DISCLAIMER

Sandia National Laboratories

Co-Located Wave Energy Converter (WEC) and Aquaculture System Annotated Bibliography

Dominic Forbush, Jessica Nguyen, Jeff Grasberger, Megan Anderson

June 2025
SAND2025-08002R

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

This annotated bibliography includes references that could aid in the design of a co-located WEC and aquaculture system off the coast of Guam. The breadth of this work covers multiple co-location archetypes such as:

1. WEC seawater desalination system
    a) Nearshore and deepwater WEC deployment
    b) Onshore and offshore aquaculture
2. WEC powering an offshore aquaculture platform
    a) Nearshore or deepwater WEC deployment
3. WEC powering an onshore aquaculture system
    a) Nearshore WEC deployment
4. Wave powered seawater pump
    a) Nearshore WEC deployment
    b) Onshore aquaculture

There are two archetypes that may be of immediate interest to the community in Guam are to service the existing Fadian Hatchery (Mangilao) and to support freshwater aquaculture activities. First, the seawater pump at the hatchery that fills the facility's seawater storage unit is broken. A nearshore seawater pumping WEC could be a solution to this issue. In addition, due to the high frequency of typhoons/extreme conditions and the island's bathymetry, the likelihood of community support for an offshore aquaculture platform or WEC deployed in deepwater is low. Proactive and resilient solutions not just for power, but for freshwater are of interest as well to support any freshwater aquaculture activities. Therefore, a nearshore WEC desalination system is another archetype to consider.

REFERENCES

[1] K. A. Abhinav, M. Collu, and J. Baquero Gómez, "Multi-purpose ocean energy platforms for offshore aquaculture farms: 3rd International Conference on Offshore Renewable Energy," Aug. 2018. [Online]. Available: https://pureportal.strath.ac.uk/en/publications/multi-purpose-ocean-energy-platforms-for-offshore-aquaculture-far

Abstract: The Blue Growth strategy was laid out by the European Union (EU) in 2012 [1], with a view to realize sustainable development of the blue economy - based on the oceans, seas and coasts. Along the lines of the Blue Growth strategy, the present work investigates the performance of a multi-purpose platform (MPP) for use in an offshore aquaculture farm. The elements of offshore wind and fish feed storage are integrated in the same platform to support the energy demands of closely co-located aquaculture farms, at a location off the Scottish coast, with a water depth of 81 m. The work presented herein is part of the UK-China Investigation of the novel challenges of an integrated offshore multi-purpose platform (INNOMPP) project [2] (EPSRC Grant no. EP/R007497/1).

Notes:

- This study explores the coupling of a 2-bladed AWT-27 turbine on an A650 feed barge model developed by AKVA
- Power requirements gathered from the Rataren fish farm in Norway was used- this facility has peak power consumption of 195 kW. So, not specifically relevant, but power needs are comparable to the Fadian Hatchery
- The results proved favorable in the ability of the turbine to mount the feed barge and provide the necessary energy requirements for the Norwegian facility

[2] G. Ayuso-Virgili, L. Jafari, D. Lande-Sudall, and N. Lümmen, "Linear modelling of the mass balance and energy demand for a recirculating aquaculture system," *Aquacultural Engineering*, vol. 101, p. 102330, May 2023. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0144860923000171

Abstract: This work seeks to understand the predominant drivers affecting energy demand for a recirculating aquaculture system (RAS) by developing a numerical model in Matlab coupled with Aspen HYSYS and validating against measurement data for a case-study site. 15 weeks of RAS operation were simulated to replicate the grow-out of Atlantic salmon (Salmo salar) from 42.5 to 322 g body weight (BW). Data on water quality parameters and the energy demand of the RAS and its equipment were generated. The water treatment loop was automated from Matlab, along with simulation of the fish tanks. Parameters were continuously updated during the quasi-steady dynamic simulation of the RAS and data was stored. Concentrations of oxygen, carbon dioxide, total ammonia nitrogen, total suspended solids and nitrate nitrogen in the fish tanks were recorded for the full 15 week grow-out. The specific energy demand of the RAS was calculated at 9.59 kWh/kg for the full grow-out. In total, 664 MWh were

needed for the complete RAS operation. Coupling Matlab and Aspen HYSYS is a viable method for modelling and simulating a RAS. The presented tool can also simulate abrupt changes in the system (such as a power outage) and resume normal operation once power is restored.

Notes:

- This study applies to any aquaculture system using an RAS, whether that be onshore or offshore. No WEC supplemented power is discussed
- The RAS model needs 4.933 MWh/bay in the beginning and jumps to 6.955 MWh/day when the oxygen cones get turned on. From start to end of the grow out, the system uses 663.8 MWh for Atlantic salmon post-smolts
- This could be useful when trying to quantify energy demands for a WEC pumping into an RAS

[3] M. Badiola, O. C. Basurko, R. Piedrahita, P. Hundley, and D. Mendiola, "Energy use in Recirculating Aquaculture Systems (RAS): A review," *Aquacultural Engineering*, vol. 81, pp. 57–70, May 2018. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0144860917302327

Abstract: Recirculating aquaculture systems (RASs) are intensive fish production systems, with reduced use of water and land. However, their high energy requirement is a drawback, which increases both operational costs and the potential impacts created by the use of fossil fuels. Energy use in RAS has been studied indirectly and/or mentioned in several publications. Nevertheless, its importance and impacts have not been studied. In aiming to achieve economic and environmentally sustainable production a compromise has to be found between water use, waste discharge, energy consumption and productivity. The current review discusses published studies about energy use and RAS designs efficiencies. Moreover, with the aim of making an industry baseline study a survey about the energy use in commercial scale RAS was conducted. The design of more efficient and less energy dependent RAS is presented, including optimized unit processes, system integration and equipment selection. The main conclusions are: fossil based fuels are less cost-effective than renewable energies; energy is of little concern for the majority of the industry, and renewable energies are of potential use in RAS.

Notes:

- This reference does not apply to the co-location of WECs and Recirculating Aquaculture System (RAS) systems, but rather a breakdown of energy use for maintaining water quality throughout a RAS.
- RASs circulate water with pumps to move water to a higher elevation or increase the overall system pressure for filtration, aeration and degassing.
- It was identified that wave and wind could be suitable sources however, due to the energy demand of 13,767 kWh/week. Though out of scope this study provides an analysis for terrestrial renewable energy systems that may could potentially supplement WEC power to an RAS system

- An exploration into different fish species and necessary environment requirements are shown in kWh/kg of fish

[4] R. Boileau, W. Raman-Nair, and M. Graham, “Numerical modelling complements physical testing in staged design of ocean wave-driven pump,” in *2014 Oceans - St. John’s*. St. John’s, NL: IEEE, Sept. 2014, pp. 1–6. [Online]. Available: http://ieeexplore.ieee.org/document/7003281/

Abstract: National Research Council Canada (NRC) is collaborating with College of the North Atlantic (CNA) to develop an ocean wave-driven pump to supply the CNA shore-based aquaculture centre in Lord’s Cove, Newfoundland. NRC provides a combination of physical model testing under controlled laboratory conditions and computer simulation using numerical modelling tools developed at NRC and commercial software. The CNA plans to demonstrate the sustainability of a shorebased aquaculture centre in the context of rural Newfoundland. The efficiency of the centre depends in part on its energy consumption, a major part of which is supplying seawater to a facility some distance from the ocean and above sea level. The development of a seawater supply pump driven by the power of ocean waves would reduce the electrical costs for the centre. The NRC is supporting a staged design program through numerical and physical model testing to select a robust design optimized for the local sea conditions at the Lord’s Cove mooring site. The wave pump is inspired by designs for wave energy converters. But since wave energy converters have not converged on a single design, there are major risks and costs in designing a wave pump, from construction and testing of physical models for competing designs to mooring failure and potential loss of the device in the hurricane-force storms typical of southern Newfoundland. Using lessons learned in the energy sector, risks can be mitigated by systematically testing the behaviour and response of proposed concepts through a staged design program, starting from characterizing the hydrodynamic characteristics of a simplified model through progressively larger, more complex physical and numerical models used in functional tests. This approach systematically directs the design process toward a single prototype optimized for performance in specified wave conditions using scaled model tests in advance of the most costly stage of sea trials. The goals of the staged design program for the CNA wavedriven pump are to evaluate various design concepts, select a design suited to the CNA mooring site, optimize the design for a typical sea state and specify a mooring robust enough to keep the platform on station during the sometimes extreme sea states at Lord’s Cove. The program began with characterization of the chosen mooring site outside Lord’s Cove. Processed wave buoy data from this site informed the estimation of mooring line loads using numerical tools developed by NRC and typical sea states on which to focus design optimization. In the second stage, a numerical tool (a) (b) Fig. 1. Hydrodynamic (non-functional) physical model (a), afloat, and corresponding numerical model (b), meshed, for one platform design concept was developed to estimate pump output and validated against test results for a physical pump. In the third stage, various wave pump platform design concepts were evaluated based on estimation

of hydrodynamic characteristics. The designs were characterized using a combination of physical model tests in the NRC 200metre wave tank in St. John's and computer simulations using Ansys Aqwa and Matlab. A sample pump platform design is shown as a scale model and a numerical mesh in Fig. 1. In the fourth stage, which will precede a full-scale prototype deployment at sea, a design has been selected and an operational scale model wave pump platform has been tested in the NRC wave facilities. Numerical modelling is used to choose a mooring for the full-scale deployment. In this staged design program, the use of physical model tests and computer simulation are complementary methods used alternatively to solve potentially costly and time-consuming problems. A selection of the problems encountered in the design of the wave pump platform is presented along with a critique of the solutions applied by NRC to build confidence in a wave-driven pump design tailored for the CNA site.

Notes:

- This paper is a continuation of "Land Based Multi-trophic Aquaculture Research at the Wave Energy Research Centre"- an in-depth look at the proposed wave-driven pump WEC servicing an onshore integrated multi-trophic aquaculture (IMTA) facility in Canada
- The purpose of this study was to evaluate different WEC and mooring design concepts to deploy at the CNA mooring site. The settles design was similar to a heaving point absorber- except with a double acting pump on board rather than an electrical PTO.
- Many hurdles were documented din this study yet, so the estimated flow rate was not shared.

[5] D. Bouret, R. Walsh, and B. Thorne, "Wave Powered Water Pump." [Online]. Available: https://repository.library.noaa.gov/view/noaa/48496

Abstract: The goal of the project was to finish the construction of a Wave Powered Water Pump (WPWP) from the previous year's work and deploy the system in random seas. The WPWP moves nutrients from a lower depth to the surface in a sustainable way using wave energy to help kelp aquaculture produce at a faster rate. This year the team performed multiple tests in the UNH Chase engineering tank to ensure the system's ability to pump water. Throughout the process of completing construction, the team developed different methods to ensure the WPWP was watertight and that the inner cylinder of the spar was kept from filling with water by testing different options to fill the space with foam. The team deployed and tested the WPWP outside the mouth of the Piscataqua River in New Hampshire in approximately 60 feet of water with the help of the R/V Gulf Challenger. The final system resulted in a flow rate of approximately 2.5 gallons per minute in 1 to 3 foot waves.

Notes:

- This work is the predecessor for Chelsea Kimball's work at UNH.
- This paper demonstrated the seawater pumping buoy in depth with brief

descriptions of the design and preliminary component tank test before deploying off the coast of New Hampshire

[6] T. Bujas, M. Koričan, M. Vukić, V. Soldo, N. Vladimir, and A. Fan, “Review of Energy Consumption by the Fish Farming and Processing Industry in Croatia and the Potential for Zero-Emissions Aquaculture,” *Energies*, vol. 15, no. 21, p. 8197, Jan. 2022, number: 21 Publisher: Multidisciplinary Digital Publishing Institute. [Online]. Available: https://www.mdpi.com/1996-1073/15/21/8197

Abstract: Higher energy efficiency and lower environmental impact have become very important aspects in the evaluation of the design and operation of technical systems. The same goes for the fish farming sector, which continuously aims to reduce its environmental footprint as well as its operating costs. This paper reviews the energy needs of the fish farming sector and their impact on the environment, and discusses the possibilities of improving the environmental friendliness of this sector by employing a higher share of renewable energy sources. The fish farming process is divided into its constitutive phases: fish breeding with associated activities, transportation, and handling of grown fish, together with relevant processes; and final processing and distribution to the customers. For these phases, the energy consumption and associated emissions, depending on the energy source, have been assessed. The parts of the process with the highest potential for the integration of alternative powering options and consequent environmental improvements are identified. The case study deals with the fish farming process in Croatia, for which a set of alternative powering options has been proposed, considering the existing energy supply, i.e., import of fossil fuels and current Croatian electricity mix, as well as renewable energy potential, which is reviewed in the paper.

Notes:

- This paper outlines the potential of col-locating renewable energy sources (RESs) with the cost considerations per kg of fish based on the energy type (wind, solar, bilofuels, etc.)
- This could be a good paper to reference if cost metrics are needed regarding the transition from diesel to electric powered aquaculture processes

[7] J. Cao, J. Liu, X. Liu, C. Zeng, H. Hu, and Y. Luo, “A Review of Marine Renewable Energy Utilization Technology and Its Integration with Aquaculture,” *Energies*, vol. 18, no. 9, pp. 1–29, May 2025. [Online]. Available: https://ideas.repec.org/a/gam/jeners/v18y2025i9p2343-d1648842.html

Abstract: This paper encapsulates the advancements in marine renewables utilization technologies globally, analyzed through the lenses of research emphasis and variations in device mechanisms. The multi-energy complementarity and the integration of marine renewable energy systems with aquaculture technologies are discussed, and the engineering applications are introduced. Tidal energy and offshore wind energy technologies have achieved mature commercial operation, while tidal current energy and wave energy technologies are undergoing full-scale

prototype testing. Temperature-difference energy technology has reached the full-scale prototype testing phase, whereas salinity-gradient energy technology remains in the laboratory verification stage. In recent years, many researchers have conducted engineering measurements, and further breakthroughs are needed in critical enabling technologies and safety measures. From the standpoint of geographical integration, the realization of aquaculture with offshore wind energy and wave energy or tidal current energy is simpler. The integration of aquaculture with marine renewable energy technologies represents a promising avenue for the future development and global utilization of marine energy resources.

Notes:

- Combining marine renewables with aquaculture is identified as a promising strategy, especially with offshore wind, wave, and tidal current energy due to simpler geographic compatibility.
- The paper emphasizes that despite progress, further advances in enabling technologies and safety measures are essential to scale up deployment and unlock broader engineering applications.

[8] Y. Cheng, Y. Hu, D. Yu, S. Dai, Z. Yuan, A. Incecik, and G. Wang, “Hydrodynamic characteristics of a wave energy converter array-offshore aquaculture cage group hybrid system,” *Energy*, vol. 328, p. 136522, Aug. 2025. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0360544225021644

Abstract: Integrating an array of wave energy converters (WECs) with offshore aquaculture cages offers a sustainable solution for meeting daily energy demands while enabling the sharing of mooring systems. This paper investigates this unanswered question by numerically simulating a hybrid system composed of an array pointabsorber WECs and a moored aquaculture cage group. The multi-body and multi-coupling interaction among WECs, mooring chains, cage nets, floating collars and cage sinkers are investigated. The results reveal that, across all simulated wave periods, rear-positioned WECs exhibit higher wave energy conversion efficiency than frontfacing units, primarily due to the reduced constraints imposed by the mooring chains. Compared with taut mooring, the catenary mooring configuration increases wave energy conversion by 50 % in long-period waves and reduces facing-wave mooring tension by 13 %. Under identical physical parameters, square and in-line cage configurations demonstrate superior wave energy conversion performance, whereas front–back arrays induce greater mooring tension. PTO units partially offset the mooring tension, so the optimal PTO damping for WECs in the hybrid system is higher than for isolated WECs and increases along with wave propagation. These findings offer valuable insights for the engineering implementation of renewable energy-offshore aquaculture hybrid techniques in the development of marine ranching.

Notes:

- This paper explores the hybrid co-location of a WEC array installed on the rope frame of a moored offshore aquaculture cage-group. Usually deployed in 20m depth

- The use of taut vs catenary mooring configurations was explored and the use of catenary mooring lines in long period waves increased energy conversion by 50%.
- The front-back array configuration experience the largest maximum energy conversion efficiency

[9] D. Clemente, P. Rosa-Santos, T. Ferradosa, and F. Taveira-Pinto, “Wave energy conversion energizing offshore aquaculture: Prospects along the Portuguese coastline,” *Renewable Energy*, vol. 204, pp. 347–358, Mar. 2023. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0960148123000095

Abstract: This paper seeks to identify promising sites and technologies, in Portugal, for co-located wave energy conversion and offshore aquaculture, whilst providing benchmark implementation references and guidelines to researchers. Accordingly, two case study sites are considered for deployment of five wave energy devices and up to six aquaculture species. A thorough analysis in terms of power ratios, efficiency, redundancy, species viability, device survivability and costs is performed, seeking to find viable co-located solutions. It is found that the Wave Dragon device yields the most promising energy demand coverage and energy output (5 226 to 6 817 MWh/year). Nevertheless, it may require rescaling towards optimal operation, while the OCECO 4 excels in terms of capacity factor (0.24–0.29) and default adaptation to the deployment sites. The WaveRoller® has the lowest single-unit cost (125 €/MWh) but requires up to nine units to cover all the energy demand targets. Larger wave farms are required for the BBDB and AquaBuOY, albeit with potentially greater economies of scale and single-unit redundancy. These sites also enable cultivation of most of the considered species, even under ideal conditions. Lastly, it is recommended that the devices enter survivability mode at a significant wave height threshold of 5.5 m.

Notes:

- This paper explores a variety of WEC archetypes for suitability for co-locating with offshore aquaculture off the Portuguese coastline
- The RM6 Backward Bent Duct Buoy, OCECO, Wave Dragon, AquaBuOY, and WaveRoller were all prospective archetypes in this study and their relative costs
- For this case study, 2 offshore locations (Figueira da Foz and Sines) were considered as well as 4 aquaculture species (oyster, salmon, seabass, and others)and their relevant energy demands/metocean condition to see what feasible pairings could be made
- It was found that the WaveRoller had the lowest LCOE and 2nd best AEP and CR. All species were considered viable at the FF site

[10] D. Clemente, P. Rosa-Santos, and F. Taveira-Pinto, “On the potential synergies and applications of wave energy converters: A review,” *Renewable and Sustainable Energy Reviews*, vol. 135, p. 110162, Jan. 2021. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S1364032120304536

Abstract: Within the scope of a changing energy market, wave energy has yet to reach a level of commercial viability that enables it to become competitive with alternative energy sources, both renewable and non-renewable. Despite the well-known advantages inherent to the resource, there are several challenges that must be overcome before wave energy gains a relevant share of the global energy market. While near-commercial stages of development are still outside the reach of most wave energy converters, it is important to find new perspectives that facilitate the development process and improve the chances of a successful deployment and operation. In this paper, a review of synergetic technologies with the potential for hybridization and/or co-location with wave energy converters is presented. Potential applications of wave energy conversion devices, within the context of nearshore and offshore niche markets that minimize/eliminate, respectively, mainland grid connection and inherent costs are also discussed. It is found that mutual gains can be attained from this complementary approach, namely in terms of infrastructure sharing, critical component protection, introduction of a beneficial shielding effect, energy storage upgrading, coastal erosion mitigation and electricity supply to various marine mobile platforms for different offshore and nearshore activities, amongst others.

Notes:

- This paper outlines the potential co-location of WECs with other activities outside of grid connection
- This could be a good motivational paper to reference behind the reason why co-located WCEs and aquaculture systems are a good idea in layman's terms
- Aquaculture is responsible for 14-16% of Europe's blue economy jobs

[11] E. Dallavalle, B. Zanuttigh, P. Contestabile, A. Giuggioli, and D. Speranza, "Improved methodology for the optimal mixing of renewable energy sources and application to a multi-use offshore platform," *Renewable Energy*, vol. 210, pp. 575–590, 2023. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0960148123004020

Abstract: The increase of Renewable Energy (RE) production to fight the climate crisis is posing new technological and financial challenges, due to the availability and variability of RE Sources (RES). These challenges can be addressed by selecting the most suitable mix of RES to optimise power production, to assure grid resilience and to promote local energy use. To facilitate the selection of such combination, this paper presents an original methodology that allows to compare mixing scenarios with different RES, also in presence of batteries and backup system. It simultaneously optimises the energy surplus with respect to the eventual external electrical load and the missing energy with respect to the same electrical load. This method, which can cope with isolated or plugged-to-grid systems, is here applied to a novel case study, an oil&gas platform under decommissioning, located in the Adriatic Sea (Italy). The RE production from wind, wave and solar panels is supposed to support other activities for the platform reuse, such as aquaculture, monitoring and mineral deposition. In this case, solar energy is

providing the greatest contribution to the optimal mix in terms of production, while wave energy assures the most relevant contribution in terms of continuity.

Notes:

- The paper introduces a novel methodology to evaluate and optimize combinations of renewable energy sources (RES), including scenarios with batteries and backup systems, to balance energy surplus and shortfall relative to demand.
- The approach is applied to a decommissioned oil and gas platform in the Adriatic Sea, repurposed to support activities like aquaculture, environmental monitoring, and mineral deposition using wind, wave, and solar energy.
- In the optimal energy mix, solar provides the highest energy yield, while wave energy contributes most to supply continuity — highlighting the value of hybrid systems for reliability and resilience.

[12] T. K. Das, C. Frost, M. Folley, and P. Brewster, "Application of an energy recovery device with RO membrane for wave powered desalination," *Desalination*, vol. 592, p. 118064, Dec. 2024. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0011916424007756

Abstract: A Wave-Driven Desalination System (WDDS) represents an efficient method for harnessing wave energy to facilitate water desalination. Nonetheless, various challenges impede its path to commercial viability. There is a requirement to connect the WDDS to an Energy Recovery Device (ERD), but this is challenging due to the inherent variations in pressure and flow. This unique study demonstrates the working of a small scale WDDS system using a Spiral Wound Reverse Osmosis (SWRO) membrane with a permeate capacity of ~2 m3/day. The study demonstrates the possibilities to reduce high specific energy consumption (SEC) in WDDS by incorporating a Clark pump as an ERD. The study is the first time an evaluation of an SWRO membrane and Clark pump in-theloop has been evaluated using variable feed flow and pressure. The utilization of the Clark pump notably reduces SEC to about 3.5 kWh/m3, which is comparable to that of commercial desalination plants. Furthermore, the Clark pump aids in maintaining a consistent permeate recovery rate of 10 % under rectified sinusoidally varying flow conditions – representing the operating conditions more closely to that of practical devices.

Notes:

- This study isn't directly applicable to any of the outlines cases, but does serve as a reference point to correct permeate flow if unstable flow rates and pressure are experienced in Guam
- This study discusses the use of a Clark pump and its effect on the performance of an RO membrane
- The inclusion of the Clark pump energy recovery device resulted in a constant permeate recovery regardless of flow rate or pressure

[13] Z. Davonski, "Considerations for a Co-located Aquaculture and Wave Energy Deployment: Quantifying Demand and Assessing Integration."

Abstract: The co-location of marine energy and aquaculture is a concept of increasing value and interest in the United States, as the desire for sustainably produced seafood and renewable energy continues to grow. With both industries being fairly nascent in their national development and facing challenges, the deployment of a wave-powered aquaculture farm requires numerous considerations. This report analyzes the energy demands of an integrated multi-trophic aquaculture system at various farm scales and discusses the preliminary technical, regulatory, and logistical considerations required for a co-located deployment. A pilot-scale deployment is outlined with potentially ideal characteristics, and an optimized planning and permitting approach is introduced.

Notes:

- This study explores the different limiting factors in the United States for a potential co-located WEC and aquaculture system.
- Permitting considerations may pose a potential barrier to entry in the US
- Outlined considerations such as, species type, cage type, from the aquaculture side and resource potential for WECs and ideal potential successful project ideas
- An outlined of permitting considerations in the US are included. This could help aid in creating/understanding Guam permitting procedures

[14] J. Demmer, M. Lewis, P. Robins, and S. Neill, "Evidence of potential synergy between aquaculture and offshore renewable energy," *International Marine Energy Journal*, vol. 5, no. 2, pp. 133–141, Sept. 2022, number: 2. [Online]. Available: https://marineenergyjournal.org/imej/article/view/121

Abstract: Worldwide increased demand for offshore renewable energy (ORE) industries and aquaculture requires developing efficient tools to optimize the use of the offshore space, reducing anthropic pressure. The synergetic development of marine renewable energy infrastructure with mariculture has been hypothesized as a way to reduce costs through shared infrastructure. In the Irish Sea, blue mussels (Mytilus edulis L.) represent 40 - 50 % of the total gross turnover of Welsh shellfish industries and the industry has been operating sustainably for over 50 years in North Wales. However, the region is also attractive for tidal energy projects, with strong tidal currents (> 2m/s) occurring, and offshore wind farms, with shallow waters (approx. 50 m) and consistent winds. In this context, it is of scientific and economic interest to study the potential impact of ORE on shellfish larvae recruitment. A numerical approach has been developed using an Eulerian hydrodynamic model coupled with a Lagrangian particle tracking model, which allowed the simulation of tidal currents, wind-driven currents and larval dispersal. Results show: 1) interannual variability of density distribution of larvae; and 2) strong connectivity between commercial shellfish beds and ORE sites. This study shows the importance of ORE site selection in order to: 1) reduce biofouling on ORE infrastructures and 2) develop multi-use platforms at sea to combine needs for ORE and for mariculture.

Notes:

- This study provides evidence for co-locating ocean renewables and aquaculture processes.
- In the Irish Sea, muscle larvae dispersal is highly dependent on tidal currents and this study documents the seasonal patterns of tidal residuals driven by wind patterns throughout the year, effecting larvae dispersion
- The dispersion of larvae will highly impact biofouling on offshore platforms integrating, in this case, offshore wind platforms with multi-use platforms at sea to decrease O&M costs due to biofouling

[15] F. A. dePeralta, "Assessment of ocean energy systems as a source of energy for a proposed aquaculture ecosystem in Guam," *Renewable and Sustainable Energy Reviews*, vol. 152, p. 111740, Dec. 2021. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S1364032121010121

Notes:

- Applicable to all cases
- This paper explains the preliminary work done on the Guam aquaculture feasibility study at Sandia and PNNL. This could be a useful when referencing previous team efforts and motivation since our white paper created in FY24 is not public.
- Specifically, OTEC and WECs are explored with details regarding the island's bathymetry, locations of interest for marine energy, existing infrastructure considerations on Guam, and minor economic details of OTEC and WECs

[16] L. Fiander, M. Graham, H. Murray, and R. Boileau, "Land based multi-trophic aquaculture research at the wave energy research centre," in *2014 Oceans - St. John's*, Sept. 2014, pp. 1–5, iSSN: 0197-7385. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/7003181

Abstract: The collapse of the Atlantic cod fishery in the 1990s devastated the economies of many coastal Newfoundland communities. While many have survived through a combination of a much reduced fishery, government funding, and off shore or out of province employment, none of these are sustainable long-term solutions. Sea-based aquaculture ("fish farming" in pens) has provided stable employment in some areas, but only where there are suitable sites with protected, deep inlets with significant tidal or river current flushing. These geographic characteristics are not usually compatible with prosecuting the inshore fishery. Sites that were close to the open fishing grounds with minimal near shore currents were prized by the small boat fishers, but wind and wave protection were a secondary concern. Thus there are many towns and villages that are significant distances from ideal sea-based aquaculture sites. While shore-based aquaculture would be possible in many coastal villages, the profitability of the industry is limited by the cost of pumping water to and through the shore based infrastructure. Many existing coastal settlements do have an abundance of energy available in ocean waves. The harnessing of this energy to pump water on shore at low cost will enable the development of profitable shore based aquaculture methods that will provide sustainable long-term economic activity for these communities. Shore-based aquaculture has the additional possibility of containing and directing effluent from the production on one species to another that can use it as a feed source (e.g., fish effluent delivered to filter feeders). This effectively "biofilters" the fish production effluent while producing other marketable product (scallops and seaweed, for example) at little or no extra cost. This paper reports on a research project being conducted by College of the North Atlantic (CNA) in Lord's Cove, Newfoundland, which has the overall goal of developing a sustainable land-based aquaculture system utilizing wave energy. Development of the pump is occurring concurrently with the design, installation and commissioning of a pilot cascaded Integrated Multi-trophic Aquaculture (IMTA) facility in Lord's Cove. In this pilot farm, the effluent from the finfish (the only organisms receiving external feed input) is directed to sea urchin production tanks. From there, water flows to scallop production tanks and finally algae culture. The algae produced is fed to the urchins, who consume this and organic sediment coming from the finfish. The suspended organic particulate in the urchin effluent will nourish the sea scallops, and the algae will reduce the dissolved inorganic load before the water is returned to the ocean (Fig. 1). Until the wave pump development is complete, water for the farm is being entirely supplied by electric pumping. We are currently undergoing scale model and sea based prototype testing of the wave driven pump. As part of the design process for this pump, the wave energy resource and bathymetry at the site was measured and documented. As a result of these activities, CNA now operates the Wave Energy Research Centre (Fig. 2). This facility is now permitted for testing of wave energy absorbers and similar devices: it includes data acquisition (wave environment, weather and device performance monitoring) as well as the necessary infrastructure to support these studies and is ready to host other device developers.

Notes:

- This study explores a nearshore seawater pumping WEC to an onshore IMTA aquaculture facility at the Wave Energy Research Center and College of the North Cove in Newfoundland, Canada
- This paper explains the current needs of the facility and issues with fish fatality due to lack of nutrients, recirculating flow, and temperature.
- The attraction and motivation of this paper is potential operational cost savings using a seawater pumping WEC and a subsequent paper has been released discussing the pilot project referenced in this paper (see "Numerical modelling complements physical testing in staged design of ocean wave-driven pump")

[17] S. Foteinis and T. Tsoutsos, "Strategies to improve sustainability and offset the initial high capital expenditure of wave energy converters (wecs)," *Renewable and Sustainable Energy Reviews*, vol. 70, pp. 775–785, 2017. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1364032116310395

Abstract: Wave energy is a nascent industry characterized by high capital costs, which impede technological development and industry expansion. For this reason, new strategies are required to improve sustainability, reduce cost and enable wave energy harnessing even in low energy seas. Six new strategies that can make commercialization of wave energy more appealing are studied. These comprise the integration of wave energy converters (WECs) in coastal defence; tourism; desalination technology; offshore aquaculture; energy security; and power plants. WECs can axe erosion by half, or even more, in sandy beaches by creating wave shadows in their lee. Therefore, an innovative way to offset WEC high initial capital expenditure is their incorporation in coastal defence, with the added benefit of electricity production. Also, WECs can directly provide pressurized seawater for reverse osmosis desalination plants, thus achieving significant energy, cost and environmental footprint reductions. The touristic trade could also benefit from educational and interpretive displays of the wave energy technology, whilst ecotourism opportunities may arise that could address tourism seasonality. Combined offshore aquaculture facilities with WECs would benefit for reduced installation, operation, and maintenance costs, as well as addressing fossil fuel dependence in aquaculture. Moreover, WECs could be used for mitigating the intermittency of established renewables (solar and wind) and advance their penetration; while a combined WEC- pump hydropower storage scheme could secure the energy supply in remote coastal areas and islands. Finally, WECs could directly supply cooling water intake structures, such as power plants, with the huge amounts of seawater they require for cooling purposes. WEC are also able to provide high purity sterile water for core cooling in nuclear reactors and also support its circulation. For example, WECs can be introduced in coastal nuclear power plants, as to minimize the loss of coolant accident and prevent disasters similar to Fukushima's 2011.

Notes:

- High capital costs hinder wave energy commercialization, especially in low-energy seas, prompting the need for innovative, multi-functional deployment strategies.
- Six integration pathways are proposed to enhance sustainability and reduce costs: coastal defense, tourism, desalination, offshore aquaculture, energy security, and power plant support.
- WECs offer dual benefits in several applications — for example, reducing beach erosion while generating electricity, or supplying pressurized seawater for desalination.
- WECs can support critical infrastructure, such as stabilizing renewable energy supply with storage systems and providing cooling water or sterile water circulation for coastal power and nuclear plants.

[18] M. C. Freeman, L. Garavelli, E. Wilson, M. Hemer, M. L. S. Abundo, and L. E. Travis, "Offshore Aquaculture: A Market for Ocean Renewable Energy (OES)," Apr. 2022.

Notes:

- This extensive OES report outlines previous offhshore aquaculture and WEC co-location projects and their lessons learned, challenges with co-location offshore, and recommendations such as regulatory process suggestions and economic impact.

[19] L. Garavelli, M. C. Freeman, L. G. Tugade, D. Greene, and J. McNally, "A feasibility assessment for co-locating and powering offshore aquaculture with wave energy in the United States," *Ocean & Coastal Management*, vol. 225, p. 106242, June 2022, publisher: Elsevier. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0964569122002186

Abstract: Offshore aquaculture and marine renewable energy (energy from waves, tides, currents, and ocean gradients) are two developing ocean-based industries. Aquaculture, an industry that has typically relied on diesel for power, is expected to grow globally, presenting an opportunity to reduce greenhouse gas emissions by switching to renewable sources as it expands. As the aquaculture industry moves further offshore and is situated in more energetic environments, the prospect to co-locate offshore aquaculture with wave energy increases. To improve understanding of this potential, a feasibility assessment was completed to estimate the energy needs and wave resource required to power offshore finfish aquaculture operations. The study found it is possible to power offshore aquaculture operations entirely with wave energy. A spatial analysis was then performed to assess the suitability of co-locating offshore finfish aquaculture and wave energy off California and Hawaii. Suitable locations were identified offshore of O'ahu, Hawaii, and northern California. Southern California was also assessed, using a lower wave resource, based on study areas evaluated by the National Oceanic and Atmospheric Administration to identify Aquaculture Opportunity Areas, and while limited there are suitable locations that may warrant further evaluation. This study presents an analysis into the potential to pair wave energy with offshore aquaculture, and how various factors can help determine suitable areas for co-location. The methods developed in this study will support future identification of potential sites for development and decision-making to optimize the success of co-locating wave energy resources and offshore finfish aquaculture.

Notes:

- This study is applicable to offshore aquaculture platforms and nearshore/coastal aquaculture in Hawaii and California
- Spatial and resource assessments, regulatory and logistical factors, military zones, ports, benthic habitat, and critical species habitat is considered when scoring the suitability of co-location areas,
- The assumed estimated energy demand of an offshore platform is 700kWh/day in this study

[20] A. Gharechae, A. Abazari, and K. Soleimani, "Performance assessment of a combined circular aquaculture cage floater and point absorber wave energy converters," *Ocean Engineering*, vol. 300, p. 117239, 2024. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0029801824005766

Abstract: Aquaculture cages must remain stable under wave forces. Also, they need electrical power for the operation of some devices. This study aims to equip the cage's floater with point absorber wave energy converters (PAWECs) to harvest energy and subsequently reduce its vertical motions under regular linear water waves. The floater's hydrodynamic behavior is modeled using slender body theory and matched asymptotic expansions. The governing equation of Euler-Bernoulli's curved beam theory combined with the equation motion of the PAWECs is utilized for the structural modeling of the floater. The calculated vertical displacement of the floater at the location of the PAWECs is used to determine the generated power. The influence of effective parameters on the generated power such as wavenumber, floater bending stiffness, number of PAWECs, and their specifications such as stiffness and damping coefficients are examined. The results indicate that by installing the PAWECs with proper specifications on a cage with a main radius of c = 18.75 m, the time-average of power around 7.5 kW per square amplitude of the incident waves can be achieved while the floater displacements reduced by 40-60 % . As a result, combining PAWECs with cages is a good strategy for reducing structural vibrations as well as energy harvesting.

Notes:

- This paper investigates the potential for integrating point absorber WECs with the floats around an aquaculture cage in order to harvest energy and reduce float motion.
- When the floats move up and down, they react against a WEC/PTO system with damping and stiffness connected by a rod underwater to a below surface weight (doesn't move much).
- The study found that the peak power occurs within expected wave conditions and the largest number of WECs considered (8) was able to produce most power, achieving the target power output of 15 kW/m^2 of wave amplitude.
- The addition of WECs was also found to successfully reduce vertical displacements of floaters which are cited as critical issues causing high tensions in mooring lines, nets, and joints.
- This paper is valuable as it suggests a potential design for which WECs can be synergistically integrated directly with an aquaculture system. It also provides sources for critical issues related to high tensions which may be able to be mitigated by wave energy.

[21] C. M. Gonzales, S. Chen, and H. E. Froehlich, "Synthesis of multinational marine aquaculture and clean energy co-location," *ResearchGate*, Oct. 2024. [Online]. Available: https://www.researchgate.net/publication/383080541 Synthesis of multinational marine aquaculture and clean energy co-location

Abstract: Marine co-location, i.e., multiple fixed ocean activities operating in the same place and at the same time, can maximize the space- and resource-use efficiency in crowded seascapes. While interest grows, commercial use is nascent and the collective benefits or limitations of co-locating aquatic food and clean energy remains scattered throughout the literature. In this study, we synthesize multinational findings of co-location scientific publications (N = 102) to better understand the patterns and knowledge gaps at the co-located ocean food-energy nexus. We track and compare food (aquaculture) and energy (tidal, offshore wind, and wave) co-located ocean activities, noting the focus (e.g., ecological), motivation (e.g., impact/risk), and assessment type (e.g., modeling), as well as nine key metrics of interest (depth, distance from shore, aquaculture yield, etc.), mainly for aquaculture co-location. We found the number of annual co-location publications increased over time and space but are largely concentrated in the North Sea (n = 39). We also found about half of publications include aquaculture, one-third of publications report at least one metric – reporting aquaculture yield was particularly rare (n = 1) – and few studies focused on impact/risk (n = 7). However, conducting a targeted post-hoc evaluation of North Sea gray literature (N = 61), due to this region's importance in the field, showed more coverage of impacts/risk (e.g., liability) and similar attention to aquaculture. Of the scientific papers that did report metrics, the ranges of depth and distance exceeded those reported for standalone sectors, indicating co-location could be facilitating a "push" of ocean activities into farther offshore and/or deeper exposed waters. Ultimately, while aquaculture is commonly cited in the co-location literature, the shortage of metrics, like aquaculture yield, and possible impact/risk evaluations – though gray literature can provide critical insights – emphasizes the need for knowledge sharing and modeling to address and explore the uncertainty, especially for co-located aquaculture production. This study provides a needed snapshot of marine colocation, particularly in emerging regions, highlighting gaps in understanding aquaculture-energy potential in the oceans.

Notes:

- This reference is a culmination of studies from around the world that explored co-located WECs (and other renewables) and aquaculture systems.
- Though not directly applicable to our work, it good be a good place to find more references if need be,

[22] A. Hasankhani, R. McCabe, G. Ewig, E. T. Won, and M. N. Haji, "Conceptual design and optimization of a wave-powered offshore aquaculture farm," ser. International Ocean and Polar Engineering Conference, vol. All Days, 06 2023, pp. ISOPE–I–23–112.

Abstract: In this paper, we present the conceptual design of a wave-powered aquaculture farm (WPAF), in which a wave energy converter (WEC) is co-located with a salmon aquaculture farm in the Northeast United States. We employ an optimization algorithm to minimize cost-per-yield (USD/kg fish) for the WPAF system and investigate the tradeoffs between different design variables in the proposed conceptual design. The optimization algorithm adjusts the geometry of the WEC, the size of the net pens in the aquaculture farm, and the fish stocking density for a specific installation site. Our results highlight key drivers for the viability of a WPAF based on deployment locations and sensitivities to these drivers.As the world's population continues to grow, aquaculture—with its ability

to produce high-quality low-emissions protein without any specific need for land, freshwater, or fertilizer—will play a necessary role in ensuring adequate food supplies. Competition for near-shore space, episodes of poor water quality, and environmental considerations have motivated farmers to move their operations further offshore (Gentry et al., 2017). However, a disadvantage of aquaculture farms is that energy needs, such as for nutrient disbursement, are mostly met by diesel generators (U.S. Department of Energy, 2019). Preliminary research has shown that it may be feasible to replace fossil-fuel power generation at offshore aquaculture farms with wave energy converters (WECs), thereby enabling the aquaculture farm to be self-powered by renewable energy. This approach has been highlighted by the U.S. Department of Energy (DOE) as one near-term application for marine renewable energy resources to power the Blue Economy (LiVecchi et al., 2019). The DOE defines the Blue Economy as "the sustainable use of ocean resources for economic growth, improved livelihoods, and jobs while preserving the health of ocean ecosystems" (LiVecchi et al., 2019).Given that WEC technology is immature and offshore aquaculture is an emerging market in the U.S., there is an opportunity to co-design the two systems for a wave-powered aquaculture farm (WPAF). The existing literature shows several recent studies assessing the co-location of WECs with aquaculture farms. Garavelli et al. (2022) studied the feasibility of co-locating offshore aquaculture farms with wave energy devices in the U.S. They identified California and Hawaii to be suitable sites based on the estimated wave energy resources and aquaculture farm energy needs. Clemento et al. (2023) found potential sites of different types of WECs co-located with offshore aquaculture farms along the Portuguese coast. Their study revealed more details about the design requirements of WPAFs but did not provide a systematic approach for the optimal design of a WPAF. Albatern, a Scottish wave energy developer, is investigating the possibility of using its WaveNET devices to power an offshore finfish aquaculture farm (Campbell, 2017). In China, the Guangzhou Institute of Energy Conversion designed a semi-submersible open-sea finfish farm powered entirely by wave and solar energy (Ma et al., 2022).

Notes:

- A multi-variable optimization algorithm was employed to explore trade-offs between energy production, farm layout, and operational costs.
- The viability of WPAFs is highly sensitive to site-specific factors like wave climate and distance from shore.
- The study identifies key design drivers and constraints that influence both energy generation and aquaculture productivity.
- It emphasizes the importance of co-designing energy and aquaculture systems rather than retrofitting one to the other.

[23] C.-K. Kim, J. E. Toft, M. Papenfus, G. Verutes, A. D. Guerry, M. H. Ruckelshaus, K. K. Arkema, G. Guannel, S. A. Wood, J. R. Bernhardt, H. Tallis, M. L. Plummer, B. S. Halpern, M. L. Pinsky, M. W. Beck, F. Chan, K. M. A. Chan, P. S. Levin, and S. Polasky, “Catching the Right Wave: Evaluating Wave Energy Resources and Potential Compatibility with Existing Marine and Coastal Uses,” *ResearchGate*, Dec. 2024. [Online]. Available:

https://www.researchgate.net/publication/233396952 Catching the Right Wave Evaluating Wave Energy Resources and Potential Compatibility with Existing Marine and Coastal Uses

Abstract: Many hope that ocean waves will be a source for clean, safe, reliable and affordable energy, yet wave energy conversion facilities may affect marine ecosystems through a variety of mechanisms, including competition with other human uses. We developed a decision-support tool to assist siting wave energy facilities, which allows the user to balance the need for profitability of the facilities with the need to minimize conflicts with other ocean uses. Our wave energy model quantifies harvestable wave energy and evaluates the net present value (NPV) of a wave energy facility based on a capital investment analysis. The model has a flexible framework and can be easily applied to wave energy projects at local, regional, and global scales. We applied the model and compatibility analysis on the west coast of Vancouver Island, British Columbia, Canada to provide information for ongoing marine spatial planning, including potential wave energy projects. In particular, we conducted a spatial overlap analysis with a variety of existing uses and ecological characteristics, and a quantitative compatibility analysis with commercial fisheries data. We found that wave power and harvestable wave energy gradually increase offshore as wave conditions intensify. However, areas with high economic potential for wave energy facilities were closer to cable landing points because of the cost of bringing energy ashore and thus in nearshore areas that support a number of different human uses. We show that the maximum combined economic benefit from wave energy and other uses is likely to be realized if wave energy facilities are sited in areas that maximize wave energy NPV and minimize conflict with existing ocean uses. Our tools will help decision-makers explore alternative locations for wave energy facilities by mapping expected wave energy NPV and helping to identify sites that provide maximal returns yet avoid spatial competition with existing ocean uses.

Notes:

- This study explores the wave resource off the coast of Vancouver Island, Canada using buoy and hindcast data.
- This paper doesn't seem to be that useful for offshore or onshore culture aquaculture. It is a great reference for avoiding use conflict regarding the different offshore fishing areas in Canada. Could be a good general reference regarding how to go about assessing areas of interest in Guam that have the least area conflict.

[24] C. Kimball, "Evaluation of a Wave Powered Water Pump Performance by Ocean Field Testing and WEC-Sim Modeling."

Abstract: A rising demand for macroalgae (or seaweed) has led researchers to seek out methods of increasing macroalgae aquaculture yields. Macroalgae is a food product, and may be used in biofuel, animal feed, and fertilizer. Applying upwelling technology to macroalgae aquaculture has been shown to increase biomass yield. A wave-powered upwelling device (or water pump) generates cold, nutrient-rich water flow to the surface of an aquaculture operation. A wave pump device developed at University of New Hampshire was refurbished and outfitted with instrumentation to determine its performance. Testing in the laboratory on both the device and instrumentation was conducted to prepare for field testing. An ocean field deployment of the device was conducted in March 2023. Five days of high-quality data were produced, revealing a maximum average flow rate of 16.5 gallons per minute, in corresponding average sea state conditions of 2.2 feet significant wave height and 5.9 second period. The maximum efficiency of the device over the course of deployment was estimated at 0.5%, which is an indicator that the current design is undersized for the tested wave conditions. A WECSim numerical model of the wave pump was created, and validated using the field data. Comparing the average WEC-Sim model data to the field data resulted in a percent difference of approximately 19% for flow rates, 22% for stroke heights, and 16% for stroke periods, which is considered a successful model validation. A conceptual design for a modified, improved wave pump was generated, where increased flow rate and drawn depth were the motivating specifications. The modified design was modeled using WEC-Sim, which produced an average flow rate of 119.6 gallons per minute, and an efficiency of 4.8%. Determining and improving the efficacy of wave pump devices to benefit macroalgae production is a developing effort.

Notes:

- This study is applicable to the nearshore pumped seawater case
- Every aspect from modeling, design, testing, deployment, and model verification are discussed in this study.
- Overall, important procedures such as installation method off the coast of Appledore Island, Maine are explained as well as the test plan for this deployment such as biological assessment, NEPA consulting, and safety considerations
- A WEC-Sim model is presented and verification with field data is presented. These data and MATLAB files exist in MHKDR
- It was found that the relationship between significant wave height and flow rate of the device is a second order relationship

[25] C. Kimball, M. R. Swift, and M. Wosnik, "Wave-powered water pump for upwelling in aquaculture: Numerical model and ocean test," *Renewable Energy*, vol. 239, p. 122040, 2025. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0960148124021086

Abstract: Wave-powered upwelling can increase the productivity and survivability of several aquaculture species. This enhancement is due to transporting cold, nutrient-rich ocean water, typically found lower in the water column, to the surface. Macroalgaes, like kelp, exhibit increased growth from these altered conditions. The University of New Hampshire's (UNH) wave-powered water pump (wave pump) is a point absorber wave energy converter (WEC) that uses ocean waves to create relative motion between a spar buoy and a concentric float which drives an internal pump. A numerical model of

the wave pump was developed using WEC-Sim to predict device performance in the ocean. Wave pump performance was evaluated during a five day ocean test near Appledore Island in Maine in March 2023, where volumetric flow rate, relative distance between spar and float, and wave conditions were measured. These data were then used for numerical model validation. The ocean deployment recorded the device's performance in a variety of sea states, with average significant wave heights up to 0.7 m. The ocean test data were compared to the WEC-Sim numerical model of the device with favorable results. Average values of device stroke period, stroke height, and flow rate agreed between the ocean test and model data to within approximately 16 to 22%. The validated numerical model provides a valuable tool for improving the design and developing a commercial-scale, wave-powered water pump for use in aquaculture.

Notes:

- Cites sources that regarding water upwelling and its ability to increase productivity and survivability for kelp species. These sources can be valuable for understanding the impact of upwelling (a potential application of WECs) on aquaculture.
- The study proposes a two body point absorber with an internal wave pump that draws water in during the upstroke and pumps it upward during the downstroke.
- WEC-Sim was used to model the WEC and water pumping PTO system according to the derived equations. The model is available on MHKDR and can be valuable for developing future models for wave powered seawater pumping.
- Ocean testing was completed off the coast of Maine and allowed for stroke length and produced flow rate to be examined. An average flow rate of 3.8 m^3/hr was generated.
- Ocean testing data was also used to validate WEC-Sim model and the WEC-Sim model was used to demonstrate the potential for design improvements (e.g., increasing pump diameter can increase flow rate by 10x).

[26] Y. Kinoue, N. Shiomi, M. Sakaguchi, H. Maeda, M. Alam, S. Okuhara, and M. Takao, "A pump system with wave powered impulse turbine," in *IOP Conference Series: Earth and Environmental Science*, vol. 240, no. 5. IOP Publishing, 2019, p. 052009. [Online]. Available: https://iopscience.iop.org/article/10.1088/1755-1315/240/5/052009/meta

Abstract: Japan is surrounded on all sides by the sea. Thus, ocean development has been carried out in the midst of environmental protection. In this consequence, a numerous researches have been conducted on various apparatus that can utilize the wave energy. In this study, a pump system based on the wave energy was developed for pumping the seawater, the facility uses (e.g. aquarium, swimming pool with seawater, etc...), the preservation of farming conditions of marine products, and the replacement of seawater by pumping of the deep water. A radial pump that can be operated by an impulse turbine used for wave energy conversion was developed. The performance of this pump system was investigated

experimentally. From the experimental results, the pump system could be started approximately in 20 seconds.

Notes:

- This paper proposes an oscillating water column (OWC) WEC that turns a turbine which powers a pump to pump water to a reservoir.
- An experiment is documented in which reciprocating airflow drives the turbine which drives the pump. The pump successfully pumps water to reservoir at the expected air speeds.
- The time required to reach steady state was found to be similar regardless of flow velocity.

[27] B. Kirke, “Enhancing fish stocks with wave-powered artificial upwelling,” *Ocean & Coastal Management*, vol. 46, no. 9, pp. 901–915, Jan. 2003. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S096456910300067X

Abstract: Ocean fisheries are declining worldwide due to overexploitation. Productivity could be enhanced and the problem alleviated by pumping nutrient-rich deep ocean water (DOW) to the surface to feed phytoplankton, the bottom end of a marine food chain, mimicking natural upwelling which sustains the most productive ocean fishing grounds in the world. Various pump types and power sources have been proposed for this purpose. The present article proposes a simple wave-powered pump to demonstrate the concept cost-effectively at prototype scale. Possible solutions to the problems of dilution and plunging of dense, nutrient-rich DOW are discussed. Two further possible benefits of this proposal are discussed: by extracting wave energy, relatively calm fishing grounds may be created close to markets, and by pumping up very large quantities of cold DOW, the surface temperature could be lowered enough to reduce coral bleaching on parts of the Great Barrier Reef.

Notes:

- This study explores the current limitations and potential improvemnts of a seawater pumping WEC (artificial upwelling) for deepwater uses
- Wave-powered inertia pumps are an idea that has been explored in the literature before. But to achieve a 50 m^3/s flow rate for optimal growth benefits form upwelling, a larger device will have to be designed and suitable to withstand extreme conditions, though it make be difficult with the size of the device’s upwelling tube (300-600m long)
- A new inertia pump design is explored with 4 improvements: 1. move the non-return valve to the bottom of the tube 2. use 3 tubes in a tripod formation 3. change the tube material to flexible fabric and 4. explore other wave archetypes for this application

[28] M. Lange and V. Cummins, “Managing stakeholder perception and engagement for marine energy transitions in a decarbonising world,” *Renewable and Sustainable Energy Reviews*, vol. 152, p. 111740, Dec. 2021. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1364032121010121

Abstract: There is a growing body of scholarship on the enabling conditions for energy transitions in various energy contexts globally. Transition measures need to address the concerns of communities that will host renewable energy infrastructure. Despite this, the consequences of energy transitions at the community level and in coastal environments have not received adequate attention. The case of the Corrib Gas field development in Ireland provides valuable insights into stakeholder issues surrounding strategic infrastructure developments. Material from case study work with over 70 stakeholders in a rural coastal region in Ireland's West is used to identify the cause of disputes in energy governance. The study shows that economic development is strongly linked to the cultural fabric, not just of the country, but of the locality. Here, a lack of trust of those in power had an influence on the conflict. The appointment of a mediator as an honest broker was a tipping point towards diffusion of tension and an adaptive response by all parties. The establishment of a body with a mandate to evaluate the application of ethical rules, based on good governance principles, is suggested as an option for a refined governance model. The insights are relevant for the energy transition in jurisdictions around the world. Given the urgent need for decarbonisation and the potential for marine renewable energy, lessons from the past, as documented in this paper, can help to inform better governance of common pool marine resources. This is increasingly important for the industrialisation of marine renewable energy and the need to reconcile the interests of government, industry and civil society.

Notes:

- This paper isn't directly applicable to a co-located WEC and aquaculture facility archetype
- This could be useful when understanding the needs of the community in Guam and serve as a guide on how to navigate gathering and incorporating stakeholder feedback in a potential co-located WEC and aqualture project with the referenced case study in Ireland.

[29] M. D. Lee, E. L. K. Feng, and P. Lee, "Small scale low height wave energy seawater pump for achieving environmental and economic sustainability," *Universal Journal of Mechanical Engineering*, vol. 8, no. 1, pp. 14–20, 2020. [Online]. Available: https://www.researchgate.net/publication/368068117

Abstract: This study aims to design and develop a seawater pump powered by low height sea wave at near shore region for delivering high pressure saline water to on shore region which is in line with the global renewable energy quest. Malaysia is blessed with the geographic location of surrounded by sea which enable this technology to be utilized. The challenge in utilizing such technology is due to the nature of the sea wave surrounding Malaysia that is classified as low height sea wave which increase the difficulty in utilizing such technology in neither electricity generation nor sea water delivery. On top of that, there is limited study available in this area especially low wave height. The prototype is designed based on point absorber concept with piston type pump configuration for water delivery. The prototype is then tested at the Mukah Beach with average recorded wave height of less than 1m. Findings demonstrated that a single prototype pump can deliver maximum pressure head of 10m with maximum flow of 1.2Litre per minute (LPM). For three pumps connected in series, the maximum pressure head can reach up to 25m pressure head with maximum flow rate of 1.5LPM. Similarly, when connected in parallel, the system capable to deliver up to 14m of pressure head and 3LPM of flow rate. It is highly recommended for future study the prototype to be pair together with more similar pumps in series or parallel configurations to form a system of pumps to create higher flow and higher head for more application. This study concludes that the designed and developed prototype is useful for delivering saline water for various application such as seawater desalination or electricity generation in near shore area.

Notes:

- Development of a WEC in Malaysia to pump seawater using energy from low height waves.
- The concept is a small array of point absorber WECs that are inspired by the design of a hand water pump. The forces from the waves move the floats up and down and the multiple intake valves take in seatwater as the floats rise and one output valve delivers pressurized water as the floats fall.
- The intended purpose is to deliver water to a reservoir which can be used as needed for traditional hydropower.
- The test results in open water show the system is able to pump up to a water pressure of 25 m head and up to 3 liter per minute flow rate.

[30] L. Li, C. Ruzzo, M. Collu, Y. Gao, G. Failla, and F. Arena, "Analysis of the coupled dynamic response of an offshore floating multi-purpose platform for the blue economy," *Ocean Engineering*, vol. 217, p. 107943, 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0029801820308982

Abstract: A multi-purpose platform is an offshore system designed to serve the purposes of more than one offshore industry. Within the context of "The Blue Growth Farm" project, an innovative multi-purpose configuration, comprising a wind turbine, wave energy converters, and an internal pool to accommodate aquaculture fish cages, has been proposed. The present work proposes a framework to assess the coupled dynamic response of the multi-purpose platform in realistic environmental conditions. A simplified parametric analysis of the structure is first carried out to propose a preliminary design of the platform. The preliminary design is subsequently investigated through hydro-elastic and aero-hydro-servo-elastic coupled analyses. Modal analysis is performed through a 3D finite-element structural model. It confirms the feasibility of rigid-body hypothesis for the dynamic analysis of the support structure and manifests that the vibration modes of the structure are not excited by wave or wind loads. In order to assess the coupled dynamic responses, an aero-hydro-servo-elastic coupled numerical model is developed. The motion and structural responses in operational and survival states are investigated. A modified mean up-crossing rate method has been employed to assess the ultimate limit state. The results obtained from the present research confirm the technical feasibility of the proposed configuration and provide a reference for further studies on similar concepts.

Notes:

- The study presents a novel offshore platform combining a wind turbine, wave energy converters, and aquaculture fish cages — developed under the Blue Growth Farm project.
- Modal analysis using a 3D finite-element model confirms that the platform behaves as a rigid body, with vibration modes not significantly excited by wave or wind loads.

[31] C. C. K. Liu and Q. Jin, "Artificial upwelling in regular and random waves," *Ocean Engineering*, vol. 22, no. 4, pp. 337–350, May 1995. [Online]. Available: https://www.sciencedirect.com/science/article/pii/0029801894000194

Abstract: Mathematical modeling conducted in this study evaluated the hydrodynamic performance of a wave-driven artificial upwelling device in ocean waves off the Hawaiian islands. The device consisted of a buoy (4.0 m in diameter) and a tail pipe (1.2 m in diameter, 300 m in length) with a flow controlling valve. Random ocean waves off the Hawaiian islands used in the device's modeling analysis were synthesized from a wave spectrum obtained from available data. For comparison, the device's performance was also evaluated in regular waves whose height and period are the same as the significant wave height and wave period of random Hawaiian waves. Modeling results indicated that an upwelling flow of 0.95 m3/sec can be generated by this device in random Hawaiian waves and an upwelling flow rate of 0.45 m3/sec can be generated in regular waves. A simple mathematical model which assumed that the device exactly follows the incident waves was used in previous studies. Analysis results also indicated that the simple model cannot satisfactorily simulate the relative velocity and acceleration of the water column in the device. Since the relative velocity and acceleration are important factors in determining the rate of upwelling flow, the simple model must be applied with caution.

Notes:

- This study is applicable to the offshore pumped seawater case study (assuming 300m upweller pipe length)
- Using a mathematical model, an upwelling flow rate of 0.95m^3/s which is better than the predicted 0.45 m^3/s that can be generated in random waves off the coast of Hawaii.
- This paper was written in 1994 and notes that efficiencies assumed in this study where less than what the upwelling device is actually capable of. Assuming since this was written, efficiencies have increased even more

[32] C. C. Liu and H.-h. Chen, "Conceptual Design And Analysis Of A Wave-driven Artificial Upwelling Device," in *OCEANS 91 Proceedings*, vol. 1, Oct. 1991, pp. 406–412. [Online]. Available: https://ieeexplore.ieee.org/document/613966

Abstract: Conceptual design and analysis of a wave-driven artificial upwelling device were conducted in this study. This study is part of a larger reserach effort of the University of Hawaii, the ultimate goal of which is to develop technology for commercially feasible open ocean mariculture using deep ocean water. The feasibility of using this device to bring up deep ocean water was investigated. Research results indicate that the maximum upwelled flow from a given ocean depth can be achieved by proper coordination of natural frequencies of the upwelling device and the ambient ocean wave.

Notes:

- This paper is applicable to the deepwater WEC (in this study, minimum deployable depth is 300m) supplying nutrient-dense pumped seawater onshore or to an offshore aquaculture platform
- The conceptual design of an upwelling WEC is discussed, yet kinematic principles for pumped seawater could be used to understand the pumped water capacity of a WEC on Guam
- This study examines WEC performance in terms of flow rate in 3m wave height and 10s wave period.

[33] J. Mi, X. Wu, J. Capper, X. Li, A. Shalaby, U. Chung, R. Datla, M. Hajj, and L. Zuo, "Ocean Wave Powered Reverse Osmosis Desalination: Design, Modeling and Test Validation," *IFAC-PapersOnLine*, vol. 55, no. 37, pp. 782–787, 2022. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S2405896322029202

Abstract: Development of alternative freshwater via desalination can address water scarcity and security. Meanwhile, sustainable renewable energy sources are critical to economically realize seawater desalination. Marine renewable energy has tremendous potential to power blue economy and is co-located with seawater. This paper proposes a compact autonomous ocean-wave-powered reverse osmosis (RO) desalination system by directly pressurizing seawater using a wave energy converter (WEC). The proposed ocean-wavepowered reverse osmosis desalination system consists of an oscillating surge wave energy converter (OSWEC) hinged on the nearshore seabed with a self-rectified piston pump and a RO desalination module on the shore. Seawater is pressurized by the WEC and pumped to the RO desalination module as feed where it then produces permeate that is free of undesired molecules and larger particles. Numerical modeling of the integrated system is created, and simulation is done under realistic irregular wave conditions. Preliminary experiment was implemented in a wave tank. Both simulation result and experiment results reveal the promising integration of ocean wave energy and RO desalination.

Notes:

- This paper is applicable to a nearshore desalination WEC case study, though the co-location of aquaculture is not considered
- This paper explores the design concept of an OSWEC with an onshore RO desalination membrane with an accumulator that is fed by ta piston pump located at the hinge of the OSWEC

- The piston acts as a double-acting pump so there could be consistent water flow to the RO membrane.
- A WEC-Sim numerical model of the system was executed to understand the pressure and permeate flow rate wrt time before running a preliminary experiment. A 95% mode confidence interval was observed
- It was found that the instant extreme pressure of the system did occasionally exceed 200bar which could damage the RO membrane.

[34] V. Ramos, G. Giannini, T. Calheiros-Cabral, P. Rosa-Santos, and F. Taveira-Pinto, "An Integrated Approach to Assessing the Wave Potential for the Energy Supply of Ports: A Case Study," *Journal of Marine Science and Engineering*, vol. 10, no. 12, p. 1989, Dec. 2022, number: 12 Publisher: Multidisciplinary Digital Publishing Institute. [Online]. Available: https://www.mdpi.com/2077-1312/10/12/1989

Abstract: In recent years, seaports have faced increasing pressure to transition towards a low-carbon and more sustainable energy model. In this context, the exploitation of the local wave energy resource may appear as a promising alternative. Therefore, the objective of this work is to present a methodology to select the best WEC-site combination to supply the energy demands of ports. To illustrate this methodology, the Port of Leixões (Portugal) is used as a case study. For the selection of wave energy sites in port areas, the methodology proposes a detailed spatial characterisation of both the wave resource and marine uses. For the area of study, having considered the main marine uses (sediment disposal, biodiversity, aquaculture, recreational and navigation), two exploitable wave energy sites (Areas I and II) with average annual energy resources of 24 and 17 kWm-1, respectively, were found. Next, the methodology proposes a techno-economic optimisation of WECs, based on the local wave conditions of Areas I and II, to minimise their associated Levelised Cost of Energy (LCoE). The results obtained confirm the effectiveness of the methodology, with the novel oCECO device, appearing as the most feasible option (with an LCoE of EUR 387.6/MWh) to exploit the wave potential in the surrounding areas of the port.

Notes:

- This study explored the energy consumption of the ports of Porto, Portugal and how it can be supplemented by WECs.
- Though not directly relevant to aquaculture, but the nearshore aspect with a known energy demand could be useful for the case of Guam
- Port characteristics, such as location, typology, orientation of coastal defense structures, energy consumption patterns and local maritime activities are considered along with extensive cost breakdowns
- OpEx was considered to be 5% of CaoEx in this study, though nearshore WECs are expected to have lower O&M costs

[35] S. Roberts, D. Howe, and J.-R. Nader, "Performance Feasibility of a Multi-Source Offshore Renewable Energy Platform for Aquaculture." [Online]. Available:

https://www.researchgate.net/publication/374140005 Performance Feasibility of a Multi-Source Offshore Renewable Energy Platform for Aquaculture

Abstract: The global aquaculture industry is facing new challenges as it strives to satisfy the continually growing demand for seafood products. The expanding industry brings with it challenges such as the diminishing availability of suitable coastal zones due to increased competition for marine-use areas, and a responsibility to limit negative impacts to the environment. As a potential solution to the negate environmental impact and continue industry expansion, operations are expected to transition further offshore. Moving aquaculture operations offshore presents several challenges, foremost of which is the provision of energy. This paper explores the feasibility of using a novel multi-source renewable energy platform to overcome the reliance on diesel in the offshore aquaculture industry. Through the development of a numerical model, this solution proposes a scalable renewable energy platform located off the coast of Tasmania utilising solar photovoltaic (PV), wind turbines and wave energy conversion. The feasibility is assessed through a numerical model based on factors such as resource availability, energy demand and conversion system efficiencies to determine how different design and resource variable influence the ability of the platform to meet the energy requirements.

Notes:

- This study explores the use of OWCs , solar panels, and wind turbines to power a battery suited for an offshore aquaculture platform off the coast of Tasmania
- The battery storage system in the model is made of 2 1MWh batteries that weigh 27 tonnes and cost $438,000.
- In high demand months (July-November), it was found that wave and wind were unsubstantial compared to solar in this region

[36] C. Rodrigues, D. Nunes, D. Clemente, N. Mathias, J. M. Correia, P. Rosa-Santos, F. Taveira-Pinto, T. Morais, A. Pereira, and J. Ventura, “Emerging triboelectric nanogenerators for ocean wave energy harvesting: state of the art and future perspectives,” *Energy & Environmental Science*, vol. 13, no. 9, pp. 2657–2683, Sept. 2020, publisher: The Royal Society of Chemistry. [Online]. Available: https://pubs.rsc.org/en/content/articlelanding/2020/ee/d0ee01258k

Abstract: A triboelectric nanogenerator (TENG) is a new energy harvester that converts small scale mechanical motions into electrical energy by a combination of triboelectrification and electrostatic induction through the periodic contact-separation and/or sliding movement between two tribo-materials with different abilities of gaining or losing electrical charges. This new approach to harvest mechanical energy can produce high power outputs capable of supplying equipment and sensors deployed in remote offshore locations and of supporting offshore activities whilst being able to be used in conjunction with traditional energy harvesting technologies. This review describes the fundamentals of TENGs and the existing energy harvesting modes, with focus on those more suitable for marine applications. Moreover, the equipment and offshore activities whose energy needs can be satisfied by TENGs are described and implementation schemes presented. We conclude that TENGs have high potential for numerous maritime applications, ranging from the demand of electronics used for metocean monitoring, signalling and surveillance, to activities such as offshore aquaculture or oil and gas exploration. The advantages of such systems as an alternative to currently existing solutions are also discussed, along with insights concerning applications that can take advantage of their high efficiency harvesting low amplitude and low frequency wave energy.

Notes:

- This is a general reference regarding the use of tribo-electric nanogenerators (TENGs) on WECs in offshore aquaculture
- The application of TENGs in aquaculture feed buoys could be a sweet spot- not a high power demand for remote inspection and feeding in offshore aquaculture farm operations
- TENGs are cheap, small, efficient, and convenient options with a 70% maximum efficiency and <1 Euro/m cost

[37] D. Silva, E. Rusu, and C. Guedes Soares, "The effect of a wave energy farm protecting an aquaculture installation," *Energies*, vol. 11, no. 8, p. 2109, 2018. [Online]. Available: https://www.mdpi.com/1996-1073/11/8/2109

Abstract: This paper assesses the impact of a farm of wave energy converters on a nearby offshore aquaculture installation and on the nearshore dynamics. The coastal area targeted is Aguçadoura, located in the north of Portugal, where the world's first wave farm operated in 2008. The study is focused mainly on the evaluation of the sheltering effect provided by the wave farm to the aquaculture cages. Furthermore, the possible impact on the coastal wave climate of such an energy park is also evaluated. These objectives are accomplished by performing simulations, corresponding to the wave conditions, which are more often encountered in that coastal environment. The SWAN model (Simulating WAves Nearshore) was adopted for this. Various transmission scenarios are considered to account for the impact of different types of wave converter farms on the downwave conditions. The results show that such a wave energy park might have a clear positive impact on the wave conditions fish farm installed downwave and it might also have a beneficial influence on shoreline dynamics from the perspective of coastal protection.

Notes:

- This paper investigates the impact of a WEC array in Aguçadoura, Portugal (Pelamis) on downwave conditions and impacts to an aquaculture farm.
- The study uses a SWAN (Simulating WAves Nearshore) model to simulate wave propagation in the target area with coefficients to represent the WEC array as an obstacle.
- The study found that the WEC array can reduce the wave conditions downwave for aquaculture and thus increase aquaculture reliability.

- This paper can be a good reference for potential synergies between wave energy and aquaculture.

[38] J. W. Simmons and J. D. Van de Ven, “A Comparison of Power Take-Off Architectures for Wave-Powered Reverse Osmosis Desalination of Seawater with Co-Production of Electricity,” *Energies*, vol. 16, no. 21, p. 7381, Jan. 2023, number: 21 Publisher: Multidisciplinary Digital Publishing Institute. [Online]. Available: https://www.mdpi.com/1996-1073/16/21/7381

Abstract: Several power take-off (PTO) architectures for wave-powered reverse osmosis (RO) desalination of seawater are introduced and compared based on the annual average freshwater production and the size of the components, which strongly relate to the costs of the system. The set of architectures compared includes a novel series-type PTO architecture not previously considered. These seawater hydraulic PTO architectures are composed of a WEC-driven pump, an RO module, an intake charge pump driven by an electric motor, and a hydraulic motor driving an electric generator for electric power production. This study is performed using an efficient two-way coupled steady-state model for the average performance of the system in a given sea state, including freshwater permeate production, electric power production, and electric power consumption. A multi-objective design problem is formulated for the purposes of this comparative study, with the objectives of maximizing annual freshwater production, minimizing the displacement of the WEC-driven pump, and minimizing the installed RO membrane area. This establishes a framework for comparison in the absence of a mature techno-economic model. The requirement that the system produces enough electric power to meet its consumption is applied as a constraint on the operation of the system. The oscillating wave surge converter Oyster 1 is assumed as the WEC. Weights on performance of the system in a given sea state are based on historical data from Humboldt Bay, CA. This study finds that (1) architectures in a series configuration allow for a reduction in the WEC-driven pump size of 59–92% compared to prior work, (2) varying the displacement of the WEC-driven pump between sea conditions does not provide any significant advantage in performance, and (3) varying the active RO membrane area between sea condition offers improvements between 7% and 41% in each design objective.

Notes:

- Co-production of desalinated seawater and power production case studies for a near shore WEC with of 4 different PTO architectures
- Results for a switch-mode and variable displacement pump archetypes in parallel and in series are explored . The series-type architecture with a switch-mode power transformer improved the power density of the WEC-driven pump significantly compared to the other architectures
- The ability to vary the active membrane area also provided improvements to overall permeate/power production

[39] V. Vassiliou, M. Charalambides, M. Menicou, N. Chartosia, E. Tzen, B. Evagelos, P. Papadopoulos, and A. Loucaides, “Aquaculture Feed Management System Powered by

Renewable Energy Sources: Investment Justification," *Aquaculture Economics & Management*, vol. 19, no. 4, pp. 423–443, Oct. 2015, publisher: Taylor & Francis _eprint: https://www.tandfonline.com/doi/pdf/10.1080/13657305.2015.1082115. [Online]. Available: https://www.tandfonline.com/doi/abs/10.1080/136 57305.2015.1082115

Abstract: Fish feed accounts for more than 50% of aquaculture farms' operating costs and thus careful feeding planning is vital. In the case of the Mediterranean, most farms have their installations in coastal waters, hence this is relatively easy to perform. Low magnitude environmental conditions (winds, waves and currents) as well as easy and quick access ensures high consumption rates and smooth operation. Nevertheless, as competition for these waters increases the option of moving to offshore waters is seen as a solution. Moving further away from shore means exposing installations to harsher environments and lower degree of onshore monitoring. As a result, environmental conditions must now be monitored on-site, especially the ones affecting operations and feeding planning. For this reason, this article presents a feed management system powered by a stand-alone renewable energy sources system. The system provides energy independence and mobility by wirelessly transmitting important parameters onshore. An investment appraisal cost model is also described. The model compares the system's costs over the fish feed cost saved by a priori feeding planning through better monitoring of on-site conditions. It concludes that such synergies have profitable potentials.

Notes:

- This study explores the use of marine energy to supplement offshore aquaculture feeding systems- mainly solar and wind
- High wind and waves are the main cause of pauses to the feeding cycle so generating renewable energy from these sources can reduce pauses in peration

[40] C. V. C. Weiss, B. Ondiviela, X. Guinda, F. del Jesus, J. González, R. Guanche, and J. A. Juanes, "Co-location opportunities for renewable energies and aquaculture facilities in the Canary Archipelago," *Ocean & Coastal Management*, vol. 166, pp. 62–71, Dec. 2018. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0964569117309122

Abstract: Integrated Offshore Management is a future challenge for the development of sustainable growth of marine economies. The progressive increase in worldwide demands for marine-based renewable energies combined with higher market demands for aquaculture-based food requires better knowledge on marine spatial planning tools that allow optimizing the use of this space for different purposes. That is the case of energy production and aquaculture activities, in which synergistic and competitive interactions must be thoroughly analyzed at an appropriate scale. The present study proposes a specific methodology that integrates several selection criteria responding simultaneously to the needs and limitations of marine aquaculture and renewable energy production, aiming to identify opportunities for the co-location of these activities. The methodology was implemented over 25km of the coastal fringe of four islands of the Canary Archipelago, applying a multi-criteria approach based on independent probabilistic suitability and mapping analysis (time series of 20–30 years) for: (i) wind and wave energy production potential; (ii) structural requirements for aquaculture cages and energy devices; (iii) limits for operation and maintenance activities; (iv) feasibility to transport energy to the grid; and (v) biological requirements for eight species of fish. A stepwise procedure was carried out, including: 1) suitability for wave, wind and aquaculture activities, with spatial resolution of 0.01° (0–1 probability scale); and 2) integrated co-location mapping, considering suitability for each activity. Opportunities for the co-location of wind and aquaculture farms were identified in the southeastern portion of the islands, while in Tenerife and Fuerteventura wave-wind devices co-location opportunities were identified. Thus, opportunities for marine aquaculture and renewable energy were demonstrated in the present case study applying a preliminary assessment of the potential exploitation of these resources.

Notes:

- This paper addresses potential for wind and near shore wave energy to support offshore aquaculture cages and O&M activities off the coast of the Canary Islands, Spain.
- Physio-chemical and biological suitability, wave/wind resource, structural suitability, operational suitability, energy transport distance, distance from ports, etc. were all parameters considered when determine suitable locations for a co-located wind, wave, and aquaculture system.
- This will be helpful to identify what parameters need additional research to determine suitability of farming certain species offshore.

[41] T. Whittaker and M. Folley, "Nearshore oscillating wave surge converters and the development of oyster," *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 370, no. 1959, pp. 345–364, 2012. [Online]. Available: https://royalsocietypublishing.org/doi/abs/10.1098/rsta.2011.0152

Abstract: Oscillating wave surge converters (OWSCs) are a class of wave power technology that exploits the enhanced horizontal fluid particle movement of waves in the nearshore coastal zone with water depths of 10–20 m. OWSCs predominantly oscillate horizontally in surge as opposed to the majority of wave devices, which oscillate vertically in heave and usually are deployed in deeper water. The characteristics of the nearshore wave resource are described along with the hydrodynamics of OWSCs. The variables in the OWSC design space are discussed together with a presentation of some of their effects on capture width, frequency bandwidth response and power take-off characteristics. There are notable differences between the different OWSCs under development worldwide, and these are highlighted. The final section of the paper describes Aquamarine Power's 315 kW Oyster 1 prototype, which was deployed at the European Marine Energy Centre in August 2009. Its place in the OWSC design space is described along with the practical experience gained. This has led to the design of Oyster 2, which was deployed in August 2011. It is concluded that nearshore OWSCs are serious contenders in the mix of wave power technologies. The nearshore wave climate has a narrower directional spread than the offshore, the largest waves are filtered out and the exploitable resource is typically only 10–20secondary power conversion every 5–10 units.

Notes:

- The Oyster WEC is an oscillating surge wave energy converter that was deployed at the European Marine Energy Centre in August 2011.
- The Oyster is bottom hinged and designed for nearshore conditions (10 - 20 m water depth).
- The Oyster pumps water through high-pressure pipelines to a high-head hydroelectric plant onshore.
- System pressure is regulated by spear valves that control flow and maintain operating pressure.
- A closed pump system was used such that freshwater was always being pumped. This was done to avoid challenges of offshore filtration, corrosion, bio-fouling, and location of the discharge pumping.
- While a seawater pump would require consideration of additional challenges, the Oyster WEC still provides an example of a successful full-scale WEC capable of pumping water.
- Design decisions and lessons learned from the Oyster deployment can be very valuable for the future of water pumping WECs in general.

[42] J. Wyban, "GUAM AQUACULTURE FEASIBILITY STUDY."

Notes:

- The Guam Aquaculture Feasibility Study is part of this project. This reference has been cited in all of our teams works so far and will continue to be the motivation of our research.
- The feasibility study explores the various fish and shellfish species and quantities that have been farmed on Guam since the 1990s. proposal for the layout of the new Guam Aquaculture Innovation Center at the University of Guam is shown as well as a site analysis for suitable locations for the facility.

[43] W. Yue, W. Wang, S. Sheng, Y. Ye, and T. Hong, "Analysis of the wave load and dynamic response of a new semi-submersible wave-energy-powered aquaculture platform," *Ocean Engineering*, vol. 248, p. 110346, 2022. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0029801821016437

Abstract: In this paper, a new type of semi-submersible aquaculture platform, which is powered by wave energy, is studied. Wave-induced loads and dynamic response are calculated using the 3D potential flow theory. Then, a selection criterion for the dominant loads of the proposed platform is established based on the stochastic method. The effect of several parameters on loads and dynamic responses, such as wave frequency, wave direction, and draught depth, is investigated and analyzed. It is found that the effect of draught on the dynamic response of the semi-submersible is significant for vertical shear force Fz and vertical bending moment My. On the other hand, horizontal bending moment Mz is not affected by draught and remains constant for different draught values. The structural response of wave torque is relatively weak compared to other wave-induced loads for the symmetry of the geometry. High-stress regions are located at the junctions between the upper deck and the columns where fatigue failure might easily occur. The results of the structural response analysis may be useful for semi-submersible aquaculture platforms with similar structures in the future.

Notes:

- The study introduces a novel aquaculture platform powered by wave energy, with wave-induced loads and dynamic responses analyzed using 3D potential flow theory and stochastic methods.
- High-stress zones are identified at the junctions between the upper deck and columns, indicating potential fatigue failure points that require careful structural attention.
- Wave frequency, direction, and draught depth significantly affect the platform's dynamic behavior — especially vertical shear force (Fz) and vertical bending moment (My), while horizontal bending moment (Mz) remains largely unaffected by draught.

[44] W. Yue, Z. Wang, W. Ding, S. Sheng, Y. Zhang, Z. Huang, and W. Wang, "Feasibility of Co-locating wave energy converters with offshore aquaculture: The Pioneering case study of China's Penghu platform," *Ocean Engineering*, vol. 288, p. 116039, Nov. 2023. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S002980182302423X

Abstract: As the aquaculture industry moves further offshore, there is an increasing prospect of co-locating wave energy converters (WECs) with offshore aquaculture. In China, the multi-use of wave energy and offshore aquaculture has already been implemented and demonstrated commercially. A thorough analysis of the power performance and dynamic and structural responses on the Penghu platform is performed in this paper to improve the understanding of the co-locating potential. The analysis is based on the potential flow theory, multi-body constrained dynamics equations, and quasi-static finite element analysis (FEA) method. It is found that powering offshore aquaculture operations is possible using wave energy paired with solar energy. In addition, the inclusion of WECs can, to some extent, reduce the platform motion, making visits to the aquaculture site more feasible. The inner pool wave elevation is slightly reduced compared to the free surface elevation outside Penghu, which is conducive to aquaculture operations. It is also shown that the structural design of the Penghu platform is very safe. Still, the hinge points must be seriously considered because of the possibility of fatigue fracture. Overall, co-locating WECs and offshore aquaculture is demonstrated as a feasible solution to the power supply problems of offshore aquaculture.

Notes:

- Great reference for nearshore (30m) WEC producing power and desalinated water to an offshore aquaculture platform for finfish farming in Penghu, China
- This study explores the power performance of the Penghu semi-submersible aquaculture platform with the Sahrp Eagle WEC, hydrodynamic performance of the platform due to WEC influence, structural safety
- The Penghu system also produces freshwater by using the WEC to power a desalination system with a flow of 250L/h and power consumption of 2.5kW
- The average wave power output on the platform was 29.156kW, lower than the rated 60kW for low wave resource. However, when supplemented with solar the platforms energy demand of 700 kWh can be met
- Also in extreme conditions, the incident wave is suppressed and the inner pool wave elevation is reduced which is good for aquaculture operations enditemize