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THESIS

DESIGN OF A SELF-SUSTAINABLE AFFORDABLE MASS-SCALE OPEN-WATER ENERGY HARVESTER CAPABILITY FOR NAVAL OPERATIONS

by

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September 2023

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The Navy is always in need of reliable energy. Acquiring energy and transporting it to widely distributed naval ships and systems is a logistical and costly burden. This thesis explored the combined use of wave energy and kelp farming as a means of harnessing energy from the ocean. The thesis designed a concept for a capability called the Kelp Ocean Farm Energy (KOFE) Wave Energy Collector (WEC) Prototype I. The thesis applied a systems analysis using digital systems engineering methods to develop the conceptual design of this novel wave energy collector. The future capability has the potential to provide energy to support long term operations around the world while reducing life cycle costs and the Navy's overall carbon footprint. This novel KOFE WEC's architecture leverages the biological advantages of naturally regenerating kelp resources as the major kinetic energy collector subsystem to deliver locally harvested energy to naval ships and systems. The design is based on simple commercial-off-the-shelf (COTS) devices combined with Navy-developed hybrid energy storage (ES) systems to reduce life cycle cost and streamline future system integration. The thesis analyzed the conceptual system using linear wave theory calculations and identified future development and experimentation plans. The KOFE WEC Prototype I is a first-of-a-kind innovative technology concept intended to produce local sustainable power for future Navy systems.

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DESIGN OF A SELF-SUSTAINABLE AFFORDABLE MASS-SCALE OPEN-WATER ENERGY HARVESTER CAPABILITY FOR NAVAL OPERATIONS

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Submitted in partial fulfillment of the
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ABSTRACT

The Navy is always in need of reliable energy. Acquiring energy and transporting it to widely distributed naval ships and systems is a logistical and costly burden. This thesis explored the combined use of wave energy and kelp farming as a means of harnessing energy from the ocean. The thesis designed a concept for a capability called the Kelp Ocean Farm Energy (KOFE) Wave Energy Collector (WEC) Prototype I. The thesis applied a systems analysis using digital systems engineering methods to develop the conceptual design of this novel wave energy collector. The future capability has the potential to provide energy to support long term operations around the world while reducing life cycle costs and the Navy's overall carbon footprint. This novel KOFE WEC's architecture leverages the biological advantages of naturally regenerating kelp resources as the major kinetic energy collector subsystem to deliver locally harvested energy to naval ships and systems. The design is based on simple commercial-off-the-shelf (COTS) devices combined with Navy-developed hybrid energy storage (ES) systems to reduce life cycle cost and streamline future system integration. The thesis analyzed the conceptual system using linear wave theory calculations and identified future development and experimentation plans. The KOFE WEC Prototype I is a first-of-a-kind innovative technology concept intended to produce local sustainable power for future Navy systems.

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LIST OF ACRONYMS AND ABBREVIATIONS

COTS	Commercial Off the Shelf
DC	Direct Current
EMEC	European Marine Energy Centre
ES	Energy Storage
KOFE	Kelp Ocean Farm Energy
MBSE	Model Based Systems Engineering
NOAA	National Oceanic and Atmospheric Administration
NSWCCD	Naval Surface Warfare Center Carderock Division
PAR	Photosynthetically Active Radiation
PTO	Power Take Off
TENG	Triboelectric Nanogenerator
WEC	Wave Energy Collector

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EXECUTIVE SUMMARY

As the need for energy increases within the Navy, research and product development continues to fulfill that need. This thesis intends to design a novel wave energy collector (WEC) concept that would support long term operations around the world while reducing life cycle cost and overall carbon footprint. The kelp ocean farm energy (KOFE) WEC Prototype I concept is designed following a digital systems engineering method with general functional requirements born from traditional WEC industry. The novel component of this design is the use of an organic macro algae (kelp) as the primary kinetic energy capturing subsystem. By replacing a major subsystem of traditional WEC with a "live" biological subsystem the KOFE WEC concept is able to meet design requirements such as reduced life cycle cost, reduced environmental impact, and long duration survivability.

The initial KOFE WEC system digital model is created in CAMEO, a model-based systems engineering (MBSE) tool. Lists of general and functional requirements are traced to subsystem components. These requirements target general disadvantages of traditional WEC while preserving advantages. Examples of general requirements include parameters for survivability, marine environment impact, and system cost. Functional requirements are used as subsystem selection criteria during the concept development phase of this product development.

The kinetic energy collector is the primary subsystem designed to interact directly with the propagating wave. Different kelp species are investigated based on proven kelp agricultural farming successes. Species are identified with blade size, growth rate, and common growth location. The intent is to use the most appropriate kelp as wave kinetic energy collectors based on operational deployment location need. This would be the simplest way of ensuring a major subsystem survivability while positively contributing to the local marine environment. Kelp reproduction is also linked to ambient carbon dioxide removal, which added further global environmental benefit.

The structural support subsystem is the main physical structure of the WEC. This provide the critical need of housing for all other subsystems while optimized for the growth of the biological subsystem. Technology is leveraged from the kelp farming industry. Line farming technology is leveraged with circular deployment design and optimized for linear wave energy capture. Kelp farming research and development demonstrated the need to optimize farm line spacing with respect to solar irradiance as the key to optimized growth condition. To serve as an efficient WEC, the physical farm line length is further optimized in accordance with the parameters of linear wave theory, which bounds line absorbers at a max distance of two times the wavelength, λ. This distance is also the max diameter of the KOFE WEC Prototype I concept.

The power take off (PTO) subsystem was traditionally the most expensive part of a WEC. This major subsystem serves the critical role of converting mechanical force into electrical energy. With cost and function as major selection criteria, the KOFE WEC Prototype I is designed with commercial off the shelf (COTS) reciprocating linear actuators. Each farm line is anchored to the circular support structure with a pair of reciprocating linear actuators. This concept provided the most cost-effective methods of energy conversion with adjustable parameters such as arm length and gear box ratio for future optimization. Multiple reciprocating linear actuators as PTOs also serve as added redundancy to the system, reducing single point failure and maintenance cost.

The energy storage (ES) subsystem is a separate required subsystem. Localized energy storage capability is a critical need in order to provide energy back to external Navy systems. Due to the simplicity of the PTO subsystem, the energy storage subsystem need to be able to effectively filter the power pulses generated by irregular energy captured. A previously demonstrated Navy developed product of hybrid energy storage system is selected as the energy storage subsystem for KOFE WEC Prototype I. This hybrid ES has the demonstrated capability of accepting high power direct current (DC) loads by efficiently switching between high power capacitor banks and high energy batteries. The Navy owned IP will also allow for future scale up and parameter optimization at lower cost.

Full KOFE WEC Prototype I is a sum of the selected subsystems. Linear wave theory can be used to predict functional performance. However, it is identified that key parameters still needed for full calculation are directly tied to environmental conditions (wavelength, wave height, etc.), and physical parameters of biological subsystem (growth area, drag coefficient, etc.). These parameters would need to be determined through future experimentation in order to create a full mathematical model of the WEC.

Future prototype reiterations and development directions are identified through this KOFE WEC Prototype I subsystem development. The kinetic energy collector selection can parallel the kelp biological species selection vs. specific regions of water condition. This is a common practice of the agriculture community. The structural support subsystem can develop into a more automated system that would adjust the energy capturing line length depending on the real propagating wave data. PTO and energy storage subsystems could be tuned through experimentation at deployment conditions. The parameters of such an experiment would follow the variables listed through the linear wave theory. Force meters are used to measure the resulting performance of individual actuator PTOs with energy storage. The collection of these improvements could be the next reiteration of KOFE WEC and further demonstrate the specific capabilities of biological based KOFE WEC systems as an energy production system for the future Navy.

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I. INTRODUCTION

A. RESEARCH OBJECTIVE

The objective of this research was to study the combination of open water kelp farming technology and wave energy harvesting technology to conceptually design a novel self-sustainable ocean energy harvester platform system which could serve as a power module for a multitude of naval "deploy and forget" scenarios.

Sustainable energy is a major area of interest for the Navy. Researchers and engineers have been attempting to harness wave energy from the ocean as early as 1974 (Salter 1974). Material issues related to survivability during long deployment and hazardous operational environments have kept the price of most ocean wave energy harvesting prototype systems too high. This has limited the advancement of wave energy harvesting technology as compared with solar and wind energy technologies. Inspired by system architecture design methodology, this thesis project designed a self-repairing, sustainable, wave energy harvester by combining technology development from the sea kelp farming industry with existing wave energy harvesting technology. Many key system design elements were shared across both industries. While kelp farming may be optimized for solar absorption vs. kelp production, a wave energy harvester can be designed to optimize wave energy capture vs. a balance of kelp growth and electrical energy production. Kelp was designed, by nature, to survive in different ocean conditions while still able to ride the waves as a method of growth and reproduction. Those natural traits can be leveraged in a system designed for capturing wave energy for numerous other applications.

B. RESEARCH APPROACH

This thesis project applied a system engineering analysis and design approach. The project began with a literature review that included research articles and available COTS technology data sheets mined from two major areas of interest: wave energy harvesting and kelp farming. This information was used to support the identification of design parameters during requirements generation before setting up the major functional and physical architecture of the wave energy harvester. The thesis incorporated qualitative assessment and subsystem selection from mature and available technology, supported by data from industry proven wave energy collector (WEC) technology and existing functional kelp farm designs. The thesis established an analytical framework for future design reiteration, test and evaluation phases by developing a fundamental mathematical computation model. The thesis also identified experimentation parameters for a small-scale prototype device to support and enable future demonstrations.

C. THESIS ORGANIZATION

The first chapter is the introduction of the thesis. The second chapter contains the relevant supporting literature reviews. The third chapter steps through the system development process including digital model creation, requirements generation, individual subsystem concept selection, and fundamental mathematical model selection. The fourth chapter includes the description of the full WEC prototype system. Conclusions are summarized in Chapter V and is followed by the list of references.

II. LITERATURE REVIEW

This chapter provides the foundational information to inform this thesis project. This includes a fundamental understanding of wave energy formation, traditional WEC technology development with example systems, and traditional kelp farm technology with examples of successful farms in production. The chapter summarizes advantages and disadvantages of traditional WEC technology and traditional kelp farm technology. These data serve as some of the general stakeholder needs for system design.

A. WAVE ENERGY

Wave energy occurs due to movements of water in a circular motion (National Oceanic and Atmospheric Administration 2023a). In general waves are formed by winds blowing over the ocean surface. Ocean wind is formed by acceleration of air over the surface of water caused by temperature differential from solar heating. This phenomenon of energy transfer from solar thermal to kinetic wave energy results in a circular water motion with velocity and in a given direction, as Figure 1. This is the propagating wave. The propagating wave carries different levels of kinetic energy. This amount of available kinetic energy can be calculated through linear wave theory by measuring the wave frequency, wave period, and wave height. The wave frequency, period and height are directly influenced by wind speed, wind duration and the resulting interaction of affected body of water with the seabed (Lemonis 2004). Additional literature sources further differentiate between the available ocean water motion into surface waves and tides. “Waves located on the ocean’s surface are commonly caused by wind transferring its energy to the water, and big waves, or swells, can travel over long distances” (Hall 2022). Hall separated the definition of tides as the movement of the entire body of water, caused by gravitational pull of the moon and the sun on Earth. Wave energy collectors are designed to collect the kinetic energy of the wave, while other ocean energy collectors can be designed to collect the potential energy of the cycling tide.

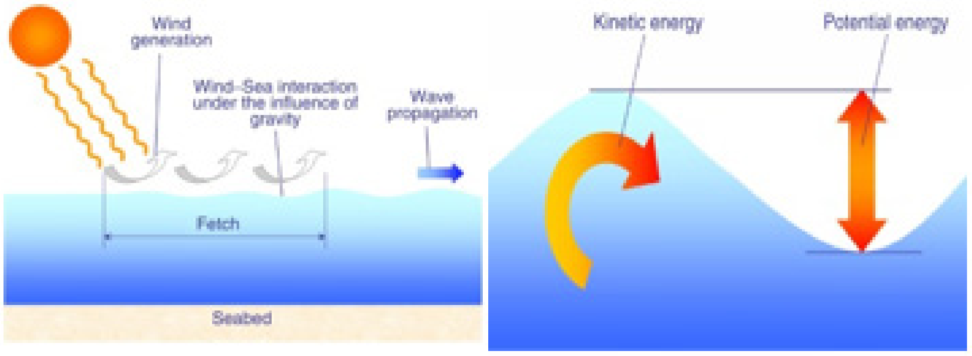


Figure 1. Wave Energy Generation. Adapted from Lemonis (2004, 386).

B. TRADITIONAL WAVE ENERGY HARVESTING TECHNOLOGIES

A variety of different wave energy harvesters are operating today. Different systems are based off of different fundamental approaches of ocean energy harvesting. If these different systems were to be separated by their fundamental methods of energy capture, then some of these simpler systems can be separated into four classes (Polinder, Henk, and Scuotto 2005). His work classified these devices as oscillating water columns devices, hinged contour devices, buoyant moored devices, and or overtopping devices.

In chapter 3, Wave Energy Technology of textbook *Wave and Tidal Energy,* author and editor Deborah Greaves, consolidate these classifications and provide descriptions for each class. In short, oscillating water column devices use water movement to push and pull trapped air internal to the energy collector. This movement of air can be used to spin turbines and generate electrical energy. Hinged contour devices rely on physical movement of different parts of the physical system, usually partially exposed to the water surface. The force generated from physical movement can then be translated into electrical power, through different designs of the power take off subsystem. Buoyant moored devices are similar to hinged contour devices in their design to translate physical system body movement into electrical power. However, the buoyant moored devices are anchored to the seabed. Force of motion are generated by system sink and float, tied to change in potential energy of each device. Overtopping devices are designed with a water reservoir which is constantly changing in volume. Water spill into the reservoir then flow downward to drive the power take off turbine.

C. WAVE ENERGY TECHNOLOGY ADVANTAGES AND DISADVANTAGES

Numerous literature and sources from government institutions such as NOAA, wave energy research literature such as Henk Polinder all describe common advantages and disadvantages to harvesting ocean energy. A news article by Dr. Mario Picazo summed up common advantages and disadvantages of most wave energy harvesting technology to date in a list of pros and cons.

THE PROS:

- Wave energy can be fed directly to electricity-generating machinery and used to supply nearby generators and power plants.
- One of the main advantages of wave energy over other alternative energy sources is that it can be easily predicted; the quantity of energy that can be produced can be calculated quite accurately.
- Unlike the impact fossil fuels have on the Earth’s surface, wave energy does not cause any damage on land. It is safe, clean, and one of the preferred methods of extracting energy from the ocean.
- Wave energy is a reliable source of energy since the ocean is constantly in motion. The average movement of waves is usually quite constant and therefore the energy generated can be used continuously. There can be seasonal and annual variations, but it always exists as a source of energy.

THE CONS:

- The biggest disadvantage of obtaining energy from waves is location, only power plants and cities near the ocean will directly benefit from its potential.
- Generating energy from waves can be dangerous for some nearby species. Machinery can alter the seabed, change habitats near the coast, and generate noise pollution. There is also some risk of spilling toxic chemicals into the water.
- Another drawback is that it disturbs commercial and private vessels. Power plants that harvest wave energy should be located along the coast

to optimize their work, and should be close to cities and other populated areas to be of maximum utility.

- Produced wave energy depends largely on the length of the wave. Wave speed and the density of the water also determine the amount of energy that can be generated. All these elements can be variable and cause uncertainty about how much energy will actually be available.
- Wave energy performance drops significantly in adverse weather conditions.
- Wave power generators can be unsightly for those who live near the shore. They also generate noise pollution, although the noise is usually less than the sound of the waves themselves.
- The cost of the technology used to harness wave energy is still high. Furthermore, the useful life of such technology is limited and its maintenance is frequent. (Picazo 2021)

1. Pelamis

Pelamis (Sea Snake) was developed by Ocean Power Delivery Ltd. According to the company's technology description (Pelamis Wave Power, Ltd. 2022b) and development history (Pelamis Wave Power, Ltd. 2022a), the 750 kW Pelamis wave energy converter was designed to be anchored, cylindrical sectional structure, and exposed to the water surface. The prototype's physical dimensions were described by the company online literature as "120m long and 3.5m in diameter and was comprised of four tube sections linked by three, shorter, power conversion modules" (Pelamis Wave Power, Ltd. 2022a). The Pelamis company technology website descriptions also summarize the design of the Pelamis system. It is intended to capture the wave-induced motion through its system joints, which contain hydraulic oil at pressure. The same source further describes the expected design operation of the WEC,

> As waves pass down the length of the machine these sections flex relative to one another. The motion at each joint is resisted by hydraulic cylinders which pump fluid into high pressure accumulators allowing electrical generation to be smooth and continuous. Control of the resistance applied by the hydraulic cylinders allows generation to be maximized when waves are small, and the machine response to be minimized in storms. All generation systems are sealed and dry inside the machines and power is transmitted to shore using standard subsea cables and equipment. (Pelamis Wave Power, Ltd. 2022b)

This is a hydraulic resistance wave power conversion system. According to the company's technology design website, the energy conversion efficiency of the initial Pelamis prototype was designed to be upwards of 40%. However, the developers do highlight the importance of installation site and its impact on energy harvesting efficacy. A demonstration unit was deployed in Portugal in 2008 and at the European Marine Energy Centre, EMEC, in 2010–2014 (Yemm 1999).

2. Archimedes Waveswing

Archimedes Waveswing was developed by AWS Ocean Energy. The AWS Waveswing is a large air chamber, which is installed just above the seabed and the upper section of the air chamber is continuously moved up and down. This system converts the motions into electrical current via a generator mounted in an advanced machine chamber. AWS Waveswing is deployed as a submerged device. Which carries intrinsic advantage such as reduced damage from storm conditions and greater maintenance windows especially when conditions above the surface become more hazardous. The only option of floating devices is to ret urn them to port for maintenance A 250kW demonstrator unit which will be tested at the EMEC (Institution of Mechanical Engineers 2023).

3. OPT PowerBuoy™

OPT PowerBuoy™ was designed by Ocean Power Technologies. Design objectives were described in the company website. Technical details reference those design objectives (Ocean Power Technologies, Inc. 2023). The PowerBuoy™ wave generation system was designed to provide continues power with a tether to a shore line gird. One of the design objective was to provide a function similar to an uninterruptable power supply (UPS) at an off shore location. According to the OPT web published info, the PowerBuoy™ was intended to be deployed between 20 to 3,000 meters of water, anchored and tethered. OPT's PowerBuoy™ wave generation system was "slack moored so the tube that houses the PTO can move following the waves' oscillations. The energy is obtained by the relative movement between the floater and the tube, which pumps the working fluid." (Soerensen 2009). The wave motion is captured by the buoy as a change to buoy's potential energy. The PowerBuoy™ operating principles is a classic example of the buoyant moored devices as classified by Henk Polinder 2005. To improve upon the basic operating principles, The PowerBuoy™ designed by OPT to have "smart" capabilities. It was designed to actively react to the changing ocean environment., with subsystem features that would make safe itself if extreme hazardous conditions were detected. System demonstration unit was deployed and a buoy installed off the coast of New Jersey. Figure 2 shows a unit in operation.

Figure 2. PowerBuoy WEC. Adapted from Ocean Power Technologies, Inc. Adapted from Ocean Power Technologies, Inc. (2023).

The success of OPT-PowerBuoy™ Technology was impart related to its clear design advantages. These advantages were described in the OPT company marketing information (Ocean Power Technologies, Inc. 2023) and leveraged as general requirements for a new WEC system design.

- "The conversion of wave energy into electric power is carried out through a direct drive generator that continuously charges an on-board battery pack (Energy Storage System)."

- “The PB3 PowerBuoy® supplies power continuously to on-board payloads or equipment located on the seabed while also providing real time data transfer and communication to remote shore facilities.”
- “The PB3 PowerBuoy® is sized and designed to store sufficient electric energy to provide reliable ‘ride through’ power in extended periods of flat-calm seas.”
- “Power from the battery is delivered to meet application and end-user needs. This is particularly advantageous for applications that have varying power requirements including continuous and larger occasional peaks.”
- “OPT has designed the PB3 PowerBuoy® to minimize operational costs (OPEX) whereby deployment and recovery thereof is simplified, leveraging vessels widely employed in offshore marine operations. Reduce mean time between maintenance cycle.”
- “A reliable source of power in any conditions.”
- “Maintenance intervals, by design, are every three years.”

4. The AquaBuOY

The AquaBuOY was a point absorber designed by Aquaenergy Group Ltd. A point absorber by the manufacture’s design definition has a small physical structure when compared against the length of the targeted wave. The AquaBuOY system was designed with a cylindrical buoy as the displacer with a large mass of water enclosed below the displacer (AquaEnergy Group, Ltd 2006). Figure 3 is a concept drawing of the of the point absorber system.

Figure 3. Concept Drawing of AquaBuOy system. Source AquaEnergy Group, Ltd (2006)

An AquaEnergy Power Plant was a concept design by the Aquaenergy Group Ltd which relied on a large network of connected AquaBuOy point absorber systems. According to the company marketing material, small cluster up to hundreds of point absorber buoys can be connected together to support different user needs. This system was designed around minimal physical structures which include: buoy, acceleration tube, piston, and hose pump. Physical subsystem descriptions and function description were provided by a University of Strathclyde online publication.

> The AquaBuOY is a freely floating heaving point absorber, reacting against a submersed reaction tube (mass of water). The reaction mass is moving a piston assembly which drives a steel reinforced elastomeric water pump (hose pump). The hose pump pushes water on a high pressure level. An accumulator is used to smooth the power output and the pressure head is then discharged onto an impulse turbine to generate electricity. Grid synchronization is achieved using a variable speed drive and step-up transformer to a suitable voltage level. (University of Strathclyde 2023)

This design still contains maintenance concerns, especially with respect to subsystem repair which may need to be conducted under water. According to the University of Strathclyde summary publications, currently the buoy would need to be dry docked to perform most maintenances and repairs.

D. TRADITIONAL KELP FARM TECHNOLOGIES

Macroalgae (seaweed/kelp) are a "category of plants, widespread in the coastal areas of the world's seas and oceans. Macroalgae are classified into three categories (Guiry

2012): green algae—Chlorophyta division; red algae—Rhodophyta division; and brown algae—Phaeophyta division" (Dziergowska, Bulgariu, and Michalak 2022). Seaweed has multiple uses in today's global environment. Macroalgae can be used for waste water treatment (Dziergowska, Bulgariu, and Michalak 2022). Macroalgae can be used as CO2 scrubbers, removing industrial emission gases form the atmosphere (Wu 2023) (Atkinson 1983) Macroalgae, seaweed, is on trend to become the forerunner in global aquaculture. As of 2019, 35.8 million tons of seaweed was produced, worldwide. Only 0.01% was produced from the United States of America. More than 97.3% was produced in Asia. (Cai 2021) (Food and Agriculture Organization of the United Nations 2021). Macroalgae are key members of the marine environment. (Lihini I. Aluwihare 2008) They are a member of the primary producers of the shallow water community. Both environmental and capital opportunities exist for greater use of Macroalgea within the United States. According to the National Oceanic and Atmospheric Administration (NOAA) under the U.S. Depart of Commerce, U.S. seaweed farming has increased in recent years, with dozens of new locations in New England, the Pacific Northwest, and Alaska. Various types of seaweed are farmed including dulse, bull kelp, ribbon kelp, and sugar kelp, etc. (National Oceanic and Atmospheric Administration 2023). After researching local commercial success stores, it would seem that the farming method is common, line/grid based farming.

1. Atlantic Sea Farms

Atlantic Sea Farms (ASF) is based off of Biddeford, Maine, and was founded in 2009. Their goal is diversifying coastal waters while making a positive impact to the economy. By partnering with local, national labs and the New England Aquarium, ASF uses line-grown kelp in order to improve the local marine ecosystem. As descripted by their online marketing material (Atlantic Sea Farms 2023), it is within their mission to provide different levels of technical support, equipment support, initial farm set-up support, and kelp farm operational training.

2. Nautical Farms

Nautical Farms is based in Machias, Maine. Founded by two locals, the farm cultivates three types of native Maine seaweeds off of a grid of buoys. The online marketing material (Nautical Farms 2023), provides a description and differentiation for the three types of seaweed. “Alaria (Alaria esculenta), which has a smaller, pointed blade with an olive taste profile, Sugar Kelp (Saccharina latissima), which have long, opulent, amber blades that grow up to 16 feet long and is very salty with savory umami flavors, and skinny kelp (Saccharina latissima forma angustissima) which is similar to Sugar Kelp but smaller and easier to process” (Nautical Farms 2023).

III. SYSTEM ANALYSIS AND CONCEPTUAL DESIGN

This chapter presents a conceptual design of the Kelp Ocean Farm Energy Wave Energy Collector (KOFE WEC) system. The chapter contains system artifacts that capture the conceptual design including a digital engineering model, energy path description, system requirements, and subsystem selections. The conceptual design and system artifacts were developed through systems analysis and analysis of alternatives methods. The subsystem selection analysis included the following subsystems: kinetic energy collector, structural support, power take off, and energy storage. The analysis includes a prediction of system function with fundamental mathematical computational models. Subsystem selections were used to inform the mathematical computational model selection.

A. KOFE WEC DIGITAL ENGINEERING MODEL

The KOFE WEC capability began as a rough idea. The high level objective is to design a long duration WEC system that would be cheap to deploy and maintain by the Navy. This WEC would also serve to provide energy to external systems that could benefit from unmanned longterm operations. Lessons learned were considered from the lack of renewable ocean energy proliferation as compared to the solar indurstry (Feldman et al. 2023) since the early 2010s. Ocean energy has the potiential to grow and join the current hydro/pump hydro to complete the full portfolio of hydro energy. Currently very little to no wave energy is considered during major assesment studies of global renewable energy market, gigawat scale (IRENA, 2020). This led to the idea for a WEC design that could simplfy both hardware and function.

For better understanding, this thesis project uses digital system modeling (in CAMEO System Modeler v19) to capture the KOFE WEC system, a simplified version was shown in Figure 4. The simplifed version was recreated in MS Powerpoint for better print quality.

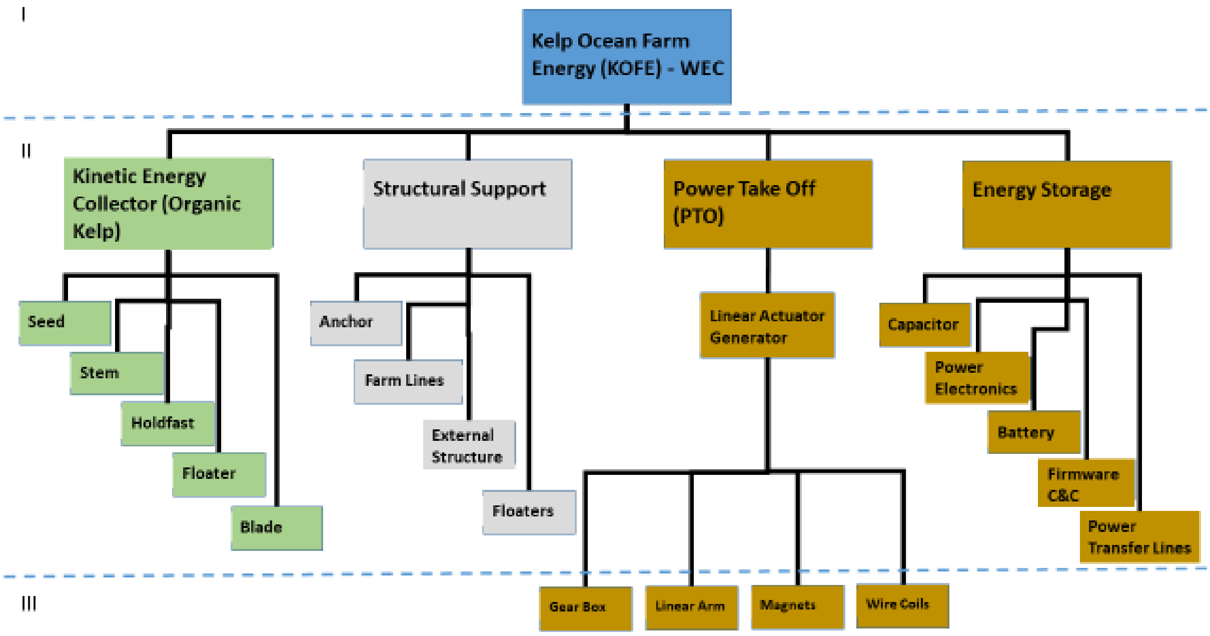


Figure 4. KOFE WEC Digital System Model

The full KOFE WEC system is broken into four major subsystems, kinetic energy collector, support structure, power take off (PTO), and energy storage. Three color schemes is applied to the model. The kinetic energy collector subsystem (shown in green) is designed to leverage biological solutions. The PTO and energy storage subsystem (shown in brown) will leverage traditional COTS solutions of energy transfer, conversion, and storage. The structural support subsystem (shown in gray) will be the external framework and super structure of the full WEC, housing all subsystems.

The simplified flow of energy is diagramed (shown in Figure 5) for the digital KOFE WEC model. Energy movement across the system and associated energy transfer efficiency data can be a measurement of demonstrated integration maturity. During the system design, higher efficiency data will be preferred for selection. It is understood that for the biological kinetic energy collector, efficiency data may not be available and future experimentation should be conducted to measure and compare.

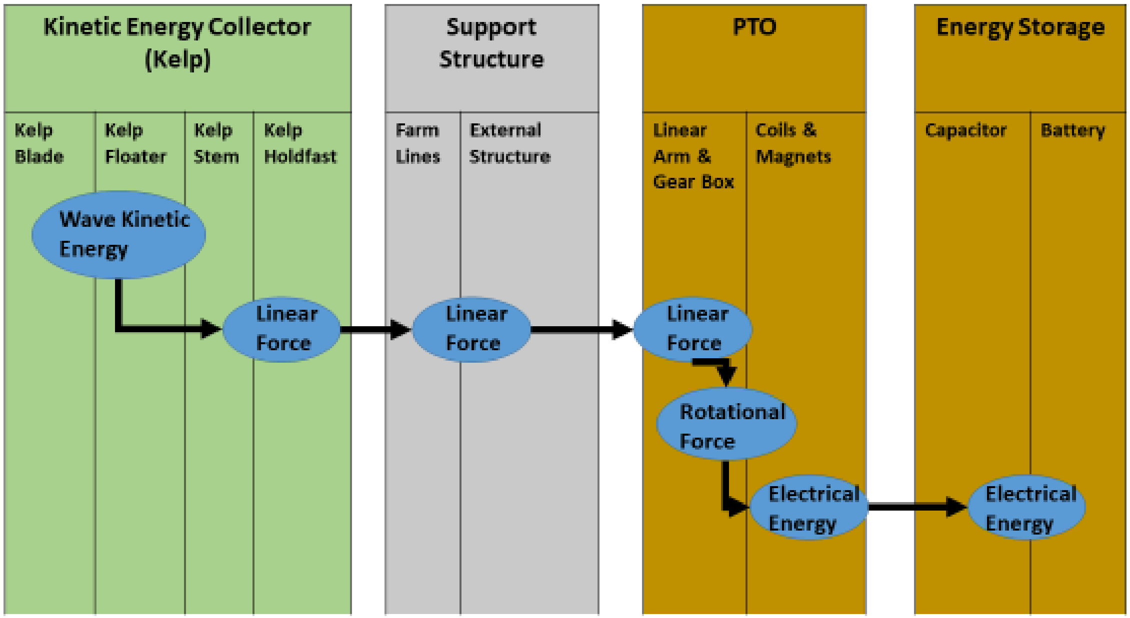


Figure 5. Energy path from collection to storage

During the creation of the digital model, requirements were collected. A list of requirements was produced. Requirements are separated into two categories, general and functional. The general requirements apply across subsystems while functional requirements may only apply to specific subsystems. The same functional requirements can reach across different subsystems. Table 1 summarizes the requirements breakdown vs. associated subsystems. These basic requirements will be used during each subsystem selection. It is noted that after subsystem selection, additional beneficial features are identified and updated back into the bottom of Table 1 as bonus features.

Table 1. KOFE WEC System Requirements vs. Subsystem

	Kinetic Energy Collector	**Structure Support**	**PTO**	**Energy Storage**
General Requirements				
Resistant to biofouling	x	x	x	x
Survivability to ocean/weather conditions and marine life	x	x	x	x
Inexpensive to manufacture	x	x	x	x

	Kinetic Energy Collector	**Structure Support**	**PTO**	**Energy Storage**
Durability over long duration missions	x	x	x	x
Easy to deploy in location	x	x	x	x
Need to fit into external structure	x	x	x	x
Functional requirements				
Self-sustainable	x			
Able to capture propagating wave energy	x			
Supports macroalgea growth	x			
Transfers linear motion / kinetic energy	x	x	x	
Buoyancy adjustable		x		
Conversion to electrical energy			x	
Store electrical energy for future use				x
Bonus features				
Navy technology ownership (available patent)				x
Environmental CO_2 capture	x			
Local marine ecosystem recovery	x			
Secondary production byproduct for profit and use	x			
Cost sharing with existing mass manufactured product across multiple industries	x	x	x	

B. KINETIC ENERGY COLLECTOR (KELP) SELECTION

As described in the previous chapter, the requirements for the biological kinetic energy capturing subsystem of the WEC will need to be self-sustainable, resistant to biofouling, able to operate in different ocean environmental conditions, and inexpensive to produce. These requirements are converted into objectives for criteria selection during the analysis of existing technology. The kelp farming industry was identified with the most potential for mature technology leverage. Kelp is algae that grows and thrives in multiple ocean conditions. Their biological properties have already demonstrated their ability to self-repair against biofouling, survive different ocean environmental conditions, and grow/ proliferate at a fast enough rate, reach maturity in months, in order to support long term operations. As an added benefit, mature kelp harvested have been used to produced food and generate biofuel for energy production. Taking account of the existing market need for kelp, its proposed usage as the kinetic energy capturing subsystem would more than satisfy the requirement of inexpensive to produce. If optimized under the right conditions the kelp based kinetic energy capturing subsystem should reduce the production cost because each cycle of mature kelp can be harvested for a profit.

After market analysis and general article reviews, four different species of kelp were found to be in mature farming markets to date. Figure 6 represents the lab notebook sketches of each of the four species of farm ready kelp. The common traits that distinguish these species from the rest are their quick growth rate, strong holdfasts, and large blades. These same trades also make them appear as kinetic energy capture subsystems. The strong holdfasts allow kelp stems the ability to hold onto stationary substrate. At the same time, these strong holdfasts would allow kinetic energy transfer from each kelp to the support structure of a WEC. If environmental conditions result in higher wave power, beyond the strength of the natural holdfasts, then weaker kelp would naturally release from the WEC and reduce the forces excreted on to the remaining system. This offers a natural protection for the WEC from infrequent extreme conditions. The large blades directly increase the surface area contact with the waves. As a general rule of thumb, kinetic wave energy captured increases with the greater blade contact surface area. Related to larger blades, is the fast growth rates. Increase growth rates directly relate to subsystem self-regenerations. This feature would allow for quicker regeneration against biofouling, extreme sea conditions, and other sources of biological damage. It is also good to note that the faster growth rate also directly equates to a quicker full deployment of the WEC.

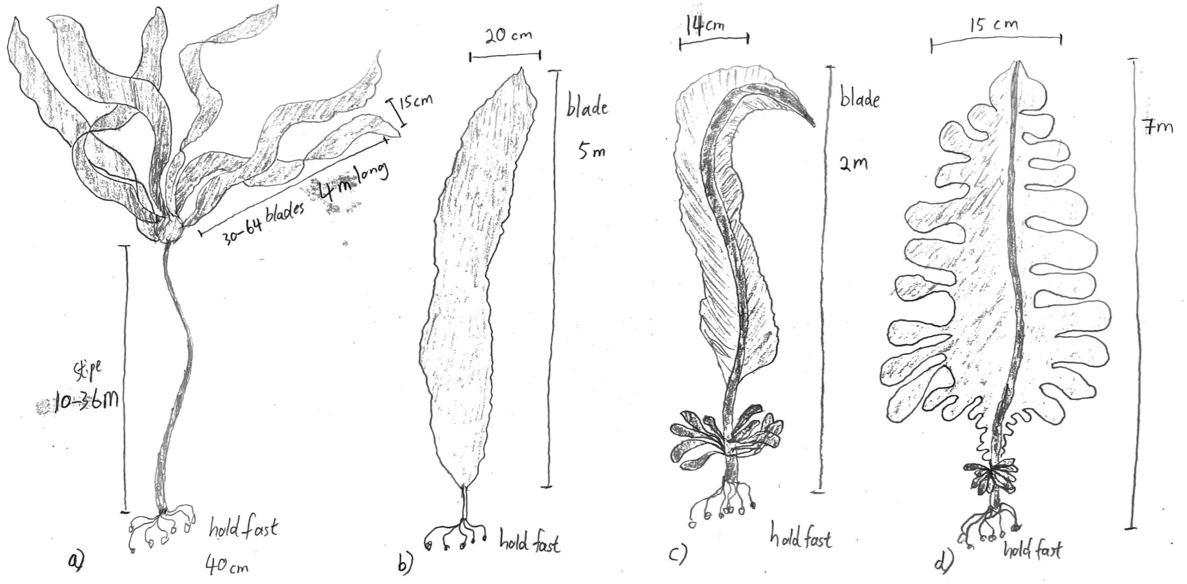


Figure 6. (a) Nereocystis luetkeana/Bull kelp, b) Saccharina latissimi/Sugar kelp, c) Alaria esculenta/Winged kelp, d) Saccharina japonica/ Kombu kelp

Ultimately the selection of a particular species of kelp for the kinetic energy capture subsystem requires a match to the location of WEC deployment/Con-ops. Table 2 is a summary of example selection data generated for each species of common farmable kelp. It is noted that the common location is the key for selection. Looking at the approximate growth rate data, it is not difficult to understand why. Through natural selection, each species of kelp has adopted to their specific climate region. Natural growth factors such as nutritional content, exposed solar intensity, and common sea wild life all play a critical role quick growth and successful reproduction. The prototype KOFE WEC intends to leverage those same reasons that nature selected them for successful reproduction, for successful kinetic energy capture and transfer.

Table 2. Kelp Comparison

Kelp Species	Number of Blades/stems	Length (m)	Width (cm)	Area/blade (m^2)	Common Location	~Growth rate (cm/day)	Sources
Nereocystis luetkeana Bull kelp	30-64	4	15	0.6	Pacific Coast USA	25	(Schoch and Chenelot 2004)
Saccharina latissimi Sugar kelp	1	5	20	1	Mid Atlantic USA	4.9	(National Oceanic and Atmospheric Adminstration 2023)
Alaria esculenta Winged kelp	1	2	14	0.28	North Atlantic Europe	0.7	(MarLIN and Assoication 2006)
Saccharina japonica Kombu kelp	1	7	15	1.05	Yellow Sea Asia	30	(Alina Furniturewalla 2023)

C. STRUCTURAL SUPPORT SELECTION

Along with other structure requirements of climate survivability, marine life survivability, ease of installation, supports kelp reproduction, and low cost, The WEC structure also serves the function of transferring the kinetic energy from capture sub system to power take off sub system. To initiate the available market research with initial selection, the low cost and ease of installation requirements are used to first categorize the fundamental principle of the KOFE as a net energy positive WEC. The mooring cost associated with a design is found to be directly related to of installation cost and complexity. The prototype KOFE WEC is designed to be categorized as

> Buoyancy–inertia self-referencing. The vertical acceleration in a wave is in anti-phase with the elevation; consequently, many machines have been designed with a buoyancy component reacting against an inertia component. This has the advantage that the whole system is self-referencing and can therefore move with a large storm wave, requiring only a compliant (and relatively low-cost) mooring system to keep the machine roughly on station. (Greaves 2018, 74).

To further simplify the KOFE system design, for reduced life cycle cost, the Buoyancy–buoyancy self-referencing category of WEC was targeted. B-B self-referencing differentiates from B-I self-referencing due to the fact that the buoyancy components of WEC react against each other. This results in an additional design requirement that different parts of the WEC to be located in different parts of the wave. This new requirement is fed back into the WEC structure subsystem digital model.

With the new updated requirements, some existing commercial kelp farming systems were examined for their ability to convert to a B-B self-referencing WEC.

Figure 7 is a representation of the simplest farm design. Adam and St-Gelais designed their system for simplicity and reduced cost. A single farm line is used with chain mooring at either ends for anchor. The farm line is slightly submerged in order to help with storm wave survival in the North East Atlantic. For this design to work as a B-B self-referencing WEC, the length of the line would need to be optimized for the wave length of the target wave, and different ends of the anchored line would need to be kept in different parts of the target wave. As a proof of concept, this seems achievable. The downside of this single line design is that it is not optimized for kelp growth vs. deployment area.

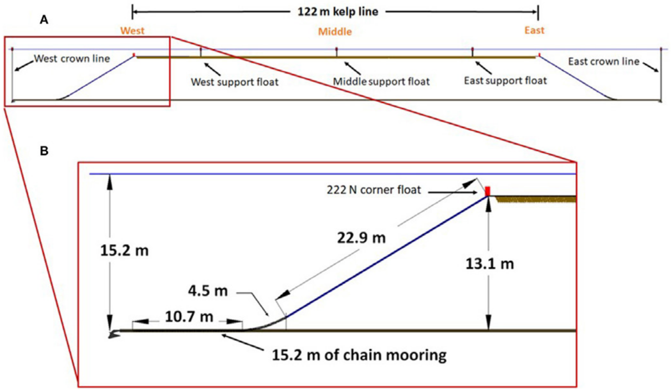


Figure 7. Single line low cost kelp line design. Source. (St-Gelais 2022).

Expanding beyond the single line design, Figure 8 depicts additional available designs that further optimized for kelp growth area vs. installation simplify. These designs still share the commonality that farm lines are used for kelp reproduction. The differences in the designs revolve around number of available farm lines vs. smallest modular installation.

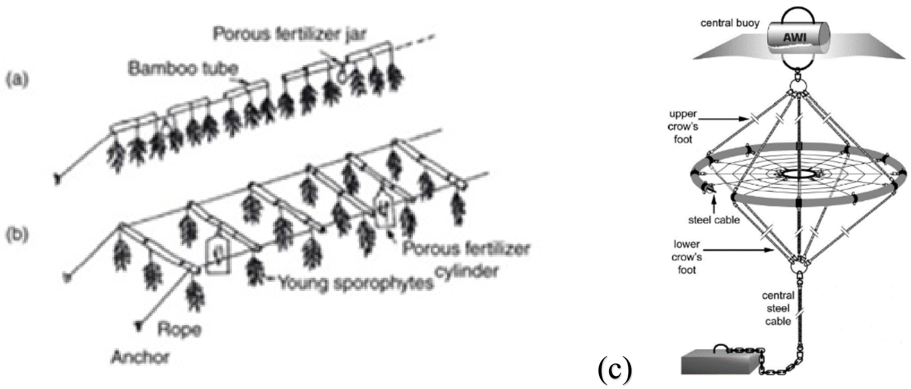


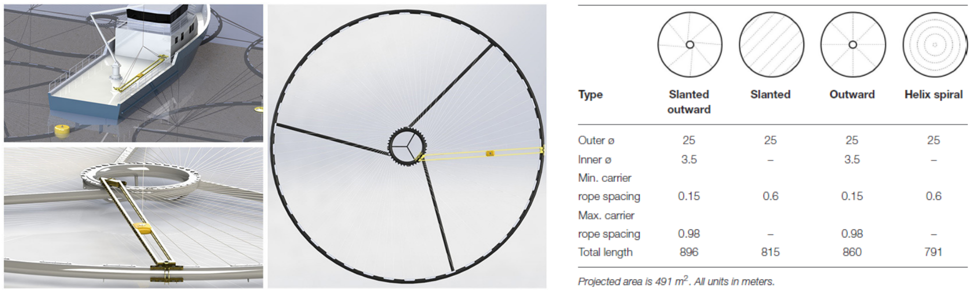
Figure 8. Traditional single line farming, b) expanded double lined ladder farming method, c) Ring carrier design. Adapted from Su (2017) and Buchholz (2004).

For the prototype KOFE WEC structure selection, two main assumptions are made:

1. It is fundamentally possible to treat a single line with kelp growth as a B-B self-referencing WEC.
2. WEC mooring numbers are directly tied to installation simplicity and cost.

Torfinn and team attempted to conduct an optimization of the circular farm design in their 2021 study. Line patterns and spacing were optimized vs. kelp available growth area and available light, calculated by PAR given the structure geometry.

Figure 9 summarizes their findings. Torfinn and team chose to further pursue the slanted outward model for automation design, due to the fact that this line pattern resulted in the longest total line length. This circular design is intended to be a single moored installation similar to that of the Buck design in Figure 8c.



Type	Slanted outward	Slanted	Outward	Helix spiral
Outer ø	25	25	25	25
Inner ø	3.5	–	3.5	–
Min. carrier rope spacing	0.15	0.6	0.15	0.6
Max. carrier rope spacing	0.98	–	0.98	–
Total length	896	815	860	791

Projected area is 491 m^2. All units in meters.

Figure 9. Photosynthetically active radiation (PAR) and Macroalgal cultivation is area. Adapted from Torfinn (2021).

In-order to convert the Torfinn designs into WEC, the line length needs to be variable vs. target wave length. A complex automated system can be designed to adjust the line length of the Slanted outward design by rotating the center core as response to incoming wavelength. For prototype development, the Slanted design would offer advantage of prepositioned variable line length without the complexity of added automation for line length adjustment. The disadvantage of the Slanted design is obvious. The efficiency of the energy harvested is not optimized to the incoming wave. However, as an initial prototype for system functional feasibility, design simplicity was part of the concept selection. This parameter could be associated to the sub system low cost requirement. The circular WEC structure with slanted line patterns was selected for the initial KOFE prototype design.

D. POWER TAKE OFF SELECTION

The Power Take Off is the primary power conversion subsystem for the KOFE prototype as defined by the digital model. The high level PTO power conversion functional requirements include the need to physically fit in the WEC structure and generate positive energy. Given the previous selection of the B-B self-referencing WEC structure design, the PTO power conversion subsystem will need to covert linear motion, kinetic energy, transferred from the kelp farm line to electrical energy. This linear motion defines the search boundaries for an existing power conversion PTO. This refines the energy generation requirement. Aside from these functional requirements, general PTO subsystem requirements of survivability, cost, and availability as defined by the KOFE WEC digital model still apply and were converted into selection criteria, if functional requirements were met.

The state of the art in motion to electrical energy conversion research is conducted on the materials level. More specifically, triboelectric nanogenerator (TENG). These nano scaled energy conversion devices are created with piezoelectric material which during mechanical movement, generate electron movement between the cathode and the anode. Mechanical forces normally compression or tensile applied to a solid surface, and the resulting electrical energy pass to an energy storage medium. In general, TENGS have higher instantaneous output power, responds to quicker transients, durability, and customizable selection of materials. (Weon-Guk Kim 2021)

Research currently exists to design WECs based on TENGS. Figure 10 describes a modular network of TENG WECs. Ning and team modified the physical shape of the TENG material into shapes inspired by natural kelp blades. As the blades rotate and vibrate in flow, electrical energy was generated. Ning and team were able to demonstrate an output current of about 10 μA and voltage of 260 V can be given by a single unit. These levels of low power density also highlight the disadvantage of TENG based PTOs. TENG base PTOs are better suited for vibrational energy conversion on the $\mu W \cdot cm^{-2}$ level.

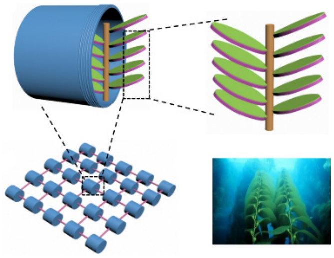


Figure 10. Kelp inspired TENG. Source Ning (2019).

One of the design objectives of the KOFE WEC is to produce usable energy and serve as an operational platform for external systems, such as communications, GPS, UUV refuel, etc. Influenced by this objective, other COTS energy conversion PTOs are investigated, especially for higher power production. Linear alternators were considered. A linear alternator is commonly used to convert back-and-forth motion directly into electrical energy. This back-and-forth motion approximates the anticipated motion of the farm line from the WEC structure.

Figure 11 represent a cross sectional drawing of a permanent magnet linear alternator design originally published by Famaouri and team. The moving piston attached translator would be attached to the WEC structure line in-order to generate power. Linear alternator designs heavier depending on the magnet; the size of the generators is upwards of hundreds of kW with large enough magnet (Mainspring Energy 2023). The disadvantage of using a linear alternator is directly tied to the cost of the magnets, raw minerals. Current available commercial systems are tied to combustion engine systems, larger and more expensive for the current KOFE Structure. Current demonstrated COTS technology would be too big, physically, to operate within the KOFE WEC support structure.

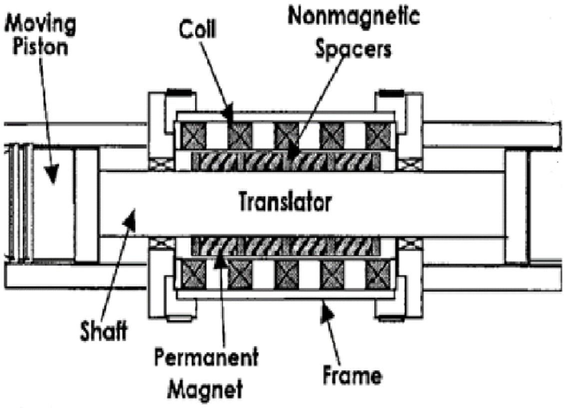


Figure 11. Cross Section of Permanent Magnet Linear Alternator. Source Famouri (1999).

Continuing the search through available COTS linear motion power conversion solutions, reciprocating linear actuators as power generators were investigated. Linear actuators convert linear force to rotational force differentiating from Linear alternators which traditionally eliminates the need for a rotary motion in-order to drive a rotary generator. COTS linear actuators are simple machines that rely on gears to convert force to energy. Affordable COTS products exist at multiple sizes and power levels.

Figure 12 is a COTS list of available linear actuators highlighting customization and simplicity of the system. This design simplicity is directly reflected in the production cost. An example of these COTS linear actuator performance is pulled into Table 3. For an application in KOFE WEC PTO subsystem, the stroke length can be tailored to the push/pull force, to be determined through experimentation. Differential gear boxes can be added to increase the rpm per linear pull/push.

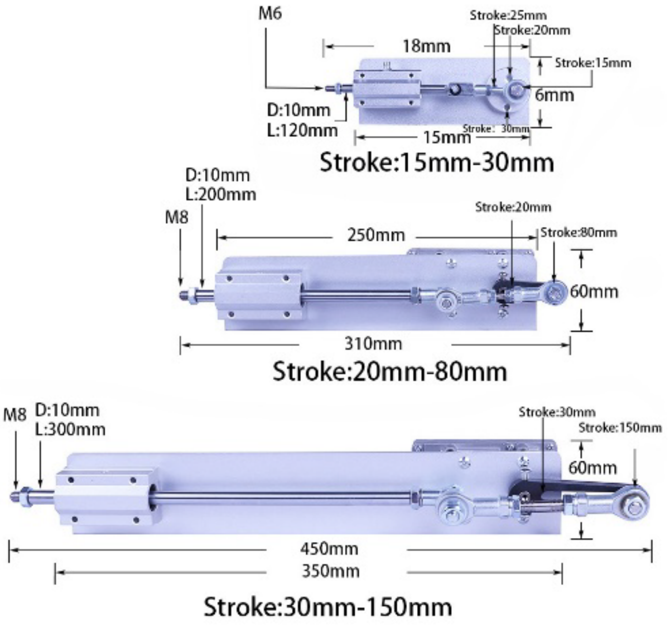
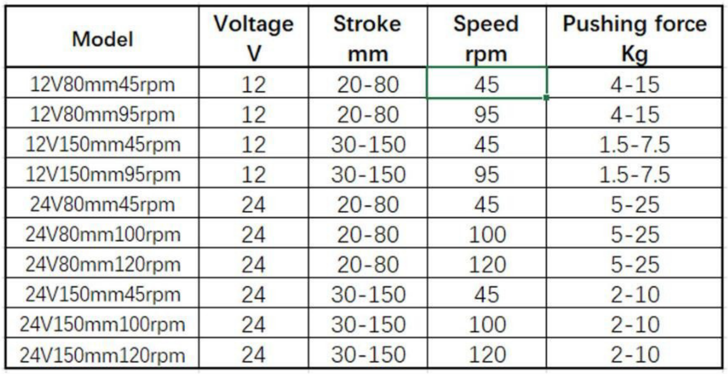


Figure 12. Commercial off the shelf linear actuators. Source RobotDigg (2023).

Table 3. Table of Commercial off the shelf linear actuator performance. Source RobotDigg (2023).



Model	Voltage V	Stroke mm	Speed rpm	Pushing force Kg
12V80mm45rpm	12	20-80	45	4-15
12V80mm95rpm	12	20-80	95	4-15
12V150mm45rpm	12	30-150	45	1.5-7.5
12V150mm95rpm	12	30-150	95	1.5-7.5
24V80mm45rpm	24	20-80	45	5-25
24V80mm100rpm	24	20-80	100	5-25
24V80mm120rpm	24	20-80	120	5-25
24V150mm45rpm	24	30-150	45	2-10
24V150mm100rpm	24	30-150	100	2-10
24V150mm120rpm	24	30-150	120	2-10

The reciprocating linear actuator for power generation seems to meet all the functional and general requirements of the KOFE WEC PTO. Anticipating the need to improve the power conversion for push and pull forces, mechanical springs help improve the pull forces vs. push forces exerted by the moving wave. This use of the spring was already demonstrated in existing designs.

Figure 13 depicts a VIVACE configuration design for linear to rotational force conversion by Bernitsas and team in 2008. The spring wrapped around the bearing magnifies the linear force and increases rotational force conversion.

The reciprocating linear actuator for power generation could benefit from this spring feature and increase the functional performance of linear wave energy conversion. This combined subsystem could be better suited for the KOFE WEC PTO.

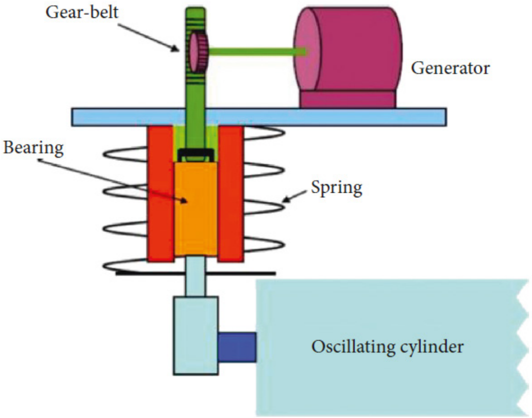


Figure 13. The VIVACE configuration for converting linear force to rotational force. Source Bernitsas (2008).

E. ENERGY STORAGE SELECTION

For the KOFE WEC energy storage subsystem, a combination of battery and capacitors could be hybridized for power and energy storage. The added functional requirement from the digital model includes efficient storage of power and energy converted from the PTO. General requirements of safety, survivability, durability, and inexpensive manufacturability were converted to selection criteria. In other WEC examples where the position of the WEC is closer to shoreline, the energy storage subsystem can be omitted. Those PTOs would be hard wired to the shore electrical infrastructure. The usage condition of the KOFE WEC is long endurance missions at open water locations off the cost. Given this, a dedicated energy storage system would be essential for providing power and function to additional external systems, such as communication, GPS, UUV recharging bay, etc. Given existing safety concerns of Li-ion batteries and approval process tied to Navy usage of Li-ion batteries, the initial KOFE WEC energy storage subsystem would prefer to start with a non-lithium solution.

Anticipating variable power from the PTO, and KOFE design objective of supporting long endurance missions, the KOFE WEC energy storage system need to be high power capable and high energy dense. An originally hybrid energy storage architecture was designed at Naval Surface Warfare Center Carderock Division (NSWCCD) by James Mulford, Kevin Lin, and Thomas Jiang (Mulford 2022). Associated technology patents are in submission, owned by the Navy. Electronic command and control with commercial components intended to efficiently load and or store high frequency power with low rate high energy density storage technology. In the most basic sense, the hybrid system manages sending power to one load from one power source. The battery handles baseline and steady-state loads while the supercapacitor's output remains off. When a sharp increase in load demand occurs, the battery's output is switched off and the supercapacitor's output powers the entire load. Only when the load demand returns to steady-state does the hybrid system switch from supercapacitor to battery power. There is a small amount of current sharing during the transition between the battery and supercapacitor, but ultimately only one source is supplying power to the load at a time.

The schematic in Figure 14 reflects the as-built test bed in the Power Systems Experimentation Laboratory (PSEL) at NSWCCD. Note that Power Supply #1 is the principal source of electrical energy for the Hybrid System, which powers the electronic motor speed controller and its 3-phase brushless motor (a high-transient representative load) as well as charges the supercapacitor array. Power Supply #2 solely serves as a low-current 10 VDC source for the supercapacitor charger's PWM MOSFET driver board (for proper operation). Three high-impedance decade resistor dividers serve to monitor voltages at Power Supply #1, the supercapacitor array, and the load input, while four Hall effect current sensor boards observe the current flowing at those points (in addition to the pulse-width modulated charging current to the supercapacitor array). An Arduino Mega2560 serves as the host controller for the follow list of sub components; voltage sensors, current sensors, and the LTC4355 ideal diode-OR integrated circuit.

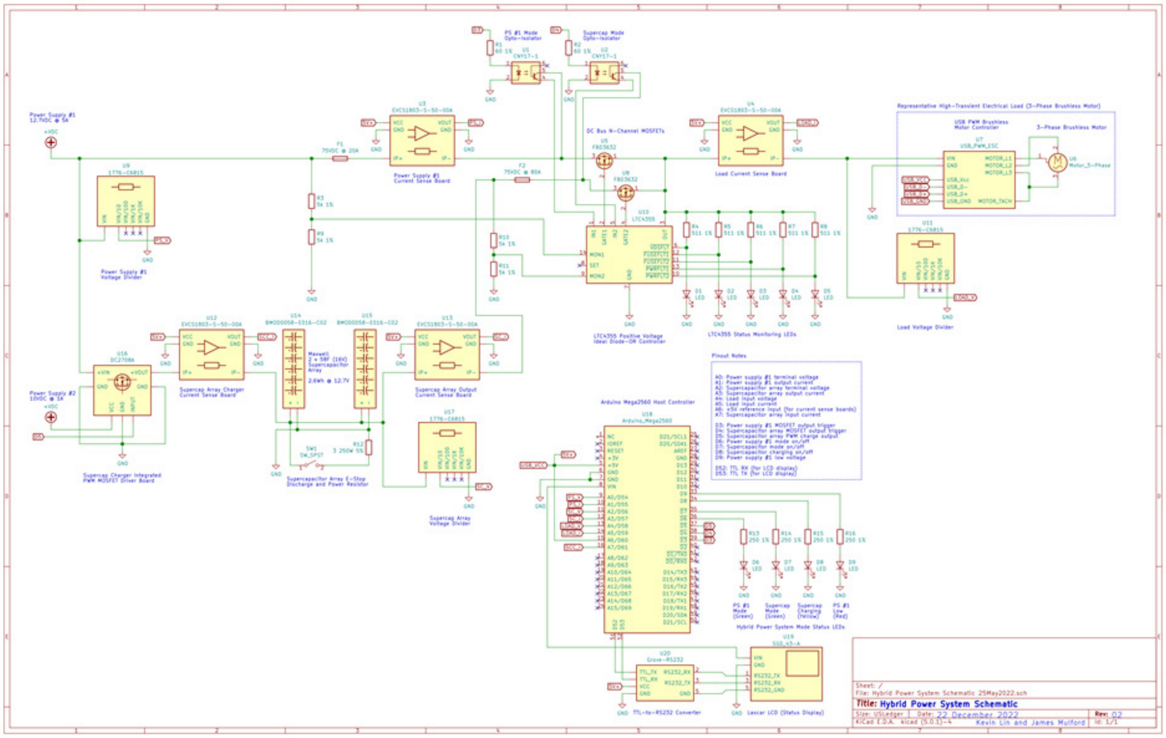


Figure 14. NSWCCD Hybrid System Electrical Diagram

Battery, supercapacitor, and load voltages are measured by the microcontroller through high-impedance decade resistor dividers, while currents are measured through scaled voltage outputs from the Hall effect sensor boards. As previously mentioned, a MOSFET driver board is placed between the battery and supercapacitor to provide isolation and control supercapacitor charge current. Through the hybrid system's software, empirically-derived PWM duty cycles are sent to the driver board, which then applies the averaged voltage value to the gate pin of a 5A MOSFET. As voltage increases on the supercapacitor array, so does its effective impedance on the main power supply, necessitating the charging MOSFET to be turned on for longer periods of time. In response, the system's software will send higher duty cycles as the supercapacitors' voltage increases. Figure 15 shows the hybrid system control layout with the LTC4355, battery and supercapacitor output MOSFETs, and Arduino Mega2560 at the heart of the system.

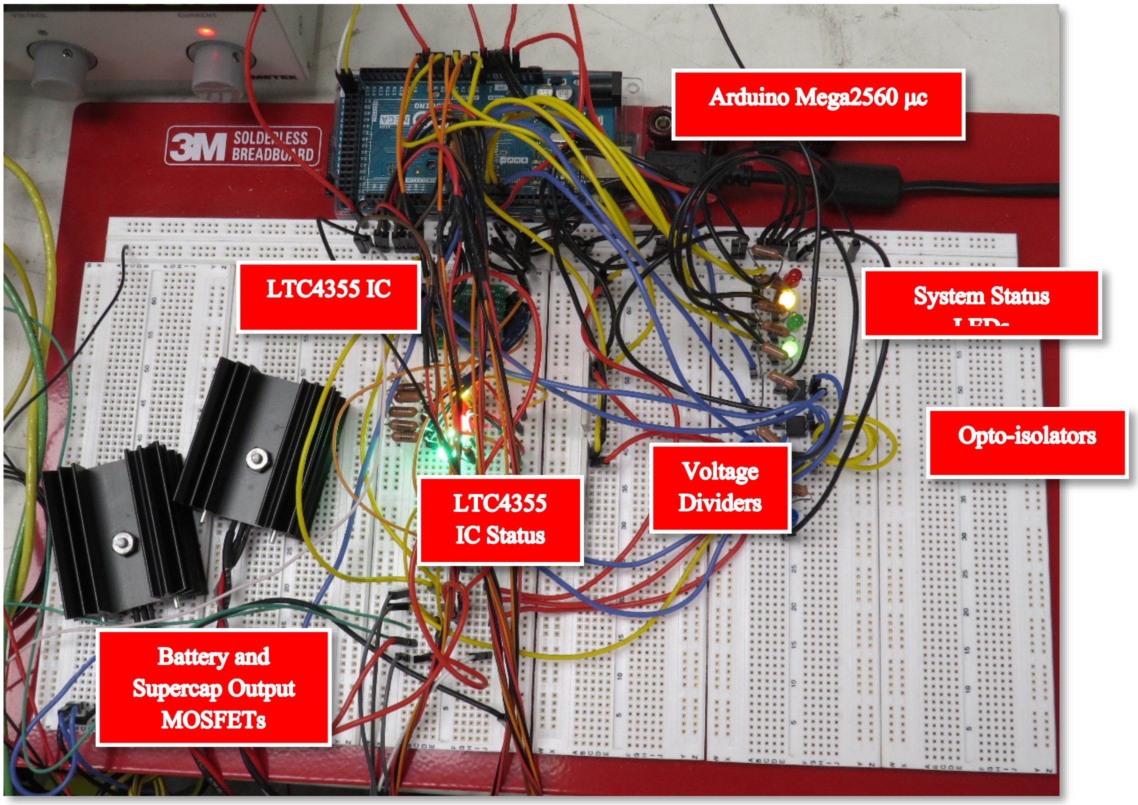


Figure 15. NSWCCD Hybrid System Control Layout

The system pinout of the microcontroller is shown in Figure 16. When a sudden spike in the load current occurs, as read by A5, the LTC4355 is triggered to switch to the supercapacitor. The supercapacitor on-time can be adjusted as needed for other loads and power sources. Pins D3 and D4 connect to the LTC4355 and signal to the IC when to switch between the battery and supercapacitor. Pin D5 sends a variable duty cycle PWM square wave to the supercapacitor charge MOSFET driver board. Four status LEDs are triggered by pins D6-D9 depending on their corresponding MOSFET's ON or OFF states. For situational awareness, pins D52 and D53 send pertinent data to the custom LCD in shown in Figure 17.

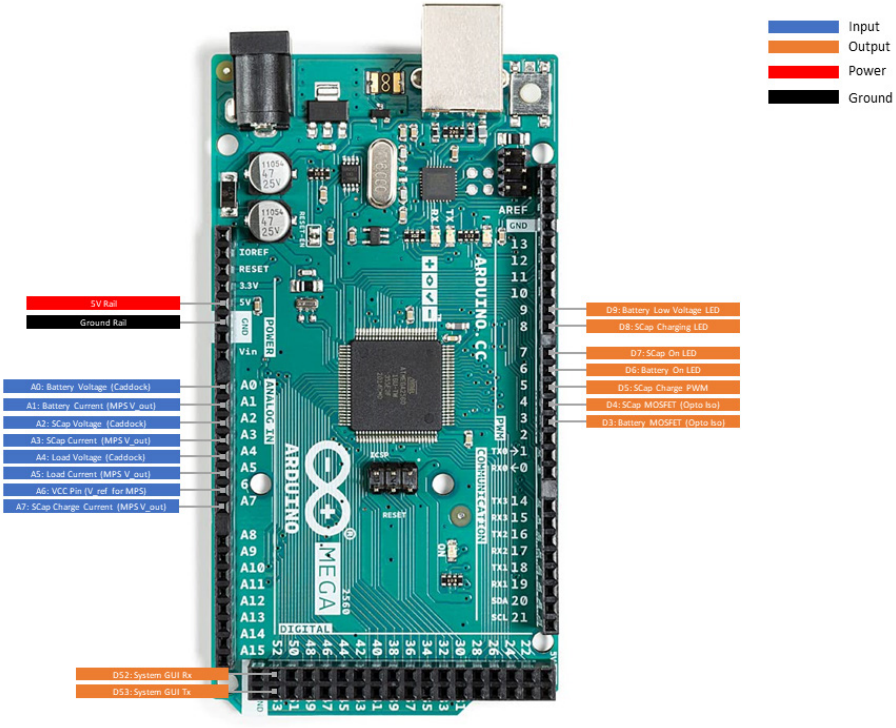


Figure 16. Microcontroller (Arduino Mega2560) Pinout

Figure 17. Hybrid System LCD (Top Left: System Idle; Top Right: Supercapacitor Charging; Bottom: Supercapacitor ON)

The characterization of the hybrid system test bed revealed positive attributes and limitations of the system's architecture. The limitations should be addressed in fielded applications, which are further discussed in Hybrid design report (James Mulford 2022). The average switching time through demonstration between the battery and supercapacitor was an average of 456 µs. Chosen as the KOFE energy storage system the NSWCCD hybrid system's peak power can be tailored to the anticipated peak wave power. This energy storage solution has the added benefit of technology patents already owned by the Navy. This selected KOFE energy storage subsystem meets the functional requirement of energy storage and all general requirements of safety, survivability, durability, and inexpensive manufacturability.

F. MATHEMATICAL COMPUTATIONAL MODEL FOR POWER AND ENERGY PREDICTION

The proposed KOFE WEC would use lines populated with kelp in order to capture and transfer the power of offshore waves. This design is intended to be based on buoyancy–buoyancy self-referencing wave energy capture. The secured ends of each farm line is intended to be positioned in different parts of the wave. The theoretical optimized design is to match farm line length to the length of the propagating wave. It is understood that the initial KOFE WEC will be designed with different farm line length with the purpose of adjusting variable propagating wave lengths during long duration missions. Attempting to simplify the theoretical calculations for energy and power, a single farm line can be approximated as a traditional line absorber device. For fundamental approximations of available wave energy after a deployment location has been selected, basic energy and power equations based off of Simple Wave Theory were used. Available average energy is determined with equations (3), derived from equations (1) and (2).

$$Total\ energy\ (E) = potential\ energy\ (E_p) + kinetic\ energy\ (E_k) \tag{1}$$

$$E_k = E_p = \frac{1}{16}\rho g H^2 \lambda \tag{2}$$

$$\overline{\mathrm{E}} = \frac{E}{\lambda} = \frac{1}{8}\rho \mathrm{g} \mathrm{H}^2 \tag{3}$$

where:

g = the acceleration of gravity

ρ = the mass density of sea water

H = the vertical distance between crest and trough of the wave

To assist the design of the PTO and energy storage, the wave power also needs to be approximated for a given deployment location. For wave power, the incident wave power, P_{inc}, is approximated using regular wave equations in deep water. For deep water, assumptions are made that waves are unaffected by depth, and have little or no influence on the seabed. Wave period numbers can be used to determine other propagating wave parameters such as celerity and wavelength. Average Power is determined with equation (4).

$$P_{inc} \cong H^2T \tag{4}$$

where:

T – the period of the wave

Research has been conducted on existing line absorber systems where the theoretical capture length for a line based on hydrodynamic of wave energy conversion has been determined to be limited by heave motion alone. Table 4 captures the findings from Rainely RCT, based off of the Pelamis WEC in 2001.

Table 4. Theoretical limits to capture width. Source (Rainey 2001).

		Heave
Line absorber	Offshore	λ/2 (L = λ) 3λ/4 (L = 2λ)

To fully characterize the contribution of the entire kinetic energy capturing subsystem, and to understand the parameters of the kelp biological structure that impacts the force transfers to the PTO, approximate pull force calculation need to be conducted. As a first step to approximate the theoretical force produced to inform PTO selection, the Morison equation is used. Equation (4)

$$F = \rho C_M V_a + \frac{1}{2}\rho C_D Au\,|u| \tag{5}$$

where:

F – Force

C_M – inertia coefficient

C_D – drag coefficient

V_a – Volume of the structure

Au – Area of the cross-sectional perpendicular to the flow direction

All of the variables from the Morison equation should be determined experimentally. This is part of the tailoring process of the PTO and farm line spacing for a prototype KOFE WEC given a targeted deployment location. In lab measurements and approximated after a species of kelp has been selected could be designed to produce a data distribution for each variable as a parameter. Experimentation could be done in partnership with a local commercial kelp farm. Standard force meters such as the OMEGA High Accuracy Digital Force Gauge model: DFG55-50, could be used to measure the total force of existing kelp populated farm lines. This force data along with measured kelp growth density per line, and line length could be used directly for a KOFE PTO selection if the commercial kelp farm shares the same location as the KOFE WEC targeted deployment location.

Due to time and scope limitations of this feasibility design study, a realistic case study was not conduced and real parameters of the biological kelp kinetic energy capturing subsystem was not measured. However, the equations laid out in this section would be used to conduct the power and energy approximations necessary for tailored configuration of KOFE structure, PTO, and energy storage system to any deployment area. For future work and extension of the fundamental calculations, a detailed computational fluid dynamic (CFD) model can be created for KOFE WEC. Detailed modeling can be expanded to arrays of WEC and access the feasibility of increase modular stacking as a method to increase power production. Increased power production could directly increase the usability of connected external system to be powered by a KOFE WEC network. It is predicted that a biological based network would scale upward and demonstrate greater local environmental, cost, and infrastructure benefits.

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IV. KOFE WEC PROTOTYPE I

This chapter describes the KOFE WEC Prototype I as a full concept system that can provide capability to the Navy. This thesis demonstrates the KOFE WEC Prototype I as an innovative conceptual design through the sum of its subsystem successes. Deployment parameters and experimentation parameters were highlighted for future configurational testing. An affordability assessment was conducted with an initial bill of materials generated in support of KOFE WEC Prototype I. Expected benefits and limitations were highlighted, including directions for future development reiterations for prototype II, III, and Final.

The KOFE WEC Prototype I design is a sum of subsystem selections. The initial WEC system digital system model included objectives revolved around long term operations at an affordable life cycle cost. With those parameters in mind the KOFE WEC Prototype I concept is intended to demonstrate simple component level subsystems for manufacturability, ease of maintenance, deploy and operations. Ultimately, the KOFE WEC concept system is intended to provide locally sustainable power for increased Navy capabilities. With a fully functional and deployed KOFE WEC systems around major cost lines especially areas of warm waters, optimized for increased kelp growth rate such as those conditions near the Pacific Islands, The Navy would have a new source of sustainable local logistical energy. This could directly support missions such as long endurance UUVs, glider, sensors, and provide refueling energy for diver systems.

Figure 18 represents an artistic rendering of the KOFE WEC Prototype I concept from the top down view. Colorations in the diagram follow that of the digital model. Support structures colored in grey, biological kinetic energy collectors represented in green, and PTO with energy storage subsystems colored in brown. At this top down view, it clearly depicts the circular main body and support structure of the prototype I. The farm lines are meant to house kelp growth pods which over time grow to fill the space between each line. The distance between each line and length of each line will depend on the target deployment location. From the energy and power prediction section, it is noted that the upper limit and optimized length for a linear absorber to capture the heave motion is related to the λ wavelength of the propagating wave. Depending on deployment need, the farm line length of prototype I will be at maximum 2λ. This parameter can also be the approximate max diameter of the circular support structure, resulting in a modular prototype I that is circular with a max diameter of 2λ. PTOs are designed to be attached to each end of the farm line. This design reduces the distance for energy transfer, as a result increase energy transfer efficiency. With smaller PTOs distributed across the entire prototype support structure, it would be possible to track energy collection efficiency of different farm lines vs. wave condition and kelp growth. This data could be very useful in future design iterations targeting optimization of these parameters to increase power and energy generation.

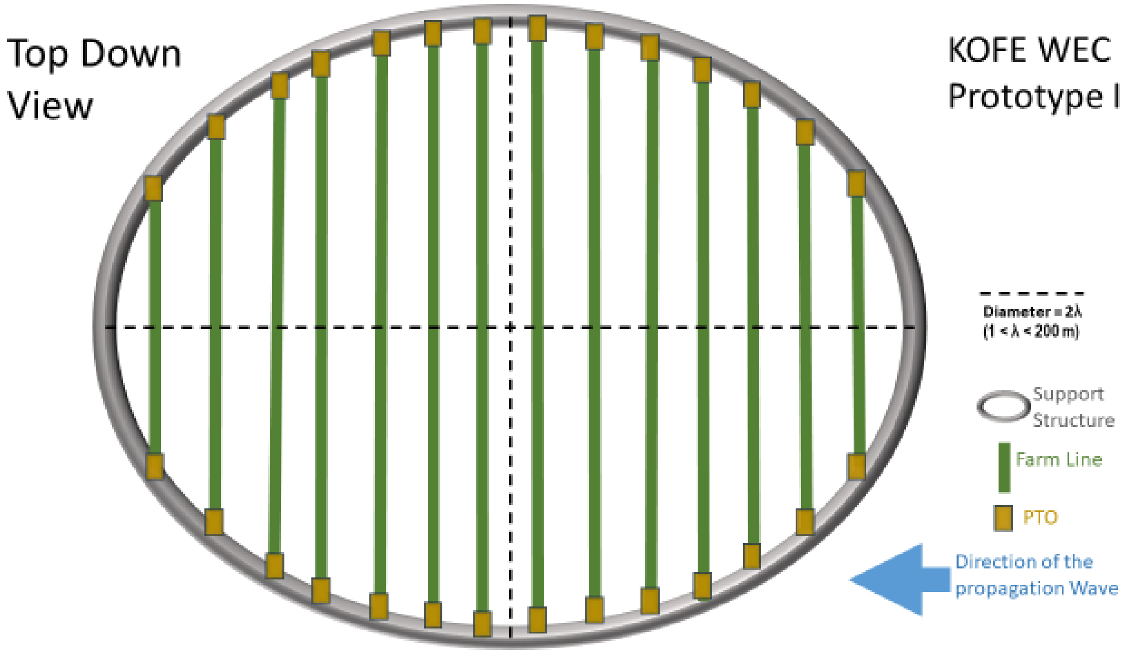

Figure 18. Artistic Rendering of KOFE WEC Prototype I (Top Down)

It is noted that the KOFE WEC prototype I is also designed as a proof of concept and testbed for future reiterations. Aside from the main floating structure pictured in Figure 18, the KOFE WEC prototype I has additional subsystem closer to the sea floor. Figure 19 depicts envisioned KOFE WEC prototype I as deployed in open water conditions. Floating buoyancy buoys can be secured to circular support structure as an additional means of buoyancy adjustment. The black dotted lines represent mooring chains which anchor to the sea floor. This anchoring method can be as simple as possible to reduce deployment cost and material cost. The mooring chains could also very depend on wave conditions of target deployment locations. Maximum drag of the KOFE WEC system can be calculated and match to the minimum tension requirement of mooring chains. This could further replace heavy metal material with synthetic ropes which meet the design requirement. The energy storage subsystem of KOFE is designed to be between the main floating structure and anchor. This purposed separation of space increases the safety of the energy storage subsystem while providing potential cooling and compression benefits from locating at great depth.

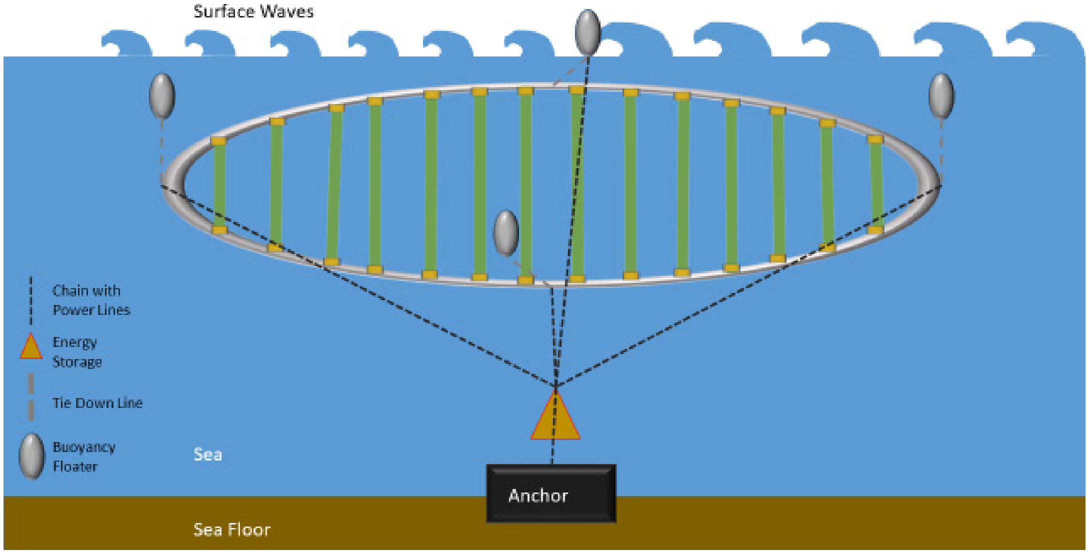

Figure 19. Artistic rendering of KOFE WEC Prototype I deployed in open water

For a better depth understanding of each subsystem with respects of the water line, Figure 20 was generated. The KOFE WEC prototype I is pictured to be deployed parallel to the water surface. The main circular support structure is allowed to sink and rest 2 meters below the water surface. This distance below the surface was also selected by St-Gelais and team during their kelp farm design in order to increase the survivability of the farm during extreme weather conditions in the North East Atlantic (St-Gelais 2022). The KOFE WEC prototype I farm lines are designed to be located just below the support structure connected with PTOs. Overtime kelp growth will fill the space underneath the circular support structure, represented by the green colored band in Figure 20. Deep water wave motion is depicted by circular rolling arrows, unaffected by the sea floor, and passes through the green kelp growth. As kelp growth picks up energy from the moving waves, they will transfer to the farm lines then convert to electricity by the local PTO. Electrical lines that trace the mooring lines carry the energy from PTOs to the single hybrid energy storage system located deeper underwater. In the event of catastrophic failure of the energy storage system, the damage will be contained to deeper waters. This design feature is intended to separate any hazards related to a stored energy source away from the main support structure, increasing serviceability and reducing maintenance cost.

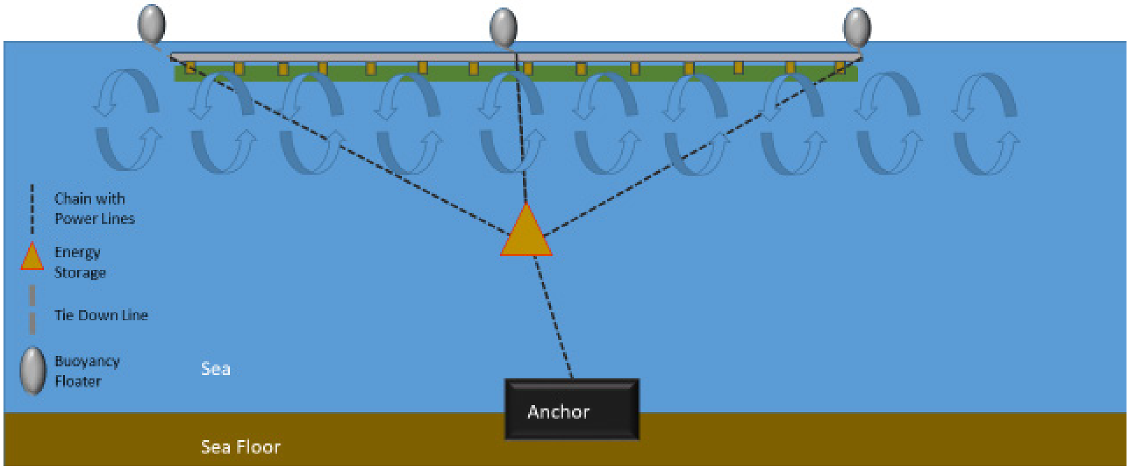

Figure 20. Concept rendering of KOFE WEC Prototype I deployed parallel to the water surface.

To better understand the KOFE WEC prototype I cost, a bill of materials (BOM) was generated, Table 5. Materials are identified and associated to each subsystem, however, quantities are not defined. Due to the customizability of prototype I to deployment location, the specific material quantities will vary.

Table 5. KOFE WEC Prototype I Bill of Materials

Subsystem	Materials	Description
Kinetic Energy Collector	Nylon Rope	Farm line and floater line
	kelp seeded fertilized pods	Farm starter
Support Structure	HDPE Ring	High-density polyethylene floating ring, main KOFE circular support structure, thickness tuned to WEC physical size
	buoyancy floaters	Cable Floats used to adjust the total system buoyancy, keep the farm lines below the water surface
Power Take Off (PTO) Energy Storage	reciprocating linear actuator	COTS hobby shop Linear actuator / generators, to be positioned at each ends of the farm line
	electrical wiring	connect PTO to Energy Storage
	Arduino Mega2560	Host microcontroller for hybrid control
	Arduino Micro	Host microcontroller for testing MOSFET PWM driver
	Analog Devices LTC4355	Positive voltage ideal diode-OR IC for battery and supercapacitor
	Texas Instruments 60V/ 105A TO-220 MOSFET	MOSFET for battery and supercapacitor output; MOSFET for supercapacitor charging
	Chip Quik Inc. DFN-14 to DIP-18 SMT Adapter	Board for mounting LTC4355 IC
	Maxwell 16V 58F Medium Cell Module	Supercapacitor Module
	Analog Devices LTC7001 Gate Driver	MOSFET PWM Gate Driver for Supercapacitor Charge
	MPS Linear Hall-Effect Sensor	Current Sense Board
	Cegasa Zinc Air Battery	example of non-lithium battery Zinc Air Array

A quick analysis of the BOM shows that most of the materials are readily available through various large common distributers such as, Amazon, Walmart, AliExpress, etc. Certain electronic components such as MOSFETs and chips will need to purchase from specific digital component stores. However, these are common enough that cost and supplies are acceptable for system builds. The only specialized material less common to everyday consumers or hobbies, was the fertilized kelp seeded pods. Specific costs are related to species and availability within the targeted deployment location. This is accounted for within the total system design. The envisioned system level cost savings would come from a mix of cost sharing with potential local existing kelp farms and profit from excess kelp production over the growth cycle of the specific kelp, ~6-12month. Given these data, the KOFE WEC prototype I could be produced at for as low as $1000, while generating usable energy and a yearly profit from kelp sales. Overtime the system could recuperate the cost of the initial build and contribute to supporting system life cycle maintenance cost.

The KOFE WEC Prototype I as the first of its concept, is not without limitations. One of the limitations of such a system is the dependence on subsystem charge transfer efficiency following the digital energy transfer model described in chapter three. As efficiency decrease across physical system boundaries, it will directly reduce the overall KOFE WEC system efficiency. One obvious deployment limitation is the delay between initial deployment, kelp seeded, vs. full deployment, fully grown kelp. This will impact the amount of energy harvested over the period of initial deployment to full deployment. Fully deployment time could vary depending on kelp species and ocean conditions, six to 12 months. Other deployment limitations will depend on the location environment. This system may reduce local ocean surface area, currently designated as ship lanes or for recreational activities. Additional environmental impact studies would need to be conducted on specific locations of intended deployment. It is expected that similar environmental benefits as operating kelp farms should transfer directly over to KOFE WEC systems. Energy stored overtime under the surface would power external systems, with interface still to be determined. Future reiteration of the KOFE WECs, (Prototype II, III…etc.) could attempt to explore the options of intelligent farm line length adjustment vs. real propagating wavelength data.

V. CONCLUSION

In conclusion the KOFE WEC Prototype I is a complete system that demonstrated the conceptual framework of novel WEC with subsystems designed from cross industry technology. This novel WEC contains an architecture that leverages the biological advantages of naturally regenerating resources, kelp, while delivering the intended stakeholder need of electrical energy harvested in open ocean. Throughout the system design, a full system perspective is tracked through requirements and utilization of the digital system engineering model. This integration of MBSE early into the system development simplified the selection criteria and focused each subsystem development around the minimal functional needs as defined by traditional WEC industry. The end result is a Navy WEC that has the potential for low life cycle cost, mass fielding, and added electrical energy generation capability. Each subsystem leverages technology that are already COTS demonstrated or developed from Navy owned IP. The KOFE WEC system can be tailored to all costal deployment area that already sustains natural kelp growth and serve as a modular power and energy platform for external system.

Future prototype reiterations and development directions are identified through this KOFE WEC Prototype I subsystem development. The kinetic energy collector selection can parallel the kelp biological species selection vs. specific regions of water condition. This is a common practice of the agriculture community. The structural support subsystem can develop into a more automated system that would adjust the energy capturing line length depending on the real propagating wave data. PTO and energy storage subsystems could be tuned through experimentation at deployment conditions. The parameters of such an experiment would follow the variables listed through the linear wave theory. Force meters can be used to measure the resulting performance of individual actuator PTOs with energy storage. The collection of these improvements could be the next reiteration of KOFE WEC and further demonstrate the specific capabilities of biological based KOFE WEC systems as an energy production system for the future Navy.

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