEC prototype is designed to be bench-tested in a dry environment to prove the efficacy of a rack-and-pinon in harnessing wave energy. For future iterations of this device, it would be useful to explore weatherproofing and corrosion resistance; however, these analyses were omitted from the scope of our design. Additionally, we omitted the buoy from our prototype and designed with the assumption of a "perfect buoy" that transmits 100% of the vertical heave force of the wave to our system.

Linear Mechanical

The linear system's purpose is to follow the vertical motion of the waves, translate this motion to the rotational system, and take horizontal loads. A 3-D model of the full linear system is shown in Figure 7.

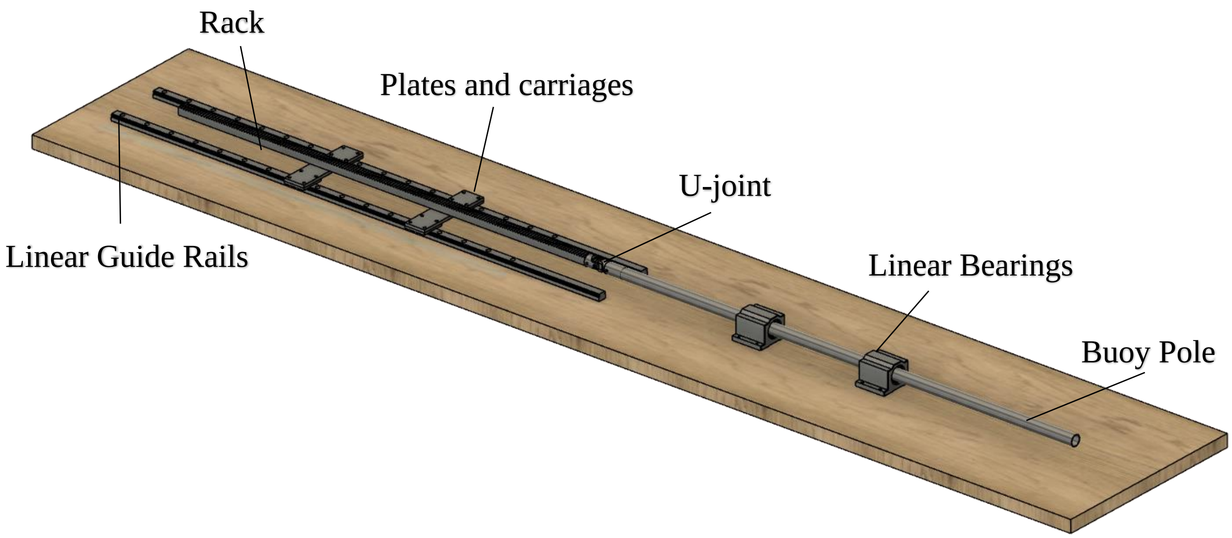


**Figure 7**: Full linear system.

The pole would have our buoy connected to the bottom of it, which would float as the ocean rises and falls, accelerating the system. The pole is used to create space between the ocean and rotational assembly which will be kept above the water. It is also used to transmit the horizontal loads in the ocean to the mounting structure so that the rack does not take horizontal loads from the pole. To keep the pole in the vertical plane, linear bearings are used to support the pole and take the horizontal loads experienced. The pole is connected to a rack which moves up and down with the pole. They are connected through a flexible u-joint to allow for decoupling and small deflections in the pole. Isolated compression testing was done on the U-joint, confirming that this would be a good connection solution. The U-joint is welded to the rack, and there is a spacer which connects the u-joint to the pole through a press fit and bolt. This connection between the pole and rack is shown in Figure 8.

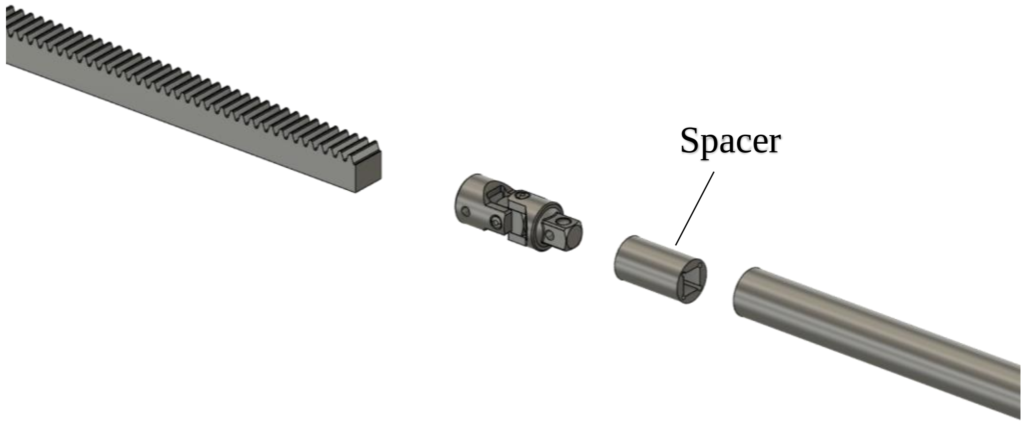


**Figure 8**: Rack to buoy pole connection exploded view.

The rack is attached to linear bearings to ensure it is not experiencing horizontal loads that could affect the mesh of the rack and pinion, if the rack deflects. These linear bearings slide on guide rails which are mounted rigidly. The guide rails are used to further maintain meshing between the rack and pinion as the rack translates. The carriage linear bearings will take the horizontal load that the pinion will cause on the rack. The guide rails also allow for the device to be simply hoisted out of the water when ocean conditions are too stormy. In our testing, we will mount the prototype on a wood base, due to its low cost and ease of machining.

<u>Rotational Mechanical</u>

The rotational mechanical subsystem starts with a 50 mm pinion to convert the linear velocity from the rack into angular velocity. The pinion sits on a 15 mm shaft that is supported by a bearing on one end and is attached to a one-way roller bearing on the other to ensure that the system only spins from the upward heave of waves. This shaft is coupled to a 10:1 gearbox which increases the angular velocity to match the desired 600 RPM for the output shaft. This output shaft is 15 mm in diameter and has a flywheel with an inertia of .05 $\frac{kg}{m^2}$ attached to smooth the output to the generator and reduce the deflection of the shaft during the downward heave of the wave. The output shaft is then connected via a flexible coupling to the generator at the start of the electrical subsystem.

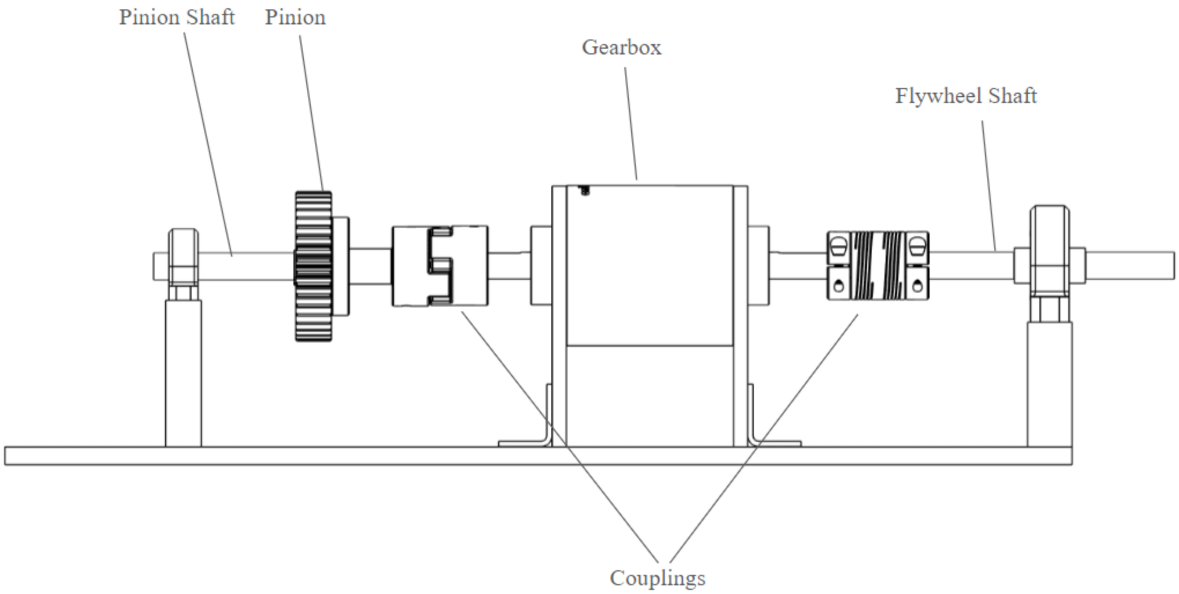


**Figure 9**: Side view of rotational mechanical subsystem.

The image shown in Figure 9 does not show the flywheels attached as we fabricated two different sizes of flywheels to test with, but they are included in the final assembly. Both bearings and the pinion are held in place with retaining rings. Keys are placed in the couplings and pinion to allow torque transfer between components. The two bearings sit in pillow blocks attached to a baseplate with through holes and the gearbox is sandwiched between two plates and fastened with L-brackets to the baseplate.

### 2.2.2. Electrical Subsystem

The electrical system involves all the components that are used to generate electricity and store it for use outside of the WEC. The electrical system begins with an AC generator spun by a shaft connected to our system's pinion. A bridge rectifier is then put in series after the generator to convert the AC signal to a DC signal. This DC voltage is fed into the input of the charge controller which changes its output current to the battery depending on the input at any time. This helps prevent damaging the battery as well as taking some of the responsibility off the microcontroller. The microcontroller uses relay coils acting as switches to determine and control the device's operational state. In the case when the battery should not be charging, the power from the generator goes to a dump load. When a AUV is ready to charge, the battery will stop charging and begin powering the AUV charger.  When the AUV is done charging and moves away, the relays will flip back and charge the battery again. The charge controller sends a signal to the microcontroller when the battery's voltage is either too low or too high. This signal determines if the produced electricity is going to the charge controller or the dump load. The microcontroller receives power from a buck converter stepping down the battery voltage stored on the device.

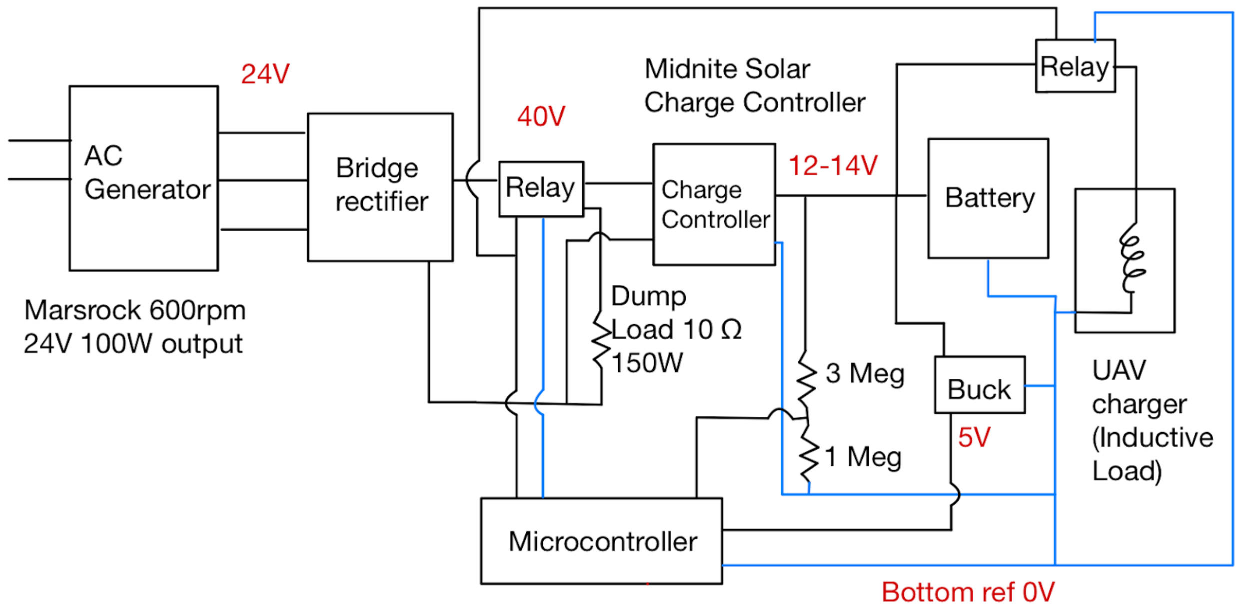


**Figure 10**: High level system schematic.

The generator is one of the most important devices in the electrical system and a part that caused a bit of trouble last year. There were not an abundant number of options for low RPM but high-power generators, and many were not from reputable sources. In the end, the Marsrock Permanent Magnet generator was picked because of its 100 W, 24 V rated output at around 600 RPM. This generator also had a small start-up torque requirement and was available from Amazon.

Last year's Cal Poly MECC team performed extensive research into their charger controller, choosing the Midnite Solar Classic 150 Charge Controller. This charge controller has two key features that make it an excellent choice for Marine Energy usage. Midnite Solar has an MPPT mode specifically for hydro systems where the controller sweeps from the highest voltage to the battery voltage and identifies the highest power generating point. To verify that it stays accurate for the ever-changing waves, the controller will sweep through the voltages again based on a programmed time interval and find the new maximum power point. The second reason this charge controller is great for this design is that it has an auxiliary port that is meant to act as a control signal for relay coils. This prevents the known issue of having two controllers that have conflicting commands which can improperly regulate the power flow of the system.

The previous year's bridge rectifier was chosen since it has been verified to work with most of the same system. This rectifier was already purposely overrated to account for extreme ocean conditions for the previous year's design. Since the system for this year was scaled down, using this rectifier means it has a huge safety factor for voltage and current spikes in the device.

The battery chosen for this project was the LiTime 12V LiFePO4 battery. Compared to lead acid batteries, lithium iron phosphate batteries have a much longer cycle life and a faster charging time. This battery has more than enough storage capacity for charging smaller AUVs with its rating of 100 Ah and 12V. Since this was one of the batteries used in the 2023 design, the battery was charged and discharged to evaluate its storage capacity.

To dissipate the power from the generator when the battery is charged, an appropriate dump load was needed. This resistor was sized by applying Eqn. 1 using the output voltage and power at the output of the bridge rectifier. The final dump load chosen was 10 Ohm and 150 W.

$$R = \frac{(Vdc^2)}{Pmax} \qquad \text{Eqn. 1}$$

All interconnections within the system were fed into and out of a PCB (Printed Circuit Board). This circuit was designed to control where the produced power was going and provide an organized system for interconnection between electrical components. This reduced the risk of a short circuit caused by loose connections. The PCB schematic and layout can be found in Appendix 3.

To control the power flow of this design, relay coils were used between the bridge rectifier, charge controller, battery, and AUV charger. The relay chosen was one compatible with a PCB and was significantly smaller than the preceding relay. It has a maximum current capacity of 10A, which matches the scale of our system since the highest current we expect is around 6A. The coil voltage is 5V which lines up with the output of the microcontroller, making it easy to control.

Both relay coils are controlled by a signal from the microcontroller applied to the base of the BJT in the figure below. The resistance values chosen were $R_{base}$ = 1K Ω and $R_{emitter}$ = 24 Ω. These two resistance values pull 90 mA of current through the BJT and the relay coil. The G5Q-14 DC5 relay coils have a switching current of 80 mA and a minimum switching voltage of 3.75 V. So, the 90 mA pulled through this BJT will be enough to change the state of both relay coils. The circuit below is used once for each relay coil. For note, these relay coils are rated for 80 Amps and 300 Watts which exceeds any current or power produced by the system. The flyback diode was used to protect the coil and BJT from surge current, specifically when the relay coil discharges its current after the BJT switches off.

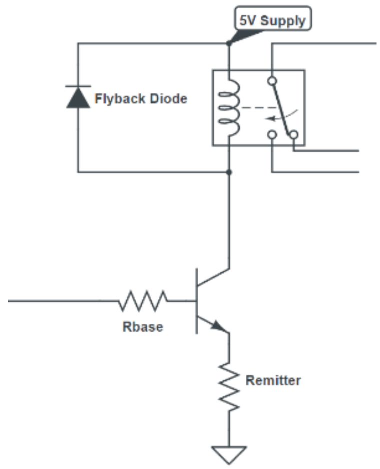


**Figure 11**: Current amplification circuit using a BJT.

The microcontroller chosen for this system is the NUCELO-F303K8, a developmental board that is a part of the STM32 series. It has 22 configurable I/O pins and can run on a 5V power input.

To power our microcontroller with the onboard battery, a buck converter was used to convert the voltage of the battery to a 5V node. This buck uses the Texas Instruments TPS5430DDAR switching converter as the main controller along a standard buck configuration. It can take between 5.5V and 36V and output a constant 5V across different loads. The part values were chosen based on the datasheet's equations and followed one of the sample set-ups for a 5V output.

### 2.2.3. Testing Subsystem

Once we learned that we were not allowed to test our device in open water and could not access a wave tank to test our WEC, we decided to design our own dry bench testing setup. The goal of the bench testing was to drive the "buoy pole" with a linear actuator powered with a stepper motor. The six wave profiles, which are shown in the Wave Scaling and Characterization section of the Build and Test Challenge, were programmed into the stepper motor using MicroPython on a STMicroelectronics NUCLEO development board. Figure 12 shows the electronics driving the testing system.

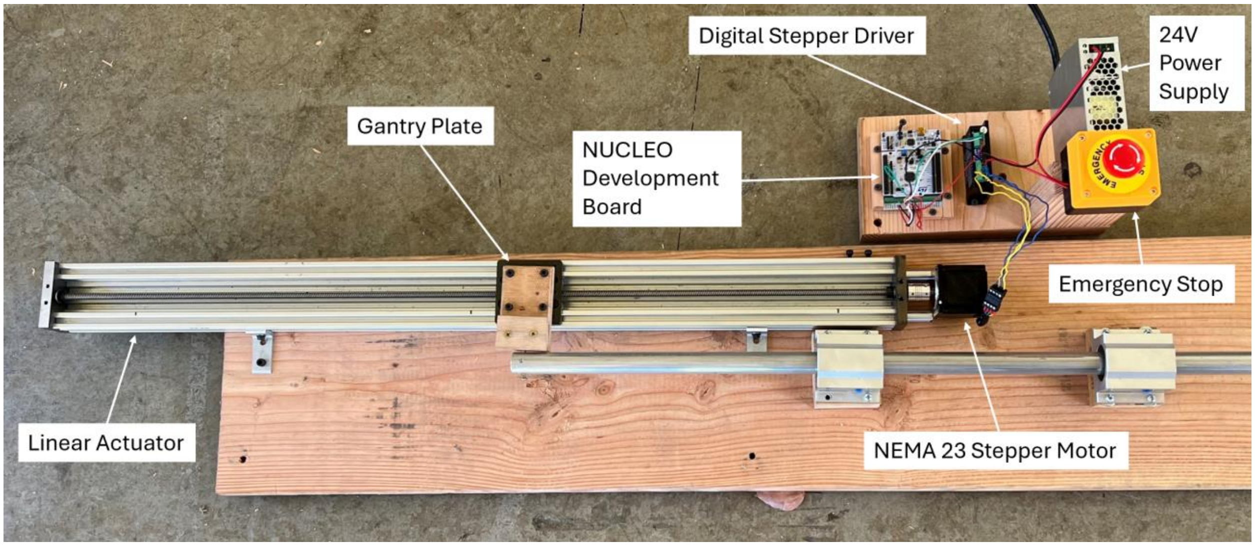


**Figure 12**: Electronics driving the linear actuator.

An emergency stop allowed for immediate shutoff of the stepper motor in case of malfunction. In Python, pulse-width modulation (PWM) was adapted to drive the stepper motor at its fastest. Because stepper motors are driven with alternating on-off pulses, the duty cycle was set to 50% and the frequency was varied to achieve the desired motion. We ran code to calculate the frequency as a function of time every millisecond, using the scaled height and period of the test case. Eqn 2 is the function for the position of the stepper shaft.

$$x(t) = \frac{H}{2}\sin(\omega t) \qquad \text{Eqn. 2}$$

Because the stepper motor frequency accepts input in units of steps per second, a velocity input is needed rather than position. Eqn. 2 was differentiated, and units were converted from meters per second to steps per second by measuring gantry plate travel over 20,000 steps.

$$x'(t) = \frac{H\omega}{2}\cos(\omega t) * \left(\frac{20{,}000 \text{ steps}}{0.4048 \text{ m}}\right) \qquad \text{Eqn. 3}$$

The linear actuator could drive our system and generate power, but not at the scale required. At high speeds, vibrations became a problem for the lead screw. Rotating imbalance in the lead screw would cause the stepper motor to skip steps, resulting in incomplete sine waves. A recommendation for future Cal Poly teams is to employ a more robust linear actuator testing subsystem, if a team opts for full bench testing again. Higher-order wave profiles could also be applied to a linear actuator to eliminate the need for "manual" testing.

Manual testing involved two team members pushing the buoy pole by hand according to the height, period, and general shape of each wave profile being tested. The Data Processing and Results section addresses the downsides of manual testing.

## 2.3. Performance Analysis

### 2.3.1. Load and Stress Analysis

To ensure our design could withstand our testing loads, a stress analysis was conducted on the transmission shafts in the rotational system and the buoy pole in our linear system. The following calculations aided us in selecting the shaft dimensions and materials so that we can achieve infinite life, as well as allowing us to analyze the safety factors on our manufactured parts.

For the rotational system, the pinion shaft and flywheel shafts were analyzed because these were parts that we designed and manufactured and transmitted the major loads of the system. The loading of the shafts was based on the testing loads that could be applied from our linear actuator motor. A MATLAB code was made to conduct a fatigue analysis on these shafts based on Shigley's Mechanical Design Engineering book. This tool could also be used for scaling purposes in future iterations or scaling. For the pinion shaft, the loads and stress diagrams are shown in Figure 13.

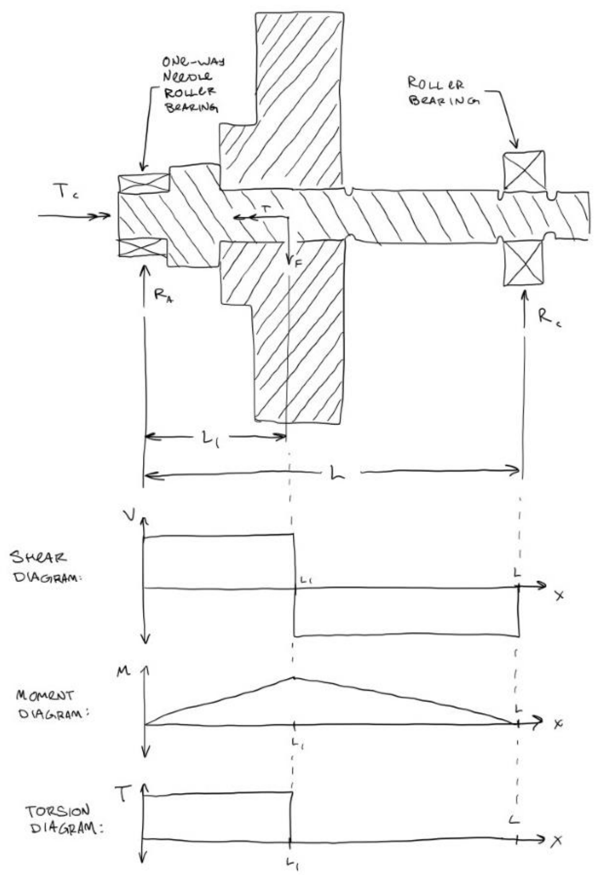


**Figure 13**: Shear, moment, and torsion diagrams for the pinion shaft.

While designing the shaft, the critical location was at the center of the pinion where the max moment occurs. Fully reversed loading was assumed, which is a conservative assumption since the negative torque will not be as large as heave from wave on upward torque. The endurance limit was calculated for infinite life because our design should have a long life so that maintenance of the device is minimal. Von mises stress was used, and a design factor of 1 was achieved using Goodman's method(Nisbett, Budynas 333).

Following manufacturing, the small radius on the shoulders of the shafts were recognized, and additional MATLAB code was made to analyze the stress at the concentration, finding that the safety factor at the shoulder for infinite life is below one. The life for this shaft as manufactured was $8.5 * 10^5$ cycles, which is very close to the $10^6$ cycles for infinite life. The shoulder fillet radius that was needed for the shaft to achieve infinite life was 1.5 mm, which would be considered for future iterations.

For the flywheel shaft, assumptions made were that there is a steady state max torsion (which is conservative because the torsion will be below max when the one-way clutch disengages), the fully reversed bending is due to only the flywheel weight, and the stress concentration from the shoulder is at the critical location with the max moment. Goodman's factor of safety for infinite life on the flywheel shaft is 1.10 with a 15 lb flywheel.

Stress analysis was also conducted for the buoy pole, which would be taking the load from the waves and transmitting it to the rotational system. The MATLAB tool created for the buoy pole includes inputs for an axial force on the buoy, and a horizontal (sideways) load on the buoy pole. This was a consideration because although we are only capturing vertical motion, our device also must take horizontal loads in the ocean. For a member in compression, buckling is also a concern, and the buckling critical load was calculated as 891 N, which is much greater than our test load of 112 N. The safety factor, pole deflection, and bearing slopes are all calculated as well with the MATLAB tool, and Table 3 shows the results for a varying horizontal load on the pole.

**Table 3**: Effects of Horizontal Load on Buoy Pole

| Horizontal Load (N) Along with 112 N vertical load | Yield Safety Factor | Pole Max Deflection (mm) | Bearing Slope (Radians) |
|---|---|---|---|
| 0 | 203 | 0 | 0 |
| 56 | 2.32 | 5.7 | 0.011 |
| 112 | 1.16 | 11.5 | 0.022 |
| 168 | 0.77 | 17.2 | 0.033 |

Table 3 shows the stark difference a horizontal load on our pole makes on the safety factor and deflection. Ideally, this member would be ductile enough to take some deflection and the continuous loading in the horizontal and vertical directions without yielding. Finite element analysis (FEA) was also utilized which shows where the lowest safety factor occurs at different load cases. Figure 14 below shows FEA results at the worst-case bearing position, and the incoming load at 60 degrees.

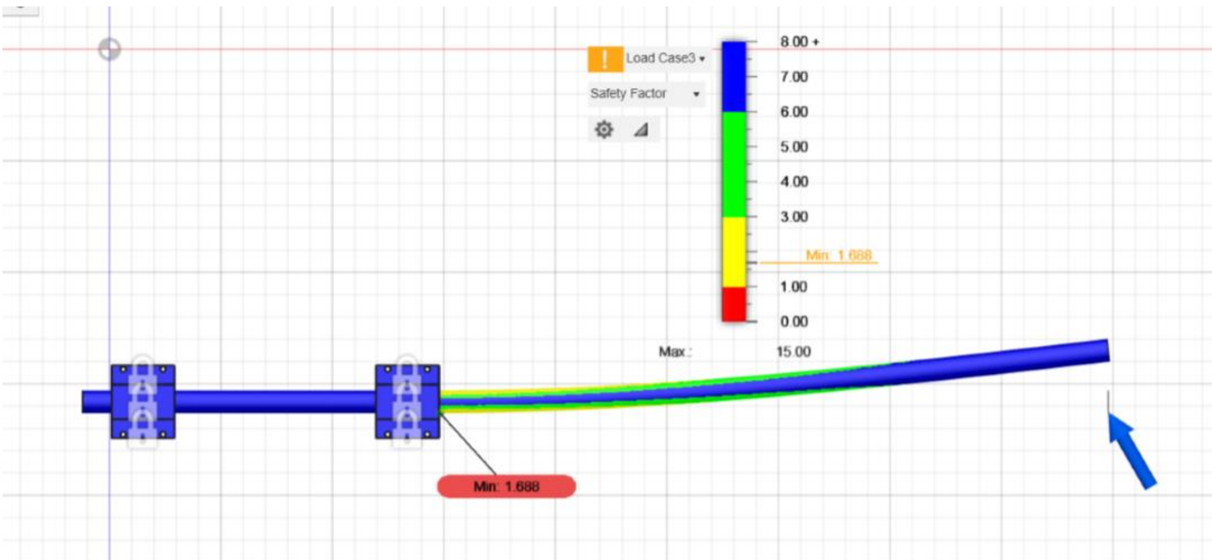


**Figure 14**: FEA for 60 degree load angle respectively

Note that a fatigue analysis for the buoy pole would be crucial for future iterations, as the pole would be under repetitive loads in the ocean. This analysis would be challenging because of the varied loading magnitude and direction in the ocean, and the pole constraints are constantly changing as it slides up and down through the linear bearings.

### 2.3.2. System Dynamics Model

To simulate our model, we used Simscape Driveline, a MATLAB add-on which allowed us to model our design and input our different scaled down wave conditions to see what our output shafts angular velocity would be based on different wave conditions. Our model can be seen in Figure 15. Although this model gave us a good estimate of the range of output RPMs, there are some limitations to mention. First, we were unable to model an AC generator, so we assumed a constant load torque of 0.12 N-m on the output shaft, which is the required generator startup torque as specified by the manufacturer. This value is quite low, and we expected that the generator would provide a much greater load while running. A better model for the future would include the AC generator as part of the model which would allow a more accurate estimate of the output angular velocity and torque as well as an estimate of the current and voltage generated. Also, it was very difficult to estimate each individual bearing damping coefficient, so our estimates of these values may not be accurate. Finally, this model assumes that our buoy can be modeled as a spring, but we did not have a buoy attached during testing. Using this model, we were able to deduce that our output shaft angular velocity would spin at a maximum of 670 RPM (largest wave conditions) and a minimum of 230 RPM (smallest wave conditions).

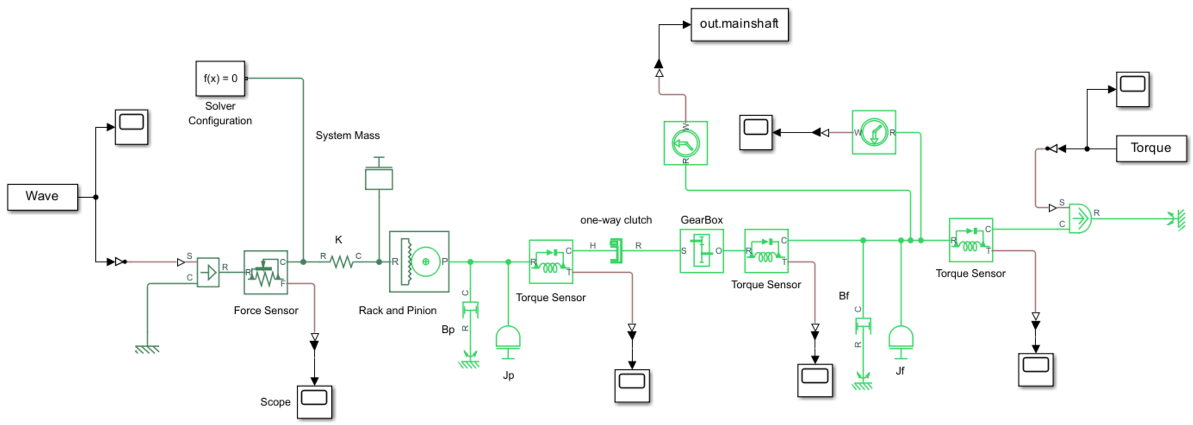


**Figure 15**: Simscape Driveline system model

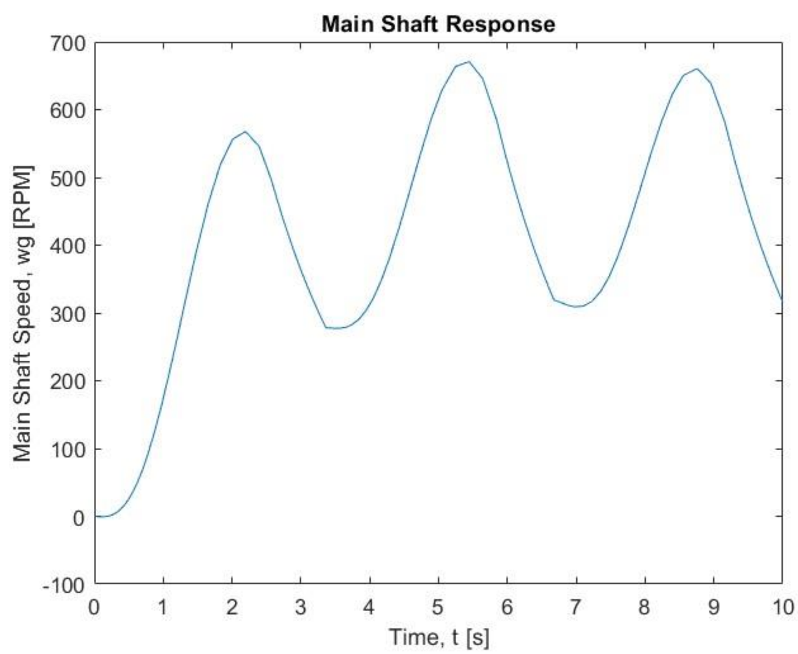


**Figure 16**: Plot of the output shaft angular speed

### 2.3.3. Power Analysis

Using our MATLAB model and inputting our scaled down wave profiles (discussed in section 1.1.14), we calculated our expected power output, $P_o$, through the output shaft for the largest wave conditions. Our input force, $F_i$, is equal to ~1700 N, and using our input shaft diameter of

15mm we can calculate a Torque, $T_i$ of 25.5 N-m. With our gear ratio of 10:1, our final output shaft torque, $T_o$ is 2.55 N-m. Using the final output shaft angular velocity, $\omega_o$ of 670 RPM, we calculated the power transmitted through the output shaft to be 179 Watts. We arrive at this value by assuming no electrical losses from the generator and no mechanical losses through friction in the gear meshing and bearings. Accounting for these mechanical and electrical losses, we estimated our conversion efficiency to be, at maximum, 50%, giving us an adjusted value for power transmitted through the output shaft of 89.5 Watts at 670 RPM.

Based on the generator's information, with the input shaft spinning at 600 RPM, the power produced by the generator should be up to 100W at 24V and 4.16Amps. The bridge rectifier connected to the output of the generator will dissipate around 5% of the total power due to the drop across the device's internal diodes.

The battery has an energy storage capacity of 1.2 kWh. This is quite large compared to the generator's production capabilities; however, this battery will never be fully discharged. Since all controller parts of the system are powered by the battery, the charging process was designed to only charge the battery from around 11 volts to 13 volts so that the buck converter always has power. The extra capacity allows for the battery to stay at a high charge even after a few hours of little to no energy generation, which helps address the intermittency issues associated with changing wave heights. For future iterations, this battery was a bit oversized for this scaled down system and ordering a new, smaller battery would be advised.

Our scaled average raw wave power for our largest wave conditions was 365 Watts. This number came from linear wave theory, multiplying average wave power per unit crest length by the planned buoy diameter of 0.33 meters for the scaled model. Using our adjusted power value from our Simscape model of 89.5 Watts, we estimate that our system will have around a 24.5% conversion efficiency from raw wave power to usable electrical power.

## 2.4. Safety, Durability, Maintenance & Repair

The device built by our mechanical and electrical teams is an early prototype of a WEC that uses a rack and pinion mechanism to convert the vertical heave of the wave to rotational, and then electrical energy. This prototype was intended for on-land bench testing and satisfied the safety requirements of on-campus facilities at Cal Poly during the fabrication, assembly, and testing process.

We conducted a Failure Modes and Effects Analysis (FEMA) as well as a DesignSafe Risk Assessment to identify the potential points of failure and address them using preventative measures in our detailed design and testing. The FMEA lists all the systems and components in our design along with their respective function, failure mode, the effect of the failure, and the relative severity of the failure with respect to the system's overall function and safety. The DesignSafe Risk Assessment follows a similar procedure of decomposing the maintenance of the device into specific tasks and assessing their respective hazard, severity of risk, and risk mitigation strategy. The DesignSafe Risk Assessment can be found in Appendix 3.

Overall, to minimize the maintenance and repair of our device, we opted for a simpler design with fewer components. We especially focused on minimizing the number of components submerged in water, both to make the operation safer for marine life and to minimize the wear due to full submersion in saltwater. A full-scale device installed on a pier or offshore oil rig platform would include waterproof housing to minimize exposure to the corrosive marine environment and would use marine-grade materials.

Additionally, the buoy-pole that floats at the water's surface would be the only moving component stored outside of the waterproof housing. By keeping all electrical systems and most of the moving parts out of the water, we minimize the hazard to sea life and reduce the risk of mechanical and electrical failures.

Since this device is intended to be attached to a fixed platform, maintenance would be less rigorous and demanding than an underwater WEC. Maintenance and installation costs for the Financial Analysis section of the Business Plan were based on scaled-up estimates of the cost of materials for the engineering build, the estimated lifetime of the device's components, and additional research regarding standard maintenance and installation costs for full scale devices.

# 3. Build and Test

## 3.2. Design Process

Our team began the design process by performing significant research into the Blue Economy, exploring current wave energy converter designs, and collaborating with the business team to identify the market and end users our device would serve. Our team was interested in expanding upon the research done by Cal Poly's previous MECC team by focusing on wave energy.

Early in our research and ideation, we identified an interest in coastal communities and autonomous underwater vehicles as the target market for our device. Both end users lend themselves to creating a device that could be installed on a pier, which is easier to install and maintain as it does not require anchoring to the sea floor. Once the business team finalized their market decision to focus on autonomous underwater vehicles, we moved forward with a pier-mounted design and spent time understanding the specific needs of AUV charging stations.

To guide our ideation process and define our design objectives, we created a boundary diagram and performed functional decomposition to identify the necessary functions of our device so that we could come up with ideas to address each functional need.

Throughout our brainstorming process, we created preliminary prototypes to communicate our ideas. We used Pugh Matrices, as seen in Figure 17, Morphological Matrices, and weighted decision matrices to combine our ideas and narrow down our design before creating a more robust prototype and preliminary CAD model, which we presented to our peers to gain feedback.

| Concept / Criteria | 1. [illegible] (winch) | 2. Cyl. OWC | 3. rectangular OWC | 4. rack & pinion | 5. linear generator | 6. crank [illegible] | 7. cylinder cam | 8. paddle & crank shaft | NOTES |
|---|---|---|---|---|---|---|---|---|---|
| Cost | DATUM | + | + | + | − | + | + | + | |
| Portability (compact) | DATUM | S | S | + | + | + | + | S | |
| Weight | DATUM | + | S | + | + | + | + | + | |
| Appearance | DATUM | + | S | S | + | + | + | + | |
| Ease of Installation | DATUM | + | + | + | + | + | + | − | All will be smaller |
| Ease of Maintenance | DATUM | − | − | + | − | S | S | − | |
| Power Output | DATUM | − | − | + | S | + | + | − | |
| Safety | DATUM | + | + | S | + | S | S | − | |
| Σ+ | | 5 | 3 | 6 | 5 | 6 | 6 | 3 | |
| Σ− | | 2 | 2 | 0 | 2 | 0 | 6 | 4 | |
| ΣS | | 1 | 3 | 2 | 1 | 2 | 2 | 1 | |

**Figure 17**: Pugh Matrix example.

While there were many ideas discussed throughout our brainstorming process, we decided on a rack and pinion design. The ideation and prototyping process can be seen in the different levels of prototypes created as we progressed through each stage of prototyping and review.

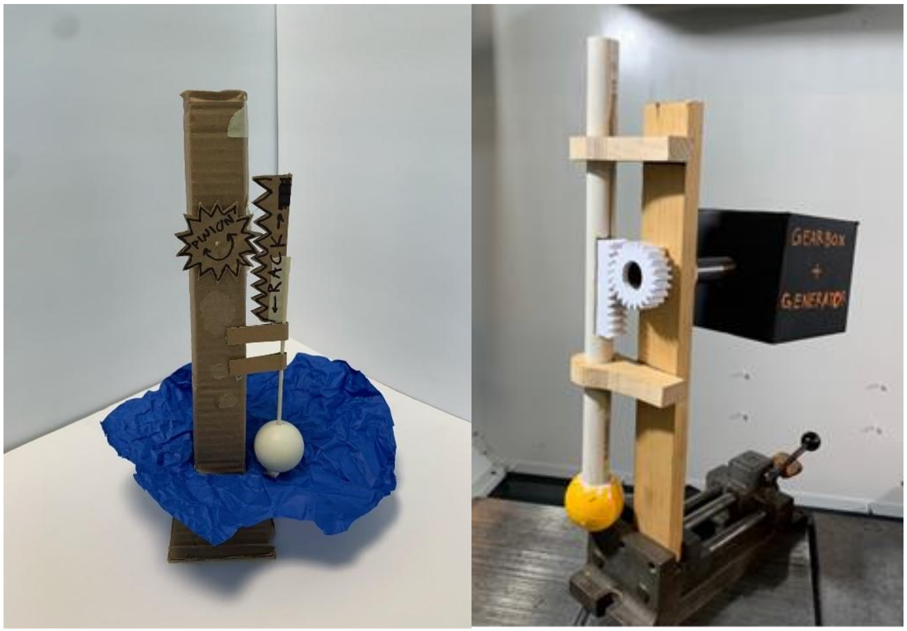


**Figure 18**: Progression of rack-and-pinion prototypes.

Incorporating the feedback into our initial design, we progressed with detailed design, analysis, component selection, and CAD modeling, which we then presented to our peers for a second round of feedback. During the detailed design phase, we made significant changes to our design to accommodate a different testing setup than we initially expected.

### 3.2.1. Design Iteration

Throughout our design process, we solicited peer feedback through two formal design reviews. One of the main changes we made because of the feedback was to decouple the motion of the buoy-pole from that of the rack to minimize deflection in the rack that could hinder adequate gear meshing and cause wear. We implemented a universal joint (u-joint) coupling to allow the buoy pole to transmit linear motion when it is at an angle, without transmitting the deflection to the rack.

Midway through the detailed design of our WEC, we received a clarification stipulating that testing in the ocean at the Cal Poly pier was not allowed per competition rules. Since we could no longer test in the ocean and were not able to gain access to a wave tank on such short notice, we decided to design our own bench testing setup and adjust our initial design to match the new testing environment. We performed an ideation and design process for the testing setup itself and used the sizes and characteristics of available parts to guide the scale of our design.

The testing setup we designed is detailed in the Testing Subsystem section of this report. Notably, the linear actuator in our testing setup required that the wave profiles we planned to model had a maximum travel of 0.7 m and supplied a maximum force of 112 N to the buoy-pole on our WEC.

To complete a full build and test of both a WEC and a testing apparatus, we opted to purchase less expensive, non-marine-grade materials, and focus on studying the effectiveness of a rack and pinion as a rotational to mechanical transformer for use in WECs. With our limited time, we had to sacrifice time and attention on the full WEC build to allow us to build a testing setup.

We also encountered several issues with part procurement and made late-stage changes to some of our part selection: particularly, the gearbox. This is discussed further in Section 2.6.9 of this report, Part Procurement.

### 3.2.2. Wave Scaling and Characterization

A major part in our design process was to decide how we would test the efficacy of our device in real-world conditions. To do this we developed wave profiles to represent different environmental conditions, which we would then use to test our device's performance. To test meaningful wave profiles, we needed to acquire wave data in a location of interest. Our device was designed to suit waves in the Gulf of Mexico, where our business team found a market of offshore oil rigs. To find wave data, maps of oil rig locations were compared to NOAA's National Data Buoy Center (NDBC) buoy locations. Based on overlap with an area of high oil rig density, Station 42091 was chosen as the best data source (US Department of Commerce). Figures 19 and 20 show both maps.

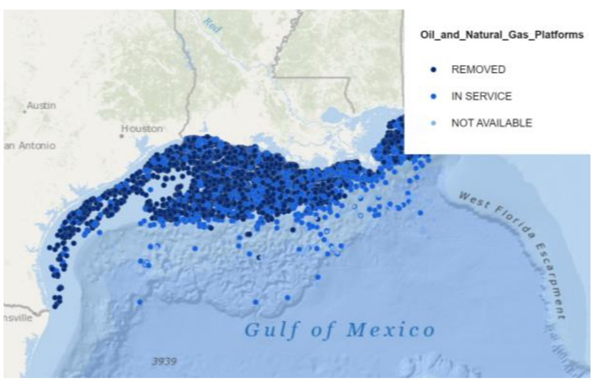


**Figure 19**: Oil platforms in the Gulf of Mexico ("Offshore Oil and Gas in the U.S. Gulf of Mexico").

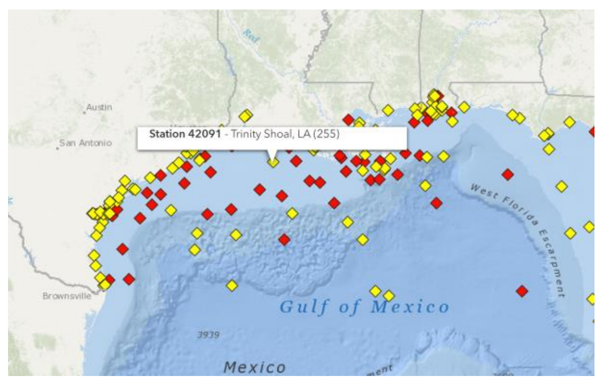


**Figure 20**: Chosen data buoy based on proximity to shore and oil platforms (US Department of Commerce).

At Station 42091, wave height data was listed as significant wave height, the average of the largest 1/3 of waves for each minute. Period was evaluated using the dominant period in each minute (US Department of Commerce). While analyzing data from buoy #42091, we found that the area received large height, short period waves in the winter (higher energy), and shorter height, longer period waves in the summer (lower energy). At this data buoy, January was the month in 2023 with the largest waves, while August saw the smallest waves (based on average significant wave height) (US Department of Commerce). From this data, we tested our WEC in waves with the average significant wave height and average dominant wave period for both January 2023 and August 2023.

We needed to define the scale of our device from the largest wave we deemed capturable. The device's travel (the maximum wave height capturable) was matched to the 90th percentile significant wave height in 2023 at buoy #42091, a height of 2.05 meters (US Department of Commerce). Fitting a wave with a height of 2.05 meters into our 0.7-meter linear actuator defined our device as a 3-scale model. This case is described as "survival mode" in Table 5.

When scaling each wave for testing, the height and period were scaled using the Froude number, a ratio of inertial to gravitational effects. Table 4 shows that while wave height scales linearly, many other characteristics do not.

**Table 4**: Froude number scaling for wave characteristics. The scaling factor, μ, corresponds to the model scale. For example, a 1:3 scale model corresponds to μ = 3 [Farjana, Table 3].

| Quantity | Scaling factor |
|---|---|
| Linear displacement | $\mu$ |
| Angular displacement | 1 |
| Translational velocity | $\mu^{0.5}$ |
| Angular velocity | $\mu^{-0.5}$ |
| Translational acceleration | 1 |
| Angular acceleration | $\mu^{-1}$ |
| Mass | $\mu^{3}$ |
| Force | $\mu^{3}$ |
| Torque | $\mu^{4}$ |
| Power | $\mu^{3.5}$ |
| Linear stiffness | $\mu^{2}$ |
| Angular stiffness | $\mu^{4}$ |
| Linear damping | $\mu^{2.5}$ |
| Angular damping | $\mu^{4.5}$ |
| Wave height and length | $\mu$ |
| Wave period | $\mu^{0.5}$ |
| Wave frequency | $\mu^{-0.5}$ |
| Power density | $\mu^{2.5}$ |

Analysis of the waves was conducted to determine the applicable wave theory. Using Le Mehaute's diagram, we found the waves of both August and January were classified as second order waves, meaning both the peaks and troughs were higher than the sinusoidal waves (Zhao et al.). See Figure 21 for overlaid plots of sinusoidal and second order waves in both August and January 2023.

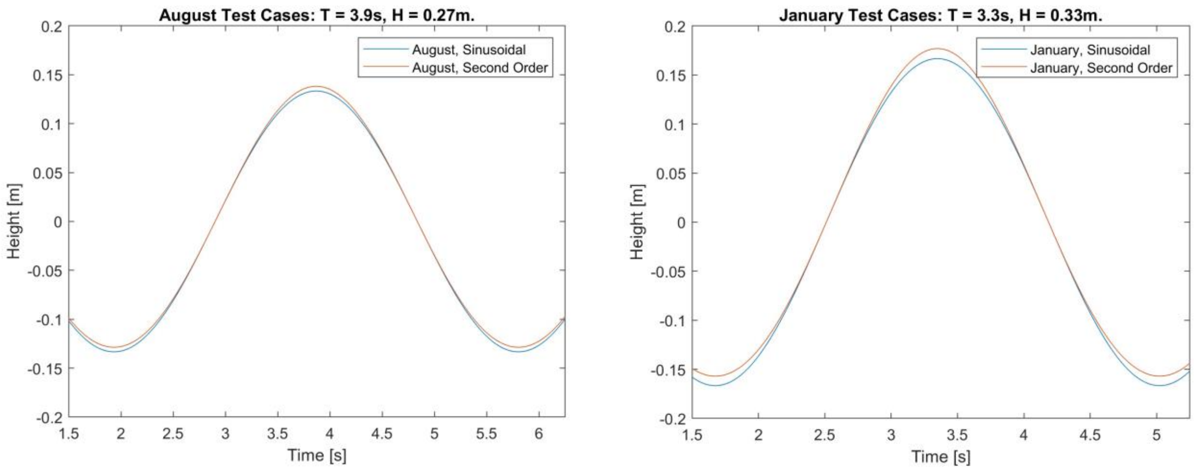


**Figure 21**: Linear (sinusoidal) and second order wave heights, overlaid.

As expected, the steeper waves in January reflect greater deviation between the sinusoidal and second order wave theories. While Le Mehaute's diagram indicated that the August test case be considered a second order wave, Figure 21 showed that the sinusoidal approximation yielded very similar sea surface heights. Therefore, we opted to treat August as a linear wave for testing simplicity, while considering January as both linear and second order in separate tests. Table 5 describes the six test cases selected.

**Table 5**: Descriptions of the six waves tested.

| Test # | Name | Description | Height (scaled) [m] | Period (scaled) [s] | Testing Method |
|---|---|---|---|---|---|
| 1 | Survival mode | Simulates a storm condition to test the device's durability. | 0.68 | 3.3 | Manual |
| 2 | January, linear | Sinusoidal (linear) waves from the highest energy month. | 0.33 | 3.3 | Manual (Planned for linear actuator) |
| 3 | August, linear | Sinusoidal (linear) waves from the lowest energy month. | 0.27 | 3.9 | Manual (Planned for linear actuator) |
| 4 | January 2nd order | Second-order waves from the highest energy month. | 0.33 | 3.3 | Manual (Planned for linear actuator) |
| 5 | Low energy sea state | Small-scale waves suited for the linear actuator. Allowed for consistent data collection. | 0.1 | 3.0 | Linear actuator |
| 6 | Average sea state | Period and height halfway between each respective value for August and January. | 0.3 | 3.6 | Manual (Planned for linear actuator) |

As described in the testing subsystem section, our linear actuator lacked the power necessary to power our system for several of the intended tests. Despite the "low energy sea state" test not matching directly with data from Station 42091, we desired to run a test with the consistent input from the linear actuator. We planned to use the linear actuator to test wave cases 2-6 but resorted to manual testing for all but test 5.

In all failure analysis, we assumed that the entire linear system moves in sync with a particle on the surface of a wave using linear wave theory. This assumption was conservative for failure analysis but would predict a greater power output from our device.

## 3.3. Fabrication and Assembly

### 3.3.1. Part Procurement

During our design, we budgeted $10,000 of the competition award for the procurement of our parts. All required parts, travel costs, and event costs were documented in an expense tracking spreadsheet to ensure we stayed within our budget. Even with last-minute changes and the addition of a testing subsystem, we stayed well within our budget.

All materials were purchased using our awarded funds through Cal Poly's Mechanical Engineering Department and were delivered to Cal Poly's campus. Unfortunately, there were numerous instances throughout the year of parts not getting properly ordered once purchase requests were submitted or orders getting delayed. This resulted in an accelerated build and test timeline and necessitated the selection of alternate parts, like a gearbox.

In addition to purchased parts, we ordered stock from which we could build custom parts in the Cal Poly Machine Shops. Custom parts are noted in the Bill of Materials found in Appendix 4 and are described in detail in the following sections.

### 3.3.2. Fabrication

Many of our purchased parts needed to be manufactured or modified to be implemented in our device. All machining was done by our engineering team in the Cal Poly student Machine Shops.

For the linear system, the rack, u-joint, and pole were modified. The rack had tapped holes added to the back to connect to plates which would connect to the linear bearings. The u-joint was welded to the rack, and had a hole drilled in it to connect to the pole. The pole was cut to length and a hole was drilled in it. Another part we manufactured was the spacer, which connected the u-joint to the pole through press fits and a bolt. The spacer was turned on the lathe to get the correct diameter and length, then milled to create the square pocket for the u-joint. Figures 22 and 23 show the components of the rack-u-joint-pole assembly.

**Figure 22**: Machined spacer to connect the u-joint to buoy pole.

**Figure 23**: Welded u-joint to rack, buoy pole and u-joint connected with the spacer in Figure 22.

Parts manufactured in the linear system include the plates, which were cut with a waterjet with a slot allowing for position adjustment of the rack. Figure 24 shows the waterjet setup for this part. Wooden mounts were cut to size and drilled for mounting the linear bearings on the pole.

**Figure 24**: Mechanical team member Brendan secures an aluminum plate to cut out the rack plates on the Cal Poly waterjet.

For the rotational system, we machined the pinion, flywheel, pinion shaft, flywheel shaft, and mounts. A keyway was broached in the pinion on an arbor press using a custom broach guide made on the lathe to fit our pinion. The result of this operation is shown in Figure 25.

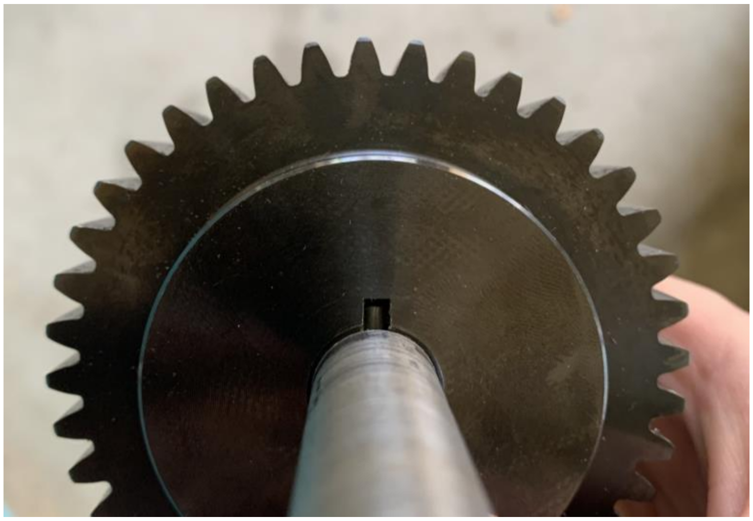

**Figure 25**: Broached keyway in the pinion, with shaft and key in place.

The shafts in the rotational system were manufactured on the lathe to meet designed dimensions. Mounts for the gearbox and generator, as well as the flywheels were waterjet cut, and wooden mounts were cut to size for the pillow block bearings.

**Figure 26**: Mechanical team member Derek machining the pinion shaft.

For the electrical system, the only components that needed fabrication were the PCB and the wire connections and housings. The PCB was soldered by hand using a heat gun and soldering iron. The wire housings were crimped and soldered to meet safety guidelines.

#### 3.3.3. Assembly

Our entire mechanical subsystem was bolted down on 2x12 foot wooden planks. Through holes were drilled into the planks and t-nuts were used so components could be attached. The t-nuts made the set-up very easily to assemble and disassemble, which was important to us during testing. This arrangement also allowed us to easily carry and transport the device.

Most of the electrical subsystem was placed on the ground near the mechanical system. The generator, dump load, and bridge rectifier were mounted to the same wooden plank as the gear box with the battery, charge controller, and PCB next to them. Everything was connected using 18-gauge wire roughly 3 feet long so we could move around components in the system without disconnecting anything.

### 3.4. Testing Methodology

Testing of our system started with isolated tests of the mechanical and electrical subsystems separately before integrating and testing the overall device performance. Our testing objectives focused on evaluating device performance and verifying that each of our engineering specifications, listed in Table 6 below, were satisfied. Because we were unable to test our device in open water or a wave tank, we attempted to use a linear actuator and a stepper motor to move the rack according to programmed wave profiles. This linear actuator testing along with manual testing allowed us to dry-land test the performance of the device. The testing verified our simulations and highlighted improvements for future iterations.

Before the full mechanical and electrical systems were assembled and tested, the mechanical and electrical teams performed testing on their subsystems and individual components. These subsystem tests are discussed in the Isolated Mechanical Testing and Isolated Electrical Testing sections of this report.

Each test performed was developed with our engineering specifications in mind, so that we could verify that each specification was met within tolerance. Table 6 lists each engineering specification, which were identified in the design objectives section and addressed throughout our design. The table also describes how each specification is evaluated: using a test (T), analysis (A), or inspection (I), or by assessing the similarity to an existing design (S). Specifications assessed with tests will be discussed in the following sections.

Specifications for weight, size, and cost to manufacture were all satisfied. Maintenance frequency and operating cost were not analyzed for the scaled-down device but were discussed in detail for a full-scale device in the Business Plan report sections.

**Table 6**: Engineering specifications with plans for assessment

| Spec No. | Description | Requirement or Target | Tolerance | Compliance Assessment |
|---|---|---|---|---|
| 1 | Power Output | 100 W | ± 20 W | T |
| 2 | Weight | 150 lb. (Able to be lifted by two team members) | ± 25 lb. | A, I |
| 3 | Size | 100 $ft^3$ | ± 25 $ft^3$ | I |
| 4 | Cost to Manufacture | $10,000 | Max. | A |
| 5 | Energy Storage | 1.2 kWh (1 battery) | + 1.2 kWh<br>- 0.0 kWh | T |
| 6 | Efficiency | 35% | ± 5% | T |
| 7 | Noise Level | 75 dB | Target + 25 dB | T |
| 8 | Safety - MECC Safety and Tech. Inspection | Pass/fail | - | I |
| 9 | Operating Cost | 5% of initial cost | Max. | A |
| 10 | Maintenance Frequency | Quarterly | Max. | A |
| 11 | Range of Travel | 0.7 m | +0.1m<br>-0.0 m | T |

## 3.5. Isolated Mechanical Testing

Our first mechanical test was to determine whether an off-the-shelf universal (u) joint would fit the needs of our project. We could not determine from manufacturer’s ratings, since the ratings listed were for a torsional load, not axial. We adapted two different sizes for compression testing using an Ametek Lloyd LD Series testing machine. The jaws of the machine could grip the “male” end of both u-joints, and a plate was welded to the “female” end to transfer load in the compression direction. See Figure 27 for a pre-failure testing photo and Figure 28 for an image of the u-joint in the testing machine.

**Figure 27**: Pre-testing configuration.

**Figure 28**: Male end of u-joint in testing vise, welded end compressing into bottom vise.

Testing revealed that the compressive axial load for both u-joints exceeded our design load by a factor of over 100. Figure 29 displays the force vs. time from the Ametek test of the 3/8" drive u-joint; the ½" drive exceeded the force of the Ametek.

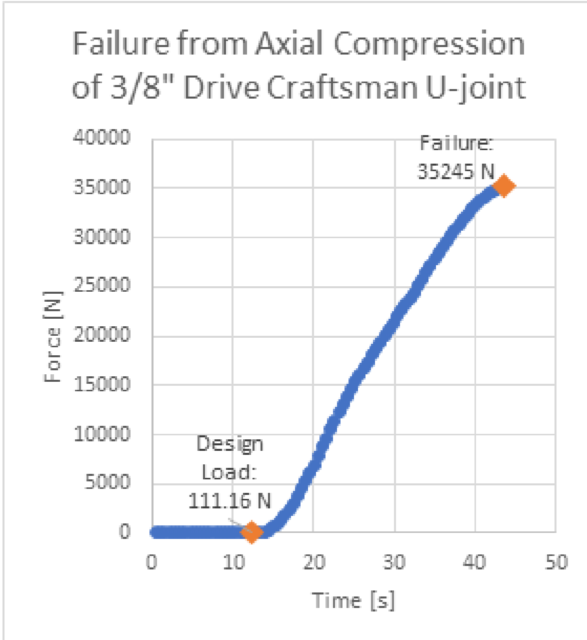


**Figure 29**: Ametek test results.

Although we predicted the u-joint handling our design loads, we are reassured to know that the amount of force seen will hardly affect the component. Our design includes the ½" u-joint due to the additional circumference for welding.

Once the mechanical subsystem was fully assembled, we performed additional tests on the isolated system to verify compliance with our engineering specifications. These included using a digital angle gauge to ensure that the rack and pinon were aligned within ±1° of one another. We also tested the function of the linear actuator testing subsystem to verify its maximum range of travel and ensure that it could run each wave profile we generated.

Before connecting the testing subsystem to the rest of the system for testing, the testing subsystem was tested individually. After confirming the stepper motor would drive the lead screw without jamming, wave profiles were run on the actuator starting small and gradually getting larger. During these tests, we realized the linear actuator could not run fast enough for testing all the intended wave profiles.

## 3.6. Isolated Electrical Testing

<u>Generator Testing</u>

This testing procedure for the generator was created to determine the power output at the end of the bridge rectifier for variable speeds. The system is composed of the generator, bridge rectifier, the I-TECH Regenerative Power System, 3 Phase AC Power, Variable Frequency Drive (VFD), and an Inductive Load for the VFD. The generator was set at different speeds around its rated speed of 600 RPM through varying the frequency on the VFD. The speed was then checked by a handheld tachometer to keep it constant through the changing loads. The current load was then modified along a range of potential load values to simulate how the charge controller works. The speed, voltage, and current were measured at each of these loads and speeds to generate IV and Power curves at every speed. Originally, this was planned to be used to program the charge controller for MPPT until the micro hydro mode was tested and proved to be more efficient for a wave-like source. However, the results from this test gave us insight into how our generator functioned around the rated speed compared to how it was advertised.

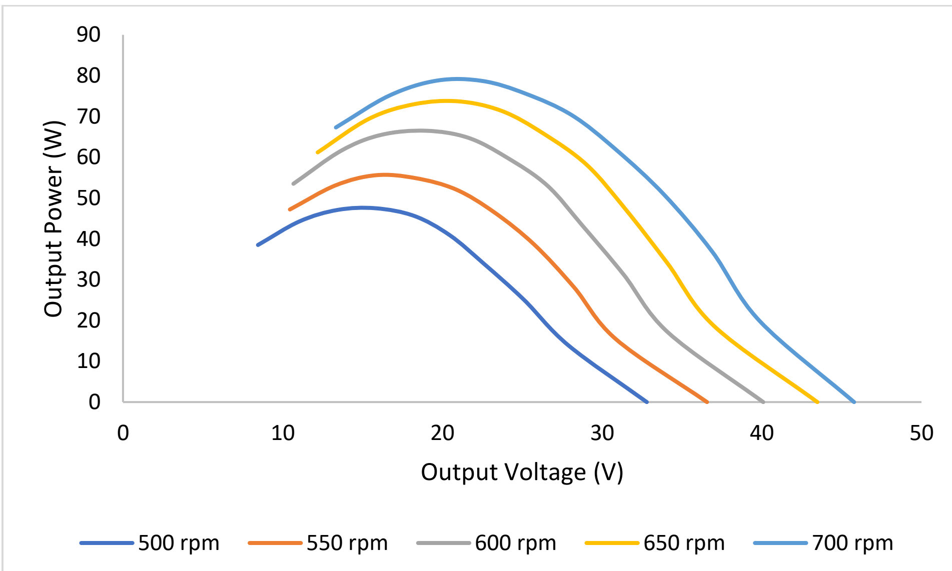


**Figure 30**: Maximum power testing.

The generator was also tested with varying speeds and a constant 10 ohm resistive load. The chosen dump load is a 10 Ohm resistor rated for 150 Watts. This test measured the expected power, voltage, and current seen across the dump load. The dump load's rated power is much greater than the generator's best power production at 800 RPM. The power vs speed curve can be linearized using the equation $y = 5.4709x + 296.9$, and is graphed in Figure 31. The dump load can safely dissipate power at speeds up to 1117.5 rpm.

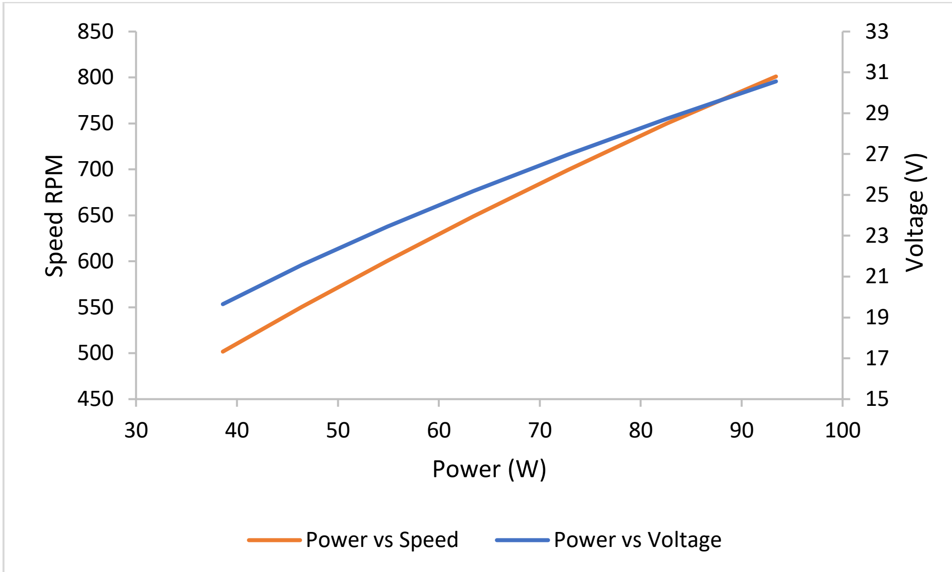


**Figure 31**: Generator characteristics for a constant load.

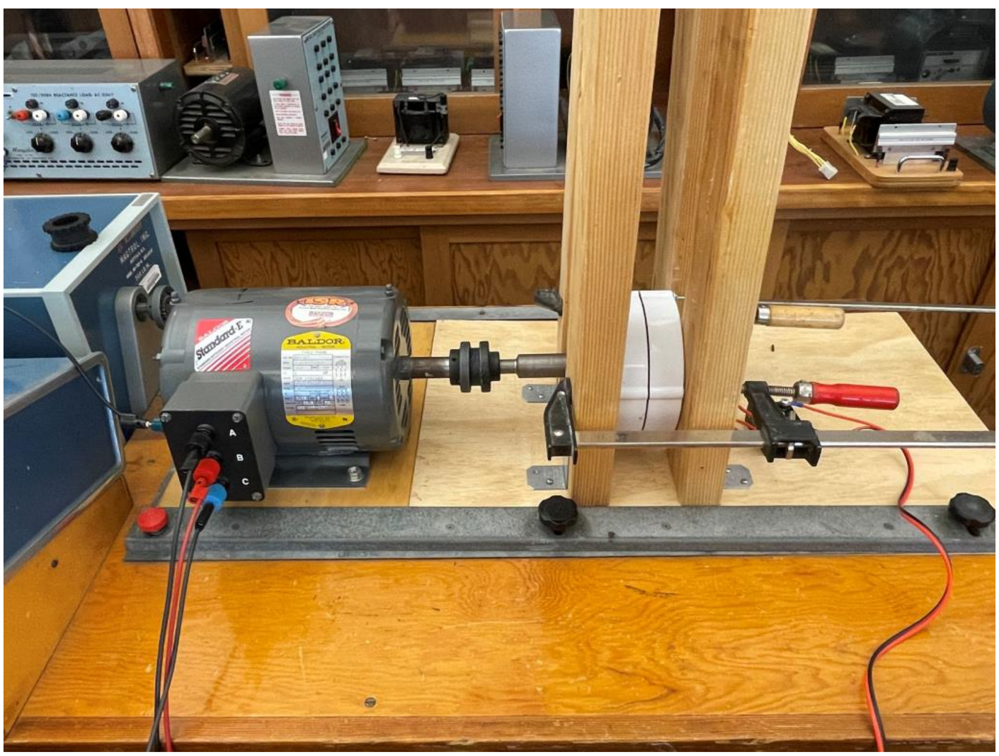

**Figure 32**: Motor and generator testing setup.

Full System Test

Full system testing was required to confirm that the microcontroller and PCB could control the power flow for different states in the system. The PCB with microcontroller were connected at the center of the system between the charge controller, bridge rectifier, dump load, and battery. The generator was then connected as mentioned in the generator testing and set to a constant speed of 600 RPM. While running, the input signals representing the AUV status, charge controller input, and E-stop were changed to represent different states of the system. In each of these states, the voltages across the bridge rectifier, dump load, charge controller, and AUV output were measured to verify that the power was flowing to the correct components. The microcontroller worked for three of the four states, and a piece of the code was altered to get the fourth state working. Overall, this test proved that our system worked as intended with power generated by spinning the shaft at the input and adjusting to the correct system state.

## 3.7. Performance Task Testing

To test the overall performance of the project, we integrated the rack and pinion design with the entire electrical system. This involved connecting the generator's shaft to the gearbox output and adding flywheels to the middle of the shaft. Here, we decided to test the six different ocean state cases outlined in the next section, but a quick summary is survival mode, average August wave, average January wave, January second order wave, low sea state, and average sea state. The linear actuator was intended to drive the shaft connected to the rack and pinion; however, it was discovered that even for the scaled down system the actuator could not produce enough force to drive the rack up and down for some of the faster wave profiles. In the test where the linear actuator was used, the data collected was very consistent but also had a low power output since the speed of the input shaft was slow.

Since there were issues with the linear actuator, we decided to test most of the wave states by hand. We connected the SDL1000X Programmable DC Electronic Load to the dump load node of the system and verified that all power generated went to the dump load by choosing the state of the microcontroller. For each wave state, two people oversaw moving the input shaft back and forth at a controlled speed. While this was happening, a tachometer and the electronic load were utilized to measure and record the speed of the generator shaft, voltage, current, power, and load value for many cycles. This data was recorded whenever the generator shaft reached peak speed for every cycle, so it represents instantaneous peak power for a singular wave. Some of the wave profiles were tested with and without the flywheel to illustrate the effects that it has on the overall system.

## 3.8. Data Processing and Results

Full system testing of six wave cases showed a similar result to that obtained from benchtop electronics testing. The generator had a linear relationship between power and speed. The key difference was the additional force required by the rack and pinion to begin and continue motion. To attain greater power and rotational speed, a greater force was needed. The high and low speed simulated in these tests confirmed the marine energy device's ability to withstand the inconsistent vigorous ocean environment.

The system was tested by applying different scaled down wave amplitudes and periods to the rack and pinion. The rotational speed of the generator was measured by a handheld tachometer. The generator was connected to a variable load box set with a resistive load of 10 Ohms, the same output resistance used as the dump load. With these test conditions, when the generator spun at 1000 rpm the maximum power measured at the output was 114.6 W. The maximum power obtained from the system was greater than the expected power output. This high-power output was achieved because in some cases during testing, since we manually pushed the input shaft, we were able to achieve rotation speeds faster than predicted. At the generators rated speed of 600 rpm, the device produced 75.77 W.

Each test case utilized a different wave period, amplitude, and shape to determine the expected power output of the device. The tested results can be seen below. At each test condition, the generator's speed is varied by the force applied to the rack.

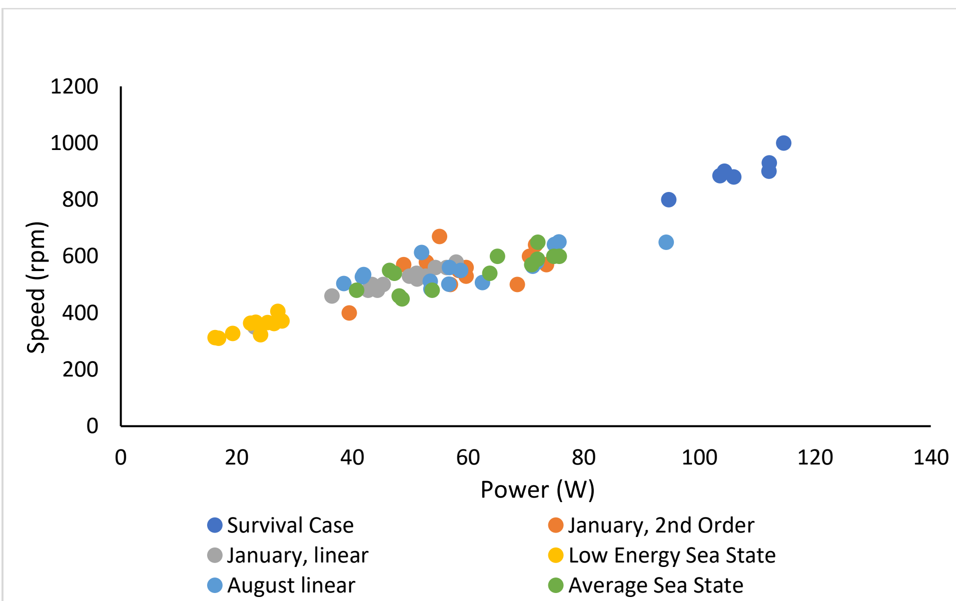


**Figure 33**: Power vs Speed graph for all six test conditions with a constant resistive 10 Ohm load.

The system was also tested with and without a flywheel attached to the generator shaft under the same test conditions. The flywheel added inertia to the shaft and displaced some of the original force applied to the system to continue rotating the shaft on the downward heave of the wave. The test showed that the generator could reach greater peak rotational speeds without the flywheel attached. This result directly correlates to the flywheel's purpose of storing energy. The measurements with the flywheel appear more linear with less variability in peak speeds. Without the flywheel, the generator produced a maximum power of 84.89 W at 723 rpm. With the flywheel, the generator produced a maximum power of 57.98 W at 580 rpm.

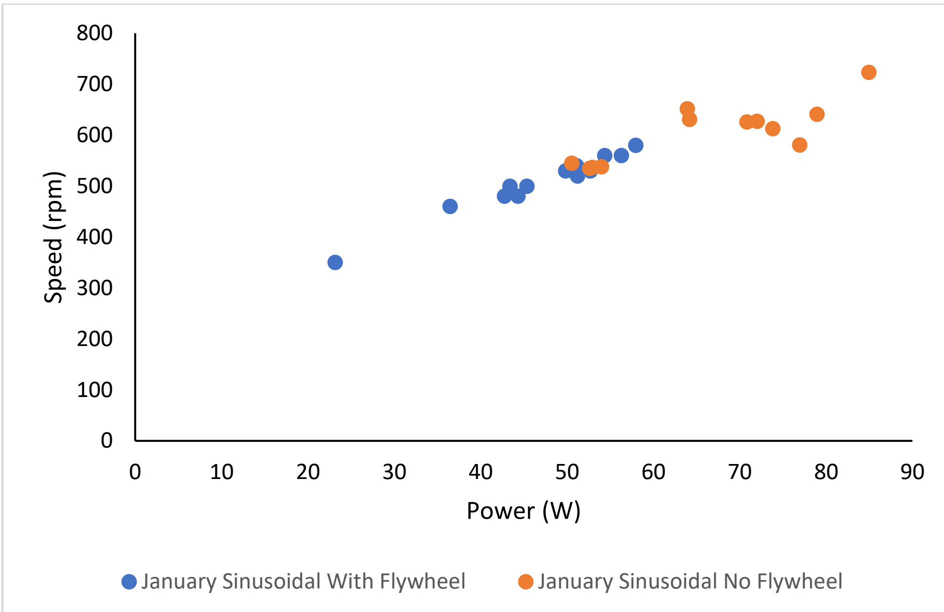


**Figure 34**: Power vs speed graph for January sinusoidal waveforms with and without flywheel measured with a 10 Ohm resistive load.

The sinusoidal waveform in August provides less speed to the generators shaft because the waves have a smaller amplitude. This is reflected in the measured power. The maximum power measured for a sinusoidal waveform in August is 27.15 W at 405 rpm. The maximum power measured for a sinusoidal waveform in January is 57.98 W at 580 rpm.

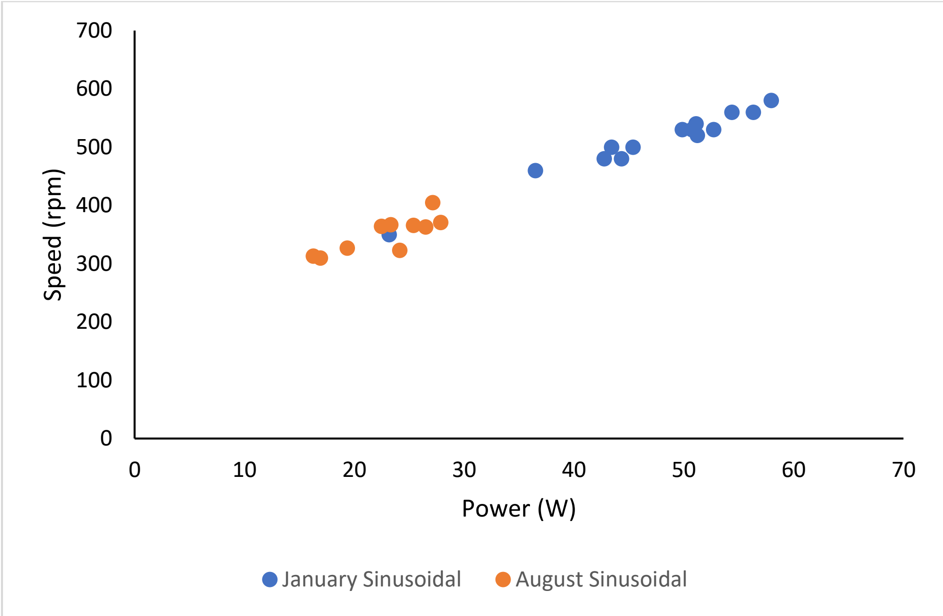


**Figure 35**: Power vs speed graph comparing January sinusoidal waveforms with August sinusoidal waveforms measured with a 10 Ohm resistive load.

Our testing revealed that the output shaft was spinning at between 300-1000 RPM during testing, generating a maximum power of 114 W. Comparing this to the results predicted by our Simscape model, our model did not predict that the system would reach RPMs of up to 1000. The main reason behind this is that the inputs to our model were the scaled down wave profiles, however during testing, we pushed the system by hand because our linear actuator could not produce enough force. This meant the rack was being moved at much higher speeds than in the simulation, leading to a higher RPM at the output shaft. Future testing should be done with a larger linear actuator which can produce the forces needed.

Testing each wave profile with the linear actuator would have been preferable to manual actuation. As shown in Figure 33, the low energy sea state the, which was the only linear actuator test, had significantly more consistent data on the power vs. speed plot than any of the manual tests. We tried to differentiate between linear and second order waves while pushing but the differences were too subtle, and inconsistencies between each data point were more significant than differences between wave profiles. If we utilized a more powerful linear actuator, we might have recorded more accurate data that could reflect the differences between first and second order waves.

# 4. Conclusion and Recommendations

This project has taught us many lessons about marine energy, project planning, and implementation. We learned about markets in the Blue Economy, the challenges of marine power generation, and investigated the viability of a rack and pinion wave energy converter for AUV charging. Our wave energy converter worked as intended when subjected to bench testing, successfully transmitting the translational motion input to rotational motion which ran a generator and charged a battery.

One challenge for this design is the horizontal forces from waves on our buoy pole. As mentioned in the load and stress analysis section, additional analysis that should be done is a fatigue analysis on the pole. This would include finding horizontal loads that occur with waves. Testing the device in a wave tank would also be a good next step to investigate this.

Another unexpected factor was the amount of damping in our device that caused a larger force than expected to accelerate the device. Now that we know the force to overcome this damping, implementing this into the Simulink model would give better predictions on efficiency and power output. The amount of damping also caused the output shaft to slow to a standstill on the downstroke of the device. Iterative design of a flywheel large enough to maintain rotational inertia of the system is another future improvement of the device. Additionally, because our linear actuator testing setup could not accelerate the device, a redesign of the testing set-up should be considered which is less limited in power and speed.

Our device also omitted the buoy, and design of the buoy and connection to buoy pole is a necessary next step to be able to test in a wave tank and eventually the open water. Determining the specifics on where on the offshore oil rig the device would be mounted and how it will attach is another step once the device is ready for implementation.

Electrically, some changes could include surface mount fuses between offboard connections and onboard circuity to reduce the risk of damage caused by reversing the biasing of a connection. It may also be helpful to include an on and off switch to electrically disconnect the battery from the electrical system rather than physically needing to disconnect the battery. Also, a smaller battery could have helped reduce the system's overall weight and matched the system's storage capacity to generation capability. Another electrical change that would have been useful would be labeling the connectors entering the PCB on the board design making it easier to move connections around without needing to check the board schematic.

A potential issue with AUV charging from our device is that charging stations tend to be located on the ocean floor. Because our device is to be mounted above water, transmission of electricity from the device to the charging station and energy losses must be considered.

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# 6. Appendix

## Appendix 1. Five Year Financial Model

| Per unit/year | Prototype year | Producing, not selling 3 units | Producing/selling 30 units | Producing/selling 60 units | Producing/selling 120 units |
|---|---|---|---|---|---|
| | **Year 1** | **Year 2** | **Year 3** | **Year 4** | **Year 5** |
| **Capital/Funding Needed** | $ 1,200,000.00 | $ 1,600,000.00 | | | |
| **Beginning Cash** | $ 1,200,000.00 | $ 1,700,621.62 | $ 463,428.79 | $ 2,275,285.43 | $ 7,760,678.73 |
| **Units Sold** | 0 | 0 | 30 | 60 | 120 |
| **New Sales Revenue** | $ - | $ - | $ 2,177,892.48 | $ 4,355,784.97 | $ 8,711,569.94 |
| **Recurring Revenue** | $ - | $ - | | $ 384,840.00 | $ 1,154,520.00 |
| **Total Revenue** | $ - | $ - | $ 2,177,892.48 | $ 4,740,624.97 | $ 9,866,089.94 |
| **Total Cash Available** | $ 1,200,000.00 | $ 1,700,621.62 | $ 2,641,321.27 | $ 7,015,910.40 | $ 17,626,768.66 |
| **COGS/Variable Costs** | | | | | |
| Materials | $ 7,378.38 | $ 22,135.14 | $ 221,351.40 | $ 442,702.80 | $ 885,405.60 |
| Installation | $ - | $ 86,538.46 | $ 865,384.62 | $ 1,730,769.23 | $ 3,461,538.46 |
| Shipping | $ - | $ 20,769.23 | $ 207,692.31 | $ 415,384.62 | $ 830,769.23 |
| Maintenace | $ - | $ 15,750.00 | $ 157,500.00 | $ 315,000.00 | $ 630,000.00 |
| **Total COGS/Variable** | $ 7,378.38 | $ 145,192.83 | $ 1,451,928.32 | $ 2,903,856.65 | $ 5,807,713.29 |
| **Contribution** | $ (7,378.38) | $ (145,192.83) | $ 725,964.16 | $ 1,836,768.32 | $ 4,058,376.65 |
| **Gross Margin/Contribution Margin** | | | | | |
| **Expenses/Fixed Costs** | | | | | |
| Total Salaries | $ 950,000.00 | $ 950,000.00 | $ 950,000.00 | $ 950,000.00 | $ 950,000.00 |
| Operating Expenses | $ 142,000.00 | $ 142,000.00 | $ 142,000.00 | $ 142,000.00 | $ 142,000.00 |
| **Total Expenses/Fixed Costs** | $ 1,092,000.00 | $ 1,092,000.00 | $ 1,092,000.00 | $ 1,092,000.00 | $ 1,092,000.00 |
| | | | | | |
| **Total COGS and Expenses** | $ 1,099,378.38 | $ 1,237,192.83 | $ 2,543,928.32 | $ 3,995,856.65 | $ 6,899,713.29 |
| **Operating Profit** | $ (1,099,378.38) | $ (1,237,192.83) | $ (366,035.84) | $ 744,768.32 | $ 2,966,376.65 |
| **Ending Cash** | $ 100,621.62 | $ 463,428.79 | $ 2,275,285.43 | $ 7,760,678.73 | $ 20,593,145.31 |

| Operating expense: | |
|---|---|
| Rent | $ 72,000.00 |
| Utilities | $ 10,000.00 |
| Legal | $ 20,000.00 |
| Accounting | $ 10,000.00 |
| Insurance | $ 25,000.00 |
| Office supplies | $ 5,000.00 |

| Salaries: | |
|---|---|
| President | $ 200,000.00 |
| General manger/operations | $ 180,000.00 |
| VP Engineering | $ 180,000.00 |
| Finance | $ 90,000.00 |
| Marketing/Sales | $ 180,000.00 |
| Admin Staff | $ 120,000.00 |

| | | | |
|---|---|---|---|
| | One device VC: | | |
| installation: | $ | 28,846.15 | |
| shipping: | $ | 6,923.08 | |
| maintenance | $ | 5,250.00 | Sell for: |
| materials | $ | 7,378.38 | Markup of 50% |
| | $ | 48,397.61 | $ 72,596.42 |

| | | | |
|---|---|---|---|
| | $ | 5,250.00 | maintenance cost/unit |
| | $ | 5,440.00 | labor costs for maintenance |
| | $ | 10,690.00 | total maintenance fee |
| | $ | 12,828.00 | maintenance fee plus 20% markup |

## Appendix 2. Safety & Hazard Assessment

Wave Energy Converter Final Prototype 2/20/2024

**designsafe Report**

| | | | |
|---|---|---|---|
| Application: | Wave Energy Converter Final Prototype | Analyst Name(s): | Derek Tom, Nora Riedinger, Miles Mikkelsen, Brendan Stratford |
| Description: | | Company: | PolyWave Energy |
| Product Identifier: | | Facility Location: | San Luis Obispo |
| Assessment Type: | Detailed | | |
| Limits: | | | |
| Sources: | | | |
| Risk Scoring System: | ANSI B11.0 Two Factor | | |

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

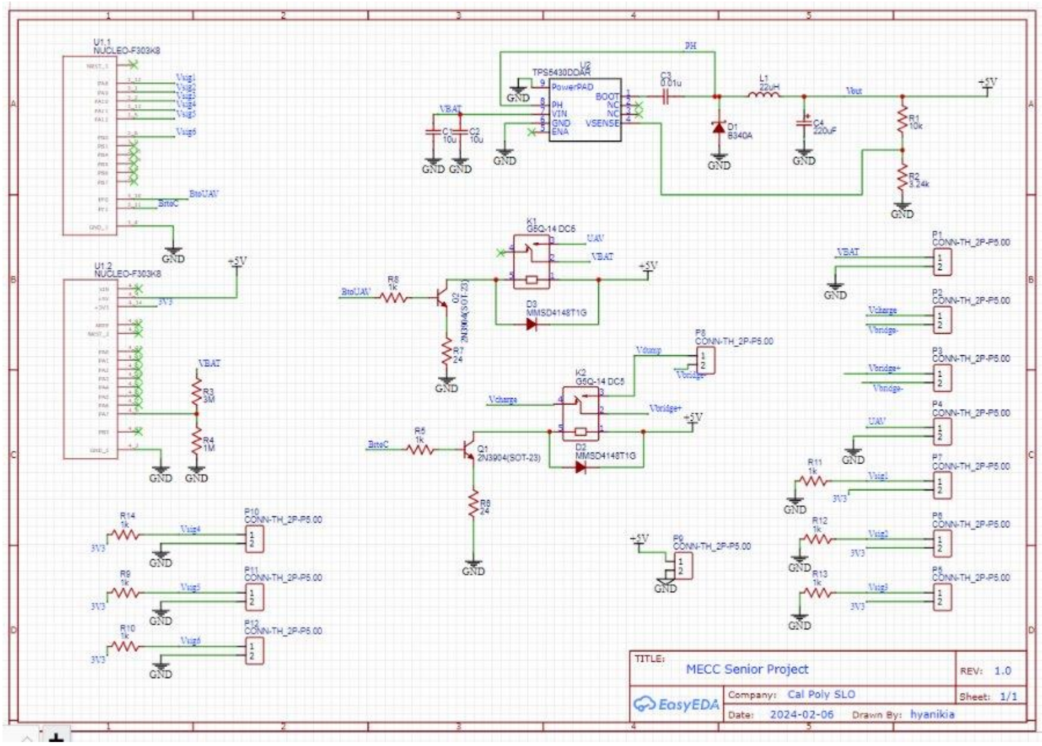
| Item Id | User / Task | Hazard / Failure Mode | Initial Assessment Severity Probability | Risk Level | Risk Reduction Methods /Control System | Final Assessment Severity Probability | Risk Level | Status / Responsible /Comments /Reference |
|---|---|---|---|---|---|---|---|---|
| 1-1-1 | operator<br>normal operation | mechanical : drawing-in / trapping / entanglement<br>Rotating parts | Serious<br>Unlikely | Medium | adjustable enclosures / barriers, warning label(s), special clothing | Serious<br>Remote | Low | TBD [5/1/2024]<br>Miles |
| 1-1-2 | operator<br>normal operation | mechanical : pinch point<br>Rack and pinion meshing | Moderate<br>Unlikely | Low | awareness barriers, special procedures | Moderate<br>Remote | Negligible | TBD [5/1/2024]<br>Nora |
| 1-1-3 | operator<br>normal operation | mechanical : machine instability<br>Mounting | Moderate<br>Unlikely | Low | Properly mount device and all fixed points | Moderate<br>Unlikely | Low | In-process<br>Brendan |
| 1-1-4 | operator<br>normal operation | noise / vibration : fatigue / material strength<br>Failure of shafts or u-joint | Serious<br>Unlikely | Medium | Fatigue analysis on parts, compression testing of u-joint | Serious<br>Unlikely | Medium | Complete [2/9/2024]<br>Derek/Brendan |
| 1-2-1 | operator<br>basic trouble shooting / problem solving | mechanical : unexpected start<br>If device is jammed/stuck | Moderate<br>Unlikely | Low | Turn off power when maintenece needed | Moderate<br>Remote | Negligible | On-going [Daily]<br>Miles |
| 1-2-2 | operator<br>basic trouble shooting / problem solving | material handling : instability<br>Large and unbalanced device | Minor<br>Unlikely | Negligible | Take care when transporting device | Minor<br>Unlikely | Negligible | On-going [Daily]<br>Derek |

| Item Id | User / Task | Hazard / Failure Mode | Initial Assessment Severity Probability | Risk Level | Risk Reduction Methods /Control System | Final Assessment Severity Probability | Risk Level | Status / Responsible /Comments /Reference |
|---|---|---|---|---|---|---|---|---|
| 2-1-1 | electrician / controls technician<br>repair / replace wiring / systems | electrical / electronic : energized equipment / live parts<br>Generator/battery/electrical circuit | Catastrophic<br>Unlikely | Medium | Warning labels, enclosure | Catastrophic<br>Unlikely | Medium | TBD [4/23/2024]<br>Zach |
| 2-1-2 | electrician / controls technician<br>repair / replace wiring / systems | electrical / electronic : lack of grounding (earthing or neutral)<br>Touching non-grounded parts | Serious<br>Unlikely | Medium | Warning labels, enclosure | Serious<br>Unlikely | Medium | TBD [4/23/2024]<br>Zach |
| 2-1-3 | electrician / controls technician<br>repair / replace wiring / systems | electrical / electronic : shorts / arcing / sparking<br>live shorts between generator, charge controller, and battery | Serious<br>Unlikely | Medium | Warning labels, enclosure | Serious<br>Unlikely | Medium | TBD [4/23/2024]<br>Zach |
| 2-1-4 | electrician / controls technician<br>repair / replace wiring / systems | electrical / electronic : unexpected start up / motion<br>Buoy isn't raised so the shaft is still spinning while attempting repair | Moderate<br>Unlikely | Low | Warning labels, enclosure | Moderate<br>Unlikely | Low | TBD [4/23/2024]<br>Zach |
| 2-2-1 | electrician / controls technician<br>troubleshooting | electrical / electronic : energized equipment / live parts<br>Generator/battery/electrical circuit | Catastrophic<br>Unlikely | Medium | Warning labels, enclosure | Catastrophic<br>Unlikely | Medium | TBD [4/23/2024]<br>Zach |
| 2-2-2 | electrician / controls technician<br>troubleshooting | electrical / electronic : lack of grounding (earthing or neutral)<br>Touching non-grounded parts | Serious<br>Unlikely | Medium | Warning labels, enclosure | Serious<br>Unlikely | Medium | TBD [4/23/2024]<br>Zach |
| 2-2-3 | electrician / controls technician<br>troubleshooting | electrical / electronic : shorts / arcing / sparking<br>live shorts between generator, charge controller, and battery | Serious<br>Unlikely | Medium | Warning labels, enclosure | Serious<br>Unlikely | Medium | TBD [4/23/2024]<br>Zach |
| 2-3-1 | electrician / controls technician<br>grounding panels / controls / machinery | electrical / electronic : energized equipment / live parts<br>Generator/battery/electrical circuit | Catastrophic<br>Unlikely | Medium | Warning labels, enclosure | Catastrophic<br>Unlikely | Medium | TBD [4/23/2024]<br>Harmon |
| 2-3-2 | electrician / controls technician<br>grounding panels / controls / machinery | electrical / electronic : lack of grounding (earthing or neutral)<br>Touching non-grounded parts | Serious<br>Unlikely | Medium | Warning labels, enclosure | Serious<br>Unlikely | Medium | TBD [4/23/2024]<br>Harmon |
| 2-3-3 | electrician / controls technician<br>grounding panels / controls / machinery | electrical / electronic : shorts / arcing / sparking<br>live shorts between generator, charge controller, and battery | Serious<br>Unlikely | Medium | Warning labels, enclosure | Serious<br>Unlikely | Medium | TBD [4/23/2024]<br>Harmon |
| 2-4-1 | electrician / controls technician<br>install / test / repair circuit | electrical / electronic : energized equipment / live parts<br>Generator/battery/electrical circuit | Catastrophic<br>Unlikely | Medium | Warning labels, enclosure | Catastrophic<br>Unlikely | Medium | TBD [4/23/2024]<br>Harmon |
| 2-4-2 | electrician / controls technician<br>install / test / repair circuit | electrical / electronic : lack of grounding (earthing or neutral)<br>Touching non-grounded parts | Serious<br>Unlikely | Medium | Warning labels, enclosure | Serious<br>Unlikely | Medium | TBD [4/23/2024]<br>Harmon |
| 2-4-3 | electrician / controls technician<br>install / test / repair circuit | electrical / electronic : shorts / arcing / sparking<br>live shorts between generator, charge controller, and battery | Serious<br>Unlikely | Medium | Warning labels, enclosure | Serious<br>Unlikely | Medium | TBD [4/23/2024]<br>Harmon |
| 2-5-1 | electrician / controls technician<br>adjust controls | electrical / electronic : energized equipment / live parts<br>Generator/battery/electrical circuit | Catastrophic<br>Unlikely | Medium | Warning labels, enclosure | Catastrophic<br>Unlikely | Medium | TBD [4/23/2024]<br>Harmon |
| 2-5-2 | electrician / controls technician<br>adjust controls | electrical / electronic : lack of grounding (earthing or neutral)<br>Touching non-grounded parts | Serious<br>Unlikely | Medium | Warning labels, enclosure | Serious<br>Unlikely | Medium | TBD [4/23/2024]<br>Harmon |
| 2-5-3 | electrician / controls technician<br>adjust controls | electrical / electronic : shorts / arcing / sparking<br>live shorts between generator, charge controller, and battery | Serious<br>Unlikely | Medium | Warning labels, enclosure | Serious<br>Unlikely | Medium | TBD [4/23/2024]<br>Harmon |

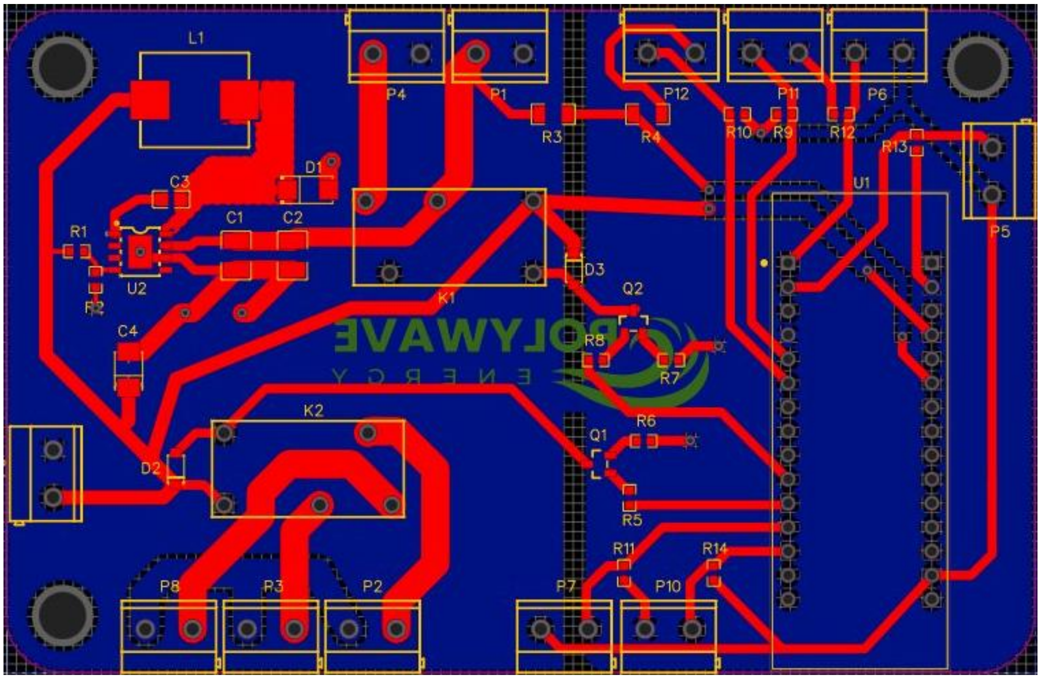
| Item Id | User / Task | Hazard / Failure Mode | Initial Assessment Severity Probability | Risk Level | Risk Reduction Methods /Control System | Final Assessment Severity Probability | Risk Level | Status / Responsible /Comments /Reference |
|---|---|---|---|---|---|---|---|---|
| 3-1-1 | passer by / non-user walk near machinery | mechanical : crushing Large pole translating up to 0.7 m | Moderate Likely | Medium | awareness barriers, | Moderate Unlikely | Low | On-going [Daily] Brendan |
| 3-1-2 | passer by / non-user walk near machinery | electrical / electronic : energized equipment / live parts Generator/battery/electrical circuit | Serious Unlikely | Medium | adjustable enclosures / barriers, | Serious Unlikely | Medium | TBD [5/1/2024] Nora |
| 3-1-3 | passer by / non-user walk near machinery | slips / trips / falls : falling material / object If design is not properly mounted or fails, parts could fall | Serious Unlikely | Medium | Design analysis, mount all fixed points, awareness barriers, | Serious Unlikely | Medium | On-going [Daily] Derek |

# Appendix 3. Electrical Drawings

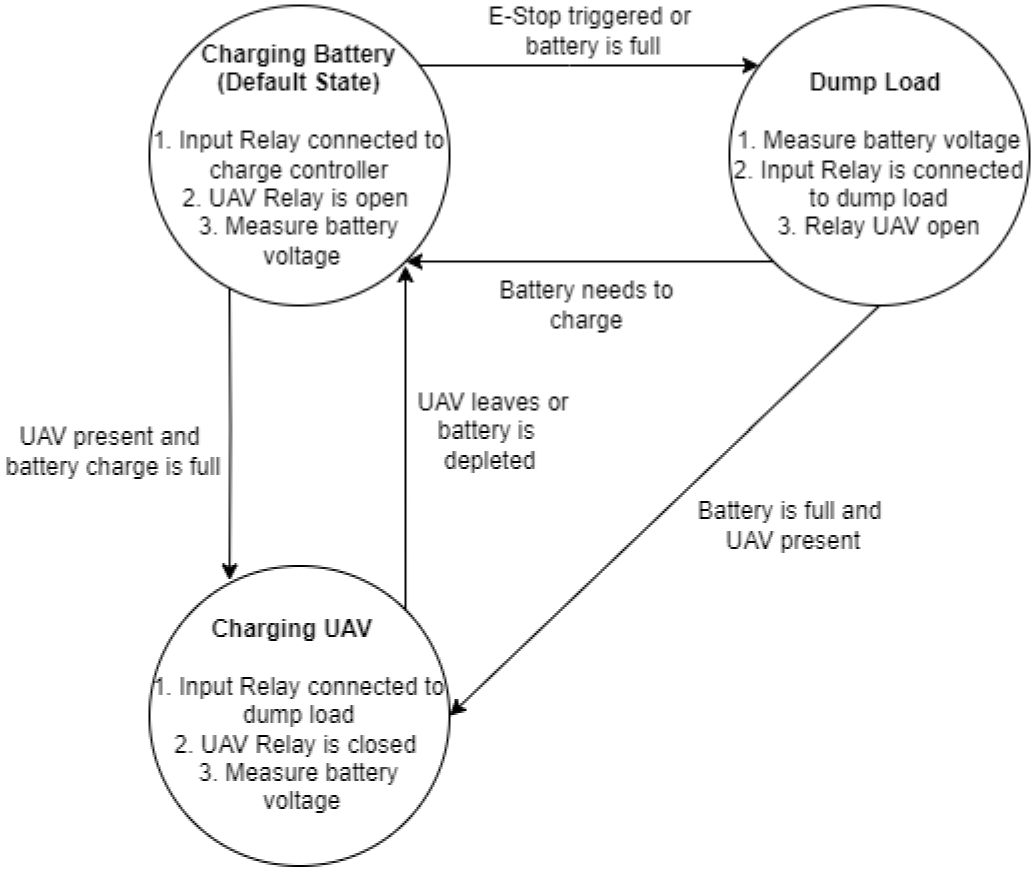
## Appendix 3a. PCB architecture



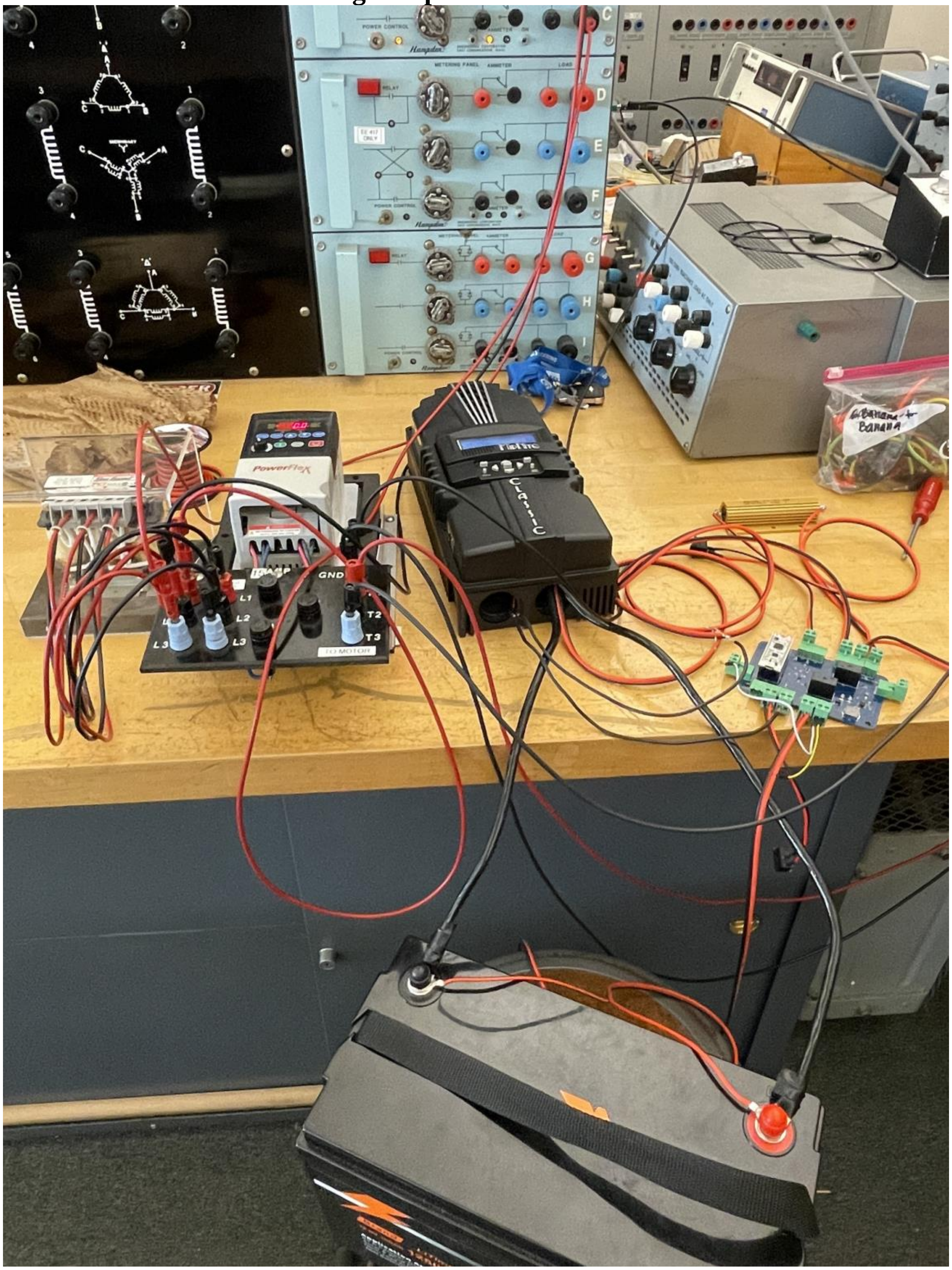
## Appendix 3b. PCB Layout



**Appendix 3c. State Diagram for Microcontroller**



## Appendix 3d. Full Electrical Testing Setup



# Appendix 4: Bill of Materials and Mechanical Drawings

## PolyWave Energy WEC
### Indented Bill of Material (iBOM)

| Assy Level | Part Number | Descriptive Part Name | | | | | Qty | Total Part Cost | Manufacturer Part Number | Source | More Info |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *Lvl0* | *Lvl1* | *Lvl2* | *Lvl3* | *Lvl4* | | | | | |
| 0 | 100000 | Full Assembly | | | | | | | | | |
| 1 | 110000 | | Linear Mechanical Assembly | | | | | | | | |
| 2 | 111000 | | | Rack | | | 1 | $ 192.50 | 2485N206 | McMaster | - |
| 2 | 112000 | | | U-Joint | | | 1 | $ 16.98 | CMMT99294 | Lowe's | Weld to plate for attachment to rack. |
| 2 | 114000 | | | Pole Spacer | | | 1 | | | Custom | Machined aluminum |
| 2 | 115000 | | | Pole | | | 1 | | 9056K74 | Custom | Purchase stock pole, cut to 1150 mm |
| 2 | 116000 | | | Linear Guide Rail | | | 1 | $ 74.99 | SBR20-C 1200L | Vevor | 1 Set |
| 2 | 117000 | | | Guide Carraige | | | 4 | | | | |
| 2 | 118000 | | | Carriage Plate | | | 2 | | | Custom | Cut piece from stock material |
| 2 | 119000 | | | Linear Bearing | | | 2 | $ 195.04 | | McMaster | |
| 2 | 111100 | | | Fastener Carraige to Plate: M5 | | | 8 | | 91294A211 | McMaster | only order 1, comes in pack of 100 |
| 2 | 111200 | | | Fastener Baseplate to Rack M8 | | | 2 | $ 12.93 | 91290A231 | McMaster | only order 1, comes in pack of 50 |
| 2 | 111300 | | | Fastener Rack to U-joint M8 | | | 1 | $ - | 91290A232 | McMaster | Use same as above |
| 2 | 120000 | | Rotational Mechanical Assembly | | | | | | | | |
| 3 | 121000 | | | Gearbox | | | 1 | $ 969.88 | NT92-10 | onedriveus | |
| 2 | 121100 | | | | Gearbox Mount | | 2 | | F2384 | Custom | Machined from stock steel plate, 1/4 inch thick, 4 inches wide, 2 ft long |
| 3 | 122000 | | | Pinion | | | 1 | $ 54.71 | 2664N25 | McMaster | Broached to fit a keyway that transmits torque between pinon and shaft |
| 3 | 122100 | | | | Pinion Shaft | | 1 | | | Custom | Broached to fit a keyway that transmits torque between pinon and shaft |
| 3 | 122200 | | | | Pinion Retaining Ring, 15 mm | | 1 | $ 11.91 | 98541A410 | McMaster | |
| 2 | 122300 | | | | Key | | 1 | $ 8.04 | 98870A975 | McMaster | |
| 3 | 123000 | | | Spider Coupling | | | | | | | |
| 3 | 123100 | | | | Hub1 | | 1 | $ 15.75 | 6408K13 | McMaster | Order 22mm |
| 3 | 123200 | | | | Hub2 | | 1 | $ 15.75 | 6408K14 | McMaster | Order 15mm |
| 2 | 123300 | | | | Spider | | 1 | $ 13.86 | 6408K74 | McMaster | - |
| 2 | 124000 | | | Flexible Coupling | | | 1 | $ 134.72 | 2463K72 | McMaster | - |
| 2 | 125000 | | | One Way Bearing | | | 1 | $ 23.48 | 6392K46 | McMaster | - |
| 3 | 126000 | | | Bearings | | | | | | | |
| 3 | 126100 | | | | Mounted Bearing 1 | | 1 | $ 39.30 | 4491N37 | McMaster | - |
| 3 | 126200 | | | | Mounted Bearing 2 | | 1 | $ 42.94 | 4491N39 | McMaster | - |
| 3 | 126300 | | | | Bearing 1 Retaining Rings, 15 mm | | 2 | $ 11.91 | 98541A410 | McMaster | Only order 1 packet, they come in bags of 50 |
| 2 | 126400 | | | | Bearing 2 Retaining Rings, 20 mm | | 3 | $ 13.14 | 98541A410 | McMaster | Only order 1 packet, they come in bags of 50 |
| 3 | 127000 | | | Fasteners | | | | | | | |
| 3 | 127100 | | | | M14 | | 2 | $ 5.50 | 90696A106 | McMaster | Comes in packs of 1 |
| 3 | 127200 | | | | M8 | | 2 | $ 8.60 | 91292A523 | McMaster | Comes in packs of 5 |
| 3 | 127300 | | | | M5 | | 6 | $ 16.23 | 91290A232 | McMaster | Comes in packs of 100 |
| 2 | 127400 | | | | M6 | | 8 | $ 5.88 | 91292A137 | McMaster | Buy 1 package of 25 |
| 3 | 128000 | | | Flywheel | | | 1 | $ - | TBD | TBD | Dependant on EE generator testing |
| 2 | 128100 | | | | Flywheel Shaft | | 1 | | | Custom | Machine from steel round stock |
| 3 | 129000 | | | Baseplate/Structural Support | | | 1 | | | Custom | Wood strucutre |
| 3 | 127500 | | | | Corner Bracket | | 4 | $ 31.24 | 2313n26 | McMaster | |

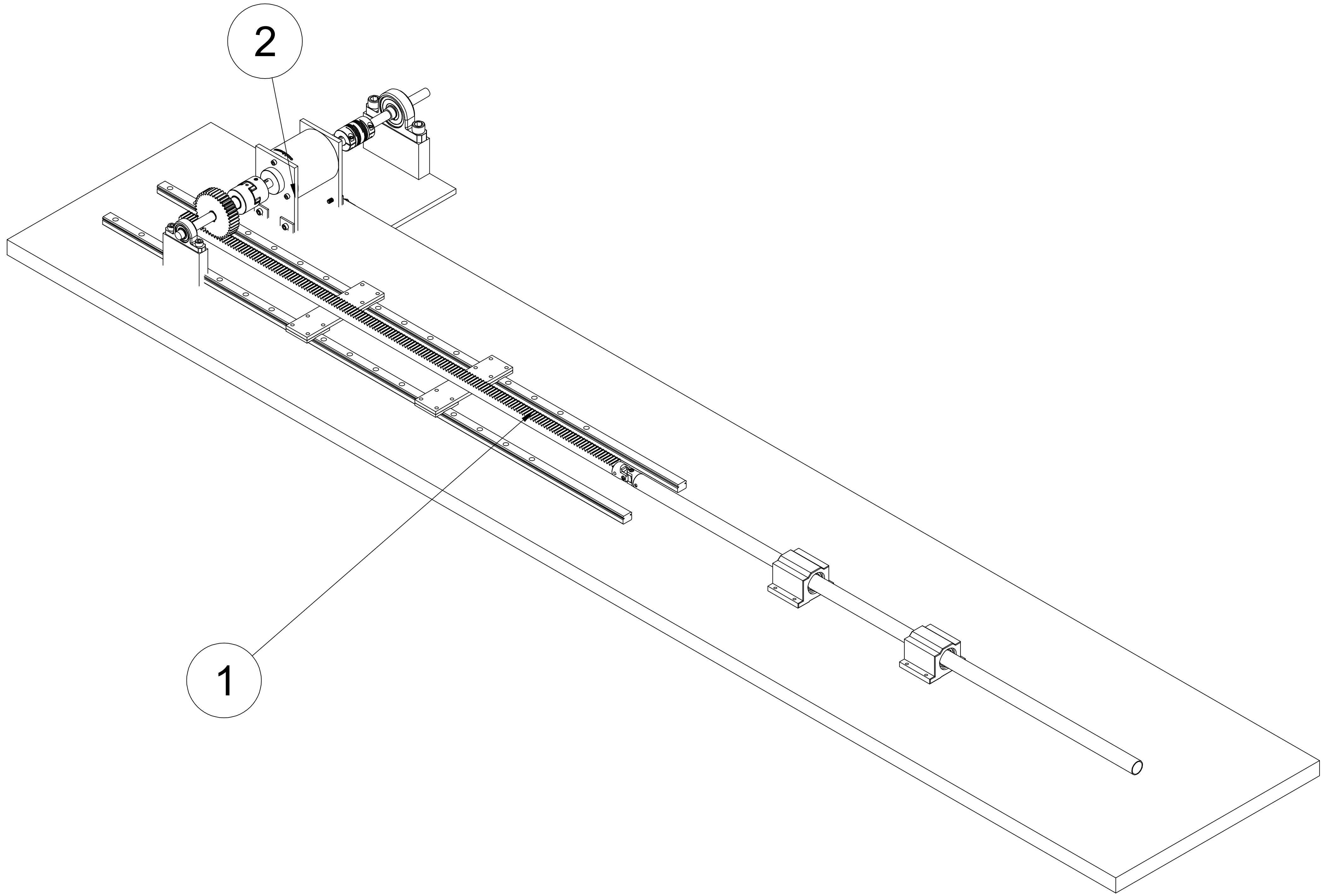
| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 130000 | | Generator & EE Subassembly | | | | | 1 | $ 300.00 | N/A | N/A | Estimate from EE team |
| 2 | 131000 | | | Generator | | | | 1 | $ 184.69 | | Amazon | Electrical subsystem excluded from current CAD |
| 3 | 131100 | | | | Generator Mount | | | 1 | $ - | | Custom | Electrical subsystem excluded from current CAD |
| 3 | 131200 | | | | Shaft Coupling | | | 1 | $ - | | N/A | Electrical subsystem excluded from current CAD |
| | **Total Parts** | | | | | | | **45** | **$ 2,438.56** | | | |

*Note: EE  Subassembly will be included in future drawing package. Testing apparatus is in included in project budget.

## Purchased Parts List

| Part Number | Descriptive Part Name | Qty | Part Cost | Total Cost | Manufacturer Part Number | Source | URL | More Info |
|---|---|---|---|---|---|---|---|---|
| 111000 | Rack | 1 | $ 192.50 | $ 192.50 | 2485N206 | McMaster | rack and pinion gears \| McMaster-Carr | - |
| 112000 | U-Joint | 1 | $ 16.98 | $ 16.98 | CMMT99294 | Lowe's | https://www.lowes.com/pd/CRAFTSMAN-1-2-in-U-Joint-Socket-Adapter/1000596081?irclickid=R71Tp%3AW6UxyLWB-wUx0Mo36KUkH1ypU-xw3hXQ0&irgwc=1&cm_mmc=aff-_-c-_-prd-_-mdv-_-gdy-_-all-_-0-_-78091-_-0 | Weld to plate for attachment to rack. |
| 115000 | Pole | 1 | $ 28.23 | $ 28.23 | 9056K74 | McMaster | poles \| McMaster-Carr | 1 in OD, 0.902 ID |
| 116000 | Linear Guide Rail | 1 | $ 74.99 | $ 74.99 | SBR20-C 1200L | Vevor | VEVOR Linear Guide Rail Set, SBR20 1200mm, 2 PCS 47.2 in/1200 mm SBR20 Guide Rails and 4 PCS SBR20UU Slide Blocks, Linear Rails and Bearings Kit for Automated Machines DIY Project CNC Router Machines \| VEVOR US | 1 Set |
| 117000 | Guide Carraige | 4 | | | | | | |
| 119000 | Linear Bearing | 2 | $ 97.52 | $ 195.04 | 9338T4 | McMaster | https://www.mcmaster.com/9338T4/ | |
| 111100 | Fastener Carraige to Plate: M5 | 8 | $ 10.36 | $ 10.36 | 91294A211 | McMaster | bolts \| McMaster-Carr | only order 1, comes in pack of 100 |
| 111200 | Fastener Baseplate to Rack M8 | 2 | $ 12.93 | $ 12.93 | 91290A231 | McMaster | m8x16 \| McMaster-Carr | only order 1, comes in pack of 50 |
| 111300 | Fastener Rack to U-joint M8 | 1 | $ - | $ - | 91290A231 | McMaster | m8x16 \| McMaster-Carr | Use same as above |
| 121000 | Gearbox | 1 | $ 969.88 | $ 969.88 | NT92-10 | onedriveus | https://www.ondrivesus.com/in-line-gearboxes/in-line-spur-gear/nt92-10 | may change gear ratio, supllier and gear box type will remain the same |
| 122000 | Pinion | 1 | $ 54.71 | $ 54.71 | 2664N25 | McMaster | https://www.mcmaster.com/2664N25/ | Broached to fit a keyway that transmits torque between pinon and shaft |
| 122200 | Pinion Retaining Ring, 15 mm | 1 | $ 11.91 | $ 11.91 | 98541A410 | McMaster | https://www.mcmaster.com/98541A410/ | |
| | Key | 1 | $ 8.04 | $ 8.04 | 98870A975 | McMaster | https://www.mcmaster.com/98870A975/ | |
| 123100 | Spider Coupling Hub1 | 1 | $ 15.75 | $ 15.75 | 6408K13 | McMaster | https://www.mcmaster.com/6408K13/ | Order 22mm |
| 123200 | Spider Coupling Hub2 | 1 | $ 15.75 | $ 15.75 | 6408K14 | McMaster | https://www.mcmaster.com/6408K13/ | Order 15mm |
| 123300 | Spider | 1 | $ 13.86 | $ 13.86 | 6408K74 | McMaster | https://www.mcmaster.com/6408K74/ | - |
| 124000 | Flexible Coupling | 1 | $ 134.72 | $ 134.72 | 2463K72 | McMaster | https://www.mcmaster.com/2463K72/ | - |
| 125000 | One Way Bearing | 1 | $ 23.48 | $ 23.48 | 6392K46 | McMaster | https://www.mcmaster.com/6392K46/ | - |
| 126100 | Mounted Bearing 1 | 1 | $ 39.30 | $ 39.30 | 4491N37 | McMaster | https://www.mcmaster.com/4491N37/ | - |
| 126200 | Mounted Bearing 2 | 1 | $ 42.94 | $ 42.94 | 4491N39 | McMaster | https://www.mcmaster.com/4491N39/ | - |
| 126300 | Bearing 1 Retaining Rings, 15 mm | 2 | $ 11.91 | $ 11.91 | 98541A410 | McMaster | https://www.mcmaster.com/98541A410/ | Only order 1 packet, they come in bags of 50 |
| 126400 | Bearing 2 Retaining Rings, 20 mm | 3 | $ 13.14 | $ 13.14 | 98541A123 | McMaster | https://www.mcmaster.com/98541A123/ | Only order 1 packet, they come in bags of 50 |
| 127100 | M14 | 2 | $ 5.50 | $ 5.50 | 90696A106 | McMaster | https://www.mcmaster.com/90696A106/ | Comes in packs of 1 |
| 127200 | M8 | 2 | $ 8.60 | $ 8.60 | 91292A523 | McMaster | https://www.mcmaster.com/91292A523/ | Comes in packs of 5 |
| 127300 | M5 | 6 | $ 16.23 | $ 16.23 | 91290A232 | McMaster | https://www.mcmaster.com/91290A232/ | Comes in packs of 100 |
| 127400 | M6 | 8 | $ 5.88 | $ 5.88 | 91292A137 | McMaster | https://www.mcmaster.com/91292a137/ | Buy 1 package of 25 |
| 127500 | Corner Bracket | 4 | $ 7.81 | $ 31.24 | 2313n26 | McMaster | https://www.mcmaster.com/2313n26/ | |
| 128000 | Flywheel | 1 | $ - | $ - | TBD | TBD | TBD | Dependant on EE generator testing |
| 140000 | Generator & EE Subassembly | 1 | $ 300.00 | $ 300.00 | N/A | N/A | N/A | Estimate from EE team miscellaneous parts not yet determined. |
| 141000 | Generator | 1 | $ 184.69 | $ 184.69 | N/A | Amazon | https://www.amazon.com/Marsrock-Permanent-Generator-Alternator-Horizontal/dp/B094QN9MY4/ref=sr_1_5?crid=19ANDMQ7EPTEW&keywords=marsrock%2B600%2Brpm%2B100w%2Bgenerator&qid=1706934670&sprefix=marsrock%2B600%2Brpm%2B100w%2Bgenerator%2Caps%2C124&sr=8-5&th=1 | Electrical subsystem excluded from current CAD |
| **Total Parts** | | **40** | | **$ 2,438.56** | | | | |

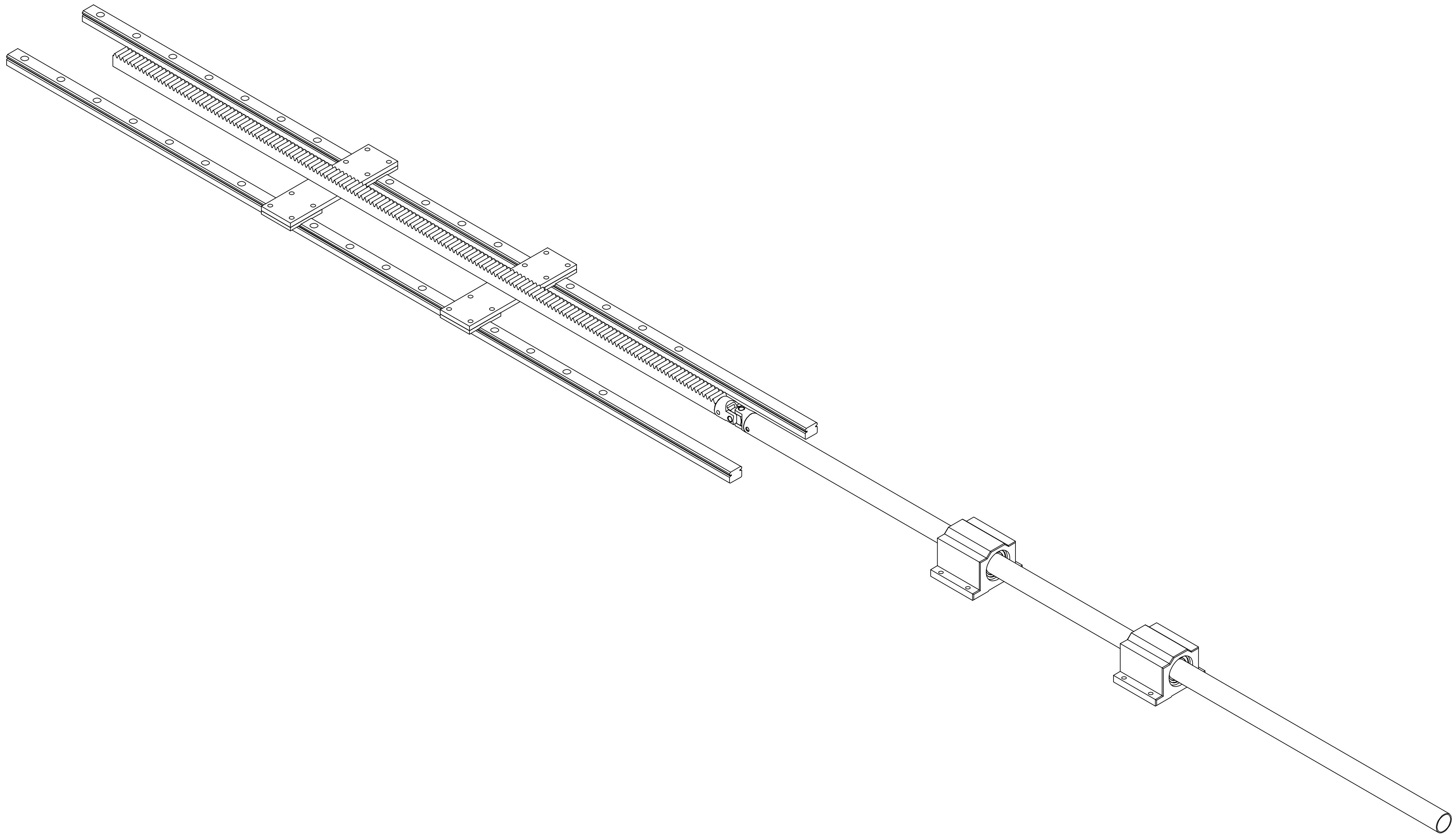
| NUMBER | ASSEMBLY |
|---|---|
| 1 | LINEAR MECHANICAL SYSTEM |
| 2 | ROTATIONAL MECHANICAL SYSTEM |



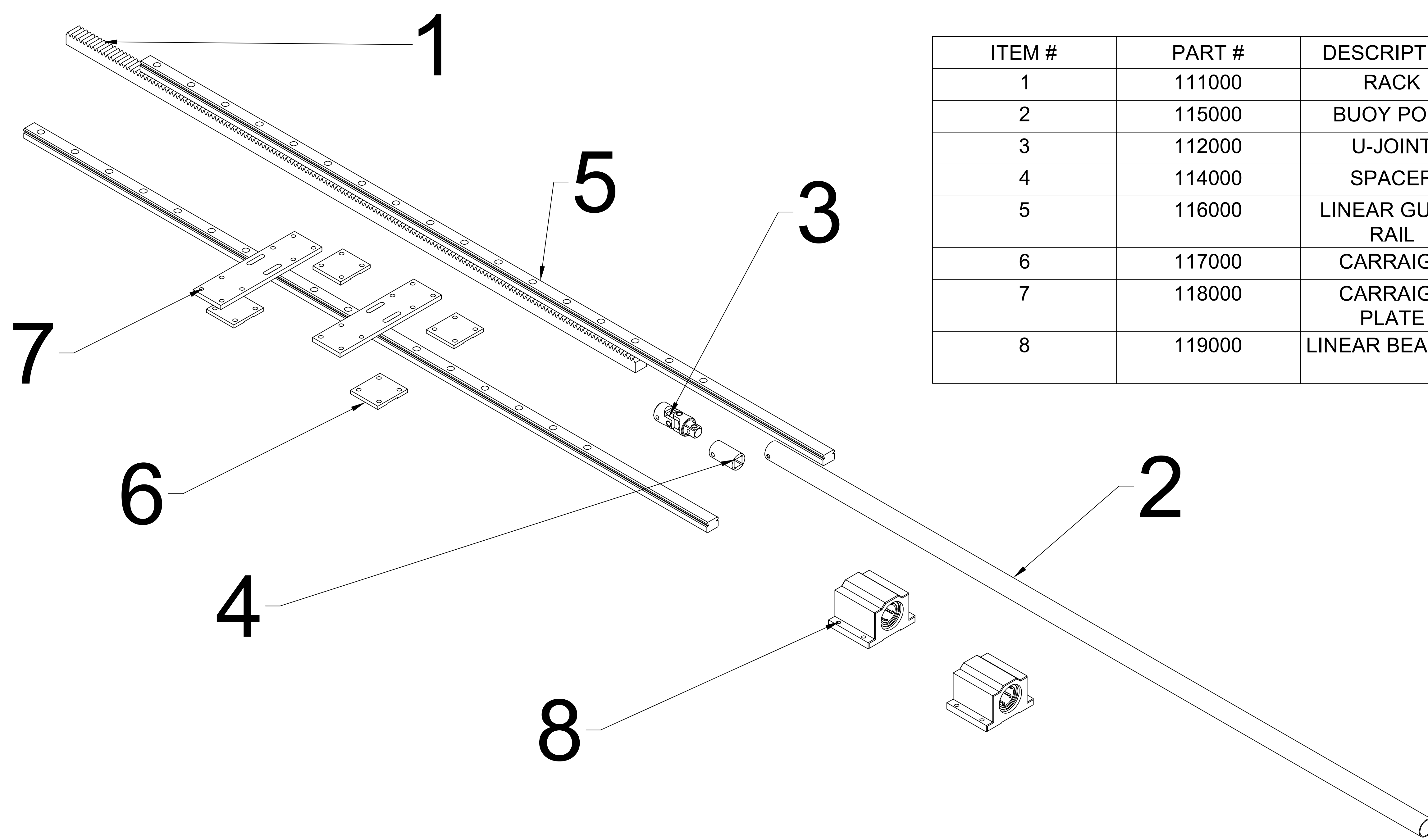

PROJECT
POLYWAVE ENERGY

TITLE
FULL ASSEMBLY

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| APPROVED | BRADLEY ALLGOOD | 2/12/24 | SIZE | CODE | DWG NO | | REV |
| CHECKED | TREVOR ORTEGA | 2/11/24 | B | | 1 | | |
| DRAWN | DEREK TOM | 2/13/2024 | SCALE 1:9 | | WEIGHT | SHEET 1/1 | |



| | | | | |
|---|---|---|---|---|
| PROJECT | POLYWAVE ENERGY | | | |
| TITLE | LINEAR SYSTEM | | | |
| APPROVED | BRADLEY ALLGOOD | SIZE | CODE | DWG NO | REV |
| CHECKED | TREVOR ORTEGA | B | | 2 | |
| DRAWN | DEREK TOM 4/28/2024 | SCALE 1:6 | WEIGHT | SHEET 1/6 | |

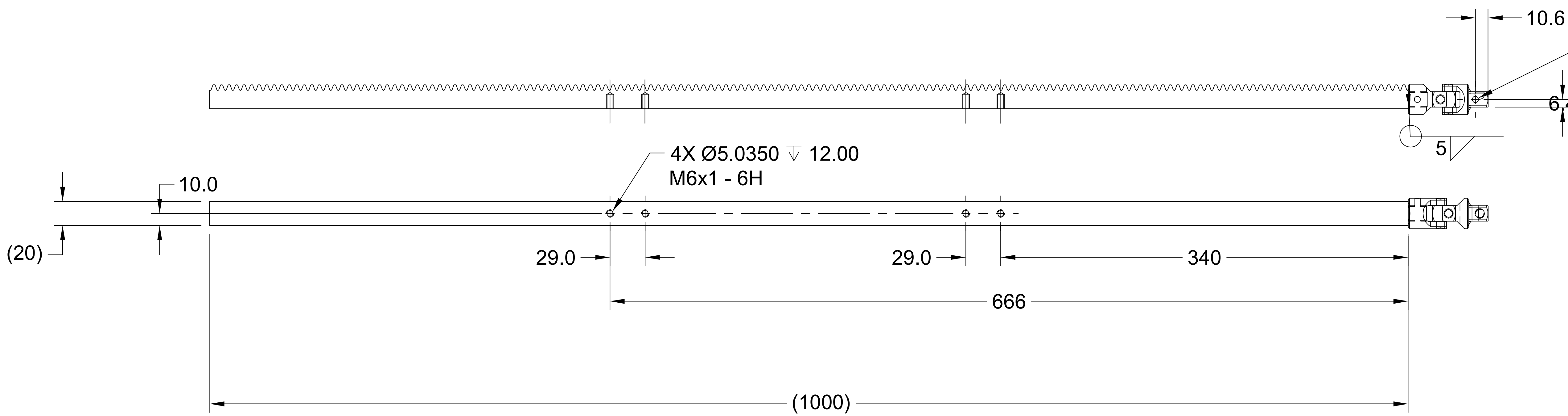



| ITEM # | PART # | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | 111000 | RACK | 1 |
| 2 | 115000 | BUOY POLE | 1 |
| 3 | 112000 | U-JOINT | 1 |
| 4 | 114000 | SPACER | 1 |
| 5 | 116000 | LINEAR GUIDE RAIL | 2 |
| 6 | 117000 | CARRAIGE | 4 |
| 7 | 118000 | CARRAIGE PLATE | 2 |
| 8 | 119000 | LINEAR BEARING | 2 |

PROJECT
POLYWAVE ENERGY
TITLE
LINEAR EXPLODED

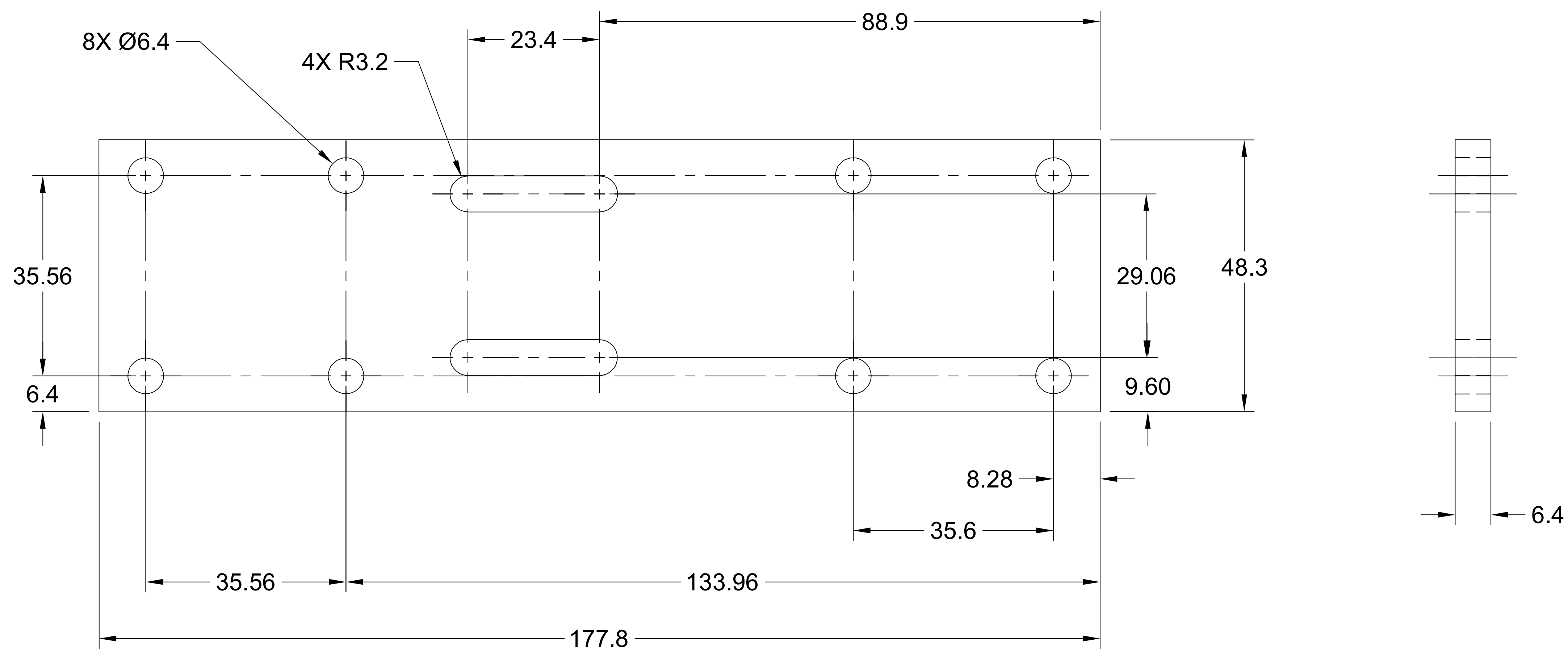
| | | | | | | |
|---|---|---|---|---|---|---|
| APPROVED | BRADLEY ALLGOOD | | SIZE B | CODE | DWG NO 3 | REV |
| CHECKED | TREVOR ORTEGA | | | | | |
| DRAWN | DEREK TOM | 4/28/2024 | SCALE 1:6 | WEIGHT | SHEET 2/6 | |

**NOTES:**
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMENSIONS ARE IN MM
2. TOLERANCES:
   X.X=±0.1
   X=±1




| | |
|---|---|
| PROJECT | POLYWAVE ENERGY |
| TITLE | MODIFIED RACK & U-JOINT |
| APPROVED | BRADLEY ALLGOOD |
| CHECKED | TREVOR ORTEGA |
| DRAWN | DEREK TOM 4/28/2024 |
| SIZE | B |
| CODE | |
| DWG NO | 4 |
| REV | |
| SCALE | 1:4 |
| WEIGHT | |
| SHEET | 3/6 |

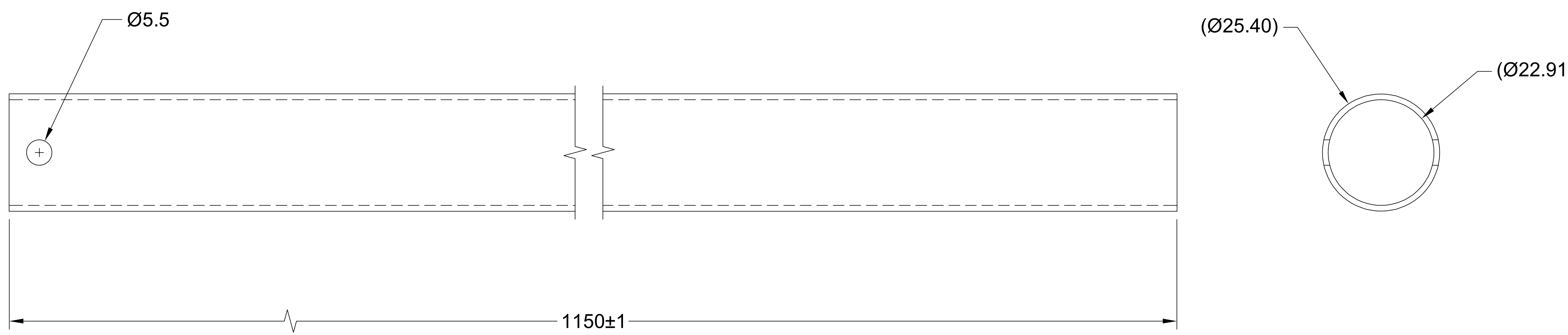
**NOTES:**
MAKE 2 OF THESE
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMENSIONS ARE IN MM
2. TOLERANCES:
   X.X=±0.1
   X.XX=±0.05
3. BREAK ALL SHARP EDGES
4. MATERIAL: STAINLESS STEEL




| | | | | |
|---|---|---|---|---|
| PROJECT | POLYWAVE ENERGY | | | |
| TITLE | CARRAIGE PLATE | | | |
| APPROVED | BRADLEY ALLGOOD | SIZE B | CODE | DWG NO 5 | REV |
| CHECKED | TREVOR ORTEGA | | | |
| DRAWN | DEREK TOM 4/28/2024 | SCALE 1:1 | WEIGHT | SHEET 4/6 |

**NOTES:**

1. ALL DIMENSIONS ARE IN MM
2. PART 115000
3. ALUMINIM 6061

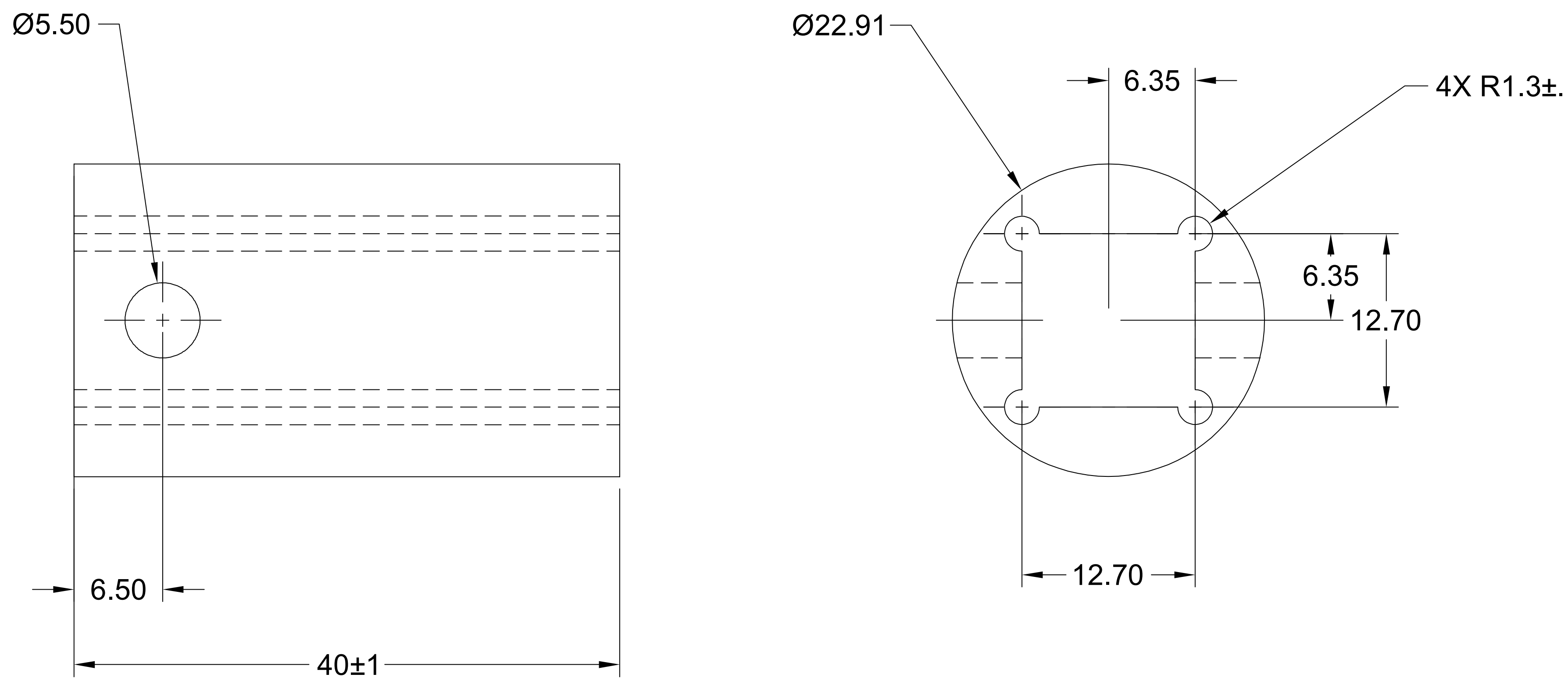



| | | | | | |
|---|---|---|---|---|---|
| | | PROJECT<br>POLYWAVE ENERGY | | | |
| | | TITLE<br>BUOY POLE | | | |
| APPROVED | BRADLEY ALLGOOD | SIZE<br>B | CODE | DWG NO<br>6 | REV |
| CHECKED | TREVOR ORTEGA | | | | |
| DRAWN | DEREK TOM 4/28/2024 | SCALE 1:1 | | WEIGHT | SHEET 5/6 |

**NOTES:**

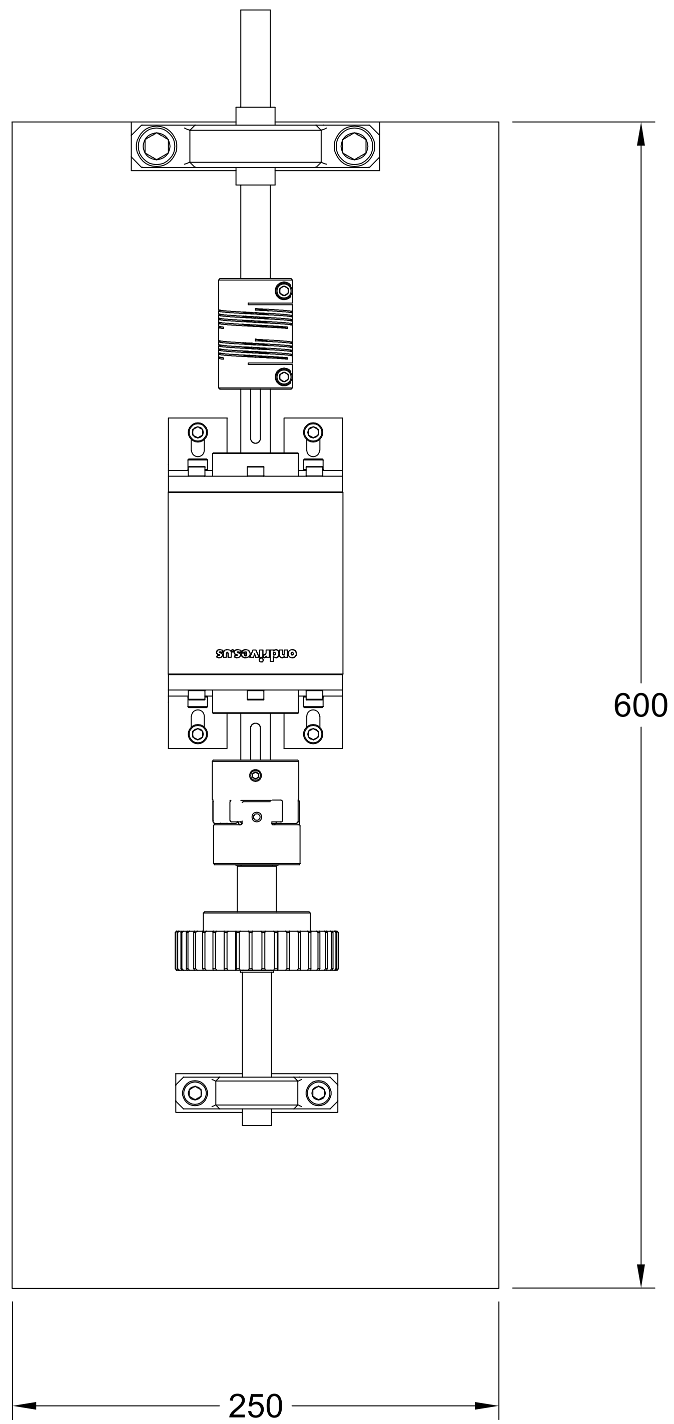
UNLESS OTHERWISE SPECIFIED:

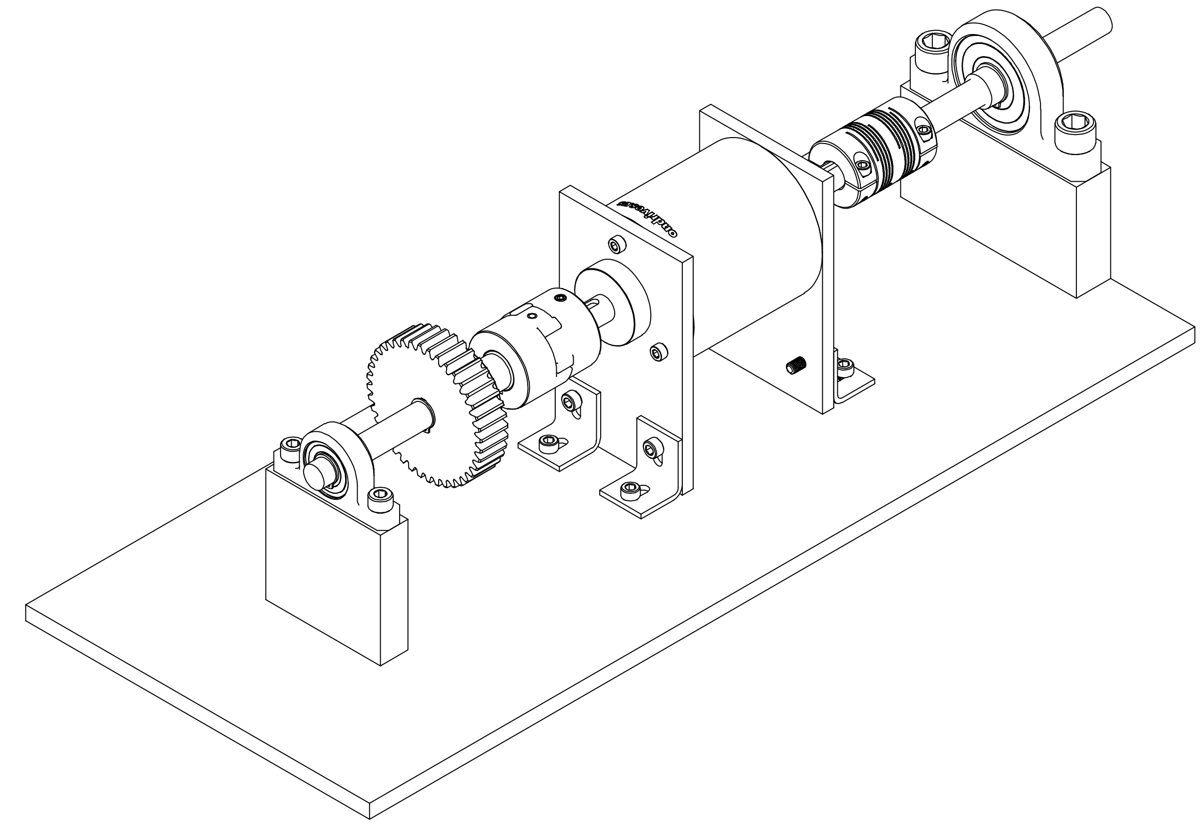
1. ALL DIMENSIONS ARE IN MM
2. TOLERANCES:
   X.XX=±0.05
3. BREAK ALL SHARP EDGES
4. MATERIAL: ALUMINUM 6061




| | | | | | | |
|---|---|---|---|---|---|---|
| | | PROJECT<br>POLYWAVE ENERGY | | | | |
| | | TITLE<br>SPACER | | | | |
| APPROVED | BRADLEY ALLGOOD | SIZE<br>B | CODE | DWG NO<br>7 | | REV |
| CHECKED | TREVOR ORTEGA | | | | | |
| DRAWN | DEREK TOM 4/28/2024 | SCALE 2:1 | | WEIGHT | | SHEET 6/6 |

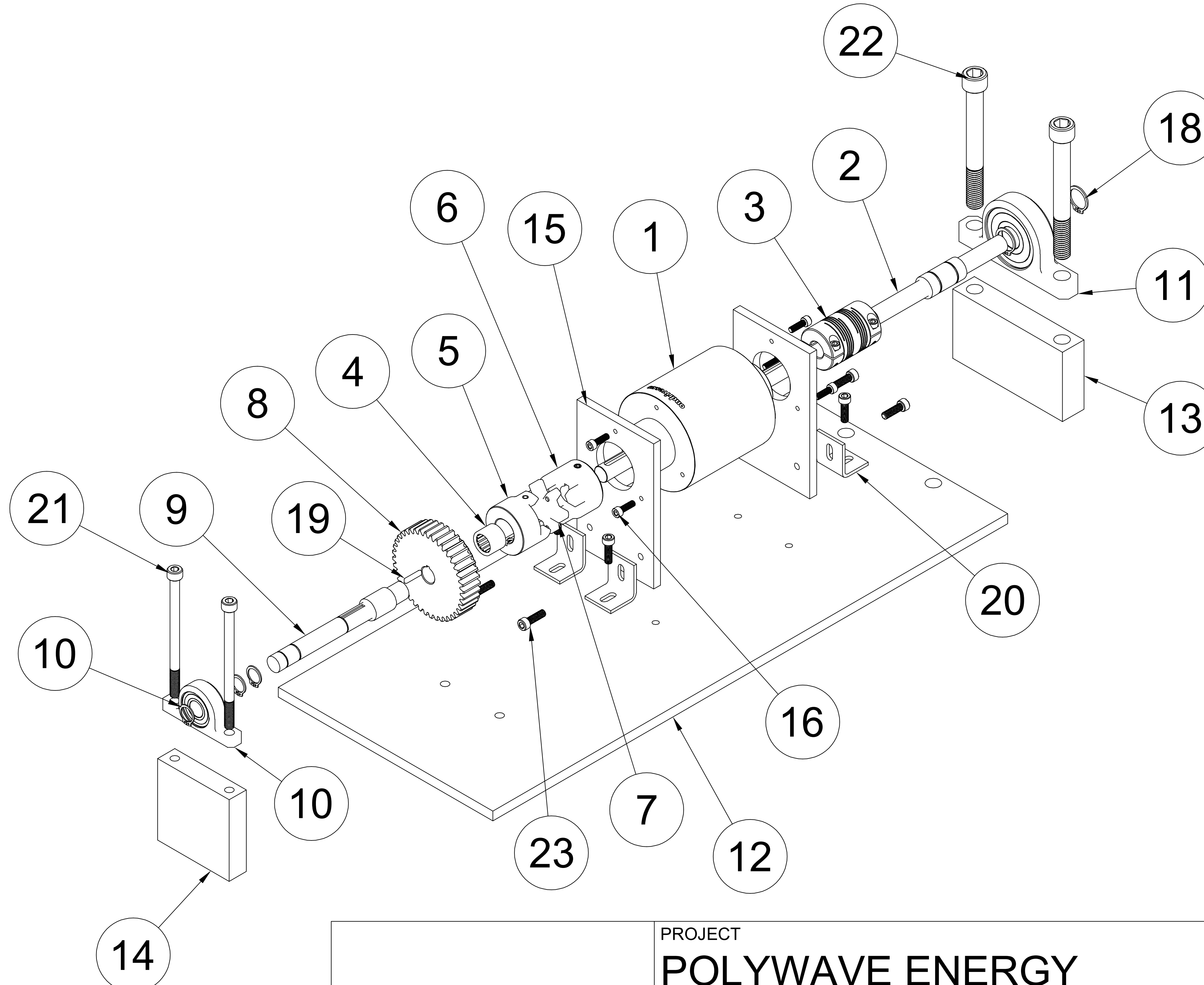
**NOTES:**
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMENSIONS ARE IN MM
2. TOLERANCES:
XX =±1mm



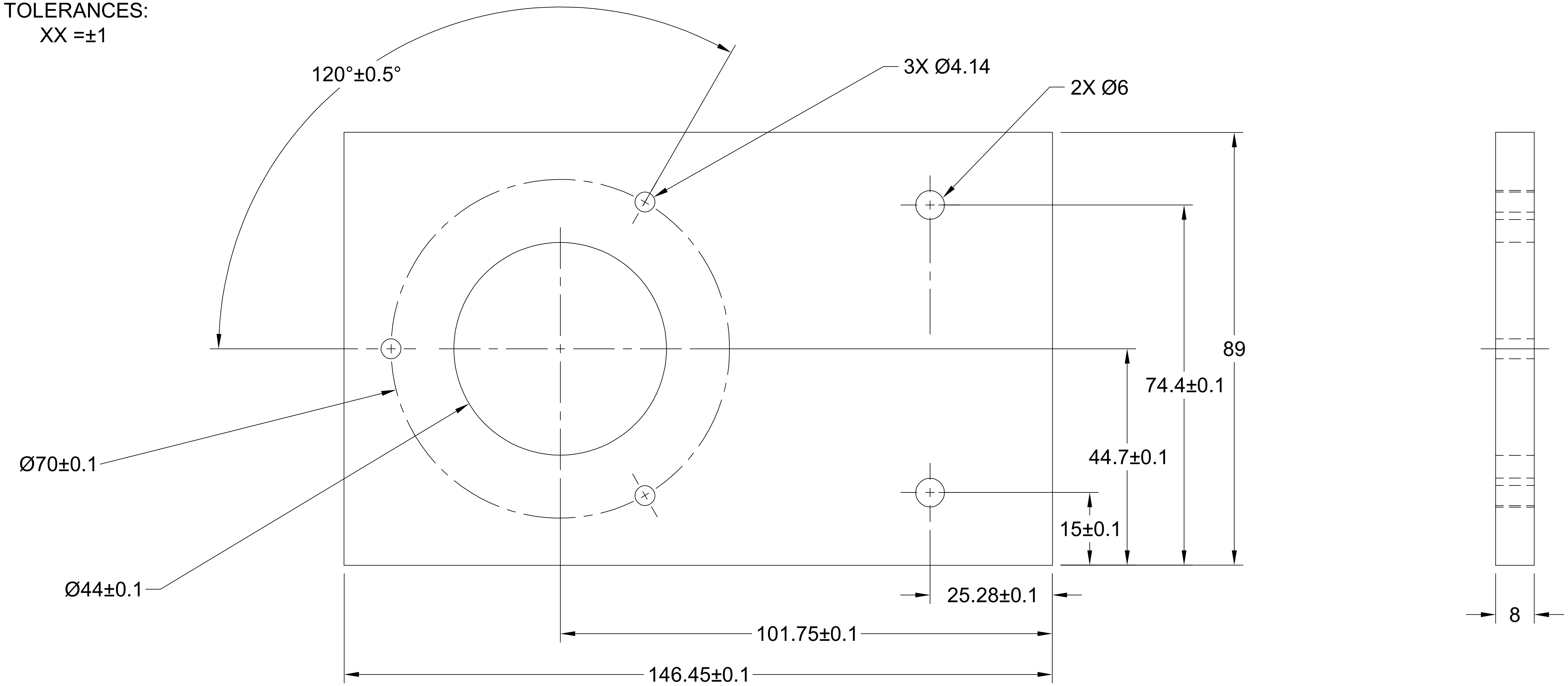
| | | | | | |
|---|---|---|---|---|---|
| | PROJECT<br>POLYWAVE ENERGY | | | | |
| | TITLE<br>ROTATIONAL SUBASSEMBLY | | | | |
| APPROVED Bradley Allgood 2/12/2024 | SIZE | CODE | DWG NO | | REV |
| CHECKED Trevor Ortega 2/11/2024 | B | | 9 | | |
| DRAWN Miles Mikkelsen 2/10/2024 | SCALE 1:4 | | WEIGHT | SHEET 1/4 | |

| Parts List | | | |
|---|---|---|---|
| Item Number | Part Number | Description | Quantity |
| 1 | 121000 | Gearbox | 1 |
| 2 | 128100 | Flywheel Shaft | 1 |
| 3 | 124000 | Flexible Coupling | 1 |
| 4 | 125000 | One Way Clutch | 1 |
| 5 | 123100 | Coupling Hub | 1 |
| 6 | 123200 | Coupling Hub | 1 |
| 7 | 123300 | Spider | 1 |
| 8 | 122000 | Pinion | 1 |
| 9 | 122100 | Pinion Shaft | 1 |
| 10 | 126100 | Pinion Shaft Bearing | 1 |
| 11 | 126200 | Flywheel Shaft Bearing | 1 |
| 12 | 129000 | Base Plate | 1 |
| 13 | 130100 | Bearing Mount | 1 |
| 14 | 130200 | Bearing Mount | 1 |
| 15 | 121100 | Gearbox Mount | 1 |
| 16 | 127300 | M5 Screw | 6 |
| 17 | 126300 | Retaining Ring | 3 |
| 18 | 126400 | Retaining Ring | 2 |
| 19 | 127600 | Key | 1 |
| 20 | 127500 | Corner Bracket | 4 |
| 21 | 127200 | M8 Screw | 2 |
| 22 | 127100 | M14 Screw | 2 |
| 23 | 127400 | M6 Screw | 8 |



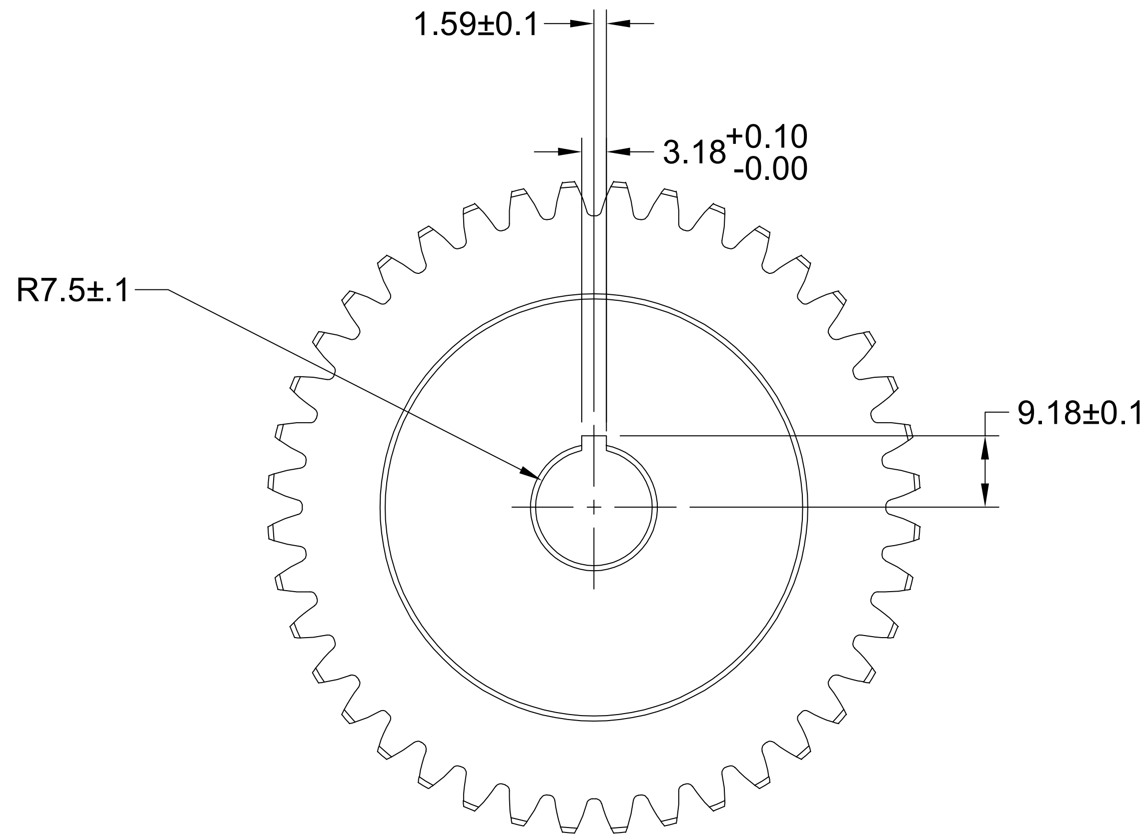

| | | | | | | |
|---|---|---|---|---|---|---|
| PROJECT<br>POLYWAVE ENERGY | | | | | | |
| TITLE<br>ROTATIONAL SUBASSEMBLY EXPLODED VIEW | | | | | | |
| APPROVED | Bradley Allgood | 2/12/2024 | SIZE | CODE | DWG NO | REV |
| CHECKED | Trevor Ortega | 2/11/2024 | B | | 10 | |
| DRAWN | Miles Mikkelsen | 2/10/2024 | SCALE 1:4 | WEIGHT | SHEET 2/4 | |

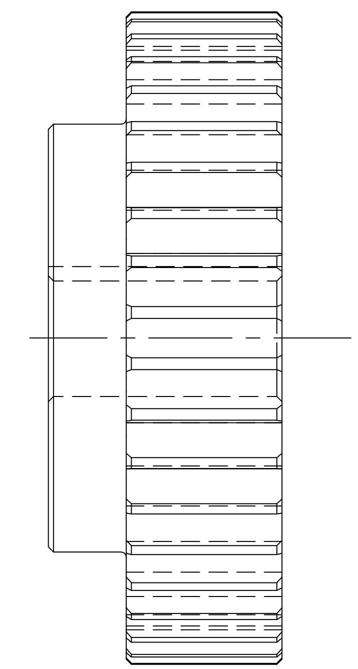
**NOTES:**
UNLESS OTHERWISE
SPECIFIED:
1. ALL DIMENSIONS ARE IN MM
2. TOLERANCES:
XX =±1




| | | | | |
|---|---|---|---|---|
| | | PROJECT<br>POLYWAVE ENERGY | | |
| | | TITLE<br>GEARBOX MOUNT | | |
| APPROVED | Bradley Allgood | 2/12/2024 | SIZE B | CODE | DWG NO 11 | REV |
| CHECKED | Trevor Ortega | 2/11/2024 | | | | |
| DRAWN | Miles Mikkelsen | 2/10/2024 | SCALE 1:2 | WEIGHT | SHEET 1/2 | |

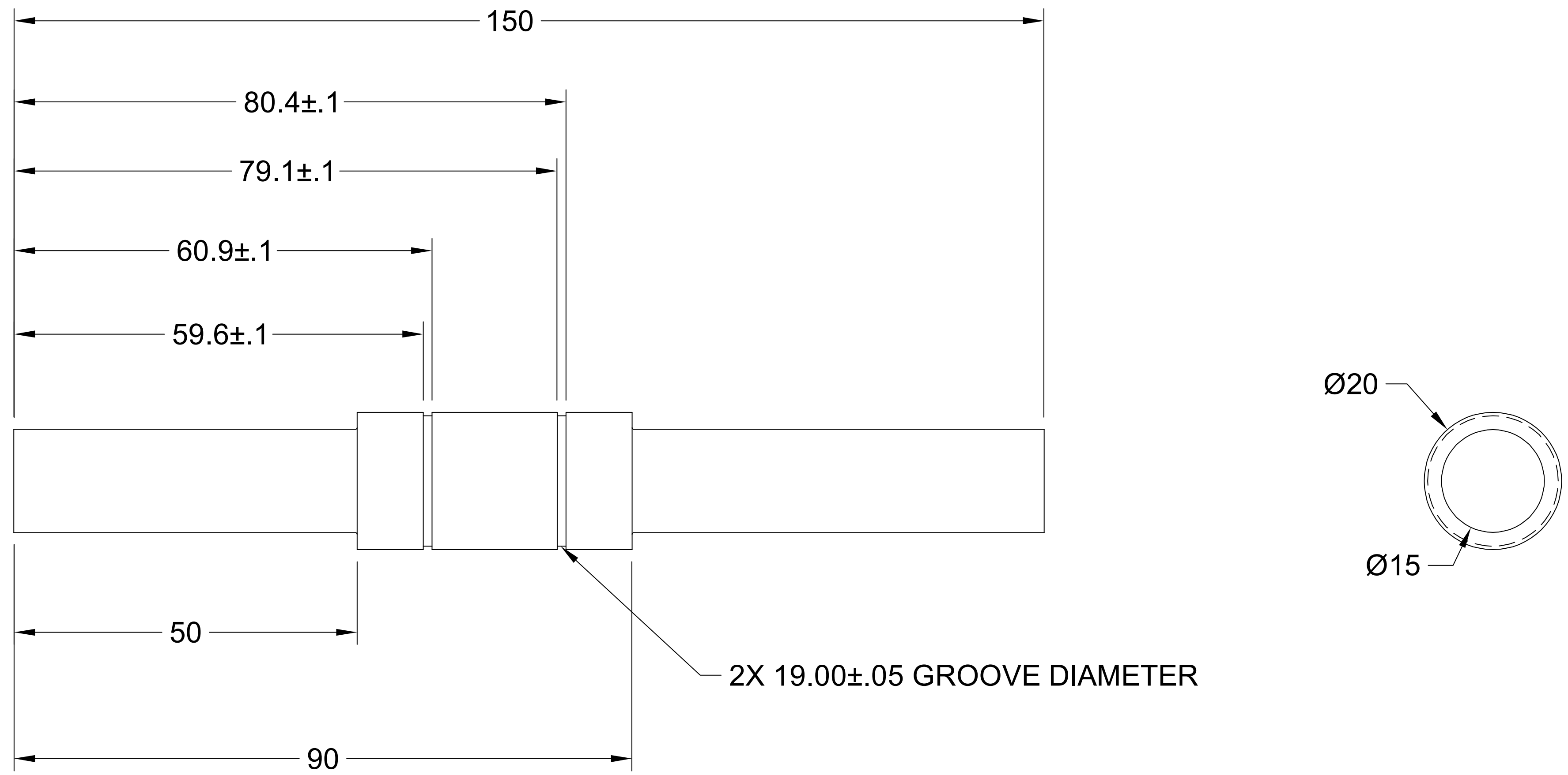
**NOTES:**
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMENSIONS ARE IN MM
2. TOLERANCES:
XX =±1



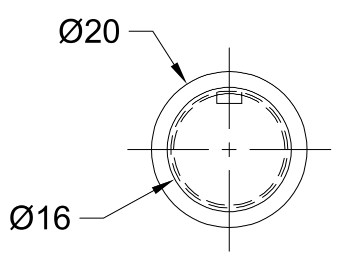
| | | | | | |
|---|---|---|---|---|---|
| PROJECT | POLYWAVE ENERGY | | | | |
| TITLE | PINION | | | | |
| APPROVED | Bradley Allgood | 2/12/2024 | SIZE: B | CODE | DWG NO: 12 | REV |
| CHECKED | Trevor Ortega | 2/11/2024 | | | |
| DRAWN | Miles Mikkelsen | 2/10/2024 | SCALE 1:1 | WEIGHT | SHEET 2/2 |

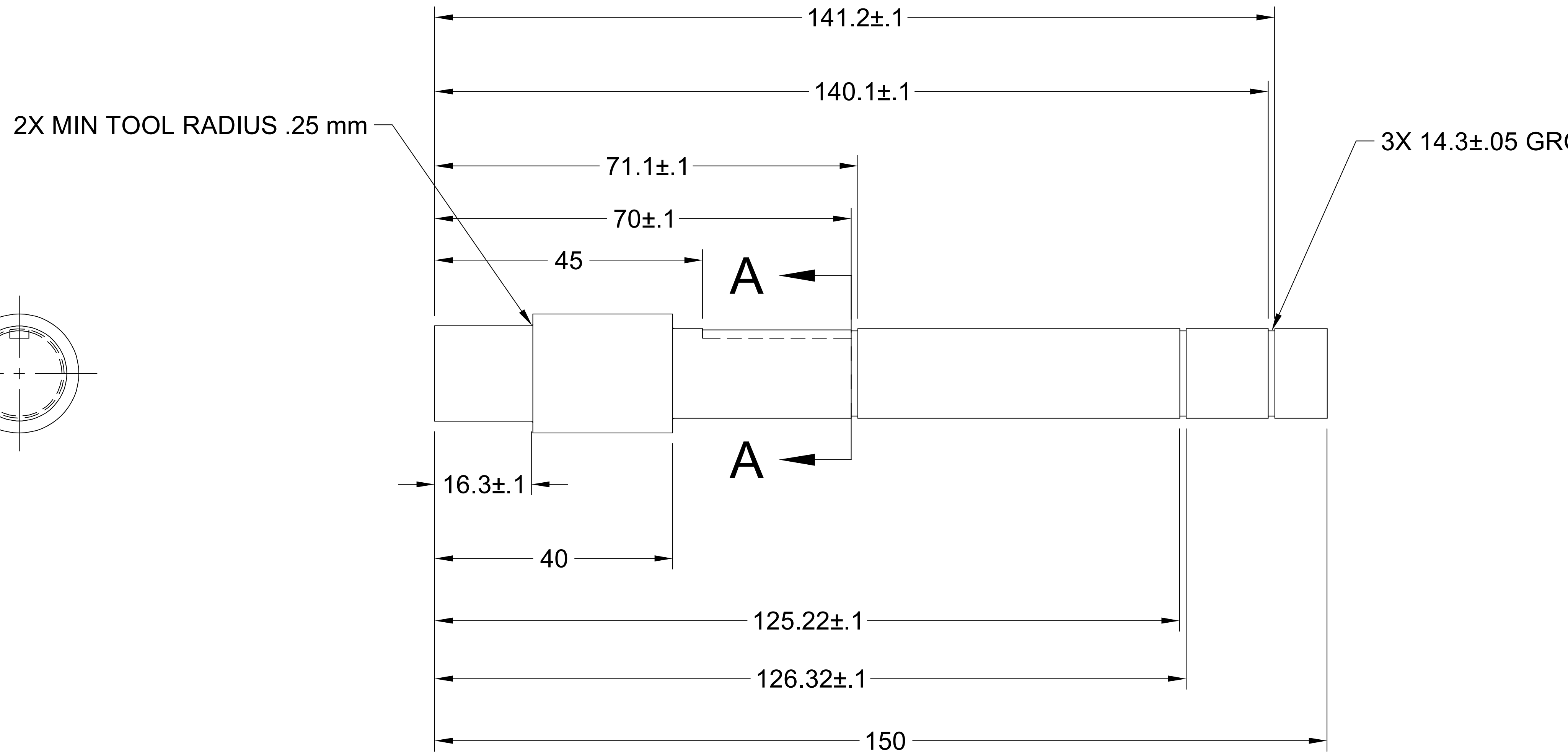
**NOTES:**
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMENSIONS ARE IN MM
2. TOLERANCES:
XX =±1mm

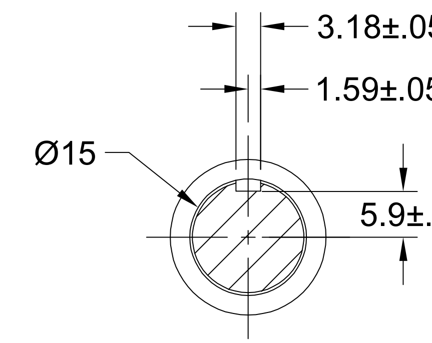



| | | | | | |
|---|---|---|---|---|---|
| | | | PROJECT<br>POLYWAVE ENERGY | | |
| | | | TITLE<br>FLYWHEEL SHAFT | | |
| APPROVED | Bradley Allgood | 2/12/2024 | SIZE<br>B | CODE | DWG NO<br>13 | REV |
| CHECKED | Trevor Ortega | 2/11/2024 | | | | |
| DRAWN | Miles Mikkelsen | 2/10/2024 | SCALE 1:2 | WEIGHT | SHEET 3/4 | |

**NOTES:**
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMENSIONS ARE IN MM
2. TOLERANCES:
XX =±1mm




SECTION A-A
SCALE 1:1

| | | | | | | |
|---|---|---|---|---|---|---|
| PROJECT | POLYWAVE ENERGY | | | | | |
| TITLE | PINION SHAFT | | | | | |
| APPROVED | Bradley Allgood | 2/12/2024 | SIZE | CODE | DWG NO | REV |
| CHECKED | Trevor Ortega | 2/11/2024 | B | | 14 | |
| DRAWN | Miles Mikkelsen | 2/10/2024 | SCALE 1:2 | WEIGHT | SHEET 4/4 | |