Resilient and Sustainable Aquaculture with Advanced Wave Energy Converters

Written Report

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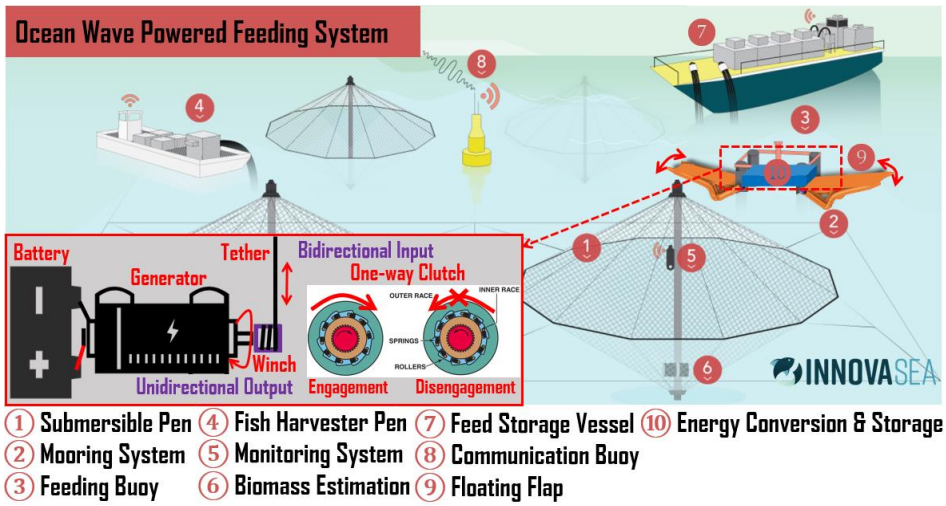
Marine Energy Collegiate Competition 2020

1. Executive Summary

The Columbia-Virginia Tech Alliance was assembled in late October 2019 with a simple and meaningful goal - to develop a business application for a sustainable marine energy technology. In the months that followed, the Team identified flap-type floating wave energy converters (WECs) to be one of the promising technologies. During interviews and surveys with marine energy experts, the Team found that the aquaculture industry is in need of energy security and sustainability. Hence the Team aims to integrate advanced power takeoff (PTO) into flap-type floating wave energy converters (WECs) and explore their potential market applications in aquaculture. In recent years, WECs have proven to be efficient at capturing and converting wave energy into a more useful form of energy for nearshore coastal regions. Significant progress in marine renewable energy has also been achieved at Virginia Tech during the past 10 years with the invention of the highly efficient PTO. By combining these efforts and developing an advanced WEC, we envision a resilient and energy sustainable aquaculture industry with self-managed, self-powered aquaculture farms in the near future. The values we bring to our aquaculture partners are not only cost savings from reducing the use of fossil fuels, but also energy resilience in the face of global energy fluctuations, reduced carbon footprint, fewer logistical concerns, and intelligent energy usage.



In this Written Report, we will examine the details of our Business Plan and Preliminary Technical Design. The Business Plan will start with a Concept Overview that describes the high level business case of our WEC application. Then the Global Market Opportunity will dive deeper into the problem and needs we are trying to solve and analyze the market potential for our WEC application. This is followed by Relevant Stakeholders which contains both our end users and other stakeholders including insights from interviews and surveys. Then in Development and Operations, we will explain our approach to research and development, manufacturing, deployment, financing and supply chain management, including potential risks and mitigation strategies. The Business Plan will end with our thorough Financial and Benefits Analysis, which examines our WEC application from both cost and potential revenue perspectives. Following the Business Plan is a detailed and graphical explanation of our Preliminary Technical Design. Incorporating the insights from our end user interviews, this section is to design and deploy a flap-type floating WEC system to power the feeding and monitoring systems of open ocean aquaculture platform, with goals of reduced cost, increased automation and reduced environmental impact for precision and clean aquaculture as shown in the above schematic diagram. By combining technology and business, we aim to develop a viable business application for WEC that will power our aquaculture industry securely, intelligently, and sustainably.

2. Business Plan

2.1 Concept Overview

The Columbia-Virginia Tech Alliance aims to integrate advanced power takeoff (PTO) into a flap-type floating wave energy converter (WEC) and explore their potential market applications in ocean aquaculture. By using the WECs to power the fish farming feeding and camera systems, the aquaculture companies can significantly reduce their diesel-related energy cost and increase their fish monitoring capacity. At the same time, as the WECs are hinged to existing platforms, the WEC installation cost can be significantly reduced and the environmental permitting process becomes more affordable compared to stand-alone WECs.

Based upon the experience of Virginia Tech in wave technology development and efforts of Columbia University students in market studies, we are developing an advanced WEC and envision a resilient and energy sustainable aquaculture industry with self-managed, self-powered aquaculture farms in the near future. Our business model replaces daunting conventional capital expenditures associated with renewable energy devices with manageable operational expenditures in the form of monthly installments. As we scale from early adoption to the majority market, we will pass down the cost savings from economies of scale to make our WECs more competitive with solar and wind energy devices. The values we bring to our aquaculture partners are not only cost savings from reducing the use of fossil fuels, but also energy resilience in the face of global energy fluctuations, reduced carbon footprint, fewer logistical concerns, and intelligent energy usage.

2.2 Global Market Opportunity

2.2.1 Problem & Needs

The concept proposed generates wave energy that can be directly used to power an offshore aquaculture farm which requires energy to power different aquaculture operations, for example, operating fish feeders, maintenance equipment, marine sensors, navigation lighting, etc. Currently, aquaculture farms mainly rely on diesel generators that visit the site daily to supply 60 kW of power over a maximum of 14 hours. According to the U.S. Department of Energy (2019), the power needs for aquaculture vary from 4 to 715 megawatt-hours per year depending on the size, location, and type of fish raising. The on-site energy generation proposed addresses the aquaculture market's need for self-sufficient offshore solutions that don't rely on external energy sources. In addition to cutting down fuel costs, the proposed system would eliminate the need for diesel transportation logistics and their associated cost. The diesel system also produces considerable emissions. A medium-scaled fish farm using diesel generators produces the same annual CO_2 emissions as 70 cars (University of Stavanger, 2017). Replacing diesel generators with renewable wave energy will help reduce the negative impacts of fossil fuels on the environment.

2.2.2 Target Market & Market Projection

The total addressable market for our WECs is the global aquaculture industry, which deals with the cultivation of aquatic animals or plants. Our serviceable available market will be the global industry of aquatic animals. The demand for fish and other seafood has been increasing in recent years due to rising middle-class income and growing demand for protein-rich aqua food. The production for aquatic animals has also been surging because of technological advancements (such as sensors, smart camera systems, and smart feeding systems) and favorable policies (MarketsandMarkets, 2019). According to Shah (2018) from BCC Research, global production is expected to increase from 90.8 million tonnes in 2016 to 126.0 million tonnes in 2022 with a 5-year CAGR (compound annual growth rate) of 5.9% (See Table 2.2.2.1). Asia has the highest per capita production of aquatic animals (16.2 kg per capita) and accounts for over 80% of global production. The global market is projected to increase from $163 million in 2016 to $226.2 million

in 2022 with a 5-year CAGR of 5.9% (Karen Shah, 2018) (See Table 2.2.2.2). Based on the interviews we did with the market stakeholders, the global market for offshore aquaculture (mainly on aquatic animals) will be our serviceable obtainable market. Offshore aquaculture, usually deploys submersible cages or floating pens that are attached to buoys or harnessed to the seafloor. Countries like China and Norway are at the forefront of the development of offshore aquaculture (California Environmental Associates, 2018); they have invested $1.5 to $2 billion in the past 3 to 4 years. The figures and tables below are detailed market values for aquaculture by region and aquaculture production by region.

Table 2.2.2.1 Global Aquaculture Production, by Region, Through 2022 (Thousand Tonnes)

Region	2016	2017	2022 (projected)	CAGR% (2017-2022)
North America	3,343.8	3,551.6	4,660.0	5.6
Europe	4,753.5	4,918.9	6,691.4	6.3
Asia-Pacific	79,406.5	82,548.0	110,397.6	6.0
South America	1,250.3	1,295.2	1,659.2	5.1
ROW	2,067.1	2,092.8	2,629.5	4.7
Total	90,821.2	94,406.5	126,037.7	5.9

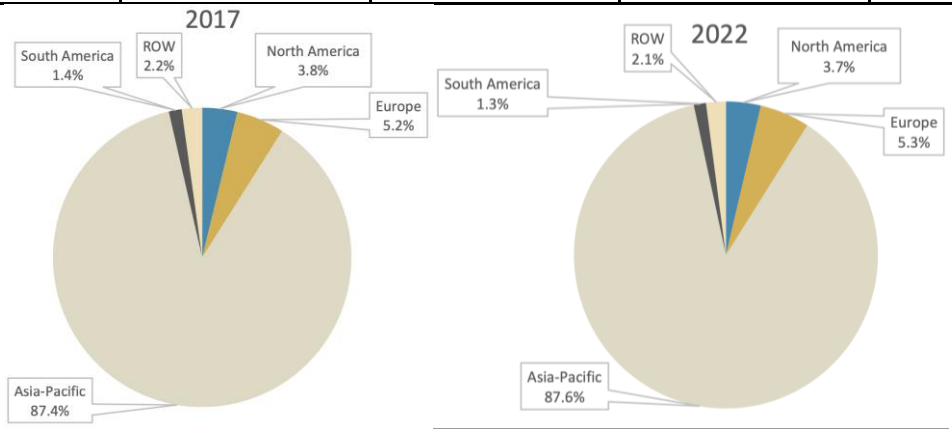


Figure 2.2.2.1 Global Shares of Aquaculture Production, by Region, 2017 and 2022 (%)

Table 2.2.2.2 Global Market for Aquaculture, by Region, Through 2022 ($ Millions)

Region	2016	2017	2022 (projected)	CAGR%
North America	6,859.7	7,292.1	9,482.1	5.4
Europe	8,174.5	8,484.7	11,237.9	5.8
Asia-Pacific	141,878.3	147,639.4	197,314.2	6.0
South America	2,418.3	2,488.2	3,179.1	5.0
ROW	3,945.6	3,990.2	4,954.5	4.4
Total	163,276.4	169,894.6	226,167.8	5.9

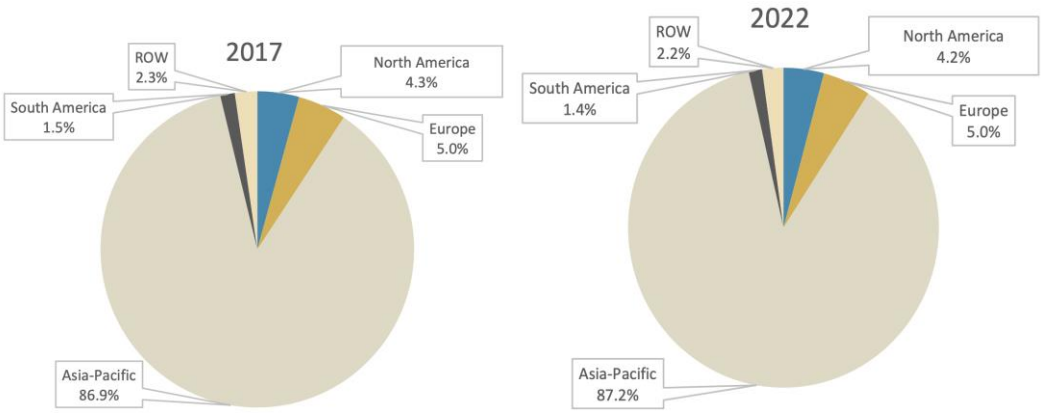


Figure 2.2.2.2 Global Market Shares of Aquaculture, by Region, 2017 and 2022 (%)

Kim and Zhang(2018) established an energy intensity model to estimate the energy use of current global aquaculture. Energy intensity is energy input per kilogram product. Four factors (i.e., climate, system intensity, natural trophic level of species, and culture technology) were selected as possible indicators to characterize the energy intensities of various forms of aquaculture. According to their analysis, about 46% of global fish production(tonnes/year) are from sites utilizing marine-based technology as shown in Figure 2.2.2.3 and those sites consume about 36% of the energy use(TJ/year) as shown in Figure 2.2.2.4.

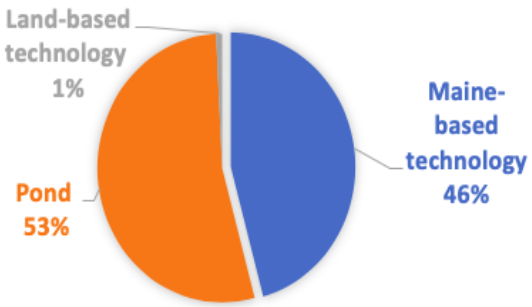


Figure 2.2.2.3 Global fish production(tonnes/year) by culture technology

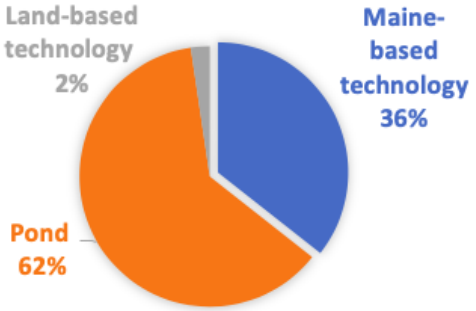


Figure 2.2.2.4 Global energy use(TJ/year) by culture technology

Moreover, *Kim and Zhang(2018)* estimated the production and energy use by country or region, and calculated their energy intensities. As we can see from Table 2.2.2.3, China has the highest global marine-based production(~19201412.7 tonnes/year**,** 87%) as well as consumes the most energy(~203777.7TJ/year, 78%), while North America produces 427837.68 tonnes/year(2%) and consumes 11450.55 TJ/year(4%).

Table 2.2.2.3 Global marine-based fish production and energy use by country/region

Region	North America	Latin America and Caribbean	Europe and Central Asia	Japan	Middle East and North Africa
Production (tonnes/yr)	427837.68	966307.68	108412.2	1094923.62	0
Energy use (TJ/yr)	11450.55	20866.56	1543.2	21990.22	0
Region	**Sub-Sahara Africa**	**South Asia Region**	**Southeast Asia**	**China**	
Production (tonnes/yr)	20.6	0	237039.2	19201412.7	
Energy use (TJ/yr)	0.4	0	2486.56	203777.7	

Figure 2.2.2.5 visualizes the relation between marine-based aquaculture's input and output. It shows that North America has the highest energy intensity(0.027 TJ/tonne), which means with the same amount of energy inputted, sites in North America produce the least amount of production. Latin America and Caribbean(0.022), Japan(0.020), and Sub-Sahara Africa(0.019) are also facing the same issue. High energy intensity indicates high energy costs that marine-based aquaculture companies have to afford and possibly their interests in advanced devices and solutions to improve energy efficiency and reduce energy costs.

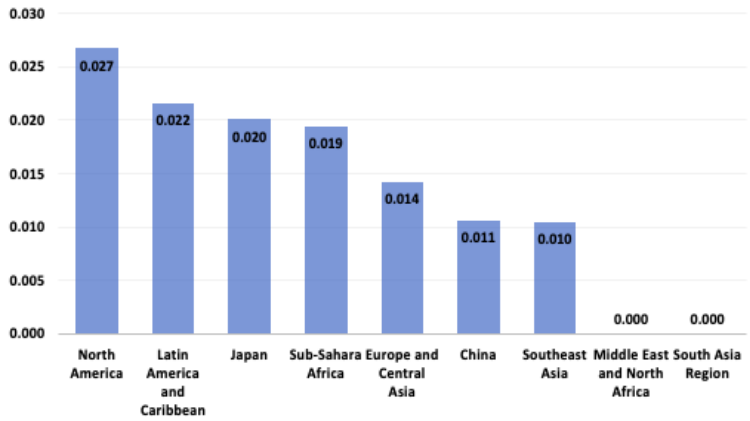


Figure 2.2.2.5 Global marine-based energy intensity(TJ/tonne) by country/region

2.2.3 Competition

As mentioned above, the onboard diesel generator is traditionally used in open sea aquaculture. Other types of renewable energy such as solar, offshore wind, and wave energy are occasionally used. Lashto Fish Farm in Haiti, for example, uses solar energy. During normal weather conditions, 63 photovoltaic modules are able to generate about 15 kW to oxygenate the fish tanks (NRG, 2018). Robert Field of Copper Beech Farm in Massachusetts uses solar panels to power a conventional floating upwelling system (Energy Smarts 2013). In the aspect of utilizing offshore wind, China's deputy chief of the Ocean Bureau announced that the 83 newly built ocean pastures in Shandong Province will feature wind turbines. They would like to assess if wind-fish farms could work (Godfrey, 2019). Table 2.2.3.1 shows the capital cost of different renewable energies according to Scottish Aquaculture Research Forum (2014) data, as well as our team's calculations of energy costs based on this data. The total cost of using wave energy is the lowest based on the report from IEA Technology Collaboration Programme for Ocean Energy Systems (2015).

Table 2.2.3.1. Capital and Energy Costs of Competing Renewable Energy Technologies in Aquaculture

Energy Source	Capital Cost ($/kW installed)	Cost of Energy ($/MWh)
Solar	3,100 - 3,800	316 - 468
Wind (large-scale)	3,800	83 - 117
Wind (small-scale)	3166 - 6332	189
Ocean Wave	2700	60-120

2.2.4 Value Proposition from the Customers' Perspective

The self-powered aquaculture farm should improve customers' experiences by facilitating the management of aquaculture farms. By divesting from fossil fuels, clients will face less logistical considerations and will produce less pollution, leading to a lower carbon footprint which is an attractive feature in a global market that's becoming increasingly conscious of environmental impact. From an economic standpoint, the customer would also find value in our system's lower maintenance costs since the energy is self-generated. Another added value from our system is that clients will have more reliable energy access, independent of the variations of the diesel market price or global energy fluctuations. All of these factors will allow customers to see our system's increased value over traditional aquaculture farms.

2.2.5 Pricing

We determine the price based on two major factors. The first is the total cost of the product itself. The total cost includes the manufacturing, transportation, installation, and maintenance costs. Since different aquaculture companies have different wave conditions and scales, the device will be customized for each company. The manufacturing cost is estimated to be in the range of $50k-220k. The transportation cost depends on the location of the customer. The installation cost will be between $290k-730k. The estimated frequency of maintenance is once per year, thus the total maintenance cost is expected to be $34k-120k. The second factor in determining the price takes into account the competition with diesel generators commonly used in offshore aquaculture. Based on our team's calculations, the levelized cost of energy (LCOE) of using diesel generators is $0.9/kWh. Based on our calculations, the LCOE cost of using our product ranges from $0.06-0.69/kWh based on the WEC type and number of deployed units (details in Section 2.5.1), which is much lower than using diesel generators.

2.2.6 State, Federal, or Other Incentives

Utilizing wave energy is an integral part of the blue economy, an economy that sustainably uses ocean resources. The blue economy has a lot of potential for growth and, as such, a number of economic incentives are being offered to develop this aspect of the economy. In 2019, the Bureau of Oceans and International Environmental and Scientific Affairs of the US Department of State pledged $1.21 billion to blue economy incentives, including the promotion of sustainable fishing practices (Bureau of Oceans and International Environmental and Scientific Affairs, 2019).

In the US, bodies of water can fall under federal or state jurisdiction. A number of states, such as Washington and Maine, already have functioning offshore aquaculture farms in their state waters. Federal waters—beginning three to nine nautical miles from the coast—currently don't have any commercial offshore aquaculture facilities, due to the complex and overly strict regulations in place (Congressional Research Service, 2019). However, President Trump recently issued an Executive Order on "Promoting American Seafood Competitiveness and Economic Growth" which would significantly help facilitate the permitting process. Specific policies will eliminate unsubstantiated offshore aquaculture regulations and ease the implementation of new sustainable aquaculture projects (Trump, 2020). This executive order complements the efforts of federal regulators in recent years who have been trying to increase the US' seafood production by allocating federal grants totaling $9.3 million to aquaculture projects in federal waters (Food & Water Watch, 2018). Furthermore, the Secretary of Commerce will allocate $300 million in fisheries assistance funding to help the American seafood industry that is negatively influenced by COVID–19. The funding is provided by Sec. 12005 of the Coronavirus Aid, Relief, and Economic Security (CARES) Act (NOAA Fisheries, 2020).

In addition, NOAA Fisheries—an office within the Department of Commerce of the National Oceanic and Atmospheric Administration which supervises the US' ocean ecosystems and resources—has a series of funding opportunities for economically and environmentally sustainable aquaculture. They have competitive grants, like the NOAA Small Business Innovation Research (SBIR) Program which provides up to $520,000 in funding for research and development, the Marine Fisheries Initiative which awards up to $525,000, and many more. NOAA Fisheries also has a Finance Program which provides loans for up to 80% of the cost of aquaculture facilities, with a financing period of up to 25 years (Office of Aquaculture, 2019). The loans can help the business owners to adopt new aquaculture facilities and technologies.

2.3. Relevant Stakeholders

Based on our interactions and interviews with experts in the aquaculture industry, our team has identified the following end users and other stakeholders.

2.3.1 End Users

Currently, there are 2 operating commercial offshore aquaculture operations using cages and 2 operations using longlines in US territorial waters and/or federal waters, also known as Exclusive Economic Zone (EEZ) based on our research and interviews. These are the past and present offshore aquaculture operations that are using or used cages:

- *Ocean Era*, grows kahala or Hawaiian yellowtail in Hawaiian waters.
- *University of New Hampshire Atlantic Marine Aquaculture Center (UNH Aquaculture Center)*, grows halibut, haddock, summer flounder, and cod in New Hampshire waters.
- *Hukilau Foods, LLC (formerly Cates International, Inc.)*, the first company to obtain an open ocean fish farm lease in the US in 2002 and raised moi in Hawaiian waters. Filed bankruptcy in 2011.
- *Snapperfarms, Inc.*, the second commercial open ocean aquaculture operation in the US, raised cobia off Culebra, Puerto Rico. Discontinued production in 2008 due to supply chain disruptions.
- *Catalina Sea Ranch*, the first and the only offshore aquaculture operation in US federal waters started in 2015, raised shellfish off the coast of Huntington Beach, CA. Filed bankruptcy in 2020.

The 2 additional commercial operations producing mussels using longlines are:

- *Isle of Shoals* in New Hampshire waters
- *Santa Barbara Mariculture* in California waters

Many offshore marine aquaculture companies rely on conventional power derived from fossil fuels to power their daily operations. The amount of power needed depends on the species that is being cultivated, farm size and location. Finfish are of particular interest due to having much higher energy requirements to cultivate. It's this market that we see could be improved by supplying energy via alternative methods such as ocean wave energy. This could significantly reduce their costs which are high due to fuel consumption in this high energy intensity industry.

Table 2.3.1.1 shows how finfish (salmon in the table) requires far more energy than the other forms of sea life like mussels and seaweed shown. Interviews with Phil Cruver from *Catalina Sea Ranch* and Bernard Friedman from *Santa Barbara Mariculture* have shown that energy consumption for mussel and seaweed farms is mainly just due to the boats which harvest the crop, and that the power usage on site is very low to none. The small power usage on site is due to monitoring buoys that are powered by small solar panels and a small wind turbine. These companies are examples of offshore aquaculture companies that do not fall into our targeted end users.

An interview with Michael Chambers from *UNH Aquaculture Center* which is a finfish farm has shown that their energy consumption is mainly due to energy needed for feeding and monitoring. For their operations a feed buoy is powered by a 20 kW diesel generator that is brought onsite by a boat. The costs associated with this are twofold; the diesel generator requires fuel which carries a higher cost than it does for conventional diesel due to the added cost of transporting the fuel out to sea, and because this entire operation needs to be manned by employees. This is an example of an offshore aquaculture site that would benefit significantly from a cheaper alternative source of energy, and is an example of our end users.

Table 2.3.1.1 Total embodied energy for equivalent area

Quantity	Seaweed culture	Mussel culture	Cage salmonid culture
Total inputs (kcal)	6.65	1.05 – 2.40	580 – 950
Solar/renewable (%)	95.5	71.4 – 85.4	81.0 – 87.4
Fossil/non-renewable (%)	4.5	28.6 – 14.6	19.0 – 12.6
Protein output (kcal)	6605	255 – 440	22420
Input/output ratio	100	410 - 545	2585 - 4235

While *Catalina Sea Ranch* and *Santa Barbara Mariculture* do not raise finfish, they provided significant insight into the challenges that our targeted end users are facing. Finfish farms are scarce in US coastal waters, in fact there are only two operational finfish farms still in existence in the US, *Ocean Era* and *UNH Aquaculture Center*. The challenge they've been faced with is regulation. For the two non-finfish aquaculture companies interviewed, they had an easier challenge since mussels and shellfish do not have as high of regulatory barriers. Despite the lower regulatory requirements for them the costs they said were enormous. *Catalina Sea Ranch* was spending $500,000 per year just for regulatory compliance. Fortunately, a lot of this looks like it will change due to desire amongst the federal government agencies to secure our aquaculture food supply. Currently *Manna Fish Farms* is about to obtain their permits within the next 2 years in order to open two finfish farms off the coasts of Florida and New York. This is a big step in expanding the US offshore aquaculture market.

Through our interviews there were significant parallels between each aquaculture company, each one had experienced major barriers not on the technical side but on the legal side. These regulatory hurdles were the result of various NGOs, environmental groups, and federal agencies that opposed the expansion of offshore aquaculture. It forced us to self-reflect and look at some of the concerns that were brought up and find answers, being in contact with the *UNH Aquaculture Center* helped us immensely because in their 20 years of experience in offshore aquaculture they themselves did studies to try and answer these concerns.

- ❑ Dumping large quantities of fish feed into the ocean could damage the ocean's ecosystems.

"We've done seabed studies and water quality studies and there has never been any changes, the only time we see significant changes is when a storm rolls by and that's due to the seabed being kicked up and has nothing to do with the fish feed." (M. Chambers, personal communication, June 26, 2020)

- ❑ Mooring lines for the aquaculture cages could entangle sea life.

"The mooring lines are high tension and taut since the cages are very large. The mooring lines are extremely strong and have never broken in the 20 years of operation. Mooring lines need to be loose and broken in order to entangle sea life, and we've never seen an issue." (M. Chambers, personal communication, June 26, 2020)

- ❑ If the fish being bred are not native to the area could they become an invasive species.

"The fish being bred are native to the area and on top of that we only have female fish in our cages so if they did escape, they wouldn't be able to reproduce."(M. Chambers, personal communication, June 26, 2020)

While more research can always be done to investigate any possibilities of environmental damage that offshore aquaculture can cause, the *UNH Aquaculture Center* has shown through their work that as of yet there has been nothing concerning enough to put a hard stop on offshore aquaculture in the US. And as we've seen in other countries who've done their own studies offshore aquaculture are expanding rapidly; *Salmar* in Norway is deploying million-dollar super structures in the ocean for offshore aquaculture.

Therefore, though we have learned the current US offshore aquaculture market is small, it's clear that there is room for a significant expansion. Our initial focus is on end users in the US but there is also potential to expand to the much larger global market in later phases of the project.

2.3.2 Other Stakeholders

2.3.2.1 Government agencies

Depending on the geographic location and characteristics of aquaculture facilities, different aquaculture regulations apply.

There are four main federal agencies in the US that would potentially exercise jurisdiction over wave projects in the marine environment. The four agencies are the Federal Energy Regulatory Commission (FERC), the US Army Corps of Engineers (USACE), the National Oceanic and Atmospheric Agency (NOAA), and the Minerals Management Service (MMS). Currently, USACE is the lead agency with jurisdiction for permitting offshore structures from state boundaries to the EEZ, while FERC regulates over the terms and rates for power supply contracts from a wave power project to a local utility. About 15 out of 40 federal regulations on marine resources are directly relevant to wave power jurisdictions. Due to the lack of clear authorities and that agency interpretation of the regulations are evolving, the cost of time and fees to obtain permits and licenses for deploying WECs and utilizing the wave power is high. Since no single federal agency is authorized to approve or permit offshore aquaculture facilities, joint environmental reviews are inevitable and therefore increase business burden.

We've fortunately been able to talk to a representative at the FERC who has given additional insight into one part of the permitting process. A pilot program needs to be done in order to evaluate the environmental impacts of the WECs. This pilot program can require a license but can also require no license. The requirements for no license are listed below:

- ❑ The technology in question is experimental
- ❑ The proposed facilities are to be utilized for a short period for the purpose of conducting studies necessary to prepare a license application
- ❑ Power generated from the test project will not be transmitted into, or displace power from, the national electric energy grid

Our design is experimental for its initial phases of development, the location utilized will only be for a short duration to determine environmental impacts, and lastly the power created will be used the offshore aquaculture cages which are not connected to the national electric grid. This bodes well for initial testing phases and reduces the costs for regulatory compliance. To deploy the WECs after this testing review however a hydrokinetic license for 4-5 years would need to be applied for from the FERC. For this application this project has a significant regulatory advantage, being that the device is below 1 MW the hydrokinetic license is much more easily obtained.

Environmental and regulatory concerns that are important to analyze in the pilot project are:

- ❑ Sound levels, which cannot be too high which could disturb sea life
- ❑ Animals resting or sitting on top of the device
- ❑ Navigational concerns, the site cannot interfere with shipping. This is another advantage of our project as the aquaculture sites have already accounted for this
- ❑ Marine mammals being injured, the WEC will have moving parts which could cause injuries to marine mammals
- ❑ Electrical signals that could impact sea life which are sensitive to electromagnetics

Many of these concerns however might be simpler and easier to determine since offshore aquaculture farms have already performed many of these analyses themselves.

2.3.2.2 Trade Associations

There are over 23 national aquaculture trade associations and over 50+ state aquaculture trade associations. Many of the trade associations are focused on a particular type of fish produce. These trade associations are mainly designed to assist and regulate aquaculture companies which means our business typically falls outside of their purview. However, there is one major benefit from participating in aquaculture trade associations, and that is to create visibility and awareness of our work with aquaculture companies that have not adopted the technology yet.

There are a bunch of different renewable energy organizations which help promote a range of types of renewable energy. The ones that might be pertinent to this project include: National Hydropower Association, International Hydropower Association, American Council on Renewable Energy, and the World Council for Renewable Energy. These organizations can often assist its members with the legislative, regulatory, technical, and public communication challenges. These organizations might be important candidates to interact which could positively impact this project.

2.3.2.3 Department of Energy

The Department of Energy (DOE) can often be a critical part of our business proposal. To attempt a project like this funding is needed and the DOE is the primary investor in lots of these types of projects. The DOE's initiative Powering the Blue Economy is helping advance a whole range research and development projects in regards to aquaculture, and renewable energy. In 2020 the DOE Water Power Technologies Office (WPTO) announced $22 million to fund research and development for marine energy.

The WPTO also provides funding for the Testing Expertise and Access for Marine Energy Research (TEAMER) which provides access to important marine testing facilities and numerical software. These facilities and software are important for the engineers developing the technology needed for the WEC to have.

2.4 Development and Operations

2.4.1 Research and Development

The overall objective of the proposed work is to design and deploy a 15-75 kW (based on power demands) flap-type WEC system to power the feeding and monitoring operations of open ocean aquaculture platform, as shown in Figure 2.4.1.1. This system would reduce costs, increase automation and reduce environmental impact to allow for clean aquaculture. Unlike the traditional feeding system using diesel, also shown in the figure below, our proposed solution will upgrade the existing feeding buoy to expand its function to also generate sustainable energy. Two flaps will be attached on the feeding buoy and can be driven by ocean waves. Then, the flap will drive the generator to produce electricity. Detailed design information can be found in Section 3.

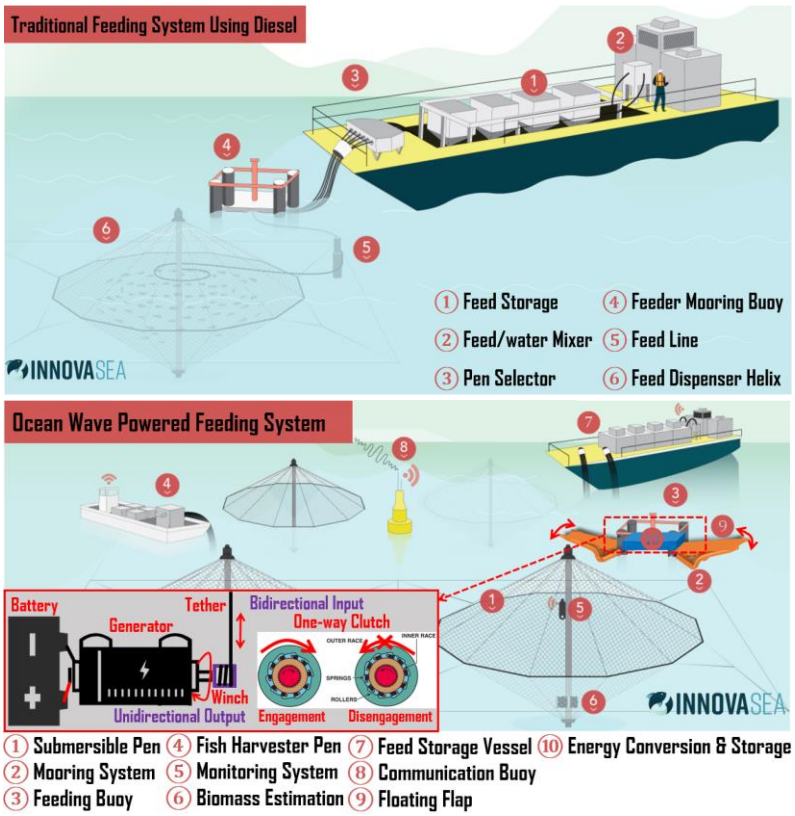


Figure 2.4.1.1 Schematic of wave powered offshore fish feeding system (top),Traditional diesel-based feeding system(bottom), Photo courtesy of Innovasea Systems Inc

As for the R&D of the proposed project, we will leverage renowned research achieved by Prof. Zuo in the Center for Energy Harvesting Materials and Systems (CEHMS). With more than ten years of technology accumulation, Prof. Zuo did fundamental research, in-lab prototype validation, wave tank tests and ocean tests on marine renewable energy, as shown in Figure 2.4.1.2. We will scale up the wave energy converters and integrate them with existing feeding buoys by cooperating with aquaculture companies, and then investigate the mass production and supply chain management with low LCOE.

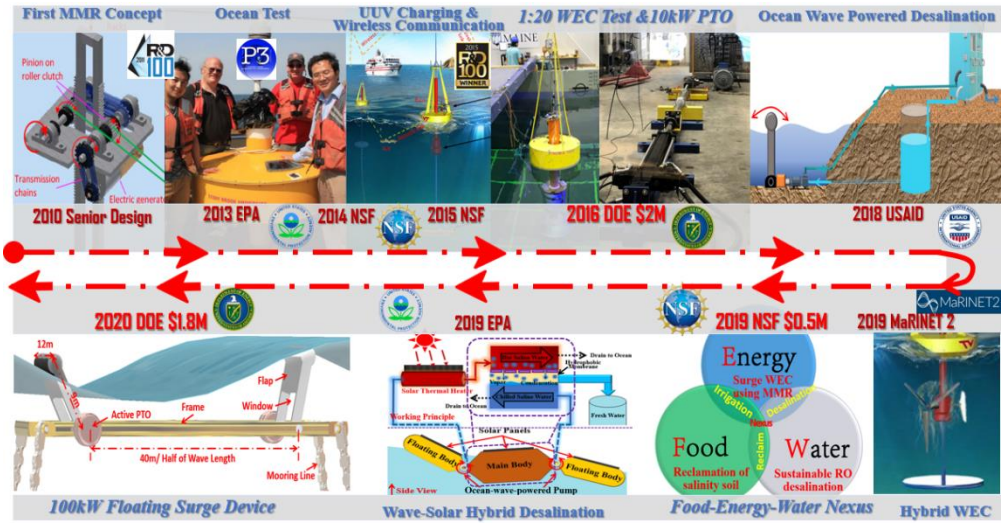


Figure 2.4.1.2 Research pathway on marine renewable energy at CEHMS

2.4.2 Development Plan

We have adopted a 3-Phase Development Plan for the next 10 years with unique aims and operation strategies for each phase of development as outlined in the figure below.

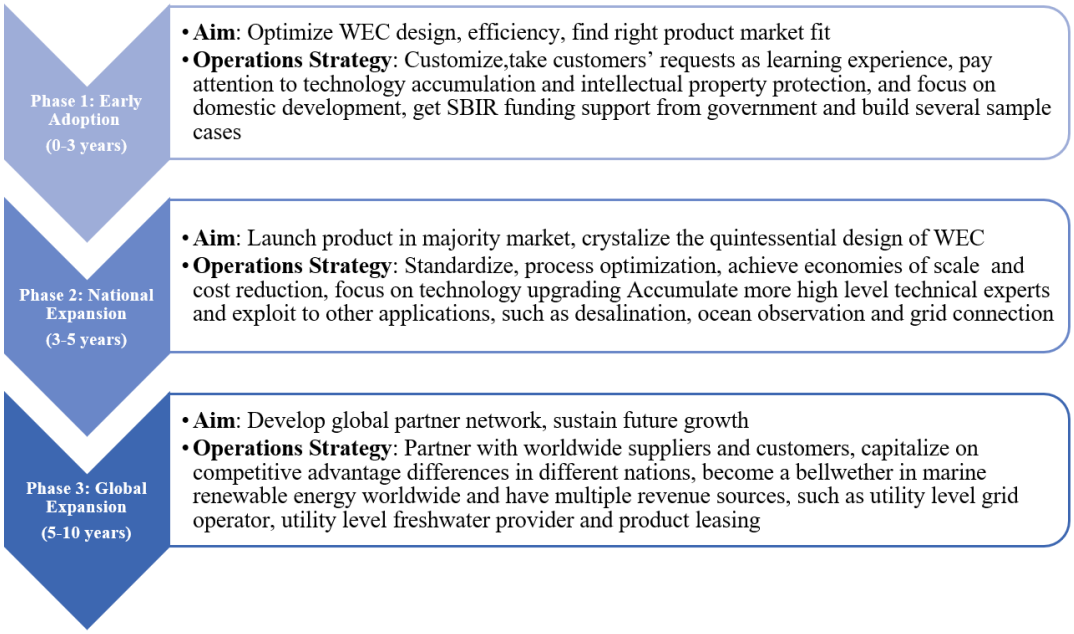


Figure 2.4.2.1 Development Plan

2.4.3 Manufacturing, Deployment, and Financing

Manufacturing of the wave energy converter will utilize the global supply chain to leverage cost efficiency, i.e. contract the manufacturing of pieces of the equipment where it is the cheapest and most reliable and assemble the majority of the equipment on site. The team has already made many parts, components, and prototypes in a shipyard in Maine State. Another potential manufacturing collaborator that the team already reached out to is Vigor Industrial.

The deployment process will be initiated with a customer request for wave energy converter by submitting the specifications on site. These specifications will be entered into a computerized model to showcase the intended product that the customers want. As customers agree to the model developed, orders of pieces of equipment will be sent to contract manufacturing and manufactured equipment will be sent together to customers' site for final assembly. Final assembly is carried out by trained personnel to ensure consistent standard and reliability of work. After final assembly, the customer will need to check the functionality of the equipment and confirm that the deployment is a success.

Instead of paying the large initial capital investment, aquaculture companies may choose to finance the wave energy convertors by monthly installments. In other words aquaculture companies are renting the wave energy convertors. This may require the collaboration with a financial institution to serve as the credit giver. The financial institution will pay us the whole capital investment while aquaculture companies will pay the financial institution back by monthly installments.

2.4.4 Supply Chain Management Strategy

Typically, supply chain management attempts to centrally control or link the production, shipment, and distribution of a product. By managing the supply chain, companies are able to cut excess costs and deliver

products to the consumer faster. As shown in Table 2.4.4.1, supply chain management is done by keeping tighter control of customer relationships, internal inventories and related suppliers via three key organizational characteristics—culture / organization, measurement and information/communication.

Table 2.4.4.1 Summary of Supply Chain Management Strategy

	Customer-Facing Knowledge	**Internal Requirement / Characteristics**	**Supplier-facing Knowledge / Characteristics**
Culture/ Organization	Work closely with immediate customer on supply chain design cost and meet the needs of aquaculture companies	Top management support; Cross-functional teams; Dedicated supplier cost management specialists;	Support key suppliers with resources to facilitate continuous improvement; Train suppliers in supply chain cost management
Measurement	Understand aquaculture companies' needs and estimate potential maintenance demands by monitoring existing customers	Set specific goals to each team, metrics aligned with cost management/other goals; High level visibility of cost management results;	Reward key suppliers with more business; Cost savings by signing tendentious contract for future collaboration;
Information/ Communication	Regularly investigate customer needs and market trends	Excellent information systems to show periodical results; Seamless understanding and communication of customer needs	Clear communication of expectations to suppliers; Estimate market trend and report to suppliers about time-varying market

Via the aforementioned supply chain management strategies, we can reduce our unit cost and improve peer competitiveness, improve product quality and expand more business, and expand the market quickly. The core achievements via supply chain management in different stages are shown in Table 2.4.4.2.

Table 2.4.4.2. Desired supply chain management core achievements

Phase	**Nondimensional Price to customer**	**Nondimensional Internal management cost**	**Nondimensional External production cost**
Early Adoption	Reduce 5%	Reduce 10%	Reduce 10%
National Expansion	Reduce 10%	Reduce 20%	Reduce 15%
Global Expansion	Reduce 20%	Reduce 30%	Reduce 30%

2.4.5 Partnerships to be Leveraged

We aim to develop partnerships with both governmental and academic institutions, as well as upstream and downstream players as shown in the table below.

Table 2.4.5.1. Summary of partnerships to be developed

Partnerships	Actions
Local governments/agencies such as NYSERDA	Apply for favorable policies, tax benefits & grants for R&D
Research institutions	Collaborate with research labs for optimizing efficiency and develop novel designs
Suppliers for contract manufacturing and partners in the supply chain	Develop revenue sharing contracts to lower initial cost of goods sold
Aquaculture companies	Participate in industry showcase for expanding business opportunities and use customer relationship management to retain customers

2.4.6 Potential Risks and Mitigation Strategies

Risks can be considered along the following two dimensions: external vs. internal, and the corresponding mitigation strategies are also summarized below.

Table 2.4.6.1. Summary of Risks and Mitigation Strategies

	Risk	Mitigation Strategy
External	Regulatory permits & blockers	Launch WECs in federal waters first where the regulations are fewer than in state waters; license or repurchase existing permits from current permit holders
	Less than expected market demand for fishery and hence WECs	Research and develop novel applications for WECs, such as desalination and coastal power generation
	Natural disaster, e.g. tsunami	Develop global footprint to reduce reliance on a particular market susceptible to natural disasters
Internal	Change in technology and technical difficulties	Focus on core technology development and iterations, and outsource non-core business to maintain a light asset strategy adaptable to changes
	Manufacturing & supply chain disruption	Develop tiers of supplier networks and ensure supplier redundancy
	Maintenance, service, and customer satisfaction	Utilize big data and analytics to develop a self-managed, self-powered aquaculture farm to reduce unnecessary maintenance; as we have stable sales volume, we can customize some key components with upstream supply chain, such as generator, battery and belt to reduce our cost and improve our delivery cycle

2.5 Financial and Benefits Analysis

Table 2.5.1 Key Economic and Financial Assumptions and Results

Wave Condition	Value
Average wave power flux	20kW/m
Water depth	30-60m
Wave period	5-18s
Wave height	0.75-6m
Active wave train duration	20h/day
Wave Energy Converter	
Capture width ratio	47%
Mechanical PTO efficiency	85%
Flap width	Type A: 1.2m/15kW;Type B: 3.0m/ 37.5kW;Type C: 6.0m/75kW
Array arrangement	1 unit/5 units/10 units
Average daily electricity production per WEC	Type A: 300kWh/ Type B: 750kWh/ Type C: 1500kWh
Desired lifespan	20 years

The estimation of LCOE for different types and unit arrangement methods is shown in Figure 2.5.1.

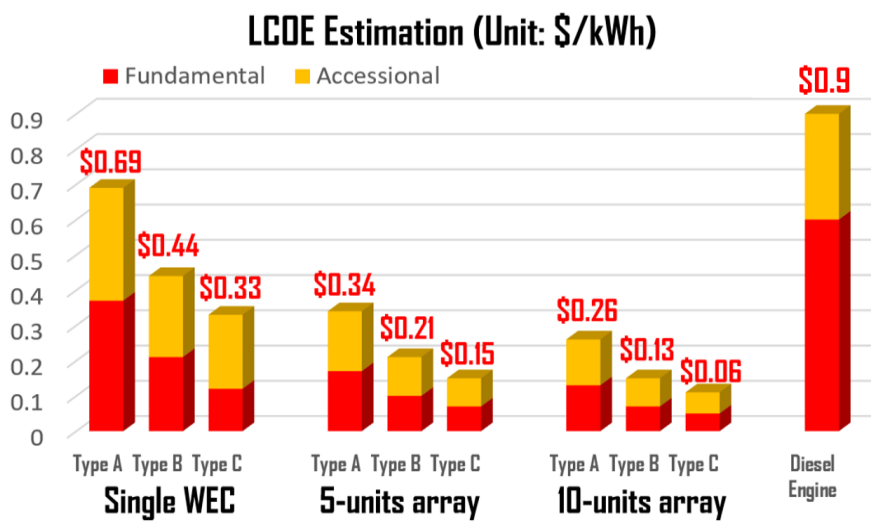


Figure 2.5.1 LCOE Estimation under different types and different array arrangement methods

2.5.2 Earning Analysis & Predictions

2.5.2.1 Summary Introduction to Financial Analysis

During the first 3-5 years, the company will be in its development stage. In this phase the important part in our companies' revenue is the service fee for designing, which includes service in production systems, energy systems, specific operating machines, etc.

The percentage distribution of the service fee is calculated based on the number of engineers that one project/part needs. We have detailed calculations in the Reference part. In the second stage of the company, we believe that the firm will be expanding rapidly and so will its revenue The main driving factor will be the growth in the number of clients and the greater service capabilities of a much larger landscape in application of marine energy technologies. As enterprise development becomes increasingly mature, the marine engineering technology will also greatly mature. With more mature marine engineering technology we hope to expand the scope of our business service, and expand to new fields that might utilize the ocean's energy. This will help ensure strong operating income growth, and keep good cooperation with customers, to protect our company's share of the marine aquaculture market.

2.5.2.2 Financial Statements Calculation for First Phase

The future profit/loss that our team estimated is concluded as below:

Table 2.5.2.2.1 Summary of First 5 Years Financial Statements (unit: thousand $)

Year	2021	2022	2023	2024	2025
Expected WEC Sales	5	15	30	60	90
Government Grants	$260.00	$270.00	$460.00	$510.00	$580.00
Sales Revenue	$1,875.00	$5,625.00	$11,250.00	$22,500.00	$33,750.00
Technical Services (Repair and maintenance) Revenue	$286.00	$572.00	$658.00	$830.10	$916.10
Consulting Revenue	$46.90	$75.00	$112.50	$140.60	$225.00
Cost of revenues*	$989.6	$2,968.7	$5,937.3	$11,314.9	$17,122.4
Operational cost	$270.00	$210.00	$420.00	$990.00	$1,560.00
R&D expenses	$800.00	$200.00	$200.00	$600.00	$1,000.00
Sales and Marketing	$562.50	$1,125.00	$1,687.50	$1,875.00	$2,250.00
Employee Benefits Expense	$263.70	$270.90	$457.20	$510.40	$582.40
Profit/Loss before income	($417.85)	$1,767.45	$3,778.50	$8,690.40	$12,956.35
Tax:IncomeTax	-	($136.98)	($292.83)	($673.51)	($1,004.12)
Tax: Sales Tax Exemption	-	$136.98	$292.83	$673.51	$1,004.12
Net Profit/Loss	($417.85)	$1,767.45	$3,778.50	$8,690.40	$12,956.35

2.5.2.3 Operating Cash Flow Analysis

Table 2.5.2.3.1 Operating Cash Flow Composition Analysis (unit: thousand $)

Year	Investment period	2021	2022	2023	2024	2025
Initial Investment in Working Capital	-$200.00				-$150.00	-$300.00
Initial Investment in Non-current Asset	-$300.00				-$100.00	-$300.00
Estimated Revenue		$2,207.90	$6,272.00	$12,020.50	$23,470.70	$34,891.10
Less: Cost		-$2,885.80	-$4,774.60	-$8,702.00	-$15,290.30	-$22,514.80
Net Profit	-$500.00	-$677.90	$1,497.50	$3,318.50	$7,930.40	$11,776.40
Add: Amortisation on Intangible Asset		$10.00	$10.00	$10.00	$10.00	$10.00
Add: Depreciation on Non-current Asset		$30.00	$30.00	$30.00	$40.00	$70.00
Net Operating Cash Flow	-$500.00	-$637.90	$1,537.50	$3,358.50	$7,980.40	$11,856.40

2.5.2.4 IRR & NPV Analysis

We used the US treasury yield rate at 5 years maturity (0.28 %) on the 29 June 2020 as the risk-free rate, and the US average market risk premium rate in 2020 is 5.6%, the beta coefficient for machinery industry is 1.25. the CAPM model will be used to calculate i, which is 7.28%. Thus, the NPV (2020-2025) equals $17,330.0, which is larger than 0, so it is worthwhile for investment.

And for IRR calculation, based on the calculation, the IRR for the investment is 153.53%, which is much larger than the cost of capital of 7.28% and also the average rate of return of listed companies in the same industry. Thus, it is worth investing.

2.5.2.5 Discounted Payback Period Analysis

The discounted payback period refers to the amount of time it takes to recover the cost of an investment or how long it takes for an investor to reach breakeven, by discounting future cash flows and recognizing the time value of money.

Table 2.5.2.5.1 DPP Calculation

Year	Investment period	2021	2022	2023	2024	2025
Net Operating Cash Flow	-$500.0	-$637.9	$1,537.5	$3,358.5	$7,980.4	$11,856.4
DR @ 7.28%	1.00	0.93	0.87	0.81	0.75	0.70
DCF	-$500.0	-$594.6	$1,335.9	$2,720.1	$6,024.9	$8,343.7
Cumulative DCF	-$500.0	-$1,094.6	$241.3	$2,961.4	$8,986.3	$17,330.0

Discounted payback period = 1.82 years

The discounted payback period is 1.82 years, which is shorter than the average payback period for listed machinery manufacturing companies. Thus, it shows the invested cost will be recovered over a very short period.

3. Preliminary Technical Design

3.1 Overall Objective

The proposed design is a flap-type floating WEC system that powers the feeding and monitoring systems of open ocean aquaculture platforms. The working principle of the WEC is shown in Figure 3.1.1. The WEC has one floating flap that is hinged to each side of the feeding buoy and moves up and down under waves. A tether is connected to the floating flap at one end and to a winch at the other. The downward of the flap rotation will pull the winch to drive the generator to generate electricity. When the flap rotates upward, the tension force in the tether will be released and the tether rope (or belt) will be rewound with the help of the one-way clutch and spring, making it ready for the next wave motion to generate electricity. A gearbox can be used to increase the rotation speed of the generator, and a flywheel can be integrated on the generator shaft to smooth the rotation speed. The energy will be stored in the battery in the fish feed buoy to power the feeding and monitoring of the fish farm. Compared with other types of power takeoff (PTO), like the hydraulic, ball screw or rack and rack-pinion based PTOs, the tether-type PTO system is located above the ocean water and under more smooth loading, as a result the tether design's capital cost, maintenance cost, and reliability are much better.

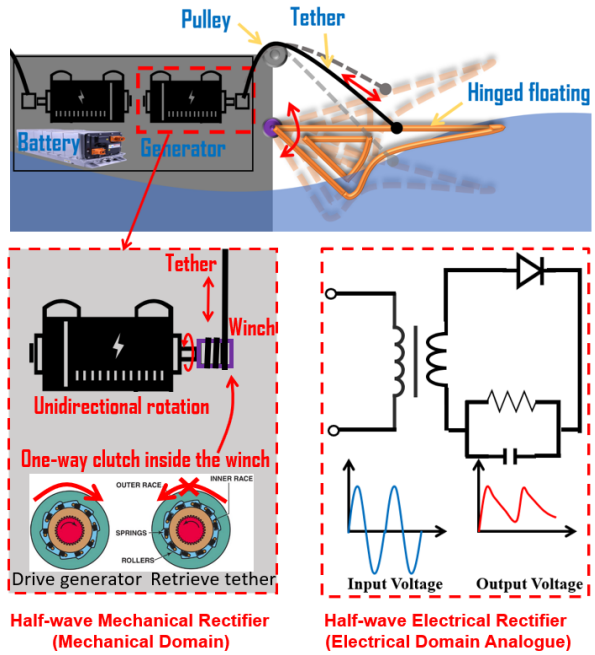


Figure 3.1.1 Design principle of the tether-based WEC using half-wave mechanical rectification

The power output of the WEC ranges from 15-75 kW depending on the flap dimensions. The following technical design is a case study for a 35-40 kW WEC with a flap width of 3m.

3.2 Innovation and Performance

3.2.1 Innovation and Impacts

The 35-40 kW output of WEC is achieved through the co-development of WEC with the fish feed buoy and seamless wave-to-wire integration of four cascaded innovations linking the hydrodynamics, mechanics, and electronics. The four proposed innovations drive the increase in power output and energy conversion efficiencies as power flows from wave to wire through the different conversion stages and system integration: wave energy is harnessed as mechanical energy and converted to electrical energy which is then stored and used in the fish farm.

Innovation 1: Zero-scattering geometric flap shape for high capture with ratio through the wave structure hydrodynamic optimization;
Innovation 2: Tether-based reliable broadband PTO using half-wave mechanical rectifier;
Innovation 3: Efficient power electronics design for energy storage and management;
Innovation 4: Integration with the off-shore fish farm in both mechanical and electrical aspects.

The proposed tether-based reliable PTO using a half-wave mechanical rectifier can convert bidirectional linear motion into unidirectional rotation, as shown in Fig. 3.1.1. Due to engagement and disengagement between the winch and one-way clutches, the inertia of the system alternatively becomes large and small, resulting in piecewise linear inertia. With the inertia nonlinearity, half-wave mechanical rectifier-based systems can achieve broadband energy harvesting performance. Dynamic modeling and numerical simulation show the proposed half-wave rectification-based energy harvesting system can obtain about two times of the average output power than previous full-wave rectification-based design while maintaining larger output power in the desired broad frequency range at the same time (details in Section 3.3.1).

Fig. 3.2.1.1 shows the design concept of power electronics and storage, a bidirectional AC-DC converter will be designed to shield the switches from the widely fluctuating wave, limiting the voltage stress to the battery voltage. Space-vector modulation at carrier frequency will be coordinated with Latching Control to prioritize energy extraction during engagement. The EMI Filter and other ancillary blocks will be designed to meet IEC, IEEE, power factor, voltage disturbance, phase-lock range, surge protection, power quality, and other standards.

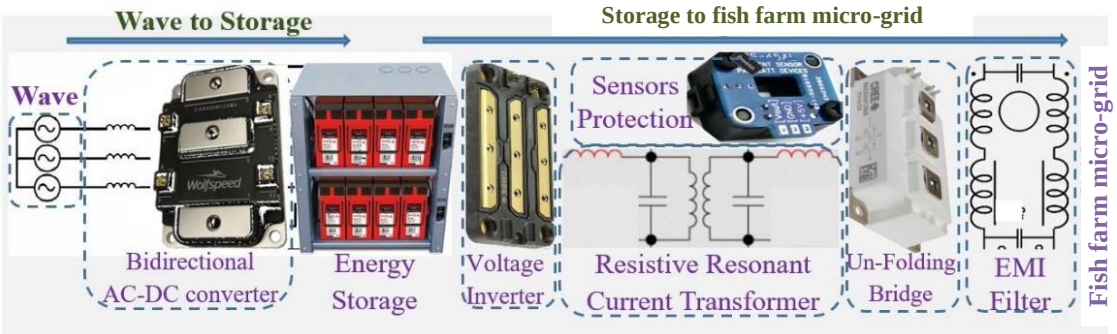


Fig 3.2.1.1 Design Concept of Power Electronics and Storage

3.2.2 First-order Performance Analysis

At the WEC deployment location, the significant wave height is set to be 2.5 m and the average wave period is 7 s. The power density can be calculated as 23 kW/m. Assuming each flap is 3 m long and 3 m wide, the input wave power can be 96 kW for each flap. Assuming a 47% capture width ratio and 85% PTO efficiency, we can estimate that two flaps can provide an ~40 kW power output on average.

3.2.3 Loads Analysis and Safety Issues

Fig. 3.2.3.1 shows the mesh details in ANSYS AQWA for BEM calculation and also shows the maximum pressure distribution on flaps under 7s/2.5m wave condition which can guide the structural design of the flaps and reduce LCOE. The hydrodynamic term includes an added-mass and wave damping term associated with the acceleration and velocity of the

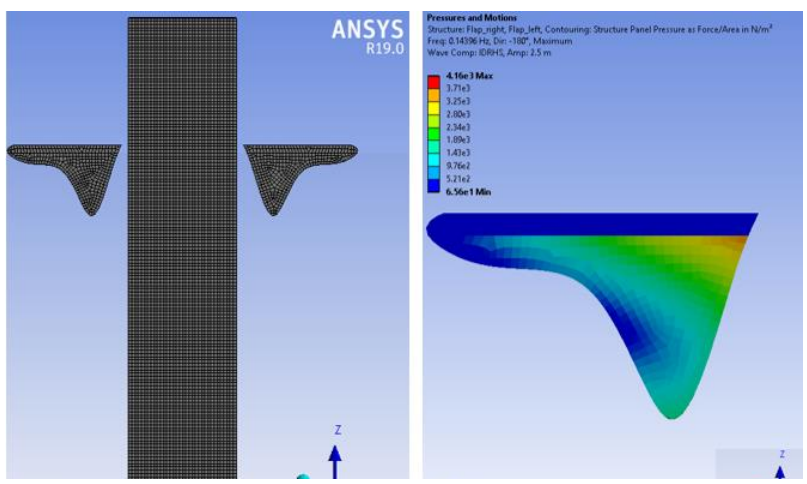


Fig. 3.2.3.1 (a)Mesh Details. (b)Loads Analysis (Pressure)

floating body, respectively. The wave excitation term includes a Froude–Krylov force component generated by the undisturbed incident waves and a diffraction component that results from the presence of the floating body. All these terms can be calculated by ANSYS AQWA.

3.3 System Dynamics and Optimization

3.3.1 Dynamics of the PTO and System

Fig.3.3.1.1 shows the proposed dynamic modelling of the EM-generator-based vibration energy harvester using half-wave mechanical rectification. As investigated in literature, there are two main forces from the harvester to the whole vibration system in the engaged case: damping force induced by back electromotive current and inertia force induced by the inertia of rotational parts in the generator. The damping force is proportional to the vertical linear velocity of the tether and the counteracting force is proportional to the acceleration of the tether.

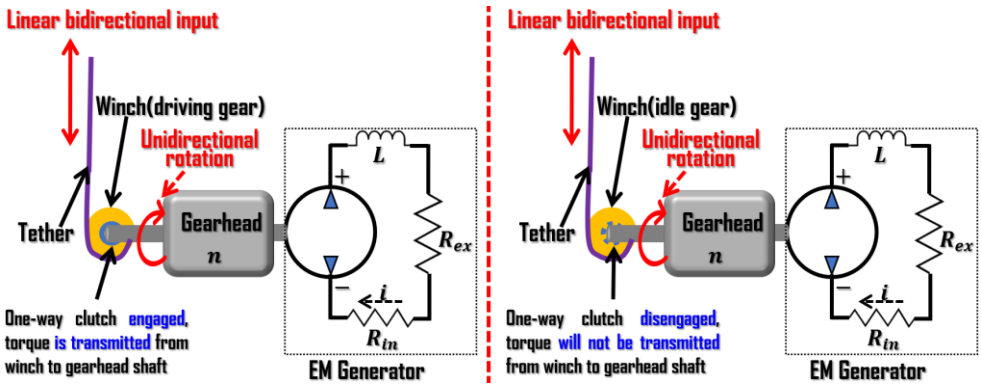


Fig 3.3.1.1 EM-generator-based PTO using half-wave mechanical rectification to convert bidirectional input into unidirectional output

When the pinion gear is decelerating to an extent that the rotational velocity of the generator shaft becomes larger than that of the pinion gear, i.e., the rotational speed of the generator shaft is equal to the rotational speed of the pinion gear, disengagement occurs.

As for the disengaged case, the whole system will be decoupled into two separated systems, as shown in Fig.3.3.1.1. In this case, there is no counteracting force from the harvester to the vibration system and the generator will rotate under the two interactional forces. Hence, the rotational speed of the generator shaft will decay as a certain ratio. The system will be engaged again once rotational speed of the pinion gear equates the rotational speed of the generator shaft . As stated earlier, there are engagement cases and disengagement cases in different conditions because of the characteristics of the one-way clutch. During the engagement cases, there are two main forces from the harvester to the whole vibration system and the dynamics of the system is the same as a traditional non-rectification system. During the disengagement period, the generator rotor will be decoupled with the rack-pinion and the whole system will be two independent systems. The flap and tether with winch will be a single vibration system with mechanical damping, and the generator with external resistance will be another independent system. The two decoupled systems will be coupled again when the input speed of the pinion gear is equal to the generator rotor. Therefore, the vibration system is a piecewise linear system because of the engagement and disengagement of the one-way clutch.

Fig. 3.3.1.2 shows the nondimensional power comparison of a single-degree-of-freedom vibration system. From the figure we can see that the half-wave rectification system can achieve larger power output at natural

frequency and maintain larger power near the desired frequency point. This means that the half-wave rectification system can achieve larger power and broad bandwidth.

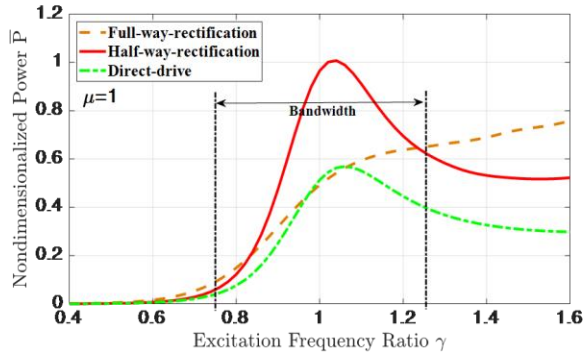


Fig.3.3.1.2 Nondimensional Power Comparison

3.3.2 System Optimization

There are two flaps in a single system; the dynamics of these two flaps will be coupled and should be optimized based on desired wave condition (7s/2.5m). Fig. 3.3.2.1 shows the average power output of the whole system under different damping coefficients of the two flaps. From Fig. 3.3.2.1 we can see the maximum power output is 37.611 kW when the fore flap damping is 2000 N·m/(°/s) and the aft flap damping is 4000 N·m/(°/s). In addition, the simulation results verified the first-order estimation in Section 3.2.2. Figure 3.3.2.2 shows the time-domain power output of each flap and the whole system under optimized parameters.

Aft Flap Damping [N.m/(°/s)]	Fore Flap Damping [N.m/(°/s)]									
	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000
1000	34.139	31.231	28.955	33.848	30.532	21.001	31.961	31.095	20.813	23.417
2000	22.392	22.501	25.669	29.156	24.033	22.812	21.686	20.961	20.491	19.109
3000	21.288	24.501	29.508	30.207	25.526	24.185	23.038	22.098	21.734	20.189
4000	21.918	37.611	26.999	30.154	27.405	24.782	23.78	23.059	22.402	21.965
5000	21.061	25.081	29.771	29.648	27.446	24.086	23.171	22.353	21.854	21.409
6000	20.957	26.791	27.651	29.896	26.578	25.974	24.102	20.332	22.021	18.997
7000	20.712	24.336	28.678	28.647	28.333	26.321	25.002	23.662	21.365	19.654
8000	20.441	23.786	24.321	23.648	31.574	24.687	29.321	23.654	23.002	20.365
9000	20.134	28.211	29.256	30.761	26.541	23.995	26.348	23.184	21.781	23.361
10000	19.897	23.145	25.378	27.856	22.364	22.641	25.225	24.621	22.147	20.361
Average Power Output [kW]										

Fig.3.3.2.1 Average Power Output under Different Damping Coefficients at 7s/2.5m regular wave

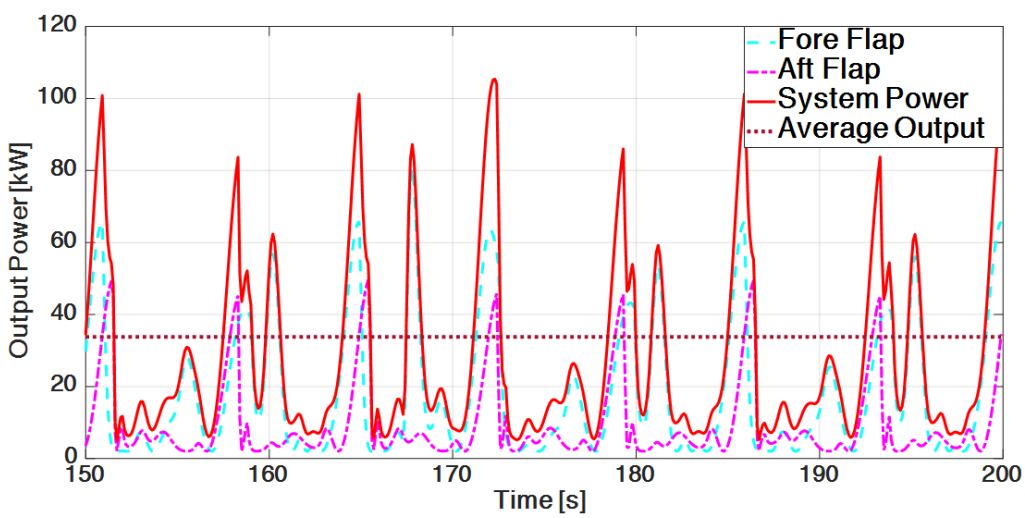


Fig.3.3.2.2 Time-Domain Power of Each Flap and System under Optimized Parameters

3.3.3 Engineering Design and Diagrams

After figuring out system dynamics, optimization and load analysis, we can design the system using the known parameters, as shown in Fig. 3.3.3.1. The flaps are hinged on the feeding buoy and can drive the tethers when they rotate. The tethers are supported by rotors and connected with winches. The conversion and control circuit is between the generator and battery which can not only regulate the input electricity to the battery but also adjust the parameters for the PTO. It shall also note that the proposed flap-type of floating WEC is totally different from the bottom-hinged oscillating surge WEC (like Resolute Marine Energy Inc) which uses horizontal surge waves. In the proposed design, the geometry of the flap will capture both heave and horizontal wave energy using zero-scattering geometric shape by borrowing some ideas from Shape Eagle to achieve a high capture-width ratio.

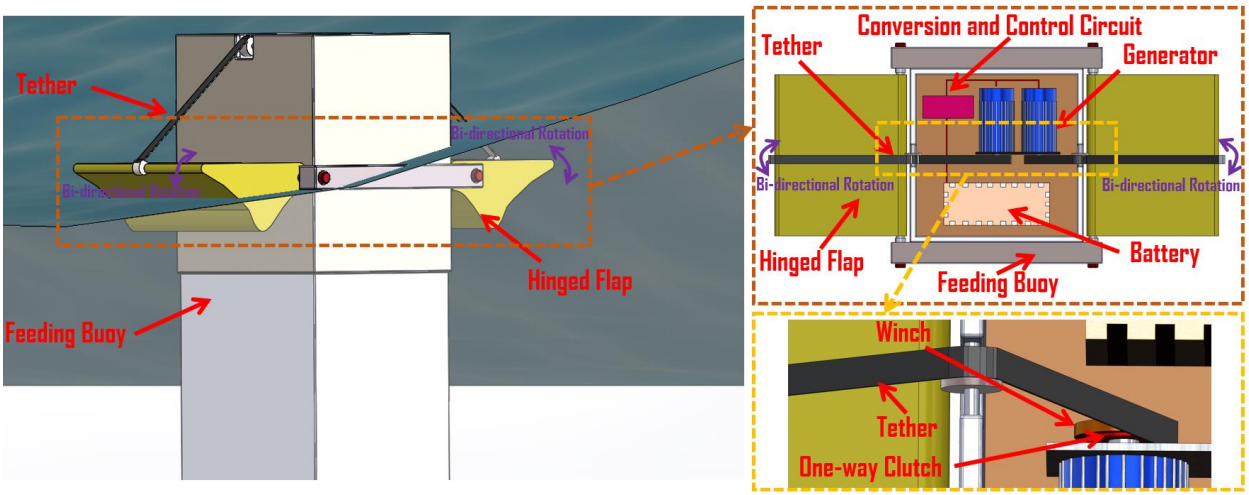


Fig. 3.3.3.1 Mechanical Drawings of the WEC with Feeding Buoy

3.4 Integration and Incorporation

To incorporate environmental and sustainability factors and user's needs, <u>we will collaborate with aquaculture companies to modify the existing feeding buoys and expand the original function of feeding stations to sustainable power generators</u>, as shown in Fig 3.4.1. This design can make full use of the existing feeding buoy and reduce the LCOE. The improved structural dynamics and hydrodynamics of the WEC (Innovation 1) will increase the conversion efficiency from ocean wave energy to mechanical energy; the reliable tether based PTO (Innovation 2), and advanced power electronics (Innovation 3) will improve conversion efficiency from mechanical energy to electric energy; and co-development of the WEC in both mechanical and electrical aspects will significantly reduce the system cost and accelerate its deployment (Innovation 4).

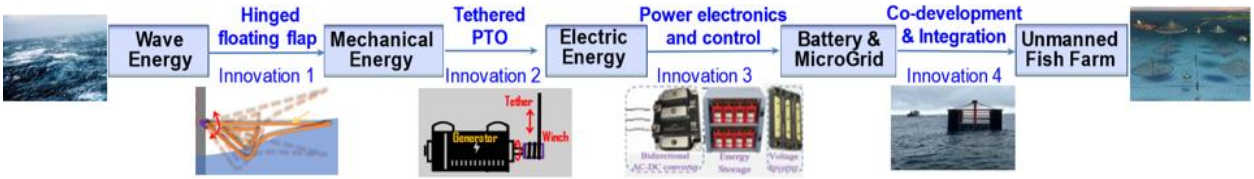


Fig 3.4.1. Power Conversion Chain and Integration

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