Report on Coastal Structure Integrated Wave Energy Converters (CSI-WECs)

Ben McGilton, Kelly Gjestvang, Katie Peterson, Sarah Hall, David Greene, George Hagerman, Bikram Singh, Jackson Smith, and Claire Wolgast

National Laboratory of the Rockies

The National Laboratory of the Rockies is a national laboratory of the U.S. Department of Energy, Office of Critical Minerals and Energy Innovation, operated under Contract No. DE-AC36-08GO28308.

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

Technical Report
NLR/TP-5700-90768
February 2026

NATIONAL LABORATORY OF THE ROCKIES

Report on Coastal Structure Integrated Wave Energy Converters (CSI-WECs)

Ben McGilton, Kelly Gjestvang, Katie Peterson, Sarah Hall, David Greene, George Hagerman, Bikram Singh, Jackson Smith, and Claire Wolgast

National Laboratory of the Rockies

Suggested Citation
McGilton, Ben, Kelly Gjestvang, Katie Peterson, Sarah Hall, David Greene, George Hagerman, Bikram Singh, Jackson Smith, and Claire Wolgast. 2026. *Report on Coastal Structure Integrated Wave Energy Converters (CSI-WECs)*. Golden, CO: National Laboratory of the Rockies. NLR/TP-5700-90768. https://www.nlr.gov/docs/fy26osti/90768.pdf.

The National Laboratory of the Rockies is a national laboratory of the U.S. Department of Energy, Office of Critical Minerals and Energy Innovation, operated under Contract No. DE-AC36-08GO28308.

This report is available at no cost from the National Laboratory of the Rockies (NLR) at www.nlr.gov/publications.

Technical Report
NLR/TP-5700-90768
February 2026

National Laboratory of the Rockies
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nlr.gov

NOTICE

This work was authored by the National Laboratory of the Rockies for the U.S. Department of Energy (DOE), operated under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Water Power Technologies Office. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

Cover photos (clockwise from left): Josh Bauer, National Laboratory of the Rockies 61725; Visualization from National Laboratory of the Rockies Insight Center; Getty-181828180; Agata Bogucka, National Laboratory of the Rockies 91683; Dennis Schroeder, National Laboratory of the Rockies 51331; Werner Slocum, National Laboratory of the Rockies 67842.

Acknowledgments

The research team would like to thank Eco Wave Power and Wave Swell Energy for their analysis and contributions to the case study. Additionally, the research team would like to extend their appreciation to Diego Vicinanza and Pasquale Contestabile with the University of Campania Luigi Vanvitelli for their expertise, guidance, and case study analysis of the OBREC. The team would like to acknowledge the U.S. Department of Energy Water Power Technologies Office (WPTO) for their support of the research on this topic and of this report. The team would also like to thank the Office of Science's Science Undergraduate Laboratory Internships (SULI) program. Sarah Hall, Bikram Singh, Jackson Smith, and Claire Wolgast contributed to this work through their summer 2023 SULI internships.

The authors express their gratitude to the following individuals from the National Laboratory of the Rockies (NLR) and WPTO for their invaluable guidance and reviews throughout the development of this report: Jim McNally (WPTO), Kerry Strout Grantham (NLR), Marty Schwarz (NLR), and Robert Thresher (NLR). In addition, Tara Smith (NLR) and Besiki Kazaishvili (NLR) created graphics, and Amy Brice (NLR) edited. We also thank Rebecca Harris Sullivan, Pika Advisory LLC, for technical writing and editorial support.

List of Acronyms

AEP	annual energy production
AHP	analytic hierarchy process
BiMEP	Biscay Marine Energy Platform
CSI-WEC	coastal structure integrated wave energy converter
CapEx	capital expenditures
EVE	Ente Vasco de la Energía (Basque Energy Agency)
ft	foot
GIS	geographic information system
IEA-OES	International Energy Agency Ocean Energy Systems
kg	kilogram
kW	kilowatt
kWh	kilowatt-hour
m	meter
MARAD	U.S. Maritime Administration
MCBH	Marine Corps Base Hawaii
MCDA	multicriteria decision analysis
MW	megawatt
MWh	megawatt-hour
NOAA	National Oceanic and Atmospheric Administration
NREL	National Renewable Energy Laboratory
OBREC	overtopping breakwater for energy conversion
OpEx	operational expenditures
OTD	overtopping device
OWC	oscillating water column
PIDP	Port Infrastructure Development Program
PTO	power take-off
ROI	return on investment
SSG	Seawave Slot-Cone Generator
SWAN	Simulating WAves Nearshore
USACE	U.S. Army Corps of Engineers
WEC	wave energy converter

Executive Summary

As the likelihood of flooding and damaging coastal erosion grows, so too does the need for new and expanded coastal defense structures such as sea walls, breakwaters, and harbors. According to the National Oceanic and Atmospheric Administration, 39% of the U.S. population lives in coastal counties that are at risk from coastal erosion and flooding, and 40% of those residents are at elevated coastal hazard risk. While coastal defense infrastructure projects are mature engineering technologies, costs remain high.

One option for reducing lifetime costs and increasing net potential benefits of such coastal defense infrastructure is to incorporate a wave energy converter (WEC) element into them—otherwise known as coastal structure integrated wave energy converters (CSI-WECs). This report investigates the promise and potential of CSI-WECs, which to date have been a largely underexplored application for wave energy in the United States.

Because coastal defense structures are generally deployed in places with significant wave resources, CSI-WECs could generate energy for local communities for a variety of applications while also enhancing their resilience. With an estimated total of 2,640 terawatt-hours per year of wave energy on U.S. coasts and 14% of the U.S. coastline currently hardened with coastal defense structures, this latent energy could benefit coastal communities if even a small percentage of it could be harvested.

Marine energy is considered, in most cases, to be a high-risk, high-reward effort. However, the research team proposes that CSI-WECs are a relatively *low*-risk, high-reward approach to harvesting marine energy. By deploying the devices on or near the shore and integrating them into coastal structures such as breakwaters or harbors, there is less overall project risk compared to wave energy deployments farther offshore.

CSI-WECs leverage the design and economic advantages of being onshore, such as reduced costs for cabling, operations, and maintenance. Moreover, should challenges arise from the energy-generation element, the shore and coastal communities remain protected, as the coastal infrastructure would remain intact. Because coastal structures are primarily designed for coastal defense and resiliency, integrating a WEC into coastal structures can add untapped value (via energy generation potential) without changing their primary design purpose.

The research team proposes that CSI-WECs are a high-value marine energy application that have been largely overlooked thus far in the United States. CSI-WECs are a unique marine energy technology that can meet a range of end-use applications—both on- and off-grid—as demonstrated by successful international deployments. This suggests that there is substantial potential for their implementation in U.S. coastal communities.

The purpose of this report is to explore the full value proposition of CSI-WECs in the United States. The report provides background information on the state of the art of the technology as well as a summary of important technology developments and a review of devices currently in operation.

We present an end-use, application-focused case study in which four U.S. sites are selected for their high-value CSI-WEC deployment potential: Puerto Rico, Hawaii, the Pribilof Islands of Alaska, and Humboldt Bay, California. For each of these sites, three developers—Eco Wave Power, Wave Swell Energy, and the combined efforts of Professor Diego Vicinanza and Professor Pasquale Contestabile—conducted an energy production analysis of their technologies for the four selected sites.

Initial results indicate significant near-term potential in the development and deployment of these solutions, with annual energy production in a range of tens of megawatt-hours per year for each device under normalized 10-meter (m) deployments. These findings were valid even in areas considered to have lower wave energy density. For areas with higher energy density, however, the potential was found to be hundreds of megawatt-hours per year. All devices included in the analysis are highly scalable, and deployments have the potential of reaching microgrid- or grid-scale (multiple gigawatt-hours per year) generation given sufficient linear space.

Additionally, through this work, the research team developed a geographic information system (GIS)-based tool to support efficient and comprehensive site assessment for optimal and high-value deployments. The parameters and framework of this tool are discussed using Puerto Rico as an example case. The output is a heat map of suitable sites based on the ranking of geospatial data input into the tool, which can be used as a visual for community engagement during the site selection process.

To further support the value proposition investigation of CSI-WECs, the research team performed a techno-economic assessment for a hypothetical CSI-WEC deployment at the Humbolt Bay site, showing that there can be favorable returns on a CSI-WEC investment when coupled with applications or deployments where the value of energy is high. For all developer devices and a dollar-per-kilowatt-hour value of $0.20, the initial capital investment is returned within 5 to 6 years, with potentially millions of dollars' worth of energy generated over a 20-year time frame. The team also identified possible funding opportunities and pathways that could support the deployment of CSI-WECs in the United States.

CSI-WECs can provide locally generated energy for a multitude of high-value applications, all while increasing community defense through coastal protection and coastal hardening. Though further development, demonstration, and analysis are required, the technology presents an opportunity for the advancement of water power technologies in the United States while adding value to coastal infrastructure projects.

Table of Contents

List of Figures

List of Tables

1 Introduction

The growing likelihood of flooding and damaging coastal erosion means that there is an urgent need for new and expanded coastal defense structures such as sea walls, breakwaters, and harbors. According to the National Oceanic and Atmospheric Administration (NOAA), 39% of the U.S. population lives in coastal counties that are at risk from coastal erosion flooding, and 40% of those residents are at elevated coastal hazard risk. While coastal defense infrastructure projects are mature engineering technologies, costs remain high.

One option for reducing lifetime costs and increasing net potential benefits is to incorporate a wave energy converter (WEC) element into coastal defense infrastructure designs—otherwise known as coastal structure integrated wave energy converters (CSI-WECs). Because coastal defense structures will generally be deployed in higher-wave-energy areas, the energy harvested by CSI-WECs could be used by local communities for a variety of applications while also enhancing local resilience. With an estimated total of 2,640 terawatt-hours per year of wave energy on U.S. coasts and 14% of the U.S. coastline currently hardened with coastal defense structures, this latent energy could provide significant benefits to coastal communities if even a small percentage of it could be harvested (Figure 1).

The technology's current state suggests that smaller-scale (rather than grid-scale) applications may be more applicable and valuable to remote and island communities. However, through focused development and the increasing integration of distributed microgrids, CSI-WECs could become part of a grid-scale energy portfolio, as is the case for the Mutriku oscillating water column (OWC) power plant in Spain and the Korea Research Institute of Ships and Ocean Engineering breakwater-integrated OWC in Korea (Kim et al. 2023) (see Section 2.2). In either case, additional benefits to coastal resiliency may include both coastal protection and resilient power supply for critical functions following extreme weather events.

CSI-WEC demonstrations have proven sustained operation in their primary roles as breakwaters, with installed capacities in the range of 8 kilowatts (kW) to 500 kW (IEA-OES 2023). These demonstrations suggest that CSI-WECs are at a technology readiness level of 7 or higher, an important achievement for wave energy commercialization. If a techno-economic case can be made for a net benefit, such as the value of the energy produced exceeding capital expenditures (or CapEx) and operational expenditures (or OpEx) over the device deployment lifetime (20–30 years), then CSI-WECs have clear viability.

The overall benefit of CSI-WECs can potentially be weighed on an application basis where the energy is used for high-impact local energy generation solutions. Such applications include using the energy to power a desalination system, as a reserve power capacity following extreme weather emergencies, and as an emergency power source to facilitate the black start of a local grid during power outages.

The significant potential advantages of integrating WECs with shoreline protection infrastructure include relative ease and reduced cost of prototyping, deployment, power take-off (PTO) maintenance, and cabling by virtue of proximity to the shore, as well as the shared cost with shoreline protection service budgets.

Because the CSI-WEC technology would be deployed either near or on shore, it offers many unique advantages over traditional offshore WECs, including:

1. **Lower operation and maintenance costs** compared to offshore sites. Instead of hiring a boat with highly specialized crew and relying on weather windows for installation, maintenance, etc., servicing the device could be as simple as a utility worker walking down a breakwater and opening a hatch.
2. The **cabling costs would be significantly reduced**, as the cables would extend only as far as the distance between the CSI-WEC located onshore and the nearest substation or port connection point, avoiding miles of cable on the seafloor, as would be the case with an offshore device.
3. CSI-WECs can also **support resiliency for coastal communities**. Coastal structures such as breakwaters, sea walls, and jetties are critical elements in protecting communities from erosion and storm surge.

A recent cost-benefit analysis focused on a small beach destination and fishing village in Portugal determined that breakwaters could save approximately $317,000 per year in flooding mitigation costs and $190,000 to $886,000 per year in erosion mitigation (Pombo, Roebeling, and Coelho 2024). By integrating a WEC into coastal infrastructure, communities will receive both protection and the added benefit of a diversified energy portfolio. Moreover, CSI-WECs can be connected to microgrids that service key buildings or operations, which can shorten the time frame of recovery efforts during extreme events and keep the lights on in hospitals, fire stations, water treatment plants, and police stations.

Another benefit of CSI-WECs is that they could help the marine energy industry advance as a whole by **lowering deployment and testing costs for potential new devices**. For example, an easily accessible onshore WEC could become a test site, as opposed to the more typical scenario of a WEC being deployed far out at sea. This would allow the marine energy community to test and de-risk technologies (turbines, control systems, PTOs) while facing a much lower deployment cost. Such testing and de-risking is currently happening in Spain at the Mutriku OWC power plant (see Section 2.2).

With wave energy technology still in a nascent stage, often characterized as high-risk/high-reward, CSI-WECs present a relatively low-risk alternative, as the primary purpose of these devices is coastal defense with an added benefit of energy generation. For example, if challenges were to occur in energy generation or system performance, the local community would still retain the gains in protection and resiliency as provided by the coastal infrastructure in which the WEC is embedded. With existing deployments proving viability of operation, such as at Mutriku, the reward aspect remains high—remote communities could be positively impacted in a relatively short time frame through the provision of both coastal defense and a robust, secure, and locally generated renewable source of energy.

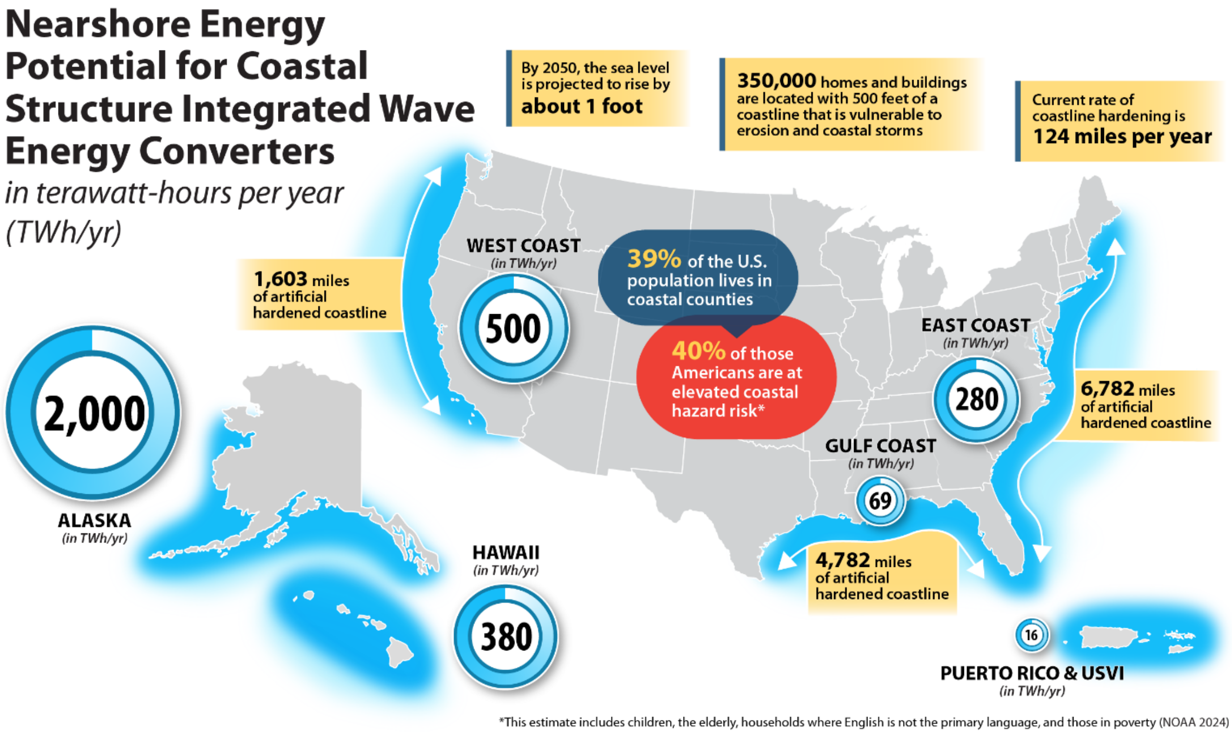

Figure 1. Approximately 124 miles of U.S. coastline are converted to hardened coast each year. Much of this coastline hardening is to protect coastal communities, where 39% of the U.S. population resides, from erosion due to wave action and storm surge. CSI-WECs can add value to these sites where the coastline is already hardened by supplementing the coastal communities' energy portfolios.

Illustration by Tara Smith, National Renewable Energy Laboratory (NREL)

2 State of CSI-WEC Technology

CSI-WEC systems have been in development for decades, with some of the earliest deployments dating back to the 1990s. Although there have been challenges and failures along the way, the research team believes that, increasingly, CSI-WEC projects exhibit successful deployment and operation in the wave energy realm as evidenced by Table 1.

Table 1 is based on the International Energy Agency Ocean Energy Systems (IEA-OES) 2022 Annual Report. As cited in this publication, just under 50% of the listed operational or recently decommissioned WEC devices are CSI-WECs or have the potential to be deployed as CSI-WECs (IEA-OES 2023).

Table 1. List of Wave Energy Devices From the IEA-OES 2022 Annual Report

Devices that the research team classify under the CSI-WEC category are highlighted in orange.

Location	Company	Device Name	CSI-WEC[a]	Type	Demonstration	Nameplate Capacity (kW)
Korea	Kriso	Youngsoo OWC Pilot Plant	Can be	OWC	Operational	500
Spain	EVE	Mutriku Wave Power Plant	Yes	OWC	Operational	296
Australia	Wave Swell		Can be	OWC	Decommissioned	200
Spain	WavePiston	WavePiston	No	WEC	Operational	200
France	Geps techno		No	WEC	Operational	150
U.S.	CalWave	CalWave 1	No	WEC	Operational	75
Italy	Enel Green Power		No	WEC	Operational	50
Korea	Kirso	OWC WEC with Breakwater	Yes	OWC	Operational	30
Italy	Mediterranean University of Reggio Calabria	REWEC3	Yes	OWC	Operational	20
UK	AWS Ocean Energy	Archimedes Waveswing	No	WEC	Operational	16
Italy	RSE	REWEC3	Yes	OWC	Operational	15
UK	Mocean Energy	Blue X	No	WEC	Operational	10
Italy	University of Campania Luigi Vanvitelli	OBREC	Yes	OBREC	Operational	22
Denmark	Exowave		No	WEC	Operational	1
India	NIOT		No	Navigational Buoy	Operational	1

[a] Devices in this column are classified as follows: “Yes” means the research team defines the device as a CSI-WEC; “No” means the device is not a CSI-WEC; “Can be” means the device is not currently a CSI-WEC but could be built into coastal infrastructure (but not for the pilot deployment).

This section examines key CSI-WEC developments and presents an analysis of the recent and historical challenges and successes in the field. Additionally, Appendix A provides an extensive list of related devices and their statuses.

A common finding with historical CSI-WEC deployments was that because of the emerging nature of the technology, the projects and their outcomes were often limited by a knowledge vacuum in many areas. Whether due to a lack of understanding of final design hydrodynamics or deployment site resources, or the use of underdeveloped PTO systems that led to lower efficiencies or capacity factors, many of these projects were discontinued.

It is the opinion of the research team and the consulted developers that these challenges can be overcome by leveraging recent advancements in wave energy PTO technology and by viewing these deployments on a project basis—as a combination of coastal defense, robust generation systems, and high-value applications—rather than as generation assets only. In short, a CSI-WEC's value can be greatly improved when it is understood to be a device that does far more than simply produce energy.

2.1 CSI-WEC Archetypes

To better classify, assess, and compare existing CSI-WEC solutions and those in development, we have identified three system archetypes (Figure 2) that are generally defined by their PTO method and orientation:

- Wall-mounted heave/hinge type
- Oscillating water column
- Overtopping device (OTD).

We also propose the "adopted" and "adapted" classification, where *adopted* signifies wave energy devices that can be added to existing coastal structures, and *adapted* means wave energy devices that have been fully integrated into the design and build of a coastal structure. Figure 3 shows examples of how each archetype is integrated into a coastal defense structure.

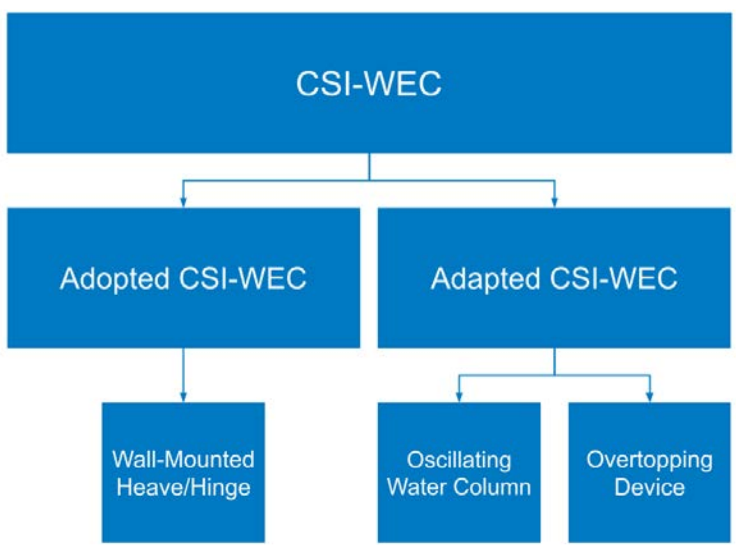

Figure 2. Classification of CSI-WECs

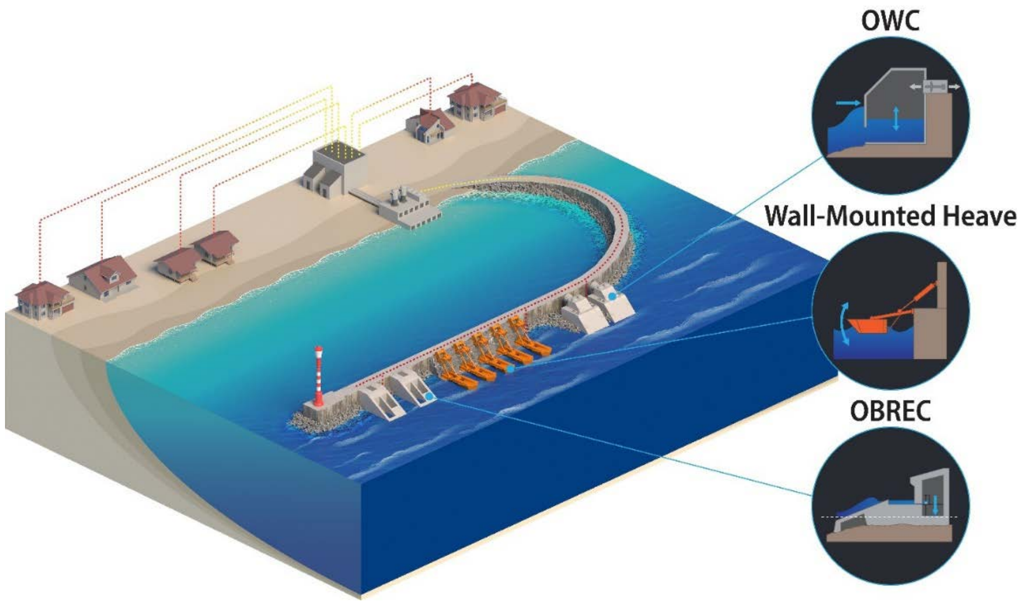

Figure 3. Example of three CSI-WEC archetypes and their potential deployment on a breakwater. The graphic shows an OWC, a wall-mounted heave device, and an overtopping breakwater for energy conversion (OBREC).

Illustration by Besiki Kazaishvili, NREL

2.2 Deployed Technologies

CSI-WECs have been deployed in multiple countries other than the United States and bear the distinction of having achieved the longest deployment times of any type of wave energy device, as exemplified by the Mutriku Plant.

This section details some of the most successful CSI-WEC projects to date, including their respective lengths of deployment. A list of all identified CSI-WEC devices can be found in Appendix A.

2.2.1 Oscillating Water Column: Breakwater WECs

Mutriku Breakwater Wave Plant; Bay of Mutriku, Basque Country, Spain

- Deployment: Commercial, full scale, grid connected
- Operators: Basque Government Department of Transportation and Public Works, Ente Vasco de la Energía (EVE; Basque Energy Agency)
- Status: Operational.

Figure 4. Mutriku Plant

Photo from EVE (n.d.)

The Mutriku Breakwater Wave Plant (Figure 4) was commissioned in July 2011 in the Port of Mutriku in the Basque Country of northern Spain (EVE n.d.). The plant was planned by EVE, the Basque Energy Agency, during the design phase of the new Mutriku breakwater, which was a much-needed public works project to make navigation of the harbor safe against the harsh conditions of the Bay of Biscay (Torre-Enciso et al. 2009).

The Mutriku plant became the world's first commercial-scale wave energy device integrated into a breakwater. Built into a vertical caisson-type breakwater, the Mutriku plant was inspired by another WEC—the Islay LIMPET (Ibarra-Berastegi et al. 2018). Mutriku features 16 traditional OWC chambers, each connected at the top to a PTO consisting of a vertical-axis, fixed-pitch, self-rectifying 18.5-kW Wells turbine, resulting in an overall installed capacity of 296 kW (Torre-Enciso et al. 2009). Each PTO is connected to a noise attenuator. Power output from each turbine is smoothed by an inertia drive, and power from the generators is first rectified and then inverted to 50 hertz alternating current and finally raised to 13.2 kilovolts for transmission to the local grid (Torre-Enciso et al. 2009). Each turbine can be individually controlled for a smooth power output, thanks to pressure sensors in each chamber, and a gravity-based butterfly safety valve allows each chamber to be isolated in case of a power failure or other emergency.

Although the expected yearly power output was estimated to be 600 megawatt-hours per year (MWh/yr), actual output was found to be 246.5 MWh/yr, between 2014 and 2016 (Ibarra-Berastegi et al. 2018). This was largely due to disruptions in the operation of the turbines, where (1) two of the chambers were improperly designed, resulting in a failure to generate the necessary pressure for power generation, and (2) maintenance activities during the measurement period meant that an average of just 10 of the 16 turbines were regularly operational (Ibarra-Berastegi et al. 2018). Additionally, the alternators used in each chamber have proven to be oversized, resulting in low efficiency; rated at 18.5 kW, they regularly produce just 3.6 kW, or

20% of their capacity. Changes in regulation strategies for pressures inside the chambers would allow for a more properly sized PTO to be used, increasing plant efficiency. As it stands, Mutriku's wave-to-wire efficiency is just 2.56% (Vicinanza et al. 2019). Lastly, storms between 2007 and 2009 resulted in some structural damage to the plant, with subsequent tests finding that initial predictions of wave behaviors and pressures inside the OWC chambers and against the device's frontal wall may have been greater than the actual structural resistance (Vicinanza et al. 2019). Despite these issues, the plant provides a regular power supply to the grid and, under the control of the Biscay Marine Energy Platform (BiMEP), acts as a host space for WEC developers and laboratories to test and validate new OWC PTO and control systems (BiMEP n.d.).

A comprehensive report on the initial construction and design of the Mutriku plant is presented in Torre-Enciso et al. (2009), and a review of the plant's electricity production and efficiency is found in Ibarra-Berastegi et al. (2018).

Wave Swell Energy UniWave200; Grassy, King Island, Tasmania

- Deployment: Pilot, full scale
- Operators: Wave Swell Energy Ltd., Hydro Tasmania
- Status: Decommissioned.

Figure 5. (Top) Conceptual example of Wave Swell Energy's device as a CSI-WEC. (Bottom) Wave Swell Energy's UniWave200 WEC deployed at King Island, Tasmania.

Images from Paul Geason, Wave Swell

Installed in January 2021, the UniWave200 on King Island, Tasmania, is a full-scale pilot of the proprietary UniWave WEC device, developed by Wave Swell Energy (Figure 5).

Altering the operation of a traditional OWC, the UniWave device utilizes a valve-controlled chamber that drives a unidirectional air turbine PTO and aims to better exploit incident wave energy (Fleming et al. 2023). Although the device works in a wide range of wave conditions, the King Island site presents mild wave conditions, consistent wave direction, and optimal water depth, making it an ideal site for the pilot (Cossu et al. 2020).

Full details on the site characterization for the pilot are given in Cossu et al. (2020). The UniWave200 was connected to the King Island grid and produced electricity before being decommissioned in 2022 (Wave Swell n.d.). Although deployed at sea, this device is classified as CSI-WEC ready, and Wave Swell presents it as a breakwater-ready device on their website.

Mukri Port; Chuja Island, Republic of Korea

- Deployment: Pilot, full scale
- Operators: Korea Research Institute of Ships and Ocean Engineering
- Status: Operational.

Figure 6. OWC wave energy plant at Mukri Port, Republic of Korea

Photo from Lee (2021)

The Mukri Plant is a 30-kW OWC-type WEC connected to a breakwater at Mukri Port on Chuja Island (Figure 6).

The system has a maximum generation capacity of 100 kW. To account for the variation in wave energy, the plant includes a dedicated battery energy storage system that supplies energy to the grid. The PTO consists of a ring-type impulse turbine with a fixed guide vane and a permanent magnet synchronous generator (Kim et al. 2023). The plant was commissioned and became operational in October 2021. Real sea performance data were collected for one year; the system was found to perform at an hourly average efficiency of 28.8% with maximum instantaneous power output of 69 kW (Kim et al. 2023).

2.2.2 Overtopping Device: Breakwater WEC

OBREC; Port of Naples, Naples, Italy

- Deployment: Prototype, full scale
- Operator: Università degli Studi della Campania Luigi Vanvitelli
- Status: Operational.

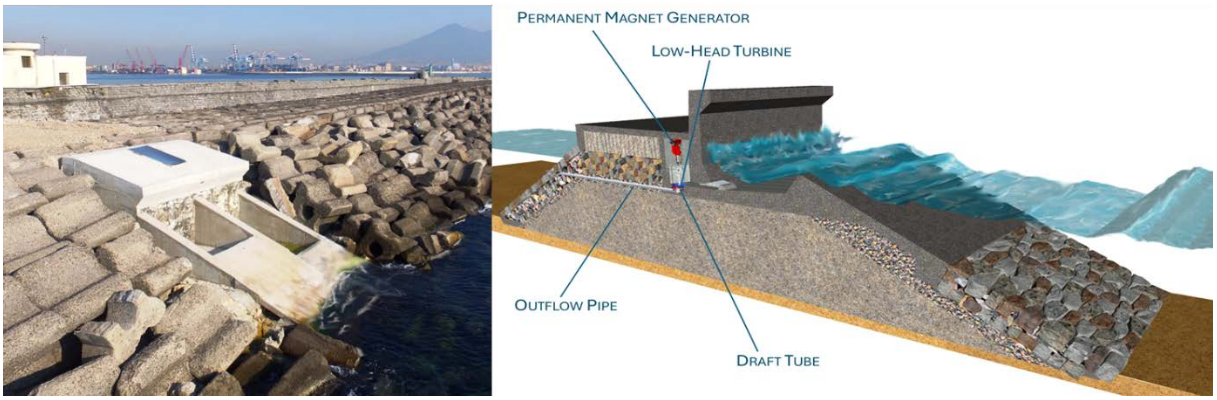

Figure 7. (left) OBREC deployment at the Port of Naples in Italy; (right) schematic of OBREC

Images from Diego Vicinanza and Pasquale Constestabile

Built into the Port of Naples's San Vincenzo rubble mound breakwater in 2015 (Figure 7), the OBREC is the world's first OTD WEC built into an existing coastal defense structure (Contestabile et al. 2016).

Inspired by the concept of the Seawave Slot-Cone Generator (SSG), the OBREC was designed as a simpler OTD, adopting a strategy of "zero moving parts" (Vicinanza et al. 2012; Contestabile et al. 2020). Specifically, the SSG used multiple reservoirs located at different heights to store water captured from overtopping waves as potential energy. The OBREC works by allowing incident waves to run up the frontal ramps of the device, filling a basin located above the still water level, and then the captured water runs through low-head turbines to generate electricity before being discharged back to the sea.

The device is designed with two main structures, divided by a wall septum, that differ in the crest height of their ramps: the Real Scale Laboratory (RS-Lab) ramp has an average height of two meters (i.e., 1.78 m and 2.28 m under low and high tide, respectively) and the Natural Waves Laboratory (NW-Lab) ramp has an average height of 1.2 m (i.e., 0.98 m and 1.48 m under low and high tide, respectively) (Palma et al. 2020, Contestabile et al. 2020). The RS-Lab, with its higher crest height, is meant to capture incident waves from the higher energetic sea states of the installation site, whereas the NW-Lab is meant to capture the mean incident waves.

In 2015, three commercial, fixed, Kaplan low-head turbines were installed in the machine room located at the rear of the device, resulting in an installed capacity of 2.5 kW (Vicinanza et al. 2019). While the OBREC benefits from a wide capture width ratio (12.6% for the RS-Lab and 12.9% for the NW-Lab) (Palma et al. 2020), it suffers from a very limited PTO system (Palma et al. 2020; Contestabile et al. 2020). Specifically, the NW-Lab does not provide a large enough hydraulic head for the Kaplan turbines to generate electricity, and the RS-Lab can only do so for the highest-energy waves (Palma et al. 2020). Additionally, as recently as 2020, the Kaplan turbine sector, did not produce turbines optimized for use in ocean (saltwater) conditions; therefore, corrosion and fatigue limit the generating potential of these turbines for OTDs (Contestabile et al. 2020). Khalid Mohammed Ridha et al. (2023) provide an updated evaluation of limitations and practical solutions for Kaplan turbines. Despite these limitations, the OBREC has proven to be compatible with a wide range of wave conditions and has shown an overtopping efficiency exceeding 20%. Outfitted with an improved PTO system with a turbine capable of operating with greater efficiency at lower water head heights, OBREC could provide significant electricity.

Contestabile et al. (2016) report the design and initial deployment of the OBREC; Contestabile et al. (2020) provide an updated state-of-the-art of the device; and Palma et al. (2020) give an updated performance assessment of the device using the OpenFOAM computational fluid dynamics environment.

2.2.3 Wall-Mounted Heave/Hinge WECs

Eco Wave Power; several devices installed worldwide

- Deployment: Pilot, full scale
- Operator: Eco Wave Power Ltd.
- Status: Operational.

Figure 8. Eco Wave Power 100-kW array, Jaffa Port

Image from Inna Braverman, Eco Wave Power

Eco Wave Power's WEC works on the wall-mounted heave/hinge principle (Figure 8), whereby an array of uniquely shaped floaters (attenuators) connected to a fixed or floating platform exploit the rise and fall of waves (Cascajo et al. 2019). The relative motion of the two bodies drives hydraulic pistons, powering a hydraulic generator, which produces direct current power

(Eco Wave Power n.d.[b]). Power is then sent to an inverter, which converters the electricity from direct current to alternating current and sends it to the grid. The device is controlled through a smart automation system, where conditions are monitored to ensure safe operation of the device. In the event of a storm, the actuators lift out of the water (survival mode), returning to their operational position after the storm has passed. The Eco Wave device can be integrated into most onshore or nearshore structures and has already been used in two successful pilot deployments.

In 2014, the company commissioned a device in Jaffa Port, Israel, which has been in operation since, producing off-grid electricity for research and system tests (Eco Wave Power n.d.[c]). In October 2018, Israel's Ministry of National Infrastructures, Energy, and Water Resources awarded a grant to Eco Wave Power for the expansion of the Jaffa Port plant to 100-kW capacity and approved its connection to the national grid. The 100-kW station has been sending electricity to the Israel national electric grid since August 2023 (Eco Wave Power n.d.[c]).

In addition, Eco Wave Power operated a 100-kW array installed in a former World War II ammunition jetty in Gibraltar (Eco Wave Power n.d.[a]) between 2016 and 2022, and a new 85-foot (ft)-long, 100-kW pilot project is planned for integration with the Port of Los Angeles, California (Eco Wave Power 2022). A 1-MW installment is planned for integration on Barro Da Douro breakwater in Portugal (Eco Wave Power 2021).

3 Case Study of CSI-WEC Deployment

To better understand the potential of CSI-WECs, we selected four hypothetical sites to illustrate both the range of possible deployment locations and the variety of on-site applications that CSI-WECs could support. Locations include ports, military bases, islands, and coastal communities. Each of the selected sites are in the United States, but the categories of locations can be found globally.

3.1 Site Selection

The four sites were selected to meet the core applications and objectives of this project, namely:

1. The presence of existing coastal defense structures in high-impact/high-value areas
2. Areas identified as likely requiring new or improved coastal defense with clear high-value end uses
3. Remote communities requiring local robust electrical supplies to improve resiliency
4. Areas with sufficient wave energy.

3.1.1 Site 1: Puerto Del Rey Marina— Fajardo, Puerto Rico

Puerto Rico has experienced severe weather events, which have caused significant issues for the populace in terms of power outages, water access, and infrastructure damage (RAND n.d.). Puerto Del Rey, on the eastern part of the island (Figure 9), for example, is remote, and a loss of power and infrastructure damage could greatly impact recovery effort following a natural disaster. The existing marina and harbor would be a prime location for a CSI-WEC, which could improve the local community's ability to respond to and recover from emergency situations.

Furthermore, Puerto Rico has challenges ensuring access to clean drinking water. Local generation assets, such as a CSI-WEC, could power a desalination plant, improving both community resiliency and quality of life, in terms of access to water and stable electricity supply.

Additionally, tourism at the marina (yachting and boat tours) constitutes a significant proportion of the local economy. The marina's location also has some of the island's highest wave energy density, suggesting that this could be a suitable site for a CSI-WEC. Installation of such a device here could provide locally generated energy to power the marina and local tourism facilities and could help power port renovations.

Marina Puerto del Rey, Fajardo,[1] is the largest full-service marina in the Caribbean, located on the east coast of Puerto Rico at the border of Fajardo and Ceiba. The marina has a 2,000-ft stone rubble mound breakwater.

This location offers an example of how a CSI-WEC can provide support in a disaster relief and recovery scenario.

[1] https://puertodelrey.com/

The marina was without power for 90 days in 2017 following hurricanes Irma and Maria. In response, the local government accelerated resiliency efforts by investing nearly $15 million in solar arrays southwest of the marina and in a 1,500-kW Caterpillar diesel generator. The marina is pursuing environmentally beneficial electricity and system redundancy (i.e., having multiple energy sources in case of failure of one asset) while maintaining a grid connection. The 1,500-kW generator is sufficient to provide power to the main building, boatyard, and boats and thus provides a target generation capacity for a CSI-WEC to meet the marina's electricity needs.

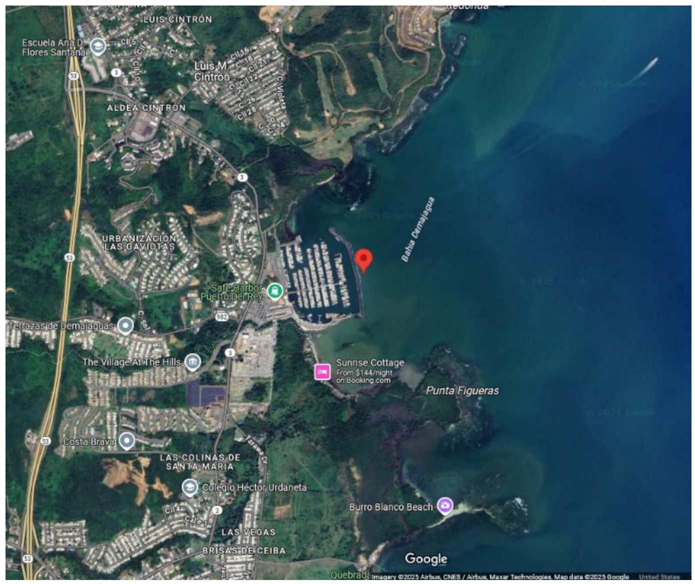

Figure 9. Case study site 1: Puerto Del Rey Marina, Puerto Rico

Maps Data: Google ©2025 Airbus, CNES / Airbus, Maxar Technologies, https://goo.gl/maps/8xNYoP459DsZKZM37

3.1.2 Site 2: Kaneohe Bay—Oahu, Hawaii

Kaneohe Bay in the northeastern part of Oahu (Figure 10) and is home to the U.S. Marine Corps Base Hawaii (MCBH). The bay's location is subject to strong wave energy conditions, which could result in significant erosion (U.S. Climate Resilience Toolkit 2024), potentially threatening Marine Corps assets without coastal defense infrastructure. The addition of a CSI-WEC here would improve the energy and erosion security of the base and provide locally generated renewable energy.

Beyond emergency operations, with the high availability of wave energy found at this site, a CSI-WEC installed here could provide locally generated energy to power the base's day-to-day electrical infrastructure, contributing to Hawaii's goal of 100% renewable energy by 2045.

The MCBH houses the Wave Energy Test Site (WETS), an offshore, grid-connected testing location for precommercial wave energy devices (Tethys n.d.). Because it houses WETS, the base is familiar with wave energy.

The base is in the process of expanding their energy mix, as indicated by the 5 MW of installed solar energy (U.S. Marine Corps n.d.). This installation includes rooftop solar for family residences as well as solar for critical facilities such as the base air terminal and aircraft rescue and firefighting building (Torres 2016).

A 2011 NREL report showed that the 2009 energy consumption of MCBH was 107,088.8 MWh (Burman et al. 2011). This figure was broken down into individual facility energy usage: 18,668 MWh/yr for the barracks, 899 MWh/yr for the main gym, 7,512 MWh/yr for the offices, 4,427 MWh/yr for the commissary, and 3,266 MWh/yr for food services.

Possible applications for a CSI-WEC at MCBH include provision of supplementary energy to critical facilities in the case of outages. Additionally, with its proximity to the airstrip, a CSI-WEC could help power airstrip energy functions such as lighting, communications, and navigation, and could provide battery storage for emergency preparedness at critical facilities.

Figure 10. Case study site 2: Kaneohe Bay, Oahu, Hawaii

Maps Data: Google ©2025 Airbus, CNES / Airbus Data USGS / Copernicus, Maxar Technologies, https://goo.gl/maps/xS8AYPBE7hTuXwMM8

3.1.3 Site 3: St. George—Pribilof Islands, Alaska

St. George is a remote community far off the coast of Alaska (Figure 11). It has a population of less than 100 people and experiences severe storms annually (U.S. Census Bureau 2020a). The main harbor is of high importance to the community, as it protects boats and is located near the airport.

The main harbor, constructed to support a growing fishing industry, has three breakwaters: two outer breakwaters and one inner breakwater. Conditions here are extreme, and a storm in 2015 damaged the southern outer breakwater. This incident required funding from the Federal Emergency Management Agency to repair the breakwater. Additional repairs completed in 2017 added berms in front of the breakwaters to help dissipate the wave energy coming in.

St. George residents are connected to a water and sewage system constructed in the 1950s (Aleutian Pribilof Islands Association n.d.). The system comprises four wells and a 250,000-gallon storage tank. Since 2011, this tank has had an issue with freezing in the winter. In 2017, ice damaged the tank's internal water line, significantly reducing the ability to withdraw water

(Kraegel 2017). During October and November 2022, the island could not provide drinkable water because of a pipe break (Fratis 2022).

To ensure power supply, St. George relies on four diesel generators: two Caterpillar 175-kW generators; a Detroit Diesel 480-kW; and a Detroit Series 60 350-kW (Alaska Energy Authority 2015). A 95-kW wind turbine was installed but eventually burnt out. Though scheduled to be replaced in the fall of 2015, the status of the turbine is unknown at the time of writing.

Fuel is barged into the island only twice a year, and fuel emergencies are common due to intense storms, requiring community rationing of fuel, heat, and water (McKenney 2021). In 2014, a waste heat recovery system with a web-based load-control system was built, supplying heat for the school, city office, and public safety building (Alaska Energy Authority 2015).

While publicly available electrical demand data are limited, a 2010 report indicated that the average electrical demand in St. George was 160 kW in the summer and 200 kW in the winter, with 300 kW of peak demand in the winter (Beatty et al. 2010). A CSI-WEC deployed at St. George could support recovery from storms that disable power, water supply, and heat and with sufficient installed capacity, could meet the peak winter demand.

Battery storage and/or reverse osmosis desalination systems powered by a CSI-WEC deployment could help support the community while they wait for proper emergency response following such events. Battery storage systems could supply immediate energy to meet power needs on the island, while desalination could provide the community with fresh water during emergency situations when freshwater access is unavailable.

A community resiliency center, such as a washeteria, could be an important addition to St. George Island. Washeterias usually contain showers, washers and dryers, fresh water, and toilets and help to reduce waterborne illnesses and water stress following an emergency or outage (Mattos and Blanco-Quiroga 2020). As there are ongoing issues with St. George’s water system, a CSI-WEC-powered community washeteria could provide increased access to clean water for residents more generally, not only in times of emergency.

Finally, the airport on St. George intermittently requires 150 kW of energy for runway lighting (Beatty et al. 2010). A CSI-WEC deployed at this harbor could provide a significant proportion of the community’s energy needs while improving resiliency.

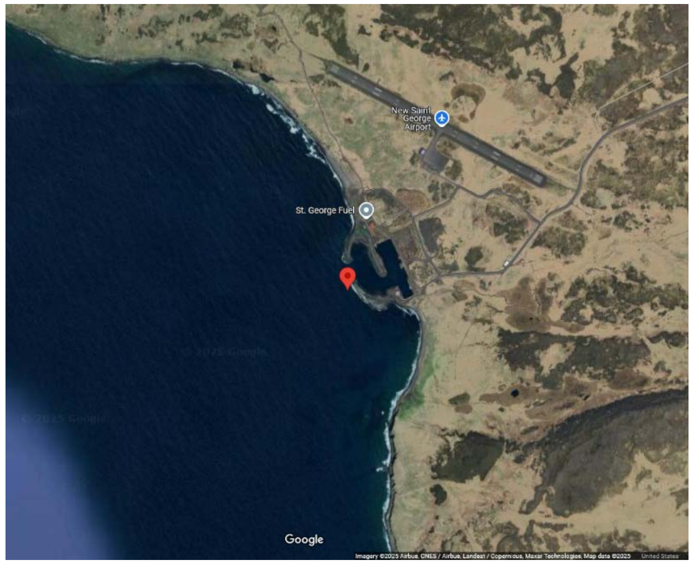

Figure 11. Case study site 3: St. George, Pribilof Islands

Maps Data: Google ©2025 Airbus, CNES / Airbus Landsat / Copernicus, Maxar Technologies, https://goo.gl/maps/wfuoeH2ow9ntDQ5aA

3.1.4 Site 4: Humboldt Bay, California

Unlike the previous locations, Site 4 was chosen to demonstrate the potential of larger-scale CSI-WEC deployments. The Humboldt Bay area (Figure 12) is well connected to the electrical grid, and California has substantial renewable wind and solar energy resources. The extensive shoreline of the Humboldt Bay area has some of the nation's largest wave resources, suggesting that it could be a prime location for a larger CSI-WEC deployment.

The location is of critical value, as multiple U.S. agencies such as the Air Force, Navy, Coast Guard, and U.S. Army Corps of Engineers (USACE) are located here. A robust energy generation asset in the area could provide auxiliary or backup power should the grid connection fail.

Two jetties protect the inlet to Humboldt Bay in Northern California. The North Jetty extends beyond the North Spit into the Pacific Ocean by about 2,200 ft, whereas the South Jetty extends about 3,300 ft beyond the South Spit. Recurring storm damage required a rebuilding of the jetties 10 times from 1911 to 1995, and in 2020, USACE began a new round of repairs, replacing stones and adding a new concrete cap (USACE 2023).

The North Jetty is at the southern tip of the Samoa peninsula, which is developed and home to a handful of communities; the South Jetty is on the northern end of an undeveloped 4-mile-long peninsula.

The jetties are directly across the bay (0.5–2-mile crossing) from the now decommissioned Humboldt Bay Power Plant and the currently operating 165-MW Humboldt Bay Generating Station. With an estimated installed power potential on the order of 30 MW across both jetties, the theoretical potential of a CSI-WEC installation supplementing 10%–20% of the capacity for power production at the Humboldt Bay Generating Station is a legitimate one. Additional breakwaters at the generating station and adjacent King Salmon beach are opposite the inlet and may have a wave energy resource that could be evaluated for CSI-WEC installations as well.

The Samoa peninsula is planning a new wastewater treatment plant with ultraviolet disinfection and pumped ocean outfall, treating an average wastewater volume of 0.07 million gallons per day (MGD). The collection system, treatment system, and treated effluent pump station have an estimated energy demand of 150 MWh/yr. The new wastewater treatment plant and outfall would be about 4 miles north of the North Jetty.

The Table Bluff Reservation of the Wiyot Tribe is located about 6 miles by road from the South Jetty. Table Bluff Reservation comprises 88.5 acres situated on coastal bluffs located in Humboldt County in Northern California. There are 37 homes on the reservation with a total of about 135 residents (Wiyot Tribe 2016). A 2019 grant from the Tribal Solar Acceleration Fund was allocated to install approximately 16 kW of solar photovoltaics for four low-income members (assumed to be households) of the Table Bluff Reservation, but no update on this project was available at the time of this report's publication (Tribal Solar Acceleration Fund n.d.). With a total of 16 kW of solar installed, the project would generate close to $120,000 in cost savings for low-income Tribal members. Using roughly 4 kW per home, the remaining 33 homes on the reservation could be powered by a CSI-WEC generating a total of 130 kW (Tribal Solar Acceleration Fund n.d.).

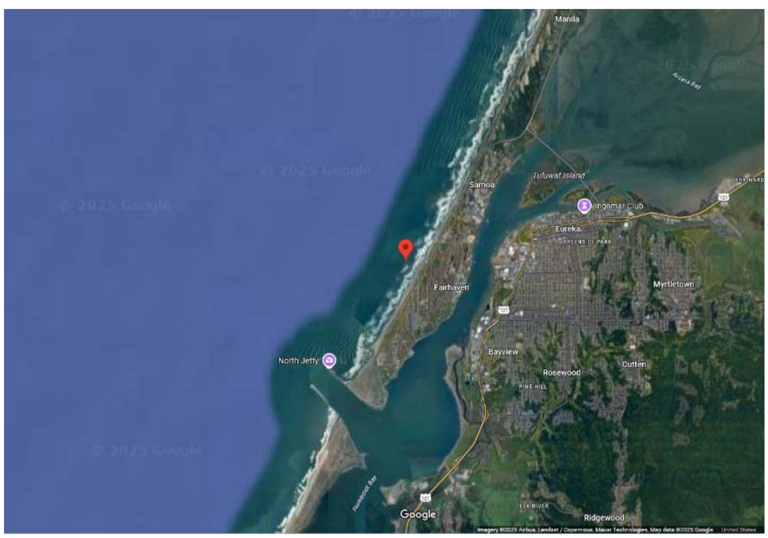

Figure 12. Case study site 4: Humbolt Bay, California

Maps Data: Google ©2025 Airbus, Landsat / Copernicus, Maxar Technologies, https://goo.gl/maps/UmEzHM3PydDNXR886

3.2 Annual Energy Production Analysis for Case Study

To assess the generation potential and feasible scales of CSI-WECs, we engaged with three developers—Eco Wave Power, Wave Swell Energy, and a team consisting of Professor Diego Vicinanza and Professor Pasquale Constestabile (OBREC Team)—to provide an annual energy production (AEP) estimate for the four sites identified in this section as high value (Puerto Rico, Hawaii, Alaska, and California).

Any full assessment would require a more in-depth study, as assumptions had to be made regarding the nearshore wave energy resource, topography, and other factors. However, because the estimates have been made by developers who have operational devices with completed deployments under their belts, there is increased confidence in the reported values. Because the operation and topology of each device vary significantly, the developers were asked to decide on the exact deployment location and the size and rating of their device. The developers conducted their analysis and sent their results to the NREL team. The NREL team normalized the developer-provided results for a deployment where the available space was limited to 10 m perpendicular to the dominant direction of incoming waves and recalculated the associated AEP results.

This case study should not be viewed as a comparison or value assessment between solutions because each device has specific advantages, and it is likely that different device types will perform better at different sites and intended end uses.

3.2.1 Case Study Results: Eco Wave Power

For Eco Wave Power's analysis, wave data were used from NOAA buoys selected based on proximity to each site (Figure 13), and then assumptions were made regarding the wave energy propagation to shore.

In St. George (Site 3), three Eco Wave Power floats could generate 152 kW of electricity, addressing the energy demand of the local airstrip, and six devices could meet the community's peak electrical demand with adequate storage.

With a deployment in Humboldt Bay (Site 4), two of Eco Wave Power's floaters could provide the generation capacity to power the wastewater treatment plant mentioned in Section 3.1.4, and an additional three devices could provide power to 33 homes in the Table Bluff Tribal Reservation.

Eco Wave Power's complete energy production analysis for each of the four sites is summarized in Table 2.

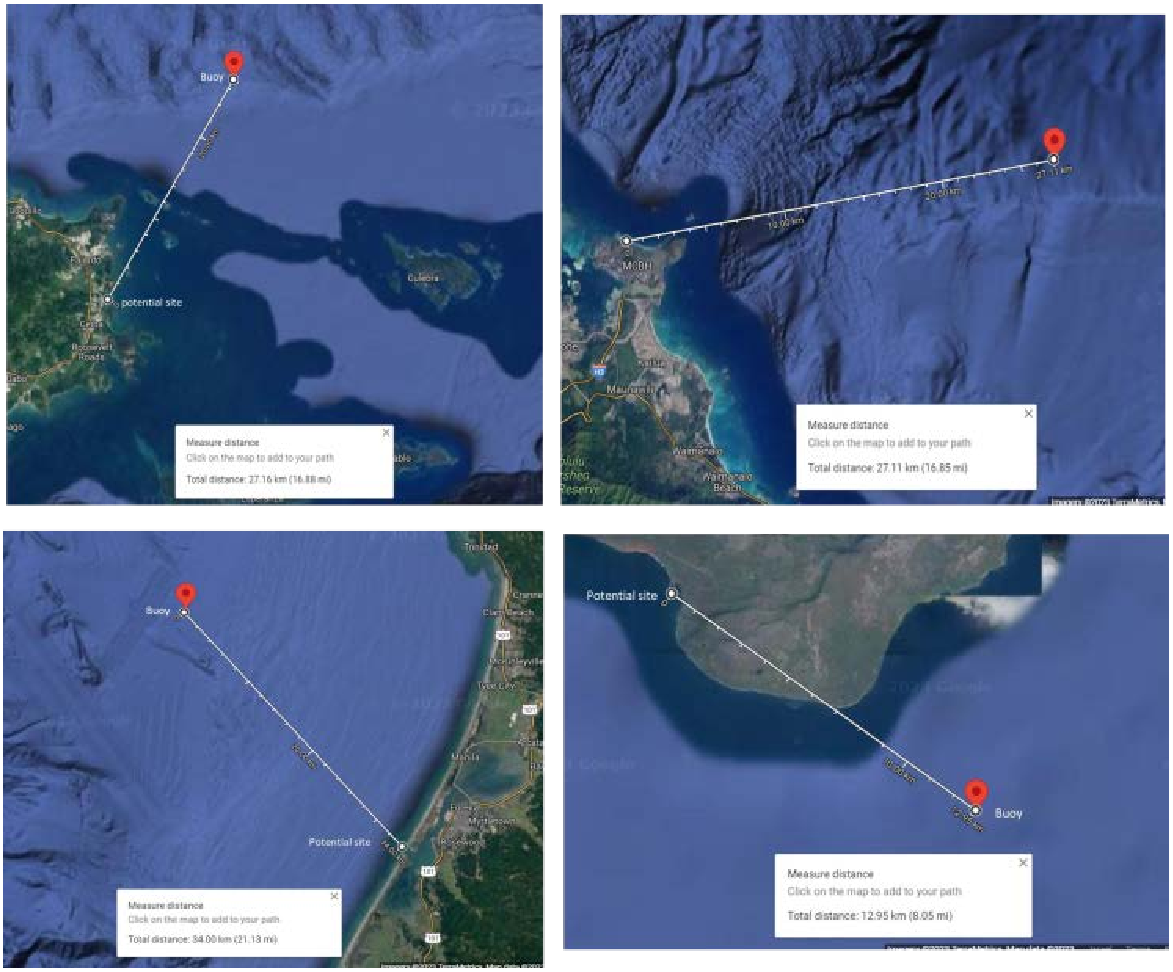

Figure 13. Eco Wave Power NOAA data buoy selection and distance to deployment sites. Top left: 27.16 km to Puerto Del Rey Marina, Puerto Rico (Site 1). Top right: 27.11 km to Kaneohe Bay, Oahu (Site 2). Bottom right: 12.95 km to St. George, Alaska (Site 3). Bottom left: 34 km to Humbolt Bay, California (Site 4).

Table 2. Energy Production Analysis for Eco Wave Power

Device/ Developer	Site	Linear Space Suggested by Developer (m)	Installed Rated Capacity (MW)	Total AEP (MWh)	Capacity Factor	Normalized Installed Capacity for 10 m (kW)	Normalized AEP for 10 m (MWh)
Eco Wave Power	Puerto Del Rey Marina, Puerto Rico	644	2.1	3,794	20.62	32.61	58.91
Eco Wave Power	Kaneohe Bay, Oahu	243	2.1	3,791	20.61	86.42	156.01
Eco Wave Power	St. George, Alaska	531	6	11,000	20.93	112.99	198.63
Eco Wave Power	Humbolt Bay, California	3,114	29.5	52,000	20.12	94.73	167.79

3.2.2 Case Study Results: OBREC

To analyze the AEP, the OBREC team first determined the available wave resource at all four sites using the Simulating WAves Nearshore (SWAN)[2] software developed by the Delft University of Technology.

SWAN computes random, short-crested, wind-generated waves in coastal regions and inland waters. The team also obtained local topography information to make high-fidelity assessments of the nearshore wave conditions (Figure 14). At each site, a water depth was estimated and the wave conditions (wave height, wave period, and wave direction) were obtained from the Marine Energy Atlas or from modeling data provided by the NREL team resulting from the PR100 study (U.S. Department of Energy n.d.).

Two potential turbines were included for the purposes of this analysis—the Very Low Head Turbine (VLH) from MJ2 technologies[3] and the NAUTILUS T Ultra Low Head Turbine.[4] For the comparison, the highest output results were selected for presentation and are shown in Table 3.

The OBREC system's primary purpose is as an energy-generating coastal defense structure: robustness is its primary function, whereas providing energy is a secondary benefit. According to the high-fidelity modeling that included topography and wave energy propagation, the device's generation potential could have a significant impact on local communities. For example, in Puerto Rico (Site 1), and assuming a port consumes 20 to 40 MWh of energy, a 10-m system would be sufficient to provide power to all port operations. Given the robust design of the

[2] https://www.tudelft.nl/en/ceg/about-faculty/departments/hydraulic-engineering/sections/environmental-fluid-mechanics/research/swan
[3] https://www.vlh-turbine.com/products/vlh-turbine/
[4] https://www.waterturbine.com/products/ultra-low-head-turbines/t-ulh.php

OBREC system, it could likely serve as an immediate energy source should the island grid be impacted by severe weather events.

Additionally, the results indicated that the system's energy production scales well with length, i.e., the system perpendicular to the incoming waves, so 60–120-m deployment could power medium-sized green ports. With 500 m of space available for device installation at the Puerto Rico site, the construction of a nearby desalination plant could produce 950 m^3 (950,000 liters) of drinking water annually.

Table 3 summarizes the AEP analysis for the OBREC system.

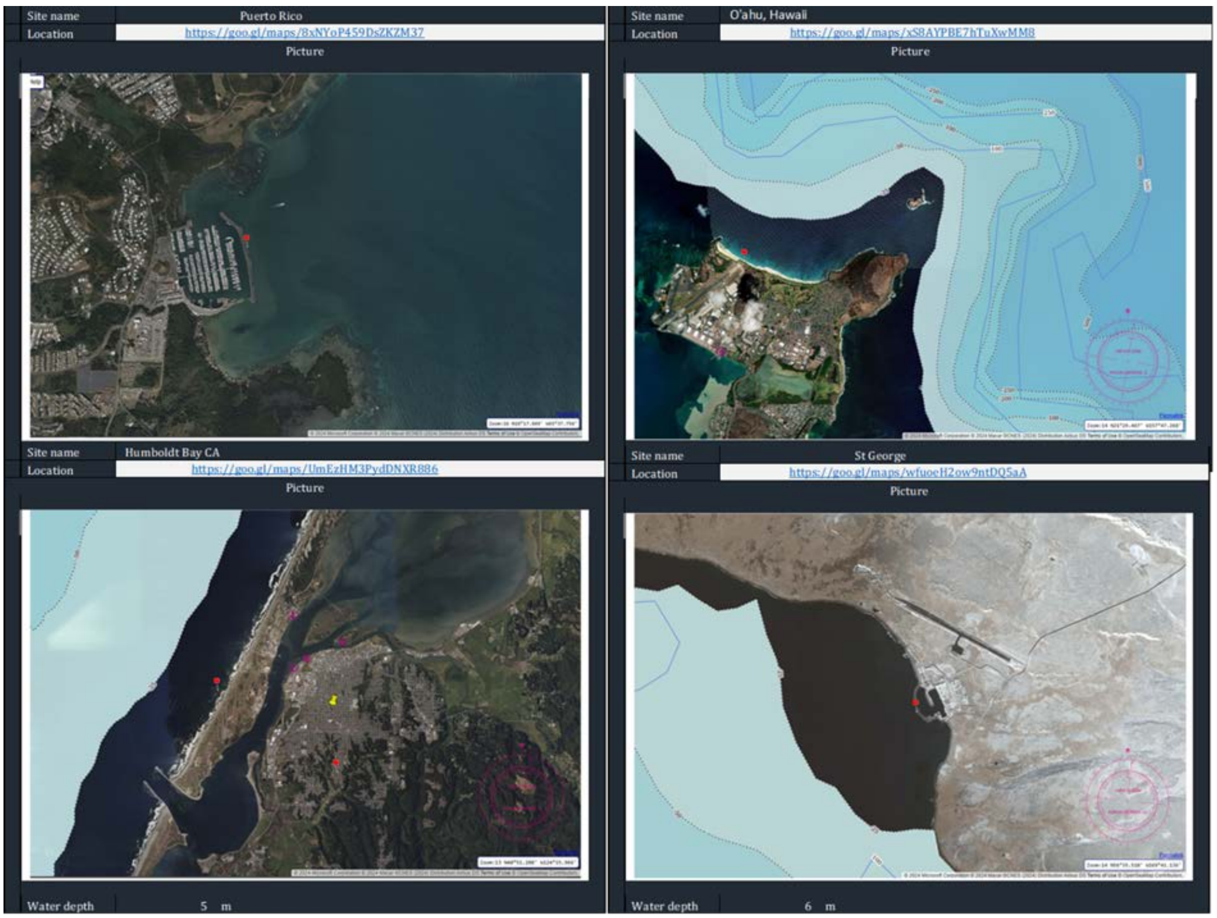

Figure 14. OBREC site analysis with bathymetry. The red dots located near the coastline indicate proposed OBREC sites in Puerto Rico; Oahu, Hawaii; St. George, Alaska; and Humboldt Bay, California (clockwise from top left).

Images from Diego Vicinanza and Pasquale Constestabile. Map data from OpenStreetMap under Open Database License, www.openstreetmap.org/copyright.

Table 3. OBREC AEP

Device/ Developer	Site	Linear Space Suggested by Developer (m)	Installed Rated Capacity (MW)	Total AEP (MWh)	Capacity Factor	Normalized Installed Capacity for 10 m (kW)	Normalized AEP for 10 m (MWh)
OBREC	Puerto Del Rey Marina, Puerto Rico	10	0.115	38	3.77	11.5	38
OBREC	Kaneohe Bay, Oahu	10	0.191	39	2.33	19.1	39
OBREC	St. George, Alaska	10	0.263	59	2.56	26.3	59
OBREC	Humbolt Bay, California	10	0.205	117	6.52	20.5	117

3.2.3 Case Study Results: Wave Swell Energy

The results of Wave Swell Energy's AEP analysis for all four sites are shown in Table 4.

A 250-m deployment at the Wave Energy Test Site in Hawaii (Site 2) could provide 13% of the Navy base's power, with the added benefits of coastal protection and a robust, local generation asset ensuring reliability of supply.

In St. George (Site 3), a deployment of just over 10 m could supply the peak island energy requirement.

Considering larger deployments in the Humboldt Bay case (Site 4), the 1-km recommended deployment could produce 80 gigawatt-hours per year, allowing for the provision of:

- 40 million m^3/yr or 29 MGD of water (at 2 kilowatt-hours per cubic meter [kWh/m^3])—for comparison, the Humboldt regional water utility currently provides 21 MGD
- 1.6 million kilograms per year (kg/yr) of hydrogen (at 50 kWh/kg).

Table 4. Wave Swell Energy AEP

Device/ Developer	Site	Linear Space Suggested by Developer (m)	Installed Rated Capacity (MW)	Total AEP (MWh)	Capacity Factor	Normalized Installed Capacity for 10 m (kW)	Normalized AEP for 10 m (MWh)
Wave Swell Energy	Puerto Del Rey Marina, Puerto Rico	1,000	3	8,000	30.44	30	80
Wave Swell Energy	Kaneohe Bay, Oahu	1,000	20	59,000	33.68	200	590
Wave Swell Energy	St. George, Alaska	1,000	29	84,000	33.07	290	840
Wave Swell Energy	Humbolt Bay, California	1,000	27	80,000	33.82	270	800

4 Techno-Economic Assessment of CSI-WECs

To explore the techno-economic opportunity for CSI-WECs, the research team performed an analysis of a hypothetical deployment of each of the developers' devices.

Site 4—Humboldt Bay, California—was selected for the analysis where, for the purpose of this study, it was assumed that a new 500-ft breakwater would be required to be built in the bay to ensure shoreline protection. Each of the devices are considered independently as part of a CSI-WEC project providing both protection and energy generation.

The approach taken for this analysis was to size each device from the values provided by the developers, such that an AEP of 876 MWh, or average power output of 100 kW over 8,760 hours in a year, was achieved. A cost analysis on the new device sizing was performed, along with a simplified return on investment (ROI) calculation, whereby the CapEx and an annual assumed OpEx of 5% of the CapEx are compared with the potential returns on the dollars per kilowatt-hour for a standard grid-scale return of $0.04/kWh and a Blue Economy price of $0.20/kWh. The Blue Economy price is intended to demonstrate how added value can be obtained by focusing on a specific application. In this case, the research team selected the offsetting of a diesel generator where the price per kilowatt-hour typically ranges from $0.10 to $0.30, using an average price value of $0.20.

4.1 Cost of Breakwaters

The high capital and maintenance costs of coastal defense structures are a key factor in the techno-economic case for CSI-WECs. As with most engineering efforts, costs can vary dramatically between regions and structure type, and although there are innovations aimed at reducing these costs, coastal engineering will likely remain large budget projects for the foreseeable future.

Though publicly available cost data on coastal infrastructure projects are limited, a 2018 Coastal Engineering publication (Igigabel and Yates 2018) evaluated coastal defense levees in France; the results are shown in Table 5. Across various construction techniques, this study found a cost range of €1,400/m to €3,200/m for levee heights in the range of 2 to 3.5 m and €5,600/m to €14,300/m for levee heights of about 8 m.

Table 5. Breakdown of Coastal Structure Costs

Table from Igigabel and Yates (2018)

Technique	Number of Recorded Operations	Linear Cost (€/m)	Surface Cost (€/m²)	Volume Cost (€/m³)	Mass Cost (€/t)
Earthwork and armourstone	2	2,000-3,100 (height between 2 and 3 m)	N/A	19-45 (earthwork)	17-24 (armourstone)
Armourstone and concrete superstructure	2	5,600-6,000 (height about 8 m)	N/A	N/A	29-33 (armourstone)
Masonry and concrete injection	2	1,400-3,200 (height between 2 and 3.5 m)	160-230 (masonry)	580 (concrete injection and anchors)	N/A
Earthwork and gabions	1	1,500 (height about 2 m)	N/A	N/A	N/A
Reinforced concrete and sheetpile	1	14,300 (height about 8 m)	N/A	N/A	N/A

Additionally, in 2015, the UK government published an extensive report on the cost estimation for coastal protection, which included an examination of state-of-the-art approaches and their associated costs (Hudson, Keating, and Pettit 2015).

The report compiled indicative capital and maintenance costs of coastal protection from two different studies prepared by the Scottish Natural Heritage and Environment Agency in 2000 and 2007 (without adjusting for inflation) (Table 6). The more recent of the two studies estimated the cost of a detached, nearshore breakwater (as distinguished from the coastal levee estimates in Table 6) to be £1,750/m to £4,300/m in 2007 currency. Assuming annual average inflation of 2.5% between 2007 and 2024, the price today would be £2,662/m to £6,542/m, or $1,017/ft to $2,500/ft.

For a 500-ft, new, nearshore breakwater build in Humboldt Bay, the cost of the structure alone could be between $508,559 and $1,249,985. While this range is subject to many different local factors, which could significantly affect the final total project costs, it is a decent initial estimate of the scale of investment required. For the purposes of this analysis, the team used an average value of $1,750/ft, and therefore the 500-ft breakwater alone would cost $875,000.

Table 6. Cost Estimation for Coastal Protection

Table from Hudson, Keating, and Pettit (2015)

Option	Significance			Indicative Cost (£/m)	
	Enabling Costs	Capital Costs	Maintenance Costs	Scottish Natural Heritage	Environment Agency Unit Cost Database
Beach recharge and breakwater	Medium	High	Medium	-	2,700–7,300
Beach recharge and groynes	Medium	High	Medium	-	1,600–4,700
Rock armour	Medium	High	Low	-	1,350–6,000
Impermeable revetments and seawalls	Medium	High	Low	2,000–5,000	700–5,400
Timber revetments	Medium	Medium	Medium	20–500	-
Rock revetments	Medium	High	Low	1,000–3,000	650–2,850
Groynes	Medium	Medium	Medium	10,000 to 100,000 per structure	-
Nearshore breakwaters	Medium	Medium	Low	400–1,000	1,750–4,300
Artificial rock dune protection	Low	Medium	Low	200–600	-
Gabion revetments	Medium	Medium	Medium	50–500	-
Beach nourishment	Medium	Medium	Medium	50–2,000	350–6,450
Shingle recycling/re-profiling	Low	Low	Low	10–200	15–120
Dune fencing	Negligible	Low	Low	4–20	-
Dune thatching	Negligible	Low	Low	2–20	-
Notes:	The Scottish Natural Heritage (SNH) costs relate to a 2000 cost base and the Environment Agency costs relate to a 2007 cost base. An allowance for inflation using a suitable index is required to update these values to present day costs.				

4.2 Estimated Costs for Each Developer Device

For each of the developer devices, estimated costs were obtained from either publicly available data or data provided directly by the developers.

- Eco Wave Power declared their target to be $1.3 million/MW–$2 million/MW, which is available from their publicly disclosed 2023 annual financial report (Eco Wave Power n.d.[d]). The Eco Wave Power device is an adopted CSI-WEC and can be added to most coastal structures; should the breakwater already exist, structure construction costs can be excluded. As in this analysis, if a new breakwater is being built, the price of the build will be reflected in the calculations. For the purpose of this analysis, an average value of $1.65 million/MW installed will be used.
- The OBREC Team provided the cost of their installation to be approximately $5,000/ft, which is inclusive of the cost of the breakwater structure.
- Wave Swell Energy set a target of $1.5 million/MW–$3 million/MW based on learning the effects once a total installed capacity of 100 MW has been achieved by the company. For the purpose of this analysis, an average value of $2.25 million/MW installed will be used. This value assumes that the structure cost is offset by the required breakwater cost, which is excluded from the stated target value and must be included for full project cost estimates.

4.3 Assumptions for Analysis

There are several variables that may affect the final costs of a CSI-WEC project, including:

- The size of the project and, therefore, the ability to benefit from economies of scale
- The large range of potential CSI structures, e.g., new-build breakwater, retrofit breakwater, rubble-mound breakwater, caisson breakwater, and seawalls
- Site-specific design characteristics, e.g., extreme wave loads and bathymetry
- Site-specific construction methodology, e.g., remote or urban project site, access to site from land, and size of installation
- Distance to grid connection point.

To procced with the analysis, we assume that:

- Loadings from the different CSI-WECs are not reflected in the costs of the new breakwater, and the cost of $1,750/ft of new structure built is the same for all devices.
- The costs of permitting and environmental impact assessments are excluded from this study.
- All connection cable costs are assumed to be the same for each device and excluded from the analysis.
- OpEx costs are the same for all devices at the stated 5% of CapEx.
- All devices are fully operational for the time period considered (20 years) and 100% of the generated energy is used.

4.4 Analysis Results and Discussion

All three devices resulted in similar total project CapEx costs—between $665,000 and $820,000—for the WEC elements only. Total project costs amounted to between $1.54 million and $1.7 million when the new breakwater build costs were included, although the required space varied significantly from 36 ft up to nearly 250 ft (Table 7 and Table 8). These ranges represent between a 75% and 94% increase in project costs compared to building a breakwater alone for the assumed device costs.

For the purposes of this analysis, it was assumed that entirely new breakwaters would have to be constructed. If there was an existing breakwater, the project costs for each device would be different. For example, assuming that a breakwater is already in place, the project cost of the Eco Wave Power device would amount to only the costs of the WEC, or $819,987. In contrast, the Wave Swell Energy device would incur costs in the required deconstruction of the existing structure, plus potential additional costs incurred at $1,750/ft for the new structure. This would amount to approximately $65,000 for the 36-ft structure required under the assumptions used in this study, though this value may vary significantly depending on project factors. This exercise highlights the importance of whole-project consideration when choosing a device, as project specifics, such as existing infrastructure, can have a significant impact on the developer's bottom line.

Considering the ROI for each device (Table 9)—at the lower fixed grid rate of $0.04/kWh—each device would generate $700,800. At this dollar-per-kilowatt-hour value, no device succeeded in paying off the initial investment when annual OpEx is included. At the higher Blue Economy rate of $0.20/kWh, each device would generate more than $3.5 million over a 20-year period; each device pays off the initial investment within 5–6 years (Figure 15–Figure 17).

Considering the range of target costs for the Eco Wave Power and Wave Swell Energy devices, a scenario-based analysis—evaluating low, average, and high costs alongside increasing dollar-per-kilowatt-hour values—allows for an expanded assessment of economic viability. As illustrated in Figure 18 and Figure 19, lower costs paired with higher energy values intuitively lead to shorter payback periods for the CSI-WEC investment and greater earning potential over the 20-year time frame. This highlights the benefits of coupling CSI-WEC projects with high energy-value applications.

Table 7. Project Space Requirements

Device/Developer	Available Space (ft)	Target AEP (MWh)	CSI-WEC Space Required (ft)	Remaining Breakwater Space (ft)	Installed Rated Capacity (kW)
Eco Wave Power	500	876	172	328	497
OBREC	500	876	246	254	1535
Wave Swell Energy	500	876	36	464	296

Table 8. Project Costs

Device/Developer	Cost of WEC ($)	Cost of Breakwater Required ($)	Combined WEC and Breakwater Cost ($)
Eco Wave Power	819,987	875,000	1,694,987
OBREC	1,228,212	445,126	1,673,338
Wave Swell Energy	665,213	875,000	1,540,213

Table 9. ROI Results

Device/Developer	CapEx – WEC Only ($)	Annual OpEx – WEC Only ($)	20-year returns at $0.04/kWh ($)	20-year returns at $0.20/kWh ($)
Eco Wave Power	819,987	40,999	700,800	3,504,000
OBREC	798,338	39,917	700,800	3,504,000
Wave Swell Energy	665,213	33,261	700,800	3,504,000

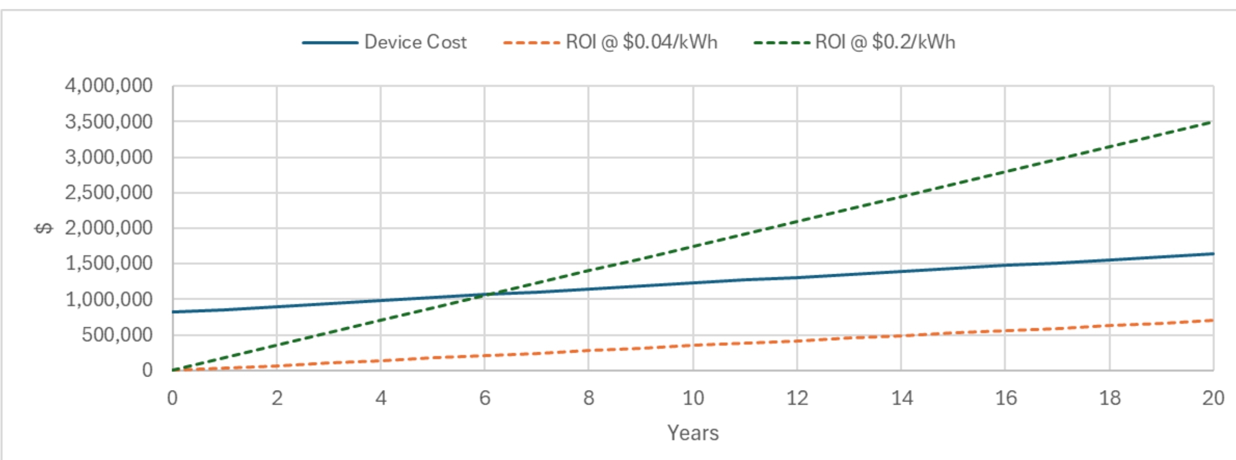

Figure 15. Eco Wave Power device cost compared with ROI for different dollar-per-kilowatt-hour values

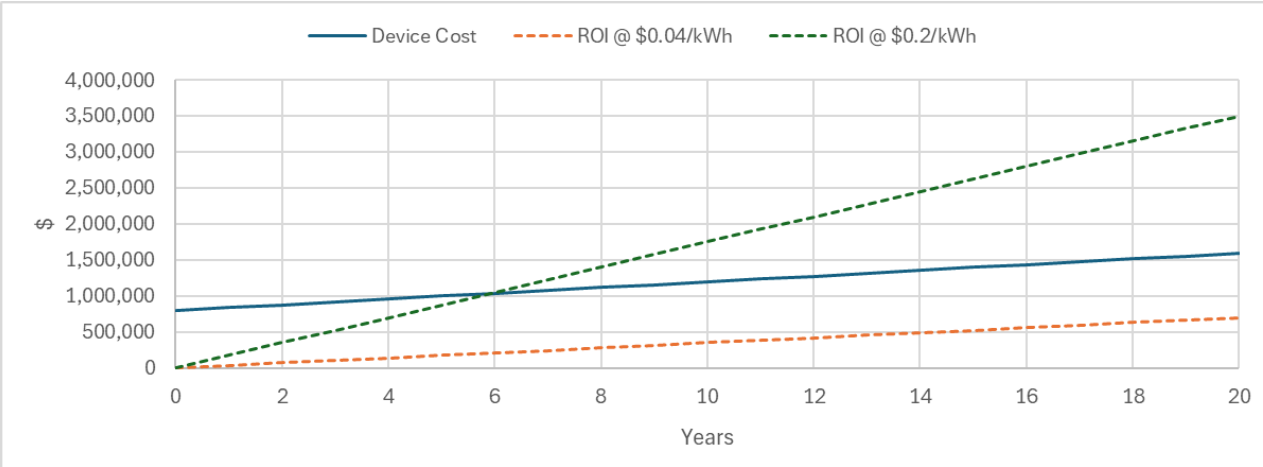

Figure 16. OBREC device cost compared with ROI for different dollar-per-kilowatt-hour values

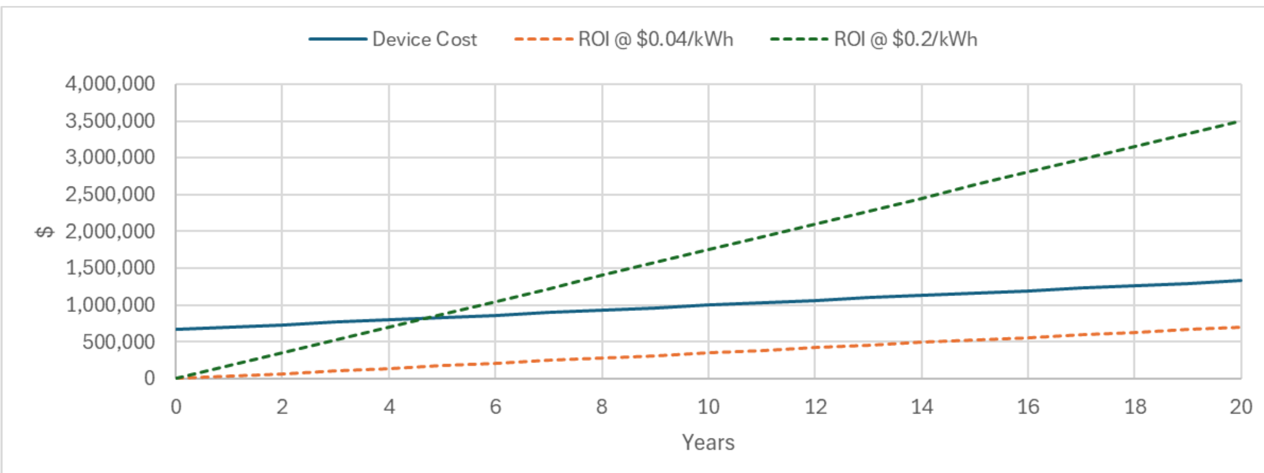

Figure 17. Wave Swell Energy device cost compared with ROI for different dollar-per-kilowatt-hour values

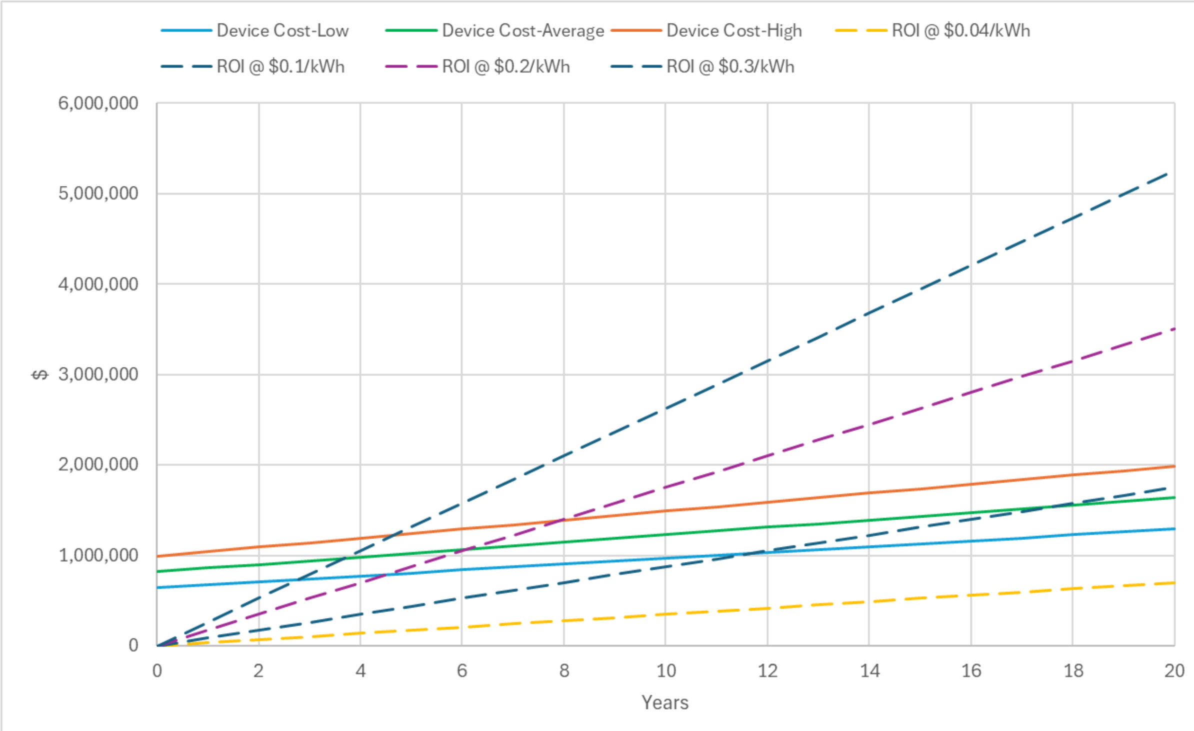

Figure 18. Eco Wave Power device ROI for different device cost targets and increasing dollar-per-kilowatt-hour values

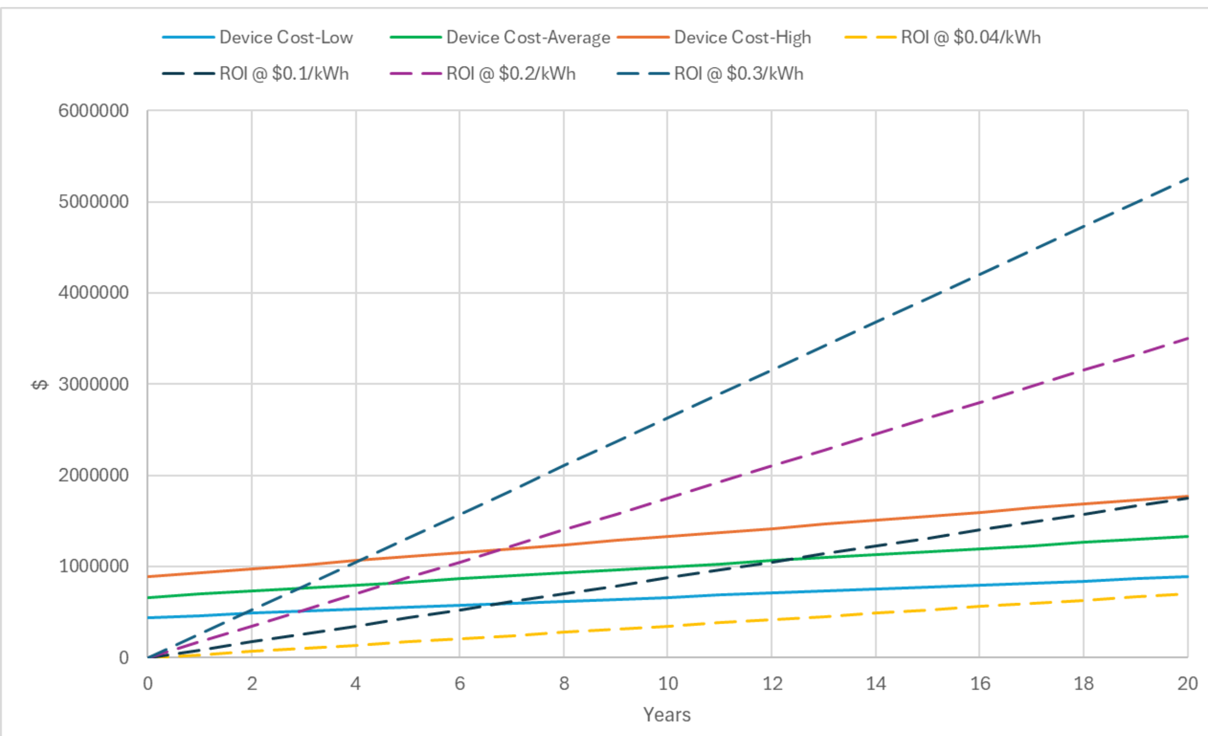

Figure 19. Wave Swell Energy ROI for different device cost targets and increasing dollar-per-kilowatt-hour values

5 Conclusion

The wave energy industry in the United States is at a critical point where viable technologies must be successfully demonstrated at full scale to prove both function and value to ultimately achieve adoption. CSI-WECs are proving their technical, operational, and economic viability in real time. The most fruitful developments in the wave energy industry to date have been courtesy of CSI-WECs, as demonstrated by several successful multiyear deployments, such as Mutriku in Spain, which have both produced sustained energy and achieved grid connection.

CSI-WECs are a near-term solution with a high technology readiness level for the wave energy industry's challenges with full-scale deployment and end-use applications. Although wave energy technology is often characterized as a high-risk, high-reward venture, CSI-WECs present a relatively low-risk alternative, as the primary purpose of these devices is coastal defense with an added benefit of energy generation. Existing deployments are proving the viability of these installations, and the reward aspect remains high—particularly for remote and disadvantaged communities that would reap the benefits of coastal defense alongside a robust renewable source of energy.

CSI-WECs are unique in that they provide protection from flooding and storm surge in coastal communities—which can reduce the costs associated with post-disaster recovery efforts—while also providing an additional energy source to these communities, which can prove invaluable in emergency situations. CSI-WECs are even able to function during storm surge events, boosting the resiliency of coastal communities, particularly when the CSI-WEC is connected to a microgrid.

Moreover, the economics add up. Techno-economic assessments support CSI-WECs as a readily adoptable technology that can enable ports and coastal communities to generate local electricity while simultaneously enhancing their coastal defense infrastructure.

The research team performed a techno-economic assessment for a hypothetical CSI-WECs deployment at the Humbolt Bay site, demonstrating favorable returns on CSI-WEC investments when coupled with applications or deployments where the value of energy is high. The team found that for all developer devices and a value of $0.20/kWh, the initial capital investment is returned within 5 to 6 years, with potentially millions of dollars' worth of energy generated over a 20-year time frame. Additionally, local jobs could be created to service the devices, although this consideration was beyond the scope of this study.

Although a comprehensive assessment of near-shore wave conditions must be completed prior to any CSI-WEC deployment, project developers have demonstrated the significant potential of these devices. With AEP projections in the tens of megawatt-hours to gigawatt-hours, there is enormous untapped potential in converting non-energy-producing coastal defense structures into generation assets that can power essential services, high-value applications, and even robust and resilient local grids. Because the developers in this case study have successfully deployed devices, their AEP estimates carry confidence and credibility, which should be considered and expanded upon for further assessment and techno-economic evaluation.

NREL supports CSI-WEC developers, local authorities, and communities in exploring the value proposition of this promising technology through siting assessments and techno-economic assessments and by providing high-fidelity data. With extensive marine energy testing facilities and capabilities, NREL can support system and subsystem testing and validation. As CSI-WEC adoption expands, the NREL team can support microgrid, grid, and Blue Economy application connection and integration.

Though further development, demonstration, and analysis are required, CSI-WECs present an opportunity for the advancement of water power technologies in the United States while adding value to coastal infrastructure projects.

References

Alaska Energy Authority. 2015. *Aleutian and Pribilof Islands Regional Energy Plan: Phase II - Report Update*. Prepared by Southwest Alaska Municipal Conference and Information Insights. https://www.akenergyauthority.org/LinkClick.aspx?fileticket=gW810xQILB0%3D&portalid=0.

Aleutian Pribilof Islands Association. No date. "St. George." https://www.apiai.org/tribes/st-george/.

Allahdadi, Mohammad Nabi, Ruoying He, Seongho Ahn, Chris Chartrand, and Vincent S. Neary. 2021. "Development and calibration of a high-resolution model for the Gulf of Mexico, Puerto Rico, and the US Virgin Islands: Implication for wave energy resource characterization." Ocean Engineering 235. https://doi.org/10.1016/j.oceaneng.2021.109304

Arena, Felice, Alessandra Romolo, Giovanni Malara, Vincenzo Fiamma, and Valentina Laface. 2017. "The First Full Operative U-OWC Plants in the Port of Civitavecchia." In Volume 10: Ocean Renewable Energy, V010T09A022. Trondheim, Norway: American Society of Mechanical Engineers, 2017. https://doi.org/10.1115/OMAE2017-62036.

Beatty, Scott J., Peter Wild, and Bradley J. Buckham. 2010. "Integration of a Wave Energy Converter Into the Electricity Supply of a Remote Alaskan Island." *Renewable Energy* 35(6): 1203–1213. https://doi.org/10.1016/j.renene.2009.11.040.

Biscay Marine Energy Platform (BiMEP). No date. "Technical Characteristics, Mutriku Area." Accessed August 1, 2023. https://www.bimep.com/en/mutriku-area/technical-characteristics/.

Bonamano, Simone, Maximo Aurelio Peviani, Calogero Giusepe Burio, Giorgio Fersini, and Marco Marcelli. 2023. "High Resolution Numerical Modeling Supporting the Evaluation of the WaveSAX-2 Power Generation in the Coastal Area Around the Civitavecchia Port." Abstract EGU23-7655 in the EGU General Assembly 2023, April 23–28, 2023, Vienna, Austria. https://doi.org/10.5194/egusphere-egu23-7655.

Buccino, Mariano, Daniela Salerno, and Mario Calabrese. 2018. "Structural Response of Seawave Slotcone Generators (SSG): Analysis of a Nearshore Device." *Proceedings of the International Offshore and Polar Engineering Conference* 2018-June: 1355–1359. https://onepetro.org/ISOPEIOPEC/proceedings-abstract/ISOPE18/All-ISOPE18/20124.

Burman, K., A. Kandt, L. Lisle, S. Booth, A. Walker, J. Roberts, and J. Falcey. 2011. *Targeting Net Zero Energy at Marine Corps Base Kaneohe Bay, Hawaii: Assessment and Recommendations*. Golden, CO: National Renewable Energy Laboratory NREL/TP-7A40-52897. https://www.nrel.gov/docs/fy12osti/52897.pdf.

Cascajo, Raúl, Emilio García, Eduardo Quiles, Antonio Correcher, and Francisco Morant. 2019. "Integration of Marine Wave Energy Converters into Seaports: A Case Study in the Port of Valencia." *Energies* 12(5): 787. https://doi.org/10.3390/en12050787.

Cheng, Yong, Lei Fu, Saishuai Dai, Maurizio Collu, Lin Cui, Zhiming Yuan, and Atilla Incecik. 2022. *Renewable and Sustainable Energy Reviews* 169: 112909. https://doi.org/10.1016/j.rser.2022.112909.

Clemente, Daniel, Tomás Cabral, Paulo Rosa-Santos, and Francisco Taveira-Pinto. 2023. "Blue Seaports: The Smart, Sustainable, and Electrified Ports of the Future." *Smart Cities* 6(3): 1560–1588. https://doi.org/10.3390/smartcities6030074.

Contestabile, Pasquale, and Diego Vicinanza. 2018. "Coastal Defence Integrating Wave-Energy-Based Desalination: A Case Study in Madagascar." *Journal of Matine Science and Engineering* 6(2): 64. https://doi.org/10.3390/jmse6020064.

Contestabile, Pasquale, Gaetano Crispino, Enrico Di Lauro, Vincenzo Ferrante, Corrado Gisonni, and Diego Vicinanza. 2020. "Overtopping Breakwater for Wave Energy Conversion: Review of State of Art, Recent Advancements and What Lies Ahead." *Renewable Energy* 147 Part 1: 705–718. https://doi.org/10.1016/j.renene.2019.08.115.

Contestabile, Pasquale, Vincenzo Ferrante, Enrico Di Lauro, and Diego Vicinanza. 2016. "Prototype Overtopping Breakwater for Wave Energy Conversion at Port of Naples." Presented at Twenty-Sixth (2016) International Ocean and Polar Engineering Conference, June 26–July 1, 2016, Rhodes, Greece. Preprint available at: https://www.researchgate.net/publication/305075313_Prototype_Overtopping_Breakwater_for_Wave_Energy_Conversion_at_Port_of_Naples.

Cossu, Remo, Craig Heatherington, Irene Penesis, Ryan Beecroft, and Scott Hunter. 2020. "Seafloor Site Characterization for a Remote Island OWC Device Near King Island, Tasmania, Australia." *Journal of Marine Science and Engineering* 8(3): 194. https://doi.org/10.3390/jmse8030194.

Eco Wave Power. 2022. "Eco Wave Power's Innovative Wave Energy Pilot Is on Way to AltaSea at the Port of Los Angeles." August 2, 2022. https://www.ecowavepower.com/eco-wave-powers-innovative-wave-energy-pilot-is-on-way-to-altasea-at-the-port-of-los-angeles/.

Eco Wave Power. 2021. "Eco Wave Power Secures 1MW Installation and Grid Connection Permit, Small-Production Unit Registration Approval for its Planned Pilot Project in Portugal." Accessed September 4, 2024. https://www.ecowavepower.com/eco-wave-power-secures-1mw-installation-and-grid-connection-permit-small-production-unit-registration-approval-for-its-planned-pilot-project-in-portugal/

Eco Wave Power. No date (a). "Gibraltar Pilot." https://www.ecowavepower.com/gibraltar/.

Eco Wave Power. No date (b). "How It Works." https://www.ecowavepower.com/our-technology/how-it-works/.

Eco Wave Power. No date (c). "EWP EDF One Pilot Israel." https://www.ecowavepower.com/israel/.

Eco Wave Power. No date (d). "Financial Reports." https://www.ecowavepower.com/investor-relations/financial-reports/

Ente Vasco de la Energía (EVE). No date. "Current Situation and Prospects for Development." Energiaren Euskal Erakundea. https://www.eve.eus/Actuaciones/Marina.aspx.

Falcão, António F. O., António J. N. A. Sarmento, Luís M. C. Gato, and Ana Brito-Melo. 2020. "The Pico OWC Wave Power Plant: Its Lifetime from Conception to Closure 1986–2018." *Applied Ocean Research* 98: 102104. https://doi.org/10.1016/j.apor.2020.102104.

Fleming, Alan, Gregor MacFarlane, S. Hunter, and T. Denniss. 2023. "Power Performance Prediction for a Vented Oscillating Water Column Wave Energy Converter With a Unidirectional Air Turbine Power Take-Off." Presented at the 12th European Wave and Tidal Energy Conference (EWTEC), Aug. 27–Sept. 1, 2017, Cork Ireland. Available at: https://figshare.utas.edu.au/articles/conference_contribution/Power_performance_prediction_for_a_vented_oscillating_water_column_wave_energy_converter_with_a_unidirectional_air_turbine_power_take-off/23097722/1.

Folley, Matt, and Trevor Whittaker. 2009. "The Cost of Water From an Autonomous Wave-Powered Desalination Plant." *Renewable Energy* 34(1): 75–81. https://doi.org/10.1016/j.renene.2008.03.009.

Foteinis, Spyros. 2022. "Wave Energy Converters in Low Energy Seas: Current State and Opportunities." *Renewable and Sustainable Energy Reviews* 162: 112448. https://doi.org/10.1016/j.rser.2022.112448.

Fratis, Jill. 2022. "After Nearly a Month, Running Water Restored to Homes on St. George Island." Alaska Public Media. https://alaskapublic.org/2022/11/29/after-nearly-a-month-running-water-restored-to-homes-on-st-george-island/.

Garavelli, Lysel, Mikaela C. Freeman, Levy G. Tugade, David Greene, and Jim McNally. 2022. "A Feasibility Assessment for Co-Locating and Powering Offshore Aquaculture With Wave Energy in the United States." *Ocean and Coastal Management* 225: 106242. https://doi.org/10.1016/j.ocecoaman.2022.106242.

Global Maritime Energy Efficiency Partnerships. No date. "Shore Power." https://glomeep.imo.org/technology/shore-power/.

Goreau, Thomas. 2012. "Marine Electrolysis for Building Materials and Environmental Restoration." *Electrolysis* 273-290. https://www.scirp.org/reference/referencespapers?referenceid=1250801.

Hall, Sarah, Katie Peterson, Kelly Gjestvang, and Ben McGilton. 2024. *GIS Supported Optimal Site Selection for Coastal Structure Integrated Wave Energy Converters: Preprint*. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5700-90299. https://www.nrel.gov/docs/fy24osti/90299.pdf.

Harrison, Kevin, and Johanna Ivy Levene. 2008. "Electrolysis of Water." In *Solar hydrogen generation: toward a renewable energy future,* 41-63. New York, NY: Springer.

Heikkinen, T., and J. Sutela. 2022. *Energy Efficiency in the Small Ports: Evaluation and Development*. Satakunta University of Applied Sciences. https://www.theseus.fi/bitstream/handle/10024/756202/2022_B_9_Energy_efficiency_in_the_small_ports.pdf?sequence=1&isAllowed=y.

Hudson, Thomas, Kevin Keating, and Angus Pettit. 2015. *Delivering Benefits Through Evidence: Cost Estimation for Coastal Protection – Summary of Evidence*. Bristol, UK: Environment Agency. Report SC080039/R7. https://assets.publishing.service.gov.uk/media/6034ee168fa8f5432c277c23/Cost_estimation_for_coastal_protection.pdf.

Ibarra-Berastegi, Gabriel, Jon Sáenz, Alain Ulazia, Paula Serras, Ganix Esnaola, and Carlos Garcia-Soto. 2018. "Electricity Production, Capacity Factor, and Plant Efficiency Index at the Mutriku Wave Farm (2014–2016)." *Ocean Engineering* 147: 20–29. https://doi.org/10.1016/j.oceaneng.2017.10.018.

Igigabel, Marc, and Marissa Yates. 2018. "Cost Study of Coastal Protection." *International Conference of Coastal Engineering Proceedings* 36: 87. https://doi.org/10.9753/icce.v36.papers.87

International Energy Agency Ocean Energy Systems (IEA-OES). 2023. *Annual Report: An Overview of Ocean Energy Activities in 2022*. The Executive Committee of IEA Ocean Energy Systems. https://tethys-engineering.pnnl.gov/sites/default/files/publications/oes_report_2022.pdf.

Khalid Mohammed Ridha, Waleed, Kazem Reza Kashyzadeh, and Siamak Ghorbani. 2023. "Common Failures in Hydraulic Kaplan Turbine Blades and Practical Solutions." *Materials* 16(9): 3303. https://doi.org/10.3390/ma16093303.

Kim, Kilwon, Sewan Park, ChangHyuck Lim, Kyong-Hwan Kim, Jeonghwan Oh, and Seung-Ho Shin. 2023. "The Performance Evaluation of 30kW Class OWC Wave Power Plant Integrated With Breakwater." *Proceedings of the European Wave and Tidal Energy Conference* 15. https://doi.org/10.36688/ewtec-2023-592.

Koutrouveli, Theofano I., Enrico Di Lauro, Luciana das Neves, Tomás Calheiros-Cabral, Paulo Rosa-Santos, and Francisco Taveira-Pinto. 2021. "Proof of Concept of a Breakwater-Integrated Hybrid Wave Energy Converter Using a Composite Modelling Approach." *Journal of Marine Science and Engineering* 9(2): 226. https://doi.org/10.3390/jmse9020226.

Kraegel, Laura. 2017. "Due to Damaged Reservoir, St. George Island Waits for Water Delivery." Alaska Public Media. https://alaskapublic.org/2017/02/07/due-to-damaged-reservoir-st-george-island-waits-for-water-delivery/.

Kramer, Morten, Laurent Marquis, and Peter Frigaard. 2011. "Performance Evaluation of the Wavestar Prototype: The 9th European Wave and Tidal Energy Conference: EWTEC 2011." Edited by AbuBakr S. Bahaj. 9th EWTEC 2011. https://vbn.aau.dk/ws/portalfiles/portal/55762154/Performance_Evaluation_of_the_Wavestar_Prototype.pdf.

Lee, M. H. 2021. "S. Korea Builds Demo Wave Power Plant." Korea Bizwire. http://koreabizwire.com/s-korea-builds-demo-wave-power-plant/204477.

Lewis, Tony. 2019. "Demonstration of the Ocean Energy (OE) Buoy at US Navy's Wave Energy Test Site." U.S. Department of Energy Water Power Technologies Office 2019 Peer Review. https://www.energy.gov/sites/prod/files/2019/12/f69/07_EE0006924_OceanEnergy_Lewis_%20Mauer_Final.pdf.

LiVecchi, A., A. Copping, D. Jenne, A. Gorton, R. Preus, G. Gill, R. Robichaud, R. Green, S. Geerlofs, S. Gore, D. Hume, W. McShane, C. Schmaus, H. Spence. 2019. *Powering the Blue Economy; Exploring Opportunities for Marine Renewable Energy in Maritime Markets*. Washington, D.C.: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. DOE/GO-1020195157. https://www.energy.gov/sites/prod/files/2019/03/f61/73355.pdf.

Martínez-Moya, Julián, Barbara Vazquez-Paja, and Jose Andrés Gimenez Maldonado. 2019. "Energy Efficiency and CO2 Emissions of Port Container Terminal Equipment: Evidence From the Port of Valencia." *Energy Policy* 131: 312–319. https://doi.org/10.1016/j.enpol.2019.04.044.

Mattos, K., and Blanco-Quiroga, T. 2020. "Water Infrastructure Brief." Alaska Native Tribal Health Consortium. https://www.anthc.org/wp-content/uploads/2021/04/Washeteria-Technical-Brief.pdf.

McKenney, Hope. 2021. "Fuel Shortage and Blizzard Leave St. George Residents Rationing Heat and Water." Alaska Public Media. https://alaskapublic.org/2021/12/16/fuel-shortage-and-blizzard-leave-st-george-residents-rationing-heat-and-water/.

Melnikov, Afanasy. 2021. "Cathodically Protected Steel Mesh as an Environmentally Friendly Material for Oyster Reef Restoration." Master's thesis, Florida Institute of Technology. https://repository.fit.edu/etd/1204.

Miller, Stefan. 2020. "Electrically Stimulated Artificial Mussel (Mytilus edulis) Reefs To Create Shoreline Protection and Coastal Habitat in St. Margaret's Bay, Nova Scotia." Accessed August 2023. https://dalspace.library.dal.ca/handle/10222/80265.

Mueller, Markus, and Robin Wallace. 2008. "Enabling Science and Technology for Marine Renewable Energy." *Energy Policy* 36(12): 4376–4382. https://doi.org/10.1016/j.enpol.2008.09.035.

National Renewable Energy Laboratory (NREL). 2021. "Battery Storage for Resilience." Golden, CO: National Renewable Energy Laboratory. NREL/TP-7A40-79850. https://www.nrel.gov/docs/fy21osti/79850.pdf.

Palma, Giuseppina, Pasquale Contestabile, Barbara Zanuttigh, Sara Mizar Formentin, and Diego Vicinanza. 2020. "Integrated Assessment of the Hydraulic and Structural Performance of the OBREC Device in the Gulf of Naples, Italy." *Applied Ocean Research* 101: 102217. https://doi.org/10.1016/j.apor.2020.102217.

Pombo, Rita, Peter Roebeling, and Carlos Coelho. (2024). "Cost-benefit analysis of a detached breakwater for coastal protection: a case study in the Portuguese seaside." *Journal of Coastal Conservation* 28(4): 61. https://doi.org/10.1007/s11852-024-01060-3.

PRIMRE. 2024. "Yongsoo OWC." OpenEI. https://openei.org/wiki/PRIMRE/Databases/Projects_Database/Devices/Yongsoo_OWC.

RAND. No Date. "Hurricanes Irma and Maria: Impact and Aftermath" https://www.rand.org/hsrd/hsoac/projects/puerto-rico-recovery/hurricanes-irma-and-maria.html.

Saaty, Thomas L. 1990. "How To Make a Decision: The Analytic Hierarchy Process". *European Journal of Operational Research* 48(1): 9–26. https://doi.org/10.1016/0377-2217(90)90057-I.

Shao, Meng, Zhixin Han, Jinwei Sun, Chengsi Xiao, Shulei Zhang, and Yuanxu Zhao. 2020. "A Review of Multi-Criteria Decision Making Applications for Renewable Energy Site Selection." *Renewable Energy* 157: 377–403. https://doi.org/10.1016/j.renene.2020.04.137.

Sifakis, N., and T. Tsoutsos. 2020. "Nearly Zero Energy Ports: A Necessity or a Green Upgrade?" *IOP Conference Series: Earth and Environmental Science* 410: 012037. https://doi.org/10.1088/1755-1315/410/1/012037.

Simonetti, Irene, Andrea Esposito, and Lorenzo Cappietti. 2022. "Experimental Proof-of-Concept of a Hybrid Energy Converter Based on Oscillating Water Column and Overtopping Mechanisms." *Energies* 15(21): 8065. https://doi.org/10.3390/en15218065.

Syse, Helleik L. 2016. "Investigating Off-Grid Energy Solutions for the Salmon Farming Industry." Master's thesis, University of Strathclyde Engineering. https://www.esru.strath.ac.uk/Documents/MSc_2016/Syse.pdf.

Tawfik, Magdy, Ahmed S. Shehata, Mostafa S. Hamad, Amr A. Hassan, and Mohamed A. Kotb. 2022. "Energy Management Strategies for a Marine Port in Egypt." *AIP Conference Proceedings* 2437: 020093. https://doi.org/10.1063/5.0092277.

Tethys. No date. "Wave Energy Test Site Environmental Assessment: Marine Corps Base Hawaii." https://tethys.pnnl.gov/publications/wave-energy-test-site-environmental-assessment-marine-corps-base-hawaii

The Queen's University of Belfast. 2002. "ISLAY LIMPET WAVE POWER PLANT." Publishable Report. Belfast, UK: The Queen's University of Belfast. https://tethys.pnnl.gov/sites/default/files/publications/Islay_LIMPET_Report.pdf.

Torre-Enciso, Y., I. Ortubia, L. I. López de Aguileta, and J. Marqués. 2009. "Mutriku Wave Power Plant: From the Thinking out to the Reality." In Proceedings of the 8th European Wave and Tidal Energy Conference. Uppsala, Sweden. Available at: https://tethys.pnnl.gov/sites/default/files/publications/Torre-Enciso_et_al_2009.pdf.

Torres, Jesus Sepulveda. 2016. "Green Future for MCB Hawaii." Defense Visual Information Distribution Service. https://www.dvidshub.net/news/200933/green-future-mcb-hawaii.

Tribal Solar Accelerator Fund. No date. "Wiyot Tribe." Accessed August 2023. https://tribalsolar.org/2019-grantees/wiyot-tribe/.

U.S. Army Corps of Engineers (USACE). 2023. "San Francisco District Website: Humboldt Harbor and Bay." Accessed August 2023. https://www.spn.usace.army.mil/Missions/Projects-and-Programs/Current-Projects/Humboldt-Harbor-Bay--/.

U.S. Army Corps of Engineers, Seattle District Website. No date. "Navigation." Accessed September 4, 2024. www.nws.usace.army.mil/Missions/Civil-Works/Programs-and-Projects/Authorities/Specifically-Authorized-Projects/Navigation.

U.S. Census Bureau. 2020a. "St. George ANVSA, AK: Profile Data." *data.census.gov.* Accessed August 29, 2024. https://data.census.gov/profile/St._George_ANVSA,_AK?g=2500000US7340

U.S. Census Bureau. 2020b. "2020 Island Areas Censuses: American Samoa" *data.census.gov.* Accessed August 29, 2024. https://www.census.gov/data/tables/2020/dec/2020-american-samoa.html.

U.S. Climate Resilience Toolkit. 2024. "Confronting Shoreline Erosion on O'ahu." Accessed August 30, 2024. https://toolkit.climate.gov/case-studies/confronting-shoreline-erosion-o%E2%80%98ahuU.S.

U.S. Department of Energy (DOE). No date. "PR100." Accessed August 2023. https://www.energy.gov/topics/pr100.

U.S. Department of Transportation, Maritime Administration. 2022. "Grants and Finances." Accessed September 4, 2024. https://www.maritime.dot.gov/grants-finances

U.S. Marine Corps. No date. "Sustainability Initiatives and Renewable Energy Projects." Marine Corps Base Hawaii. https://www.mcbhawaii.marines.mil/Sustainability-Initiatives-and-Renewable-Energy-Projects/.

Vasileiou, Margarita, Eva Loukogeorgaki, and Dimitra G. Vagiona. 2017. "GIS-Based Multi-Criteria Decision Analysis for Site Selection of Hybrid Offshore Wind and Wave Energy Systems in Greece." *Renewable and Sustainable Energy Reviews* 73: 745–757. https://doi.org/10.1016/j.rser.2017.01.161.

Vicinanza, Diego, Enrico Di Lauro, Pasquale Contestabile, Corrado Gisonni, Javier L. Lara, and Inigo J. Losada. 2019. "Review of Innovative Harbor Breakwaters for Wave-Energy Conversion." *Journal of Waterway, Port, Coastal, and Ocean Engineering* 145(4): 03119001. https://doi.org/10.1061/(ASCE)WW.1943-5460.0000519.

Vicinanza, Diego, Lucia Margheritini, Jens Peter Kofoed, and Mariano Buccino. 2012. "The SSG Wave Energy Converter: Performance, Status and Recent Developments." *Energies* 5(2): 193–226. https://doi.org/10.3390/en5020193.

Wave Swell. No date. "King Island Project: A World First Project." Wave Swell. https://www.waveswell.com/king-island-project-2/.

Wiyot Tribe Natural Resources Department. 2016. "US EPA General Assistance Program, Indoor Air Quality Needs Assessment." Wiyot Tribe Natural Resources Department. https://www.wiyot.us/ArchiveCenter/ViewFile/Item/56.

Zhang, Hengming, Binzhen Zhou, Christopher Vogel, Richard Willden, Jun Zang, and Jing Geng. 2020. "Hydrodynamic Performance of a Dual-Floater Hybrid System Combining a Floating Breakwater and an Oscillating-Buoy Type Wave Energy Converter." *Applied Energy* 259: 114212. https://doi.org/10.1016/j.apenergy.2019.114212.

Zheng, Siming, Mike Meylan, Xiantao Zhang, Gregorio Iglesias, and Deborah Greaves. 2021. "Performance of a Plate-Wave Energy Converter Integrated in a Floating Breakwater." *IET Renewable Power Generation* 15: 3206–3219. https://doi.org/10.1049/rpg2.12230.

Zhou, Binzhen, Yu Wang, Zhi Zheng, Peng Jin, and Dezhi Ning. 2023. "Power Generation and Wave Attenuation of a Hybrid System Involving a Heaving Cylindrical Wave Energy Converter in Front of a Parabolic Breakwater." *Energy* 282: 128364. https://doi.org/10.1016/j.energy.2023.128364.

Appendix A. Table of CSI-WEC Related Devices

Table A-1. All Related Wave Energy Devices That Were Identified During This Work

Name	Developer	Developer Country	Recent Deployment	Type	Stage of Development	2023 Status	Reference
			Oscillating Water Column (OWC) – Breakwaters				
Pico	Instituto Superior Técnico (IST), Azores Energy (EDA)	Portugal	Azores, Portugal	OWC	Pilot, Full-scale	Decommissioned 2018	Falcão et al. (2020)
LIMPET	Queen's University Belfast (QUB), Wavegen Ireland, Ltd., Charles Brand Ltd., Kirk McClure Morton, Instituto Superior Técnico (IST) Lisbon	Northern Ireland	Islay, Scotland	OWC	Pilot, Full-scale	Decommissioned 2011	The Queen's University of Belfast (2002)
Mutriku	Basque Government Department of Transportation and Public Works, Basque Energy Agency (EVE)	Spain	Basque Country, Spain	OWC	Commercial, Full-scale	Operational, Grid Connected (https://www.bimep.com/en/mutriku-area/technical-characteristics/)	Torre-Enciso et al. (2009)
REWEC3	Port Authority of Civitavecchia, WAVENERGY.it S.r.l.	Italy	Lazio, Italy	OWC	Pilot, Full-scale	Operational (https://www.wavenergy.it/)	Arena et al. (2017)
Wave Swell Energy UniWave200	Wave Swell Energy Ltd., Hydro Tasmania	Tasmania	King Island, Tasmania	OWC	Pilot, Full-scale	Decommissioned 2022	Wave Swell's King Island Project (https://www.waveswell.com/king-island-project-2/)

Name	Developer	Developer Country	Recent Deployment	Type	Stage of Development	2023 Status	Reference
OE35 Buoy	OceanEnergy USA LLC, U.S. Department of Energy Office of Energy (DOE) Efficiency and Renewable Energy (EERE), Sustainable Energy Authority of Ireland (SEAI)	Ireland	Oahu, Hawai'i	OWC	Pilot, Full-scale	In development (https://oceanenergy.ie/)	Lewis (2019)
Yongsoo 500	Korea Research Institute of Ships and Ocean Engineering	Republic of Korea	Jeju Island, Republic of Korea	OWC	Pilot, Full-scale	Active	PRIMRE (2024)
WaveSAX-2	RSE S.p.A., E.P.F. Elettrotecnica S.r.l.	Italy	N/A	OWC	Tank-tested at 1:5 scale (https://ui.adsabs.harvard.edu/abs/2017EGUGA..1914904P/abstract)	In development (https://www.rse-web.it/pubblicazioni/wavesax-device-conceptual-design-and-perspectives-317248/)	Bonamano et al. (2023)
			Overtopping Devices (OTD) – Breakwaters				
SSG	WAVEnergy AS, Aalborg University, Technical University of Munich, Norwegian University for Science and Technology	Norway	Denmark	OTD	Prototype	Last tested 2018 (Buccino, Salerno, and Calabrese 2018)	Vicinanza et al. (2012)
OBREC	Università degli Studi della Campania "Luigi Vanvitelli"	Italy	Naples, Italy	OTD	Prototype, Full-scale	Active	Contestabile et al. (2020)
			Wall-Mounted Heave/Hinge – Breakwaters				
Eco Wave Power	Eco Wave Power Global AB, AltaSea at the Port of Los Angeles	Sweden	Gibraltar (Formerly), Jaffa Port, Israel	OB	Pilot, Full-scale	Operational, Grid Connected	Eco Wave Power (n.d.[b])

Name	Developer	Developer Country	Recent Deployment	Type	Stage of Development	2023 Status	Reference
Wave Star	Wave Star ApS	Denmark	Roshage Pier, Hanstholm, Denmark	OB	Prototype, 1:2 scale	N/A	Kramer, Marquis, and Frigaard (2011)
Sea Horse	SEAHORSE, Alberto Luiz Coimbra Institute for Engineering and Research (Coppe), Brazilian Electricity Regulatory Agency (ANEEL)	Brazil	Port of Pecem, Brazl	OB	Prototype	Decommissioned 2017 (Clemente et al. 2023)	Clemente et al. 2023
			Recent Notable Hybrid Breakwater WECs				
WEC4PORTS Hybrid	International Marine and Dredging Consultants (IMDC), University of Porto, Institute of Science and Innovation in Mechanical and Industrial Engineering (INEGI), Eire Composites Teo (ECT)	Belgium, Portugal, Spain	N/A	OWC-OTD hybrid (HWEC)	Concept	N/A	Koutrouveli et al. (2021)
OWC-OB	Jiangsu University of Science and Technology Zhenjiang, China, University of Strathclyde, Glasgow, UK, National Ocean Technology Center, Tianjin	China, Glasgow, UK	N/A	OWC-OB hybrid (HWEC)	Concept	N/A	Cheng et al. (2022)
O²WC	University of Florence, Italy, AM3 Spin-Off, Joint Laboratory A-MARE, Italy	Italy	N/A	OWC-OTD hybrid (HWEC)	Concept	N/A	Simonetti et al. (2022)

Name	Developer	Developer Country	Recent Deployment	Type	Stage of Development	2023 Status	Reference
pWEC-breakwater	Tsinghua University, China, University of Plymouth, UK, The University of Newcastle, Australia, Shanghai Jiao Tong University, China, University of College Cork, Ireland	China, UK, Australia, Ireland	N/A	pWEC	Concept	N/A	Zheng et al. (2021)
OB-parabolic breakwater WEC	South China University of Technology, China, Donghai Laboratory, China, Dalian University of Technology, China	China	N/A	OB hybrid	Concept	N/A	Zhou et al. (2023)
Floating breakwater-OB WEC	Harbin Engineering University, China, University of Oxford, UK, University of Bath, UK	China, UK	N/A	OB hybrid	Concept	N/A	Zhang et al. (2020)

Appendix B. Review of Additional Energy End Uses

The research team conducted a literature review to identify additional possible applications of CSI-WECs that fall into non-grid-scale onshore marine energy end-use categories. CSI-WECs can supply direct electrical power for fixed assets, processes, and events and to potentially improve/support coastal ecosystem health. In addition, CSI-WECs can provide direct mechanical energy for pumping seawater or air. These types of activities can benefit coastal population centers and ports in various ways, as summarized in Table B-1.

Table B-1. Potential CSI-WEC End-Use Applications

End-Use Category	Application	Description	Power Need
Electric Power Generation for Fixed Assets	Powering ports (ports/marinas)	Direct power supply to port operations	Ranges of total energy consumption for ports of different sizes: • 20–40 MWh: 2018 energy consumption of a small Latvian port (Heikkinen and Sutela 2022) • 491 MWh: 2020 energy consumption of a medium-sized port in Egypt (Tawfik et al. 2022) • 600 MWh: 2018 energy consumption of a small to medium sized Greek port (Sifakis and Tsoutsos 2020) • 19,204 MWh: 2011 electrical consumption of a terminal in the second largest port in Spain (i.e., Valencia): 48% went to refrigerated containers, 34% to ship-to-shore cranes, 13% to lighting (Martinez-Moya et al. 2019)
Electric Power Generation for Fixed Assets	Port lighting (ports/marinas)	CSI-WEC generation sent directly to the port's lighting system	Port lighting requirements: • 98 MWh in 2020 in medium-sized Egyptian port (Tawfik et al. 2022) • >480 MWh in a small to medium sized port in Greece (Sifakis and Tsoutsos 2020) • 2,500 MWh in the port of Valencia, Spain (Martinez-Moya et al. 2019)
Electric Power Generation for Fixed Assets	Ship-to-shore power (ports/marinas)	CSI-WEC generation used for ship-to-shore power	Smaller vessels require less than 50–100 kW of power each (Global Maritime Energy Efficiency Partnerships n.d.) Larger vessels range from 100 kW up to 10–15 MW
Electric Power Generation for Fixed Assets	Navigation aids and ocean observation buoys (ports/marinas)	CSI-WEC generation used for navigation aids for ships coming in and out of the port and	Power requirements for ocean observation buoys and navigation aids: • 10–600 kW per installation (LiVecchi et al. 2019) • 40–200 W for NOAA-handled buoys

End-Use Category	Application	Description	Power Need
		observation buoys for meteorological and oceanographic measurements	
Electric Power Generation for Processes	Green hydrogen production (coastal population centers)	CSI-WEC generation powers: A reverse osmosis process to desalinate seawater and an electrolyzer to produce green H_2 OR A seawater electrolyzer	9 liters of water and 50 kWh of electricity are required to produce 1 kg of hydrogen (Harrison and Levene 2008) If reverse osmosis requires 2 kWh/m^3 water, then to produce the 9 liters of water needed for 1 kg of hydrogen, 0.018 kWh of energy is required (Folley and Whittaker 2009)
Electric Power Generation for Processes	Nearshore aquaculture (coastal industry)	CSI-WEC generation directly powers various needs for nearshore aquaculture	Offshore finfish aquaculture plant used 239–534 kWh/day (Syse 2016) Total electric consumption of growth-phase aquaculture was roughly 700 kWh/day for the various electrified loads (Garavelli et al. 2022) Peak cumulative demand of 100–120 kW during daytime feeding (Garavelli et al. 2022)
Direct Mechanical Energy	Water pumping for reverse osmosis desalination[a] (coastal population centers)	CSI-WEC powers a pump to move seawater through the system	About 2 kWh/m^3 water (Folley and Whittaker 2009) In a theoretical OBREC to RO desalination system, “final desalinated water is about 6% of the total overtopping water collected by the system” (Contestabile and Vicinanza 2018)
Electric Power Generation for	Ecosystem restoration	CSI-WEC generation used	Goreau (2012) assumed 1 kg growth/kWh

End-Use Category	Application	Description	Power Need
Coastal Ecosystem Health	through biorock growth strategies (coastal population centers)	to send low voltage current through steel structures to grow oyster or coral reefs	Melnikov (2021) found growth rate and survival rate benefits from 450mA current Miller (2020) reviewed use of mineral accretion technology for artificial reefs
Electric Power Generation for Events	Disaster response: energy storage (coastal population centers, U.S. Department of Defense)	CSI-WEC generation is stored in batteries	Depends on community needs/loads One example is Ta'u Island, American Samoa (population 600 (U.S. Census Bureau 2020b)): has 7.8 MW battery storage (NREL 2021)

[a] OBREC-specific desalination advantage: lessened environmental impact of brine discharge as it is diluted by combination with unused overtopped water (Contestabile and Vicinanza 2018).

Appendix C. Geographic Information Systems for Site Selection and Assessment

Promising CSI-WEC installation sites—beyond the four case study sites examined in Section 3—could be identified leveraging the power and promise of geographic information system (GIS) interfaces and geospatial data. These tools play a crucial role in marine energy site selection (Mueller and Wallace 2008).

GIS interfaces allow for a quick visual inspection of geospatial data, for example, enabling an easy identification of high and low values and the spatial distribution of a particular variable. Different data types can also be visualized in geospatial layers, so data that are typically incompatible in traditional analyses can be evaluated in unison through the use of overlaying layers. One can also quickly identify areas where projects can be sited by including exclusionary layers such as marine protected areas.

Because CSI-WECs can function at much lower wave power inputs than typical WECs, identifying areas with the highest wave resource is less important than would be the case for a typical WEC (Foteinis 2022). Therefore, other site attributes such as locations with hardened shoreline, the need for and cost of structure upgrades/replacements, port size and activities, and flood risk are key factors to consider in site selection for CSI-WECs. GIS allows for the integration of these factors into the site selection process.

Geospatial analysis can be used to formalize the examination of data layers through a replicable framework. Such frameworks facilitate greater transparency in site selection, which is particularly important in engaging stakeholders in the decision-making process and fostering trust. Multi-criteria decision analysis (MCDA) is a simple yet powerful geospatial analysis method that consists of ranking multiple (usually overlapping) criteria to make site selection decisions, or provide a narrowed list of options (Vasileiou, Loukogeorgaki, and Vagiona 2017; Shao et al. 2020).

The customizable nature of this framework also allows for the creation of bespoke models that account for different communities' resources, priorities, and limitations. The research team has been working on creating an internal GIS tool that utilizes MCDA methods for site selection analysis. For a preliminary GIS case study analysis, the research team selected Puerto Rico. ESRI GIS software ArcMap 10.8.2 was used for data preparation and GIS analysis. The study area extent was 3.0 nautical miles from the coastline. The following data layers, mapped in Figure C-1 and Figure C-2, were used as criteria for the MCDA analysis of Puerto Rico:

1. Coastal populated places (city locations), labeled by size
2. Ports
3. Electric power transmission lines to demonstrate proximity to infrastructure and grid connections
4. Census tracts that are at or above the 90th percentile for projected flood risk (Figure C-2)
5. 42-year average omnidirectional wave power to demonstrate theoretical wave resource (Allahdadi et al. 2021)

6. Danger zones/restricted areas by U.S. military (exclusionary criteria used as an overlay to restrict potential project sites).

Because CSI-WECs offer a unique solution to enhance coastal defense, during the criteria weighting process for this study the research team prioritized a GIS layer that represented populated or developed areas vulnerable to flooding. Puerto Rico's coastal municipalities could benefit from additional infrastructure to reduce storm surge, and combining this infrastructure with a WEC can ensure available energy supply during and immediately after weather events. For these reasons, CSI-WECs could also reduce some costs associated with recovery efforts.

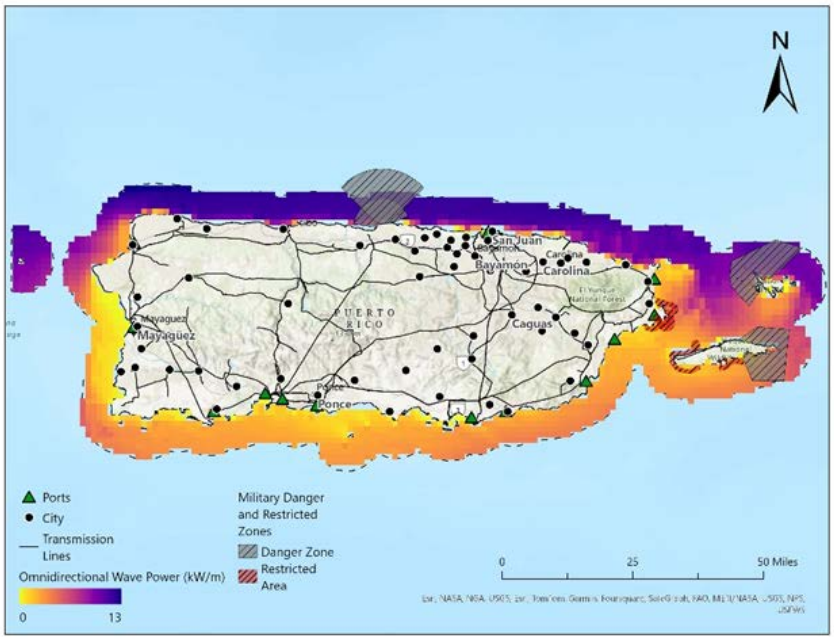

Figure C-1. Map of Puerto Rico displaying estimated wave resource, port locations, cities, electrical transmission lines, and restricted military zones

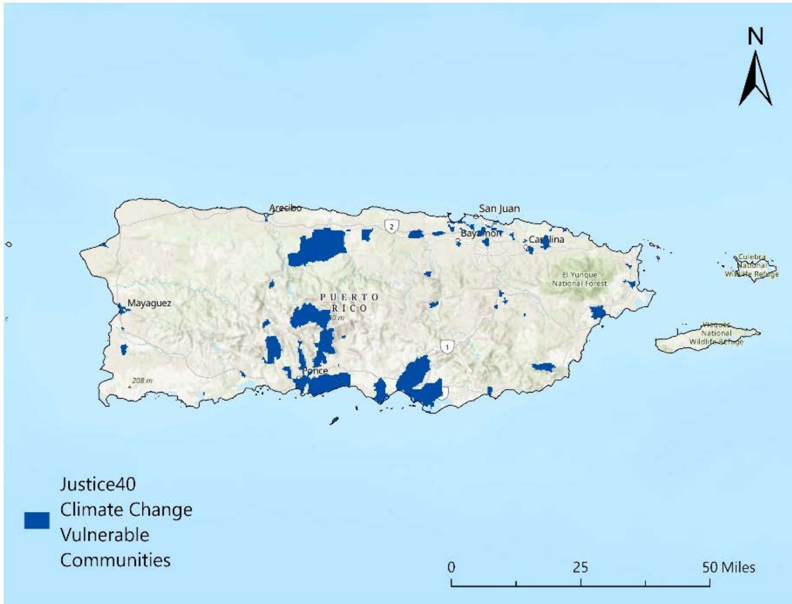

Figure C-2. Map of Puerto Rico displaying the census tracts that are at or above the 90th percentile for flood risk.

C.1 Methods

The specific MCDA method selected for this analysis was the analytic hierarchy process (AHP). AHP provides a structured approach to tackle complex and subjective decisions. For this reason, it is the most used MCDA method for renewable energy site selection (Vasileiou, Loukogeorgaki, and Vagiona 2017).

AHP involves pairwise comparisons of the site selection criteria, where two criteria are evaluated at a time and assigned values (listed in Table C-1) that represent the relative importance of one criterion compared to another. These values are used to create a decision matrix that calculates the overall criteria weights used for the suitability analysis. To assess reliability and logical consistency of the weightings, a consistency ratio (CR) and consistency index (CI) are calculated using Equations (1) and (2).

$$CI = \frac{(\lambda_{max} - n)}{(n - 1)} \tag{1}$$

$$CR = \frac{CI}{RI} \tag{2}$$

Here, n represents the number of criteria in the decision matrix, and λ_{max} is the maximum eigenvalue of the matrix. CI indicates the level of consistency in the judgements within the matrix. The random index (RI) is a reference value determined from the matrix size (Saaty 1990). By comparing CI, the actual matrix consistency, to RI, one can determine whether the pairwise judgements are reasonable or need adjustment. A CR greater than 10% indicates that the criteria weightings are logically inconsistent and should be repeated. The AHP analysis was conducted by the research team using Python. For further information on the MCDA method employed, please consult Hall et al. (2024).

Table C-1. AHP Value Scale Chart Based on Saaty's Methodology (Saaty 1990)

Intensity of Importance	Definition	Explanation
1	Equal importance	Two criteria contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one criterion over another
5	Essential or strong importance	Experience and judgment strongly favor one criterion over another
7	Very strong importance	A criterion is favored very strongly, and its dominance is demonstrated in practice
9	Extreme importance	The criteria favoring one activity over another is of the highest order of affirmation
2, 4, 6, 8	Intermediate values	

After completing the AHP, the geospatial layers were prepared for analysis. Proximity to feature class data (ports, electric transmission lines, cities, and flood risk) was calculated using the Euclidean distance tool. To ensure data compatibility, all data layers were reclassified to a standard scale of 0 to 1, where 1 represents the highest rank and 0 the lowest rank. This was done using Equation (3) in the raster calculator.

$$Raster = 1 - \frac{Raster - Raster\ Minimum}{Raster\ Maximum - Raster\ Minimum} \quad (3)$$

The data layers were then combined applying the criteria weightings in the weighted sum tool. The final raster mapped the suitability of sites across the study area. The raster was displayed using the standard deviation stretch.

C.2 Results and Discussion

In this demonstration of the GIS MCDA tool with Puerto Rico as a case example, the research team prioritized data representing census tracts with high flood risk. This prioritization was to highlight the coastal defense value of CSI-WECs. The criteria weightings derived from the AHP analysis are shown in Figure C-3.

The MCDA methodology in this study allowed the research team to include data, such as the flood risk census tracts, that are not traditionally considered in typical siting practices for marine energy projects. This GIS analysis can be applied to site selection where other attributes are important, such as geological or oceanographic features. Applying MCDA in GIS allows users to conduct a more nuanced and bespoke site selection.

The output of the MCDA in this study (Figure C-4) is a single data layer, which is a heat map of highly suitable areas for CSI-WEC siting. Within the highly suitable areas, there are numerous potential project sites. Several of these sites extend from San Juan along the north shore to the northeast coast. Additional suitable areas were identified along the southern coast, though these sites contained less wave energy resource as compared to those in northern areas. Though more remote, these southern coastal sites are adjacent to flood risk census tracts, which would benefit from the coastal protection offered by infrastructure such as breakwaters and jetties, as well as the access to energy they could provide for emergency operations or desalination.

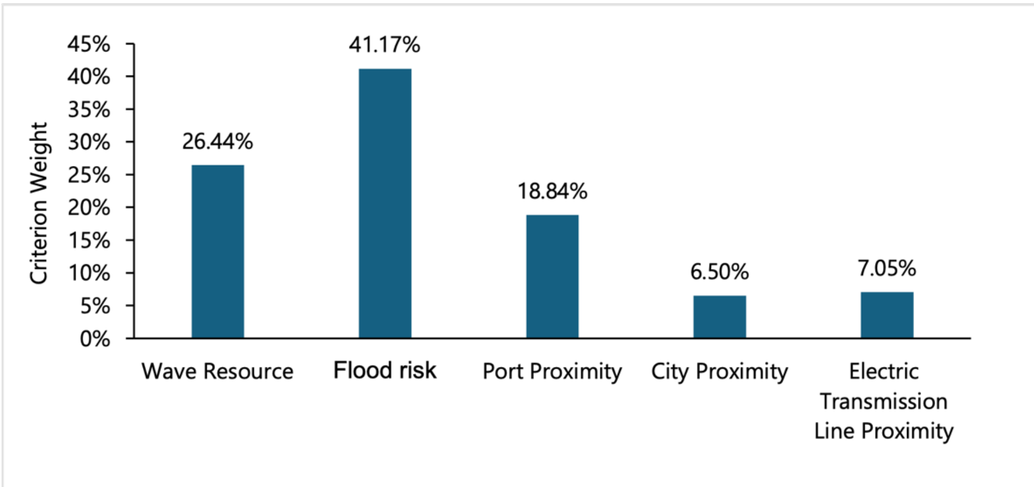

Figure C-3. Criteria weightings used for the Puerto Rico site analysis calculated from the AHP analysis

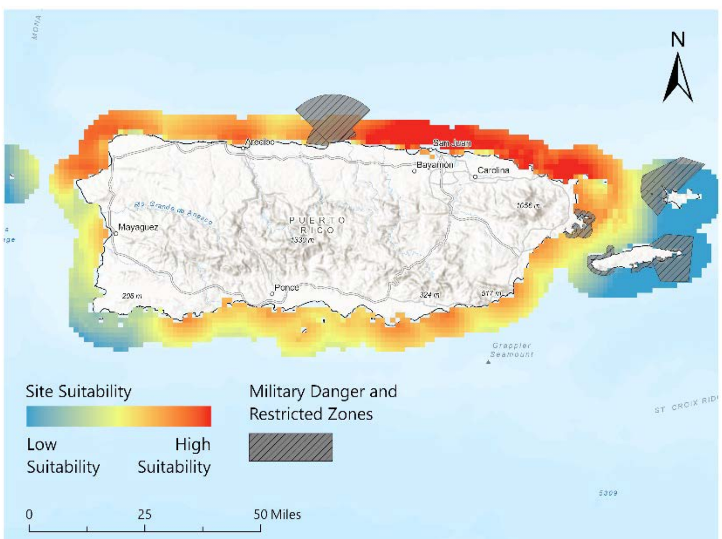

Figure C-4. Map of suitability results of the GIS MCDA site selection analysis for Puerto Rico, with the suitability of an area ranging from high (red) to low (blue). The data layers used in the analysis were the omnidirectional wave power, port locations, electric transmission lines, city locations, and flood risk.

This Puerto Rico case study demonstrates that GIS analyses can assist CSI-WEC developers in optimizing site selection in a replicable and systematic way. Moving forward, integrating additional oceanographic and economic geospatial data will be crucial for conducting comprehensive analysis. This approach may also facilitate management of marine use conflicts and early engagement with stakeholders. The flexibility of GIS-based MCDA enables its application across various site selection scenarios where sufficient spatial data are available.

Appendix D. Federal Funding Programs Relevant to CIS-WEC Harbor Protection Breakwaters

To further support the techno-economic opportunity offered by CSI-WECs, this section describes two non-U.S. Department of Energy (DOE) federal funding programs that could support CSI-WEC deployment.

Though designed primarily for harbor protection, revenues from breakwater-based production of electricity and/or fresh water could provide a mechanism for funding a local harbor district's non-federal cost share (20% to 40%, depending on water depth). This would allow the project to meet USACE's requirement to design and build the federal portion of the project (i.e., 60% to 80%, depending on water depth).

Section D.1 describes the U.S. Maritime Administration (MARAD) Port Infrastructure Development Program (PIDP), which could provide grant funding to enable the above-described techno-economic evaluation, including optimization and the front-end engineering design of a CSI-WEC breakwater. Section D.2 describes how these results would then provide the basis for a credible proposal to USACE for detailed planning and construction of the CSI-WEC breakwater.

D.1 MARAD Grant Funding of Port Improvement Studies and Capital Projects

PIDP is a discretionary grant program administered by the U.S. Department of Transportation's MARAD, through the MARAD Office of Port Infrastructure. Funds for the PIDP are awarded on a competitive basis to projects that improve the safety, efficiency, or reliability of the movement of goods into, out of, around, or within a port (U.S. Department of Transportation 2022).

The PIDP provides grant funding to ports—in both urban and rural areas—for planning and capital projects. It also includes a statutory set-aside for small ports to continue to improve and expand their capacity to move freight reliably and efficiently and support local and regional economies.

The PIDP program was funded $2.25 billion over 5 years (2022–2026), one-fifth of which ($450 million) was made available in Fiscal Year 2024. The following features are notable for the Fiscal Year 2024 PIDP solicitation:

- Projects that support seafood and seafood-related businesses are eligible for PIDP funding.
- MARAD reserved 25% of the appropriated funds ($112.5 million) for projects meeting certain requirements described in this notice for "small projects at small ports."
- Of the reserved amount set aside for small projects at small ports, not more than 10% ($11.25 million) may be used to support development phase activities at such ports.
- Development phase activities include planning, feasibility analysis, revenue forecasting, environmental review, permitting, and preliminary engineering and design work.
- MARAD placed an $11.25 million cap on any single award to a small project at a small port.

PIDP grants normally require at least 20% nonfederal cost share. Per 46 U.S.C. 54301(a)(8), the federal share of the total costs of an eligible PIDP project must not exceed 80%; however, the U.S. Secretary of Transportation may increase the federal cost share above 80% for (1) a grant for a project in a rural area or (2) a grant awarded to a small project at a small port.

In future MARAD solicitations under this program, PIDP grant funding could enable rigorous techno-economic evaluation, optimization, and front-end engineering design of a CSI-WEC breakwater. The results of such a study would provide the basis for a credible proposal to USACE for detailed planning and construction of the CSI-WEC breakwater.

D.2 U.S. Army Corps of Engineers Cost Sharing of Harbor Navigation Construction Projects

As the federal agency responsible for maintaining and improving the nation's navigable waterways and ensuring their safety, USACE:

- Manages infrastructure such as locks, dams, and channels
- Plans and constructs new navigation channels and associated structures, such as surge barriers, jetties, and breakwaters
- Performs channel dredging and clearance activities to ensure that seagoing access to the nation's harbors and waterways remains safe, reliable, and efficient for commerce.

The USACE cost share available for construction of harbor navigation projects varies depending on the water depth (USACE n.d.):

- For projects at depths of 20 ft or less, the cost share is 80% federal and 20% nonfederal.
- At depths between 20 and 45 ft, the cost share is 65% federal and 35% nonfederal.
- At depths greater than 45 ft, the cost share is 40% federal and 60% nonfederal.
- The cost share for inland navigation projects is 100% federal.

In addition, funding of operation, maintenance, repair, replacement, and rehabilitation for USACE navigation projects is 100% federal, except at depths greater than 45 ft, where the cost share becomes 50/50 for the portion of the work at depths greater than 45 ft.

Thus, for a breakwater-based CSI-WEC project, the sale of fresh water and/or electric power could be used to finance the 20% nonfederal cost share, as well as the operations and maintenance of the WEC system (but not structural maintenance of the breakwater, i.e., movement or breakage of rubble mound armor units, which would be covered 100% by federal funding). However, as no CSI-WEC projects have been deployed in the United States, these assumptions have yet to be tested.