Atlantic Marine Energy Center

Wave Energy Converter (WEC) Requirements for Powering the Blue Economy (PBE) Applications

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WAVE ENERGY CONVERTER (WEC) REQUIREMENTS FOR POWERING THE BLUE ECONOMY (PBE) APPLICATIONS

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Executive Summary

The **Blue Economy** is defined as the sustainable use of available ocean resources for economic growth [1]. Within this context, the concept of Powering Blue Economy (PBE) applications refers to energy solutions and technological innovations that enable the development and operation of key economic activities in the ocean. PBE applications require reliable and autonomous energy sources, as many operate in remote environments far from the traditional power grid. Integrating marine energy, such as wave energuy, at the required location can enhance energy autonomy and security while reducing or eliminating the dependence on traditional energy sources such as diesel.

This report provides an overview of wave energy conversion technologies and their applications within the blue economy context. It reviews the main types of Wave Energy Converters (WECs) and Power Take-Off (PTO) systems, highlighting their operating principles and implementation contexts. It also addresses key reference projects, identifies opportunities and challenges for marine energy applications, and examines suitable WEC–PTO combinations for different energy demands.

In the first part of this report, a review of the most commonly used WECs is presented, based on their operating principles and installation locations. Next, the Reference Model Project (RMP), sponsored by the US Department of Energy (DOE), is introduced, where Reference Models (RMs) 3, 5, and 6 were studied (RM3, RM5, and RM6, respectively), which focus on the conversion of wave energy. RM3 represents a two-body Point Absorber (PA) design, RM5 is an Oscillating Surge Wave Converter (OSWC), and RM6 is an Oscillating Water Column (OWC) device. While the DOE RMs (RM3, RM5, and RM6) were developed for grid-connected utility-scale installations, they can also be scaled down for PBE applications. The section concludes with a summary table presenting the main lessons learned from each RM, particularly regarding the reproducibility of numerical simulations and experimental results.

In the next chapter, a general description of the most commonly used PTO systems in combination with WECs is given. A comparative table that gathers the main characteristics and features of each PTO system is made as a reference to be used in future sections of this report. The studied PTO systems are the Hydraulic Motor Based (HMB), Direct Mechanical Drive (DMD), Direct Electrical Drive (DED) and Air Turbines (AT).

In addition, opportunities and challenges associated with the implementation of WECs in Powering Blue Economy (PBE) applications are presented, followed by an overview of the energy requirements of each sector. For this report, the following applications are considered: Offshore Marine Aquaculture; Desalination; Ocean Observation and Autonomous Vehicle Charging; as well as a brief description of the implementation of WECs in Isolated Remote Communities.

Finally, three WECs (OWC, OSWC, and PA) are matched with every key PBE application, in addition to the studied PTO systems (AT, MDD, EDD, and HMB). The functional combinations of WECs and PTO systems are selected on the basis of the requirements previously outlined, ensuring optimal performance, efficiency, and compatibility with each PBE application energy demands.

Presentations and Publications

The presentations and publications that have taken place from the project to-date are listed as follows:

1. Matamala, P., Wosnik, M., Fredriksson, D., & Hasankhani, A. (2025). WAVE ENERGY CONVERTERS (WECs) FOR POWERING OFFSHORE AQUACULTURE. In the Proceedingg of the 2025 University Marine Energy Research Community Conference, UMERC 2025, August 12–14 2025, Corvallis, OR.

Wave Energy Converters (WECs)

3.1 Introduction

In this chapter, a review of the most commonly used WECs is presented. It begins with a general classification of the devices based on their operating principles and installation locations, illustrated in Figure 3.1. This is followed by an overview of examples of the main types of WECs, highlighting their key characteristics. The Reference Model Project (RMP), sponsored by the US Department of Energy (DOE) [2], is then introduced. The RMP consists of six open-source utility-scale Marine Hydrokinetic (MHK) energy converters designs, developed to support the advancement of marine energy technologies, with adaptability for different strategic offshore locations. For this report, Reference Models 3, 5, and 6 (RM3, RM5, and RM6, respectively) are studied, which focus on the conversion of wave energy. RM3 represents a single Point Absorber (PA) design, RM5 represents an Oscillating Surge Wave Converter (OSWC), and RM6 represents an Oscillating Water Column (OWC) device. At the end of the section, a summary table is provided, presenting the main lessons learned from each reference model, particularly regarding the reproducibility of numerical simulations and experimental results.

3.2 Types

There are different types of WECs, each based on the various ways in which wave energy can be captured and converted. In 2010, Falcão et al. categorized these technologies according to their operating principles and installation locations, as shown in Figure 3.1 [3]. A general overview of each type of device can be found in [4], which served as a reference for this Section. The principal types of WECs devices are described as follows, focusing on fundamental operating principles and key characteristics.

- **Oscillating Water Column (OWC):** OWC devices operate by capturing the kinetic energy of waves. The device features a submerged inlet that allows the water free surface to oscillate vertically in response to wave action, and an upper air duct through which the pressurized air expands and contracts bidirectionally. This oscillating airflow drives a self-rectifying air turbine coupled to an electrical generator. Since the air velocity through the turbine duct remains below Mach 0.3, the airflow can be treated as incompressible, which simplifies the aerodynamic analysis and is a standard assumption in OWC modeling [5].

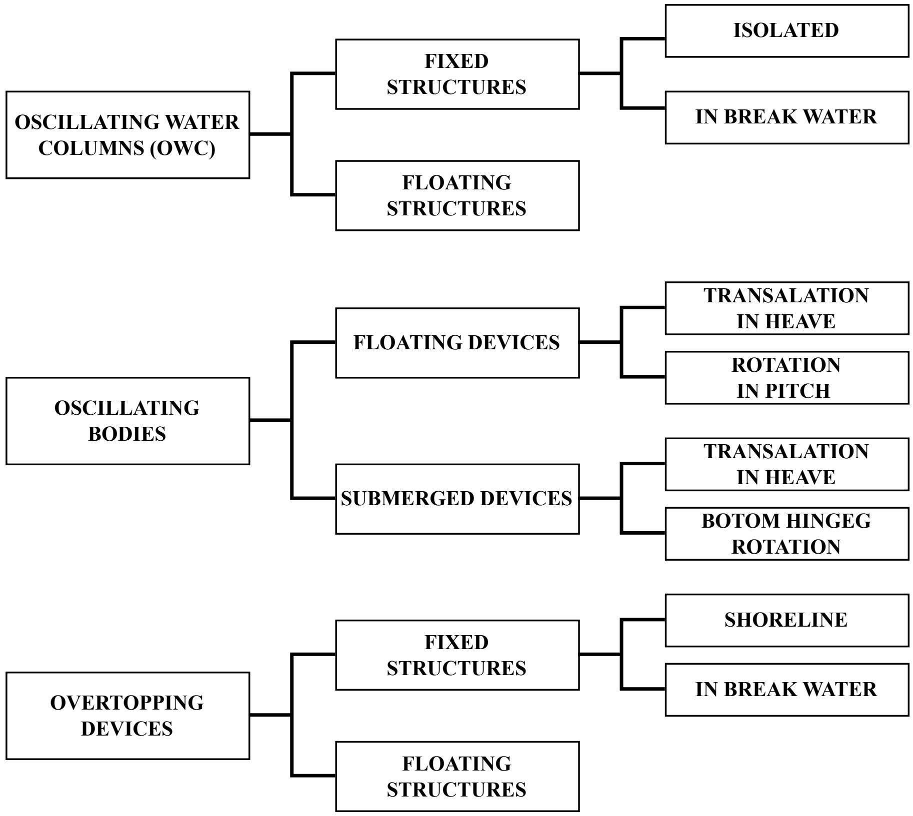

Figure 3.1: Diagram of the main concepts by operating principle and installation location of Wave Energy Converters [3].

- **Point Absorbers (PAs):** The PAs are devices that operate based on the vertical oscillation of one or two bodies (heave motion). These devices are typically designed to capture wave energy from multiple directions, making them well suited for offshore environments or exposed coastal areas. A standard two-body PA device consists of two main components: the wave follower, which moves with the wave motion, and the absorber unit, which converts the relative motion between the wave follower and a fixed or semi-fixed reference structure into usable mechanical or electrical energy.

- **Attenuator:** Attenuator devices, an oscillating floating system, generate energy by using the angular motion (pitch rotation) of one or more floating bodies. These devices operate in response to wave-induced motion, which makes the bodies oscillate. Typically, an attenuator is partially submerged and is positioned parallel to the main direction of the incoming waves. As waves pass along the length of the device, the motion between its connected segments creates mechanical energy. This energy is then converted into electricity using hydraulic or mechanical transmission systems. The floating segments are connected by flexible joints—often called universal joints—which both secure the structure and allow the necessary movement between parts.

- **Oscillating Surge Wave Converter (OSWC):** An OSWC is a submerged device that operates using a pitching motion, similar to an inverted pendulum hinged to the seabed. As waves pass over the device, they cause a back-and-forth (reciprocating) rotation of a large flap. This motion is then converted into usable energy through a hydraulic system, which transforms the mechanical movement into electricity.

- **Overtopping Device:** Overtopping structures generate energy by using the wave overtopping principle. The waves are directed into a reservoir located above sea level, where the water is temporarily stored. As water flows down due to gravity, its potential energy is converted into mechanical energy by a turbine, similar to low-head traditional hydro turbine, which is then transformed into electrical energy using a generator.

Another study [6] classified WECs not only by these five working principles but also by their location, listing onshore, nearshore, and offshore devices. A simplified illustration of the differentiation among the various types of Wave Energy Converters (WECs) based on their installation location is presented in Figure 3.2, where different experimental and commercial devices are also provided as examples.

- **Onshore devices:** These devices are installed directly on the shoreline, often in shallow waters or even above sea level. Their main advantages include easy access for maintenance and installation, as they are located on land. In addition, they typically do not require mooring systems or long subsea cables to connect to the power grid. However, waves at the shoreline carry less energy due to seabed interactions, and the availability of suitable coastal sites is limited, which can make deployment challenging.

- **Nearshore devices:** They are located a few hundred meters from the coast in moderate water depths (10–25 meters). These systems are usually mounted on the seabed, avoiding the need for moorings. However, they must be structurally strong to withstand the forces generated by passing waves.

- **Offshore devices:** They are deployed in deep waters (over 40 meters), far from the shore. These systems are generally floating or submerged structures moored to the seabed. Due to their location, they can harness the higher wave energy available in the open ocean. At the same time, their exposure to harsh ocean conditions poses challenges for durability and reliability. Maintenance operations are also more complex and expensive because of their distance from the shore.

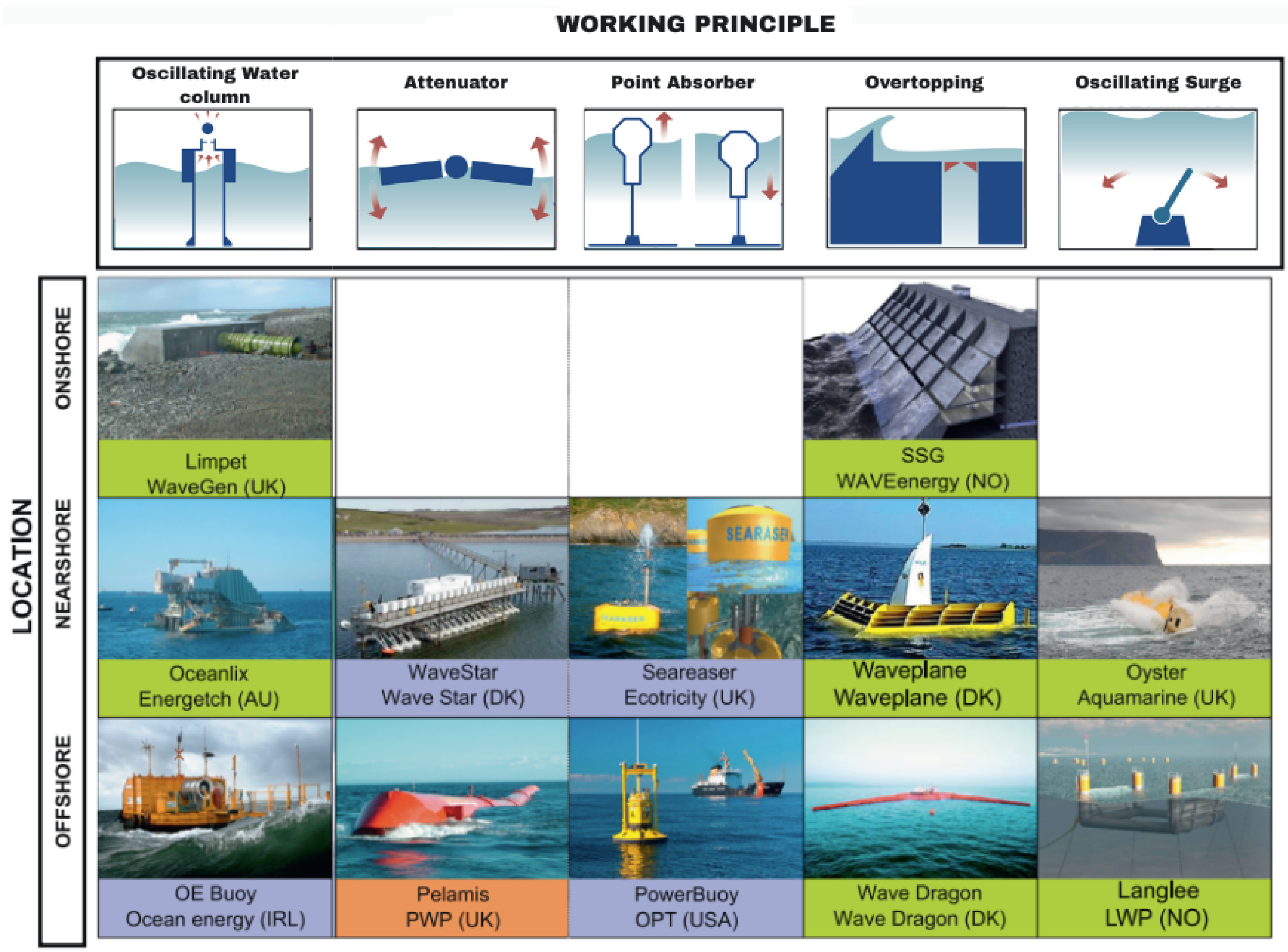

Figure 3.2: Classification of WECs per type and operation site [6] (modified with images from [7]).

3.3 Reference Models (RMs)

The Sandia National Laboratories (SNL) Reference Model Project (RMP) was created to provide publicly available, standardized designs for various MHK energy devices [2]. The project developed a set of detailed conceptual designs defined as RMs. These models cover 6 types of MHK devices, including tidal turbine, river turbine, ocean current turbine, and three types of WEC. Each RM, developed in collaboration with the National Renewable Energy Laboratory (NREL), includes comprehensive documentation of the device mechanical design, hydrodynamic modeling, structural analysis, and economic evaluation. In this report, the focus is on RMs that relate to wave energy conversion, RM3, RM5 and RM6. These WEC RMs represent different approaches to harnessing the power of ocean waves, each offering a unique mechanism to capture and convert wave energy into usable electrical power. The main dimensions of the RMs are shown in Figure 3.3, followed by a diagram of the mooring system. In addition, a summary of the main features of the RMs is presented in Table 3.1. While

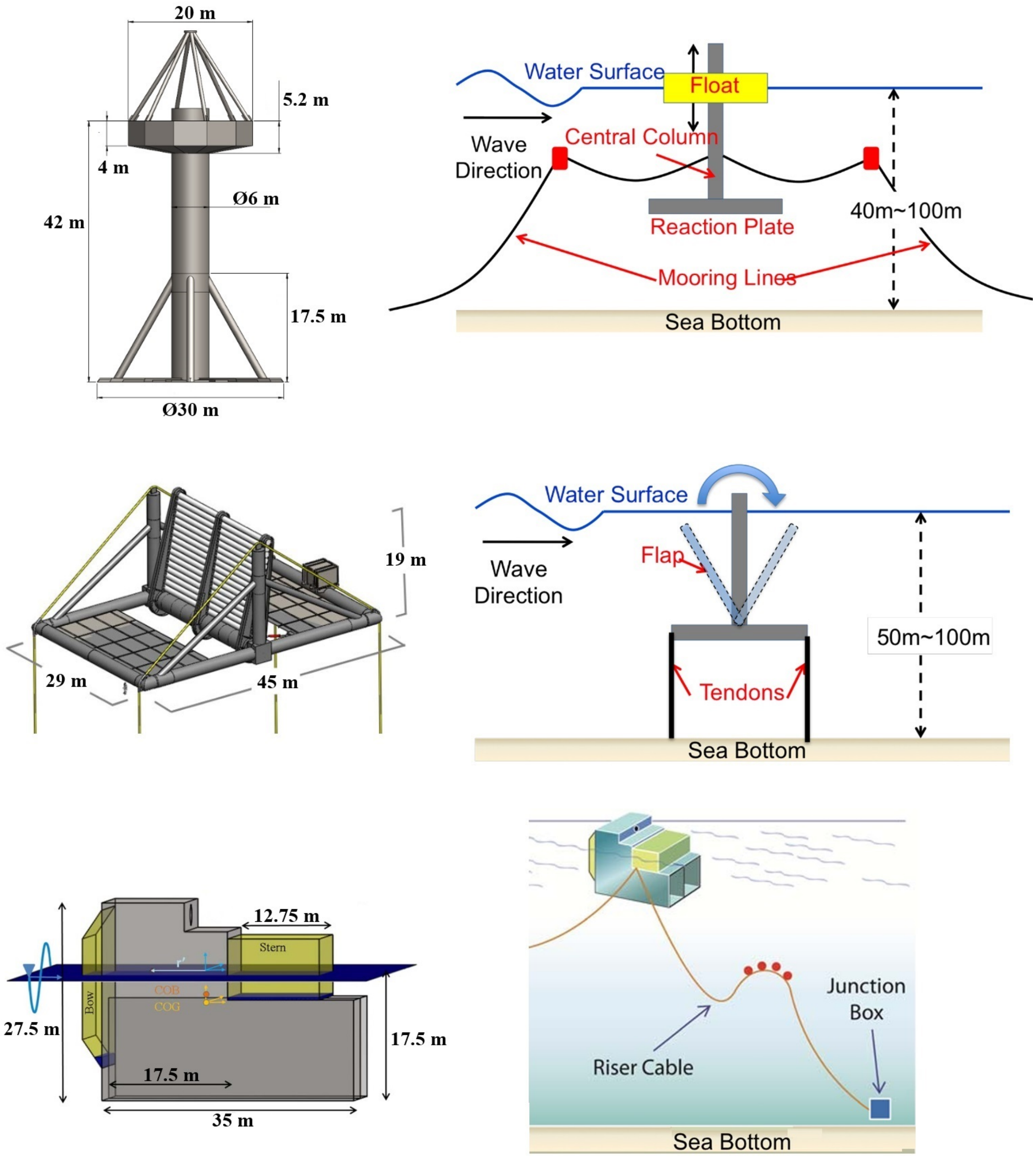

Figure 3.3: RMs main dimensions and mooring diagrams [2]. RM3 (Top) [8], RM5 (Center) [9] and RM6 (Bottom) [10].

the DOE RMs (RM3, RM5, and RM6) were developed for grid-connected utility-scale installations, they can also be scaled down for PBE applications.

- **Reference Model 3 (RM3)**: RM3 describes a two-body PA system, where a wave-following floating buoy moves relative to a submerged structure under the action of ocean waves. The resulting relative motion is used to drive an hydraulic PTO system (this kind of system is described in detail in Section 4)

[8]. The concept design was inspired by Ocean Power Technologies's PowerBuoy [11].

- **Reference Model 5 (RM5):** RM5 describes an OSWC device that captures energy from the horizontal motion of ocean waves near the surface. This model consists of a large submerged oscillating flap that is hinged on a moored submerged platform [9]. As waves pass through the device, the surge motion of the water forces the flap to oscillate. This mechanical motion is then transferred to a PTO system, which converts it into electrical energy.
- **Reference Model 6 (RM6)**: RM6 describes an OWC device of the backward bent buoyant duct variety, where the wave motion induces the increase and fall of the water columnu inside the capture chamber, which conducts the air through an Air Turbine (AT),0 activating a Power Take-Off (PTO) system [10].

3.4 Lessons Learned from Reference Models

Starting with the RMs is a valuable first step, as they provide well-defined baselines for understanding WEC performance. It is important to recognize that these models are **designed as utility scale WECs for specific locations**, reflecting local wave climates, water depths, and environmental conditions. Consequently, many of the design choices, experimental scales, and numerical assumptions are **location-dependent**, and care must be taken into consideration when interpreting or extrapolating these specific devices.

- **Model Scaling and Experimental Limitations:** Experimental scales are constrained by wave tank dimensions and device size. Smaller devices (e.g., RM3 PBEs) are tailored for use cases that require lower power, while submerged platforms (RM5) are sensitive to tank depth. Experimental datasets are often **limited, inconsistent, or not fully aligned** with specific RM configurations, making direct validation of numerical models difficult.
- **Dimensionless Numbers and Similarity Parameters:** Proper selection of dimensionless numbers (Keulegan–Carpenter, Froude, Reynolds) to characterize the device behavior is crucial for maintaining similarity between experiments scale and numerical simulations.
- **PTO Modeling and Linearization:** Linear wave theory-based numerical models (e.g., WEC-Sim and BEM methods) require PTO systems to be characterized with linear parameters. Air-pressure-based PTOs (RM6) are difficult to linearize and add complexity to numerical modeling.
- **Numerical Modeling Complexity:** Some systems, such as floating OWCs (RM6), require **high-fidelity models** (e.g., 7 DOF) to capture full motion, increasing computational cost. Simplifications such as linearization and DOF reduction improve computational efficiency but may reduce model fidelity.

Table 3.1: Review of the main features of the RM3, RM5, and RM6 devices. These RMs were originally designed for specific locations and wave climates, all corresponding to the coastal area of Eureka in Humboldt County, California, where the characteristic wave heights are given by H_s, the peak periods by T_p, and the local water depths by h.[2].

RM# [type]	WAVE AND SITE CONDITIONS	POWER OUTPUT	KEY FEATURES AND NOTES
RM3 [PA]	Sea states with H_s 0.5–6 m, T_p 5–18 s, water depths 40–100 m [2]. Two-body PA WEC for offshore designed for offshore deep-water conditions [2].	Rated power 300 kW (numerical simulations, capacity factor 30%) [2]. Estimated annual energy production 700 MWh/unit [2]. Efficiency: 5.6–32% [12]. Efficiency decreases with increasing mass (oscillatory motion challenges).	Adaptable across wide sea states [13]. Compact, flexible design for optimization [13]. Experiments: UC Berkeley 2010 (scale 1:100, locked PA, extreme waves) [14]; UC San Diego 2011 (scale 1:33, heave-only FPA, power performance) [14]; UC San Diego 2011 (scale 1:33, locked PA, extreme waves) [14]. Simulations: WEC-Sim (UC Berkeley & Sandia 2014), validated against ANSYS-AQWA, WaveDyn, OrcaFlex, and tank data [15].
RM5 [OSWC]	Sea states with H_s 0.75–6 m, T_p 5–18 s, water depths 40–100 m [2]. Two-body OSWC designed for large operational waves [2].	Rated power 360 kW (numerical simulations, capacity factor 30%) [2]. Estimated annual energy production 882 MWh/unit [2]. Efficiency: 20–60% [12].	Experiments: OSU 2016 (double flap device, hosted at Sandia) [16]. Simulations: NREL & Sandia 2014 (bottom-hinged OSWC) [17]; NREL & Sandia 2014 (floating OSWC with 4 flaps) [17].; NREL & Sandia 2020 (Passive Yaw development in WEC-Sim) [18].
RM6 [OWC]	Sea states with H_s 0.75–6 m, T_p 5–18 s, water depths 60 m [2]. Offshore OWC designed for deep-water operations [2].	Rated power 103 kW [2]. Efficiency: 2–60% [12].	Experiments: University College Cork 2014 (scale 1:50), focused on RAO performance and irregular wave spectra [19]. Simulations: OSU 2020 (OWC modeled as point absorber in WEC-Sim). WEC-Sim setups exist for floating OWC with air-turbine PTOs, but lack experimental validation [20].

- **Overall Observations:** Reference models provide **valuable benchmarks** for testing control strategies, numerical methods, and device designs. Limitations include **location-specific assumptions, insufficient experimental validation, and scaling constraints**, which need to be considered when applying these models to other designs or sites. However, a significant caveat is that none of the WEC RMs have been demonstrated at full scale, i.e., the designs and power production cannot be considered as "validated designs".

3.5 Conclusions

This chapter presented the main classifications of WECs according to their operating principles and site-specific deployment. In this context, SNL, in collaboration with DOE, developed a set of RMs for MHK systems, referred to as the RMP. Among these, RM3, RM5, and RM6 are based on different wave energy conversion principles and correspond to PA, OSWC, and OWC devices, respectively. These models were designed to operate under realistic offshore conditions representative of the U.S. West Coast, particularly near Eureka, California. Each configuration provides an estimated power output derived from local wave conditions and serves as a theoretical benchmark for comparative analysis and further numerical development.

The RMs present several challenges, including the limited extension of their applicability to broader scenarios, such as smaller scale energy generation for PBE applications. Although significant progress has been made in developing numerical schemes to estimate device performance and expected power output—commonly based on linear wave theory and potential flow approaches (e.g., BEM codes and WEC-Sim)—experimental validation remains limited, specifically, none of the three WEC RMs have been validated at full scale. When performed, such validation must account for scaling constraints associated with dimensional analysis, which define the relationship between the model and its full-scale prototype.

In summary, the analysis conducted in this chapter regarding WECs and RMs provides an initial foundation for exploring the applicability of WEC technologies in PBE applications. This serves as a preliminary step toward assessing their performance, adaptability, and potential for integration into smaller-scale energy generation systems. The identified limitations will be taken into account in future research to enhance the understanding and feasibility of WEC implementation in PBE applications.

Power Take-Off (PTO) Technologies

4.1 Introduction

PTO system of a WEC is the mechanism responsible for converting the energy absorbed by the primary converter into usable electrical energy. The performance of the PTO system has a direct impact on the overall dynamics and energy conversion efficiency of the device [21]. Accurate numerical modeling of the PTO in the early stages of development is a critical step in the successful design of any WEC project. This section provides a general description of the most commonly used PTO systems in combination with WECs, which are: the Hydraulic Motor Based (HMB) system, Direct Mechanical Drive Based (DMD) system, Direct Electrical Drive Based (DED) system and Air Turbines Based (AT) system. Finally, a comparative table is provided that summarizes the main characteristics and features of each PTO system to be used as a reference in future chapters of this report.

4.2 Types

This section will discuss the general types of PTO systems, which partially draws on the work of Amélie Tétu in the "Handbook of Ocean Wave Energy" [21] providing a comprehensive overview of wave energy conversion and introducing PTO systems in a clear and accessible manner. A more in-depth analysis is presented by Ahamed et al. (2020) [22], which describes the most common PTO configurations and their operating principles. Their study also includes a database of both commercial and experimental models, offering valuable insights into the current state of PTO technology.

Figure 4.1, adapted from Ahamed et al. [22], presents a general diagram illustrating the typical flow of energy from ocean waves to electricity, categorizing seven types of PTO systems. For the purposes of this report, and to align with the objectives of PBE applications, only four systems will be briefly discussed in the following sections: Hydraulic Motor-Based systems (HMB), Direct Mechanical Drive systems (DMD), Direct Electrical Drive systems (DED) systems, and Air Turbine (AT) systems. These four types were selected based on their direct relevance to the studied WECs designs and their level of technological maturity in both experimental and commercial applications. The discussion will highlight the main advantages and challenges associated with each system. Note that WECs can also be used as water pump with a pure hydraulic PTO, e.g., Kimball et al 2025 [23] which will not be discussed further in this report. In Figure 4.2, a simplified schematic illustrates the energy conversion workflow within these systems.

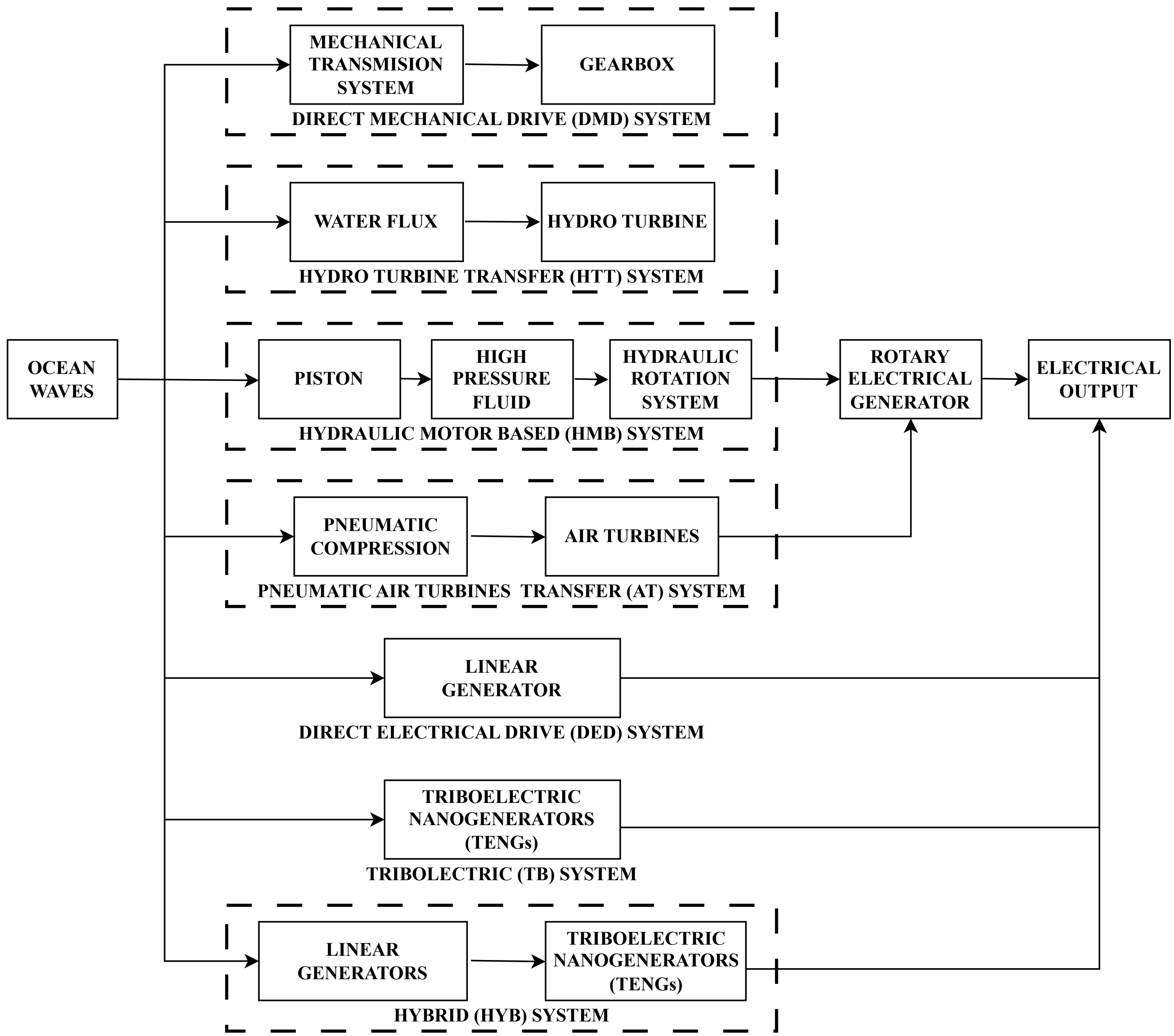

Figure 4.1: The working principles of the PTO system [22].

- **Hydraulic Motor Based (HMB):** The HMB PTO system typically consists of key components such as a hydraulic cylinder or ram, a hydraulic motor, an accumulator, and an electric generator. In general, an oscillatory motion acts on the hydraulic cylinder, which compresses a working fluid (usually hydraulic oil). This pressurized fluid ,with assistance of valves, is then directed through the hydraulic motor, converting the stored hydraulic energy into mechanical rotational energy. Finally, this mechanical energy is used to drive an electric generator, producing electrical power [22]. The accumulator plays a critical role in smoothing out pressure fluctuations and storing excess energy temporarily, enhancing system stability and efficiency. Due to their capacity to handle high loads and isolate the power conversion components from direct wave forces, hydraulic PTOs are particularly suitable for high-energy marine environments.

- **Direct Mechanical Drive Based (DMD):** The DMD system generates energy by directly converting the motion induced by ocean waves into electrical power. This is typically achieved using a gearbox that transfers the oscillatory or rotational motion of the WEC to an electric generator [22]. These systems are characterized by their mechanical simplicity and high efficiency, as they minimize the number of intermediate energy conversion steps. However, they also require robust design and materials to withstand the highly dynamic and corrosive marine environment.

- **Direct Electrical Drive Based (DED):** The DED system relies on the interaction between a translator and a stator, acting like a linear generator, producing electricity through electromagnetic induction. This approach eliminates the need for intermediate mechanical or hydraulic conversion systems. DED systems offer the advantage of fewer moving parts and reduced mechanical losses, making them potentially more reliable and easier to maintain in harsh marine environments. However, they also require precise control systems and advanced power electronics to manage the variable power output.

- **Air Turbines Based (AT):** In AT systems, commonly used in OWC devices, air is alternately compressed and decompressed within a sealed chamber due to the vertical motion of the water column caused by incoming waves. These pressure variations drive airflow through a bidirectional air turbine, which in turn drives an electric generator. These turbines are designed to rotate in a single direction regardless of the airflow, making them ideal for OWC applications. This system is advantageous as there is no direct contact between seawater and the turbine, reducing the risk of corrosion. However, its efficiency can be limited by the aerodynamic performance of the turbine and the variability of the airflow.

4.3 Main Features for PTO Systems

The selection of an appropriate PTO system is a critical aspect of designing and parameterizing a WEC. This choice depends on various factors, including the type of WEC, maintenance requirements, service life, overall efficiency, and requirements of each PBE application. For the four PTO systems discussed in this report, a comparative summary is provided in Table 4.1, highlighting key data to support their alignment with specific PBE applications in the next section (Chapter 5).

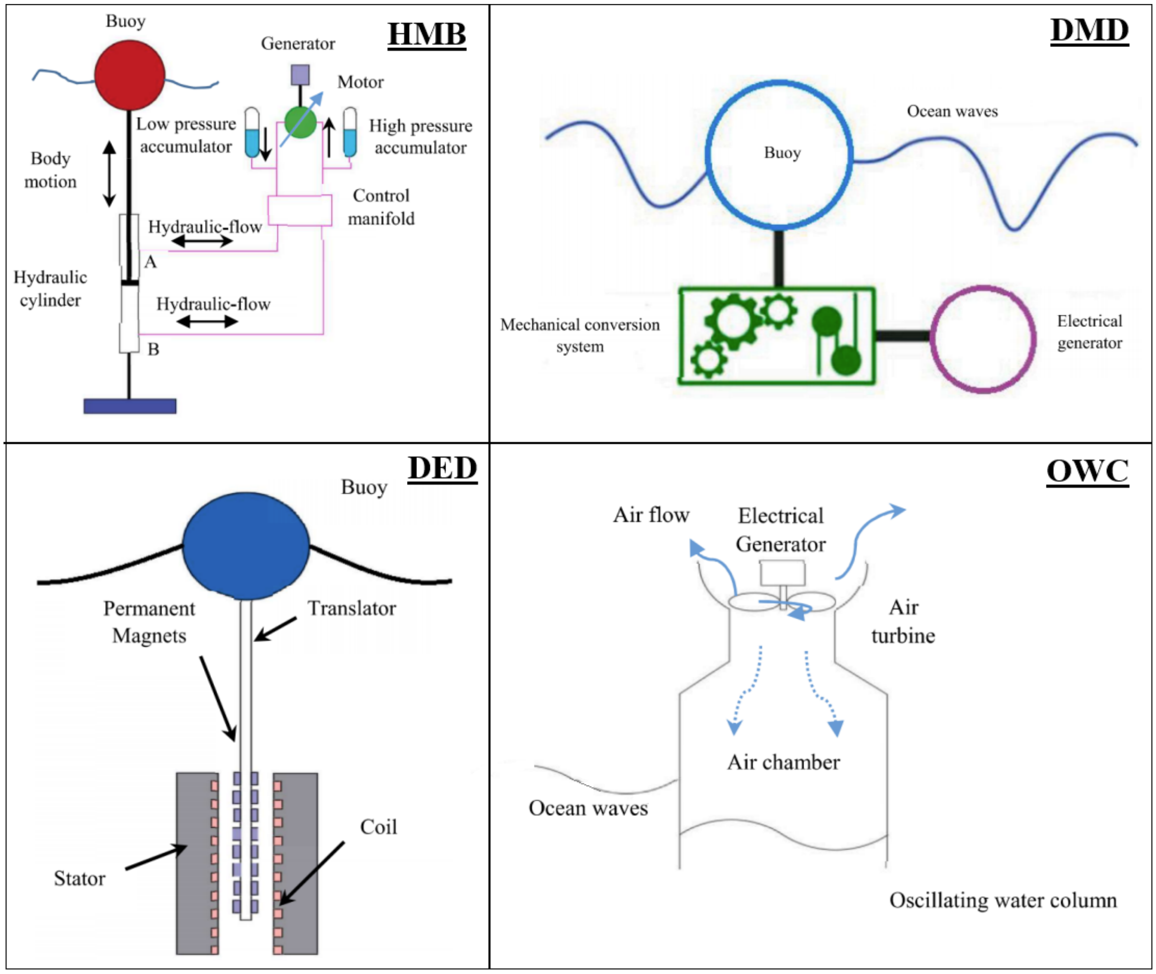

Figure 4.2: Schematic of PTO Systems. Top left, Hydraulic Motor Based system (HMB) [6]. Top right, Direct Mechanical Drive system (DMD) [22]. Bottom left, Direct Electrical Drive system (DED) [22]. Bottom right, Air Turbine system (AT) [22].

4.4 Conclusions

A PTO system is the subsystem of a WEC responsible for transforming the mechanical energy captured from ocean waves into a useful output, such as electricity. The PTO plays a central role in the overall performance, efficiency, and cost-effectiveness of WECs. This chapter analyzes four PTO systems (HMB, DMD, DED, and AT), which represent the main design options among the most common wave energy conversion devices.

The AT system is used almost exclusively in OWC devices, with its main drawback being its low mechanical efficiency. For OSWC and PA devices, the most commonly used PTO systems are DMD, DED, and HMB. The DMD system provides high mechanical efficiency but faces challenges related to scalability in experimental

Table 4.1: Main features of PTO systems. Abbreviations: AT – Air Turbines, DMD – Direct Mechanical Drive, DED – Direct Electrical Drive, HMB – Hydraulic Motor Based.

PTO SYSTEM	MAIN FEATURE
AT	For OWC, the most common PTO system is the one based on ATs [24]. Does not have environmental impact since the fluid work is air [24]. High axial thrust and high noise [25, 24]. It can be located in an easily accessible area, facilitating maintenance [24]. Wells turbines reach peak efficiencies of approximately 65–70%; however, under realistic oscillating flow conditions, the time-averaged efficiency drops significantly [25, 24].
DMD	Short lifetime and high maintenance cost [22]. The size of the gearbox is a parameter to consider in the design, and it is difficult to scale it to experimental model in wave tanks [22]. More efficient than the hydraulic motor based, due to the reduced friction. High performance, over the 95% of mechanical efficiency [26]. When coupled with a rotary permanent magnet generator, electrical efficiencies can exceed 90%, though actual performance depends heavily on the operating speed range and wave conditions [22].
DED	Without having a mechanical intermediate, avoid the associated energy losses [27]. Continuous force control through power electronics [28]. Low linear velocities, and low power-weight ratio [28]. Unequal generated voltage due to variable-speed induced by the waves [27]. The main electrical losses in linear generators are copper losses and core losses; these reduce electrical efficiency to a typical range of 70–85% for iron-cored designs and up to 90% for optimized semi iron-cored or air-cored configurations [29, 27].
HMB	Suitable for low frequency operations and large power density [30, 22]. The hydraulic motor can be used to control the WEC device, to maximize and regulate energy output [30]. Highly scalable to experimental models since the hydrodynamical response induced for the PTO can be modeled as linear loads [31]. The fluid work (generally hydraulic oil) can generate leakage due to the compression and decompression work, polluting the water [32]. Need regular maintenance due to the number of parts of the system [22]. Lower mechanical efficiency, which can result in a loss of electrical power. The overall claimed efficiency of the system varied from 69% to 80%, but in the real world could be lower [32].

testing. The DED system has no mechanical efficiency losses but presents considerable challenges in maintaining consistent output power. Finally, the HMB system offers advantages in design simplicity and experimental scalability, although it has limitations in mechanical efficiency.

In conclusion, the application of each PTO system should be carefully studied for each WEC, considering the energy requirements of the location where they are installed. The proper matching of PTO technology to WEC is essential to optimize energy extraction and ensure the feasibility and efficiency of the wave energy system.

Powering Blue Economy (PBE) Applications

5.1 Introduction

This chapter presents a summary of the main opportunities and challenges associated with implementing WECs in each PBE application of interest, followed by an overview of the application's energy requirements. To that end, the study considered the following applications: Offshore aquaculture, desalination, seawater mining, ocean observation and navigation, and autonomous underwater vehicle charging, as well as a brief description of the implementation of WECs in remote communities. The first four can be generally grouped under power at sea applications, while the last fall under community scale applications. Some PBE applications identified by the DOE are not addressed in this report. For example, marine algae is considered within the broader offshore aquaculture application due to their synergy and potential for co-location. Similarly, the coastal resilience and disaster recovery application is excluded because its objectives differ from the primary focus of this study, which is to examine the implementation of WECs and PTO devices for meeting energy demand.

5.2 PBE applications

The blue economy is defined as the sustainable use of available ocean resources for economic growth [1]. Within this context, the concept of Powering Blue Economy Applications (PBE applications) refers to energy solutions and technological innovations that enable the development and operation of key economic activities in the ocean. PBE applications require reliable and autonomous energy sources, as many operate in remote environments far from the traditional power grid. These systems often rely on diesel generators, which poses challenges for energy security, fuel transport, and the associated costs. Integrating ocean energy at the required location can enhance energy autonomy and security while reducing or eliminating the dependence on diesel. For that, the DOE established key PBE applications, where the marine energies can be developed to decrease the energy consumption costs [1].

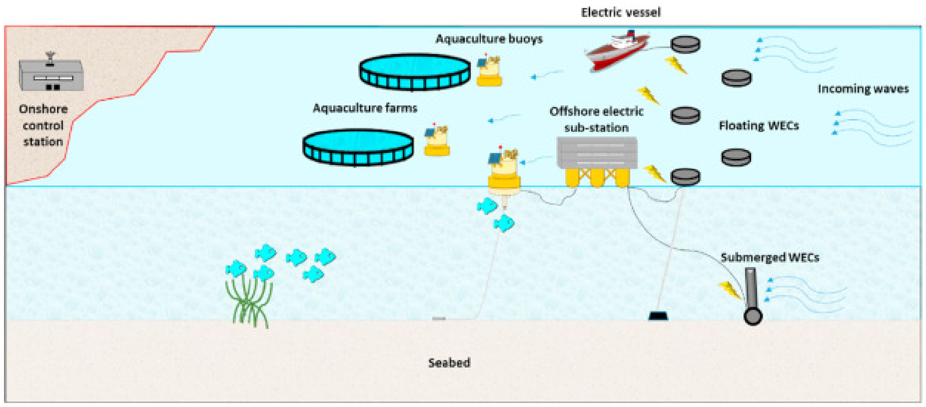

Figure 5.1: Marine energy technologies, co-located with offshore aquaculture operations. (Illustration by Clemente et al, Interdisciplinary Centre of Marine and Environmental Research, CIIMAR) [33]

5.2.1 Offshore Aquaculture

Aquaculture refers to the cultivation of marine species such as fish, crustaceans, mollusks, algae, and others, either in fresh or salt water environments. To improve production while ensuring the conservation and maintenance of coastal areas, the aquaculture industry is increasingly moving toward offshore locations. Offshore aquaculture operations require energy to support feeding systems, instrumentation, and sensors associated with safety, navigation, and maintenance. These energy demands can be partially or fully supplied through the use of marine energy.

The offshore aquaculture industry presents a great opportunity for synergy and co-location with WECs. Some WEC designs have been adapted to the location of aquaculture farms, taking into account different types and configurations to satisfy farm demand [34] [23]. Table 5.1 presents a summary of the main opportunities and challenges associated with the implementation of WECs in the offshore aquaculture industry. It is followed by an overview of the sector's energy requirements based on fish farm production volumes, along with current industry values.

It should be noted that feeding systems and instrumentation sensors differ by orders of magnitude in their power requirements — the former being significantly higher and the latter considerably lower — which implies that WECs may need to operate at different scales depending on the application.

Table 5.1: Opportunities and Challenges for Co-Locating WECs within Offshore Aquaculture Farms and Corresponding Farm Power Demand (Range and Real-World Examples).

OPPORTUNITIES [34]	**CHALLENGES** [34]	**RANGE OF POWER DEMAND [34]**	**REPORTED POWER DEMAND** [34]
Reduced energy costs via shared platforms. Synergy with multi-use operations. Lower environmental footprint WECs provide partial wave shelter to the fish farms for the waves.	Few technologies suited for offshore deployment. High investment and operating costs. Safety risks and unclear permitting. Low technology readiness/commercialization.	Small-Scale Farms: 10 kW – 50 kW Power demand: Basic feeding, instrumentation and sensors, aeration. Medium-Scale Farms: 50 kW – 500 kW Power demand: Automated feeding, lighting, instrumentation and sensors. Large-Scale Farms: 500 kW – 5 MW+ Power demand: Automated feeding, lighting, instrumentation and sensors.	Chilean Farms: 100-250 kW generators, 370 kWh/day. Scottish Farms: 1,000 tonnes production, 730 kWh/day. Norwegian Farms: 3,120 tonnes production, 700 kWh/day. Feeding systems consume over half of total energy.

5.2.2 Ocean Observation and Navigation

Considering that 80% of the ocean is inadequately studied and mapped, research, mapping and monitoring instruments become essential. Instruments such as meteorological buoys, profiling instruments, or tsunami warning devices operate in isolated areas of the ocean, where their power demand is limited by technical parameters such as battery capacity, data storage, and data transmission/collection (from the shore). Hence, the wave energy conversion emerges as a viable candidate to meet the power requirements of these instruments, offering the possibility of co-locating WECs in the operational sites or even integrating them directly into the observation and navigation devices. Table 5.2 presents a summary of the main opportunities and challenges associated with the implementation of WECs in the Ocean Observation and Navigation application. It is followed by an overview of the sector's energy requirements along with current industry values.

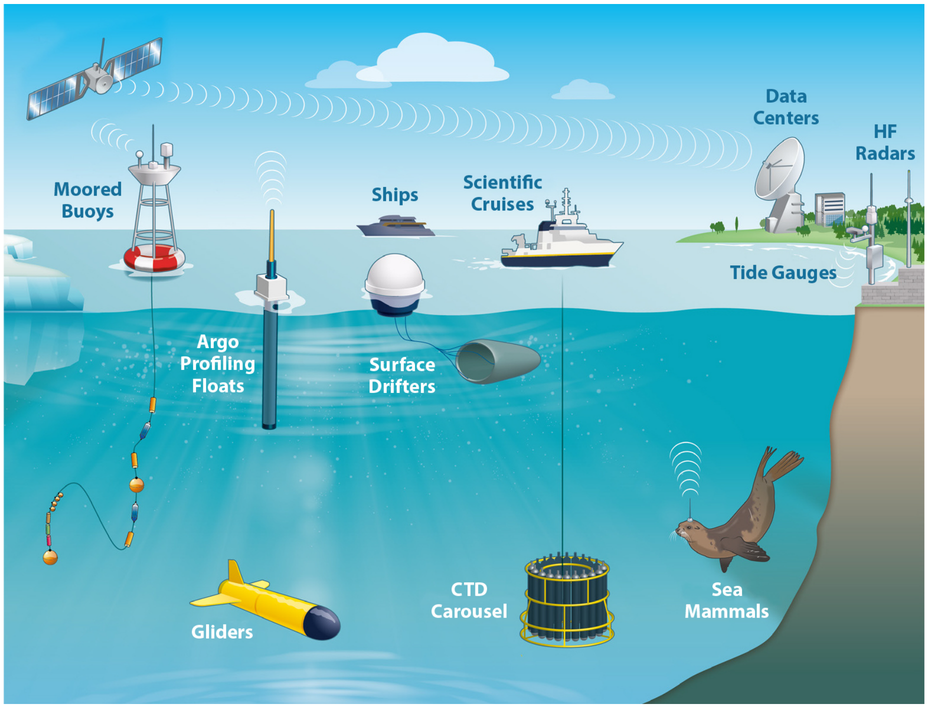

Figure 5.2: Example of a potential ocean observing network that uses multiple technologies to gather data. (Illustration by Thomas Haessig, OceanOps) [35]

Table 5.2: Opportunities and Challenges for Co-Locating WECs within Ocean Observation and Navigation devices and Corresponding Power Demand (Range and Real-World Examples).

OPPORTUNITIES [1] [36]	**CHALLENGES** [36]	**RANGE OF POWER DEMAND** [37]	**REPORTED POWER DEMAND** [36]
Ocean instrumentation is often limited by battery capacity, data storage, and transmission. Small WECs can provide sufficient power for instruments, enhance sensing and communication, and reduce reliance on batteries. Combining wave and solar energy may provide the best offshore power solutions.	Buoys and instruments need to operate globally, so there may not be a standard device for all regions. Wave energy use depends on site-specific ocean parameters.	Power demand ranges from 1 W to 20 W for different instruments. Drifting profiling floats: 1–5 kWh. Tsunami detection stations: <1 W. Weather buoys: average 5 W per day.	NDBC global network of weather buoys. Deep Ocean Tsunami Detection Stations. Drifting profiling floats and other oceanographic instruments.

Table 5.3: Opportunities and Challenges for Co-Locating WECs within Autonomous Underwater Vehicle (AUV) Chaging platforms and Corresponding Power Demand (Range and Real-World Examples).

OPPORTUNITIES [1] [36]	**CHALLENGES** [1] [36]	**RANGE OF POWER** [37]	**REPORTED POWER DEMAND** [36]
Powering AUVs with docking stations is a promising opportunity to implement WEC devices. Incorporating a WEC as a power source would potentially extend the seasonal operability and geographical range.	Underwater docking stations are under development and not yet available commercially, and the feasibility, effectiveness and efficiency of underwater charging stations needs to be demonstrated. One of the biggest challenges is integrating WEC systems into charging stations. WECs are located at or near the water surface; however, docking stations would be typically located lower in the water column or on the seafloor. The system should be able to operate over a wide depth range that is estimated to be between 50 and 1,000 m.	The average consumption of an AUV is between 100 to 300 W, with a typical maximum mission duration of 24 hours.	The AUV dock system developed by WHOI and deployed on the OOI Coastal Pioneer Array is designed to charge an AUV equipped with a single, or optionally a second, 5.4 kWh battery pack, with a listed charging duration of 24 hours.

5.2.3 Autonomous Underwater Vehicle (AUV) Charging

AUVs are a cost-effective alternative to traditional vessels for the study of the ocean, but battery capacity and data storage remain a limiting factors. Docking and recharge stations can extend the mission duration of AUVs by recharging their batteries while at sea, as well as providing a secure platform to dock vehicles between missions, reducing the need to recall vehicles to the surface and increasing the geographic range of operation. Table 5.3 presents a summary of the main opportunities and challenges associated with implementing WECs in the Underwater Vehicle Charging application, followed by an overview of the sector's energy requirements.

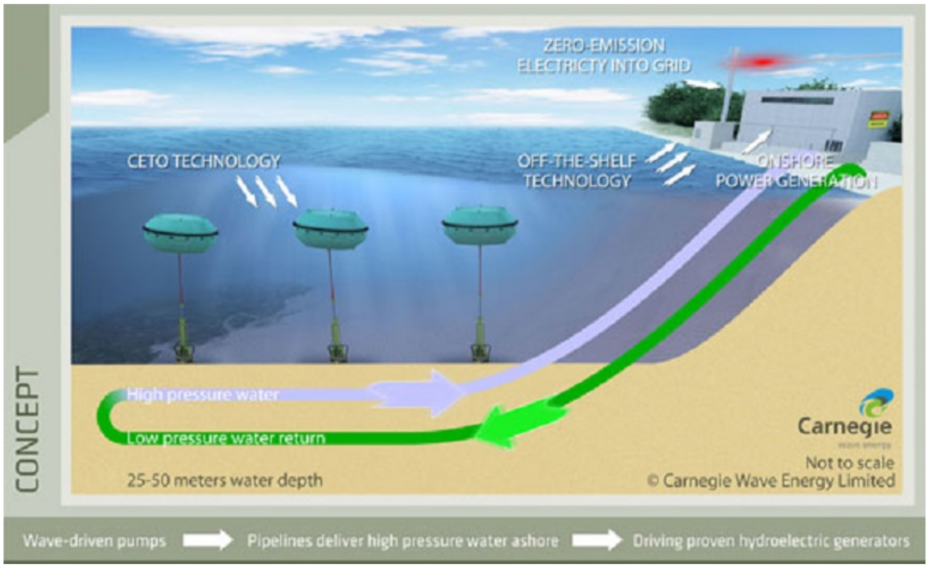

Figure 5.3: Diagram of implementation of WECs in desalination plants (Illustration by CETO Technology, Carnegie Clean Energy.) [39]

5.2.4 Desalination

Desalination is the process by which salt and other minerals are removed from seawater to make it potable. Desalination has become a key solution to address water scarcity in arid coastal regions with limited access fresh water or urban areas whose demands cannot be met by local water service. Among the most common techniques are reverse osmosis and distillation, both with challenges related to energy consumption and environmental impact. For example, to produce 1000 cubic meters of water per day, it requires about 10000 tons of fossil fuel per year [38]; hence, replacing a portion of this with marine energy could significantly reduce the fuel costs. Thus, the implementation of WECs in areas near desalination plant sites is a viable option. It should be noted that this would constitute a utility-scale application when serving a larger population, or a community-scale application when serving smaller, remote communities. Table 5.4 presents a summary of the main opportunities and challenges associated with implementing WECs in the Desalination application.

Table 5.4: Opportunities and Challenges for Co-Locating WECs within Desalination Plants and Corresponding Power Demand (Range and Real-World Examples).

OPPORTUNITIES [38]	**CHALLENGES** [1]	**RANGE OF POWER** [40]	**REPORTED POWER DEMAND** [41]
Wave energy could be used to directly pressurize seawater without generating electricity for a reverse-osmosis system, eliminating one of the largest cost drivers to produce desalinated water. Marine energy resources are inherently located near potential desalination water supplies and high population concentrations along the coast; therefore, areas that have unreliable grid connections or water infrastructure may receive dual benefits from marine energy systems.	One of the most significant technical challenges will be seassonally matching the wave energy resource with water demand. Typically, the most energetic conditions take place during the winter months and the lowest energetic conditions occur during the summer months. The magnitude of the demand and resource availability will drive storage requirements.	For 2016, the average consumption for each cubic meter of water production was approximately 4 kWh, but it is projected to decrease in the next 10 years to almost half.	The most expanded technique to desalinate water is Reverse Osmosis (RO). Since 1980, freshwater production using RO has gone from less than 100,000 to over 500,000 cubic meters per day in a single Desalination plant in recent years.

5.2.5 Mining Seawater Minerals and Gasses

Mining seawater minerals dissolved in small quantities in the ocean is an activity still under development. In view of this, a possible synergy between Desalination and this PBE application is proposed, making use of the waste from desalination plants (concentrated brine) and optimizing the process of obtaining minerals. As in the previous case, the information relevant to this PBE application is presented in Table 5.5.

Table 5.5: Opportunities and Challenges for Co-Locating WECs within Mining Seawater Minerals and Gasses Systems and Corresponding Power Demand (Range and Real-World Examples).

OPPORTUNITIES [1]	**CHALLENGES** [1]	**RANGE OF POWER**	**REPORTED POWER DEMAND** [1]
Intermittency of power is acceptable for the extraction of minerals and gasses from seawater for periods of time of a few days. Storage backup can help to maintain adequate power for essential parts of at-sea systems like navigation lights and safety gear. The power from the marine energy system could be used to operate any mechanical or electrochemical systems that the seawater extraction system would require.	Extracting elements in low concentrations from seawater requires processing large volumes of water, which can be energy-intensive and potentially cost-prohibitive. However, the coupling of marine energy and seawater extraction technologies would also require extensive development, deployment investigations, and potential design evolutions.	Seawater contains large amounts of dissolved ions and the four most concentrated metal ones (Na, Mg, Ca, K) are being commercially extracted today. However, all of the other present metal ions exist at much lower concentrations. The range of power required for the extraction varies depending on the mineral. For Lithium extraction the energy consumption goes from 0.3–1.5 kWh per kg of LiCO [42], for Magnesium 5–20 kWh per kg of Mg [43], for Uranium 200–600 kWh per kg of U [44], for Potassium 4–12 kWh per kg of KSO [45] and for Bromine 1–3 kWh per kg of Br [46]	No commercial or pilot operations are currently in use. There is a synergy opportunity with desalination plants, where the waste product from the desalination operation (brine) would become a resource for mineral extraction, thereby lowering the overall cost of the production of fresh water.

5.2.6 Isolated Power Systems

Throughout the United States, there are isolated communities that are generally disconnected from the power grid, so their energy supply depends on diesel generators. Although diesel fuel has a high energy density, it presents operational and logistical challenges, which increases its cost in these areas. In isolated coastal locations exposed to constant waves, wave energy is emerging as a viable alternative to diesel. Although the implementation of WECs in these locations is a viable option, each case requires an independent analysis, taking into account the conditions and requirements of each community. Table 5.6 summarizes key information on implementing wave energy in this PBE application.

Table 5.6: Opportunities and Challenges for Co-Locating WECs within Isolated Power Systems and Corresponding Power Demand (Range and Real-World Examples).

OPPORTUNITIES [1]	**CHALLENGES** [1]	**RANGE OF POWER** [1]	**REPORTED POWER DEMAND** [1]
The advantage of this market for developing marine energy technologies is that the cost of generated electricity for isolated communities is high; therefore, the cost and performance requirements of marine energy technology must meet are less difficult than the general electric utility market.	The main challenge remains in the specific conditions and availability of marine energy resources of each region. Wave energy conversion devices need prototype testing to determine the effectiveness of the various WEC configurations that have been designed. Some WEC types (especially floating-point absorbers) may not scale well because of resonant wave period response requirements. The survival of WEC devices in this environment needs to be demonstrated.	Remote communities typically have microgrid power systems from 200 kW to 5 megawatts (MW), with high reliability being a key objective. First adopters are expected to be environmentally conscious resorts, small villages, and military bases.	An example of WEC for islolated Power Systems was propposes for Yakutat on the Gulf of Alaska. A bottom-mounted flapping WEC. This type of WEC scales well and can be deployed in the size range that fits Yakutat's small load. That project was ultimately not funded.

5.3 Conclusions

This chapter presents a summary of the main opportunities and challenges associated with implementing WECs in several PBE application of interest, followed by an overview of the application's energy requirements. To that end, the study considered the following applications listed by the DOE: offshore aquaculture, desalination, seawater mining, ocean observation and navigation, and autonomous underwater vehicle charging, as well as a brief description of the implementation of WECs in isolated communities. The diverse nature of these applications highlights the broad potential for WEC technology to support various sectors of PBE applications.

The energy demand varies significantly across different PBE applications, influencing the design and deployment of WECs. Offshore aquaculture typically requires power on the order of less than 100 kW up to the megawatt scale, depending on the scale of operations. Desalination processes demand approximately 4 kWh per cubic meter of water produced, reflecting the energy intensity of freshwater production. Seawater mining energy requirements are highly dependent on the specific element being extracted, reaching over 20,000 kWh per kilogram for the most energy-intensive materials. Ocean observation and navigation devices generally require modest power, typically up to 20 kW in the most extreme cases, while autonomous underwater vehicle charging systems can demand up to 300 kW. Additionally, WEC implementations in isolated communities span a broad power range, from around 200 kW to 5 MW, according to recent studies. These varied energy needs underscore the necessity for tailored WEC and PTO designs that optimally meet the specific requirements of each application.

Among these applications, seawater mining and isolated communities present the highest energy demands, followed by autonomous underwater vehicle charging and big scale offshore aquaculture. Ocean observation and navigation have the lowest power requirements, making the integration of WECs particularly feasible in these sectors. Medium and small scale offshore aquaculture also presents a promising opportunity for WEC deployment due to its moderate power needs and potential for sustainable energy use.

Consideration of WECs and PTOs for PBE

6.1 Introduction

In this chapter, three WECs, (OWC, OSWC, and PA) are matched with every key PBE application considering all the information given in the previous sections. Additionally, these WECs are then paired with suitable PTO systems (AT, MDD, EDD and HMB). The functional combinations of WECs and PTO systems are selected based on the previously outlined requirements, ensuring optimal performance, efficiency, and compatibility with each PBE application energy demand. The PBE applications discussed in this section include Offshore Marine Aquaculture, Ocean Observation and Navigation, Autonomous Underwater Vehicle (AUV) charging, and Desalination.

6.2 WEC and PTO Selection for PBE Applications

6.2.1 Offshore Aquaculture

Table 6.1 presents a comparative evaluation between different types of WECs and PTO systems, considering criteria such as energy efficiency, ease of maintenance, cost of implementation, technological maturity and adaptability to Offshore Marine Aquaculture operating conditions. This selection seeks to identify the most appropriate combination to maximize the performance and sustainability of the system according to the specific needs of the sector.

6.2.2 Ocean Observation and Navigation

Ocean Observation and Navigation instrumentation require reliable, autonomous and adaptable power solutions for highly dynamic environments such as the ocean. In this context, the correct selection of WEC and PTO devices is crucial to ensure continuous power supply to measurement, communication and navigation systems at sea. The Table 6.2 presents a comparative evaluation between different types of WECs and PTO systems, considering the criteria mentioned in the previous chapter.

Table 6.1: WEC and PTO Selection for offshore aquaculture Applications

WEC	PTO	CONSIDERATION	REAL WORLD EXAMPLES
OWC	AT	As the water depth increases, the efficiency of the OWC decreases, limiting its expansion to nearshore areas. The AT is the most suitable option for this device and has no environmental impact on the ocean since it operates with air, preventing pollution of the surrounding waters near fish farms. It can be placed in strategic locations for easy maintenance. However, its high axial thrust, and noise levels could negatively affect fish health.	
PA	DMD, DED, HMB	The adaptability of PAs to offshore conditions, based on their design and the parametrization of physical and mass properties, makes them a promising technology for this PBE application. For the PTO system, DMD, DED, and HMB can be implemented on PAs, with DMD and HMB being the most common choices. For DMD, the gearbox size is a key design parameter for PAs. For DED, the main challenges are the low power-weight ratio and the unequal voltage generation. For HMB, the working fluid (typically hydraulic oil) may leak due to compression and decompression cycles, potentially polluting the water and affecting fish production.	SINN Power. Shrimp and prawn aquaculture and wave energy – Cabo Verde [34]. Aqua Power Technologies Nearshore finfish aquaculture and wave energy – Scotland [34]. Carnegie Clean Energy Offshore aquaculture and wave energy – Australia [34].
OSWC	NONE	Since OSWECs are designed for nearshore use in water depths of less than 20 m, they are not a suitable choice for offshore aquaculture applications.	

6.2.3 Autonomous Underwater Vehicle Charging

The continued operation of Autonomous Underwater Vehicles (AUVs) is highly dependent on the availability of efficient and reliable recharging solutions in remote marine environments. In this regard, the proper selection of WEC and PTO devices is essential to ensure a constant power supply compatible with the recharging needs of AUVs. Table 6.3 presents a comparative evaluation between different types of WECs and PTO systems, considering the criteria mentioned in the previous chapter. This selection aims to identify the most suitable combinations to maximize the operational autonomy of the AUVs and ensure the continuity of their missions in demanding environments.

Table 6.2: WEC and PTO Selection for Ocean Observation and Navigation Applications

WEC	PTO	CONSIDERATION	REAL WORLD EXAMPLES
OWC	NONE		
PA	DMD, DED, HMB	Considering that this PBE application relates to offshore regions (higher depths), the PA is the best option for this purpose. The PA can be integrated into moored buoys, ocean tsunami detection stations, and drifting profilers, considering the low power requirements of these devices, which can be fully supplied by small WECs housed within them.	Power Buoy 3 supplies continuous power to onboard payloads or equipment located on the seabed while also providing real time data transfer and communication to remote shore facilities [11].
OSWC	NONE		

Table 6.3: WEC and PTO Selection for Autonomous Underwater Vehicle Charging Applications

WEC	PTO	CONSIDERATION	REAL WORLD EXAMPLES
OWC	NONE		
PA	DMD, DED, HMB	Similar to the Ocean Observation and Navigation application, and considering that this PBE application is related to offshore regions (greater depths), the PA is the most suitable option for this purpose. WECs are typically located at or near the water surface, where most of the wave energy is concentrated; however, docking stations are usually positioned deeper in the water column or on the seafloor.	AUV dock system developed by WHOI and deployed on the OOI Coastal Pioneer Array, to charge an AUV which includes a single or optional second 5.4 kWh Li-ion battery pack for a listed duration of 24 hours [36].
OSWC	NONE		

6.2.4 Desalination

Desalination can benefit from wave energy due to the high energy demand of this industry. In this context, the proper selection of WEC and PTO devices is critical for the correct co-location and synergy with the desalination plant.Table 6.4 presents a comparative evaluation between different types of WECs and PTO systems, considering the criteria presented in the previous chapter.

Table 6.4: WEC and PTO Selection for Desalination Applications

WEC	PTO	CONSIDERATION	REAL WORLD EXAMPLES
OWC	AT	The main advantage of OWC devices is their adaptability to nearshore and shore platforms.	
PA	DMD, DED, HMB	The PA devices can be installed in plants installed in exposed areas. Furthermore, some arrangements of PAs can be used to dissipate wave energy around the coastal structures of desalination plants.	Choppy waters for wave desalination (CETO) [39].
OSWC	HMB	Since OSWC operates in shallow waters, it is considered an efficient option for these plants.	

6.3 Conclusions

For each PBE application discussed in this section-offshore marine aquaculture, ocean observation and navigation, AUV charging, and desalination-the selection of a compatible WEC device (OWC, OSWC, PA) and PTO system (AT, DMD, EDD, HMB) was guided by the energy demands of the application. In the case of Offshore Marine Aquaculture, the review indicates that the PA device is the most suitable due to its adaptability to various offshore conditions. The main challenge lies in selecting the appropriate PTO system, which requires further investigation in future work. For Ocean Observation and Navigation, the PA device is again preferred, primarily because of its compatibility with the small-scale instrumentation used in this sector (e.g., buoys). Given the low power requirements of these instruments, mechanical efficiency is less critical, and the key criterion for PTO selection is ease of maintenance. In the AUV Charging application, deploying deck-based charging stations presents a significant opportunity for integrating WECs to meet the power demand of AUVs. Considering the operational depths of AUVs, the PA device is the most suitable option. However, since the power requirements of AUVs exceed those of other research instruments, the PTO system must be efficient enough to satisfy these higher charging demands. Finally, for Desalination, all three WEC options (OWC, OSWC, PA) are potentially suitable due to their applicability in nearshore environments. For PA and OSWC devices, some commercial models are already available, making implementation more feasible.

Ongoing and Future Work

Task 3.4 of IIJA/BIL Activities at the Atlantic Marine Energy Center (AMEC) aims to develop a tunable Wave Energy Converter Reference Model (WEC-RM) of a two-body PA tailored for specific applications under the PBE initiative. This report addresses the first sub-task: Literature review and lessons learned from existing reference models (RMs), WEC designs, main parameters, PTO systems, and PBE applications. The ongoing and short-term future work (1 year) include:

Second Sub-Task: Define Scope and PBE Applications

- Select specific PBE application(s) for which the WEC-RM will be designed: offshore aquaculture farm.
- Design WEC and PTO systems to meet the PBE application energy requirements.
- Estimate small-scale fish farm energy demand.
- Assess the site-specific energy potential.
- Conduct experimental WEC scaling using Froude scaling; determine alternative scaling methods for PTO.
- Begin hydrodynamic simulations using Capytaine BEM with RM3.

Third Sub-Task: Develop Analytical, Numerical, and Physical Models

- Parametrize device dimensions and finalize analytical and numerical models of the tunable RM in Capytaine.
- Develop an automated algorithm to evaluate 2-body PA WEC response.
- Determine the appropriate scale for testing in the UNH wave tank.
- Identify and model a suitable PTO system in WEC-Sim, aligned with the tunable WEC-RM.

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Bibliography

[1] A. LiVecchi, A. Copping, D. Jenne, A. Gorton, R. Preus, G. Gill, R. Robichaud, R. Green, S. Geerlofs, S. Gore, D. Hume, W. McShane, C. Schmaus, and H. Spence. Powering the blue economy: Exploring opportunities for marine renewable energy in maritime markets. Report, U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Washington, D.C., 2019.

[2] Vince Neary, Mirko Previsic, Arnold Fontaine, Yi-Hsiang Yu, Michael Lawson, et al. Reference model project (rmp): Open-source reference models for marine hydrokinetic technologies. Sandia National Laboratories / U.S. Department of Energy, Marine and Hydrokinetic Data Repository, September 2014.

[3] António F. de O. Falcão. Wave energy utilization: A review of the technologies. *Renewable and Sustainable Energy Reviews*, 14(3):899–918, April 2010.

[4] M.A. Mustapa, O.B. Yaakob, Yasser M. Ahmed, Chang-Kyu Rheem, K.K. Koh, and Faizul Amri Adnan. Wave energy device and breakwater integration: A review. *Renewable and Sustainable Energy Reviews*, 77:43–58, September 2017.

[5] Michael E. McCormick. *Ocean Wave Energy Conversion*. Dover Publications, Mineola, New York, 2007. Originally published: New York: John Wiley, 1981.

[6] Iraide López, Jon Andreu, Salvador Ceballos, Iñigo Martínez de Alegría, and Iñigo Kortabarria. Review of wave energy technologies and the necessary power-equipment. *Renewable and Sustainable Energy Reviews*, 27:413–434, November 2013.

[7] Gonzalo Tampier, Cristian Cifuentes, and Carlos Parra. Wave energy technologies for chile: Critical analysis (white paper). 2021.

[8] Vince Neary, Yi-Hsiang Yu, Jeffrey Epler, Kourosh Shoele, Mirko Previsic, Michael Lawson, and Ye Li. Reference model 3 scaled geometry (rm3: Wave point absorber). Marine and Hydrokinetic Data Repository, Sandia National Laboratories, September 2014.

[9] Vince Neary, Yi-Hsiang Yu, Scott Jenne, and Bob Thresher. Reference model 5 full scale geometry (rm5: Oscillating surge flap). Open Energy Data Initiative / MHKDR, Sandia National Laboratories, September 2014.

[10] Vince Neary, Diana Bull, Chris Smith, Paul Jacob, Scott Jenne, Steve Willits, and Arnold Fontaine. Reference model 6 full scale geometry (rm6: Oscillating water column). Dataset, Marine and Hydrokinetic Data Repository, Sandia National Laboratories, September 2014.

[11] Ocean Power Technologies. Ocean power technologies, 2025. Accessed: 2025-07-02.

[12] A. Babarit. A database of capture width ratio of wave energy converters. *Renewable Energy*, 80:610–628, 2015.

[13] Bingyong Guo, Tianyao Wang, Siya Jin, Shunli Duan, Kunde Yang, and Yaming Zhao. A review of point absorber wave energy converters. *Journal of Marine Science and Engineering*, 10(10):1534, October 2022.

[14] Yi-Hsiang Yu, Michael Lawson, Mirko Previsic, Jeff Epler, and Junhui Lou. Experimental wave tank test for reference model 3 floating-point absorber wave energy converter project, 2015.

[15] Yi-Hsiang Yu, Michael Lawson, Yiheng Li, Mirko Previsic, James Epler, and Jimmy Lou. Methodology for design and economic analysis of marine energy conversion (mec) technologies. Technical Report SAND2014-9040, Sandia National Laboratories, Albuquerque, NM, USA, 2014.

[16] Yi-Hsiang Yu, Robert Thresher, Kelley Ruehl, Michael Lawson, Carlos Michelen, Katherine Lilienkamp, Diana Bull, Michael Baca, and Dillon White. Reference model 5 (rm5): Oscillating surge wave energy converter. Technical Report SAND2015-2074R, Sandia National Laboratories and National Renewable Energy Laboratory (NREL), Albuquerque, NM, and Golden, CO, USA, 2015.

[17] Yi-Hsiang Yu, Michael Lawson, Kelley Ruehl, and Carlos Michelen. Development and demonstration of the wec-sim wave energy converter simulation tool. In *Proceedings of the 2nd Marine Energy Technology Symposium (METS 2014)*, Seattle, WA, USA, 2014.

[18] Dominic D. Forbush, Kelley M. Ruehl, David Ogden, Jennifer Van Rij, Yi-Hsiang Yu, and Nathan Tom. Development and validation of passive yaw in the open-source wec-sim code. In *Proceedings of the ASME 39th International Conference on Offshore Mechanics and Arctic Engineering (OMAE 2020)*, Fort Lauderdale, FL, USA, 2020.

[19] Diana Bull and Polly Jacob. Methodology for creating a succinct wave energy converter (WEC) testing program and application to the backward bent duct buoy (BBDB) OWC WEC. Technical Report SAND2014-17816, Sandia National Laboratories, Albuquerque, New Mexico, 2014.

[20] R. So, B. Bosma, and K. Ruehl. Modeling of a wave energy oscillating water column as a point absorber using wec-sim. *Journal of Marine Science and Engineering*, 7(4):1–15, 2019.

[21] Amélie Têtu. *Power Take-Off Systems for WECs*, pages 203–220. Springer International Publishing, December 2016.

[22] Raju Ahamed, Kristoffer McKee, and Ian Howard. Advancements of wave energy converters based on power take off (pto) systems: A review. *Ocean Engineering*, 204:107248, May 2020.

[23] Chelsea Kimball, M. Robinson Swift, and Martin Wosnik. Wave-powered water pump for upwelling in aquaculture: Numerical model and ocean test. *Renewable Energy*, 239:122040, 2025.

[24] António F.O. Falcão and João C.C. Henriques. Oscillating-water-column wave energy converters and air turbines: A review. *Renewable Energy*, 85:1391–1424, 2016.

[25] Tapas Kumar Das, Paresh Halder, and Abdus Samad. Optimal design of air turbines for oscillating water column wave energy systems: A review. *International Journal of Ocean and Climate Systems*, 8(1):37–49, 2017.

[26] Markel Penalba and John V. Ringwood. A review of wave-to-wire models for wave energy converters. *Energies*, 9(7):506, 2016.

[27] Raju Ahamed, Kristoffer McKee, and Ian Howard. A review of the linear generator type of wave energy converters' power take-off systems. *Sustainability*, 14(16):9936, 2022.

[28] M. Blanco, J. Torres, M. Santos-Herrán, L. García-Tabarés, G. Navarro, J. Nájera, D. Ramírez, and M. Lafoz. Recent advances in direct-drive power take-off (DDPTO) systems for wave energy converters based on switched reluctance machines (SRM). In *Advances in Renewable Energies Offshore*, pages 487–532. Springer International Publishing, 2022.

[29] Muhammad Fariz Umar, Totok Ruki Biyanto, and Gunawan Nugroho. Performance of linear generator designs for direct drive wave energy converter under unidirectional long-crested random waves. *Energies*, 14(16):5098, 2021.

[30] João C.C. Henriques and António F.O. Falcão. Strategies for active tuning of wave energy converter hydraulic power take-off mechanisms. *Renewable Energy*, 94:382–395, 2016.

[31] Simone Giorgi and Ronan Costello. Hydraulic PTO model emulator for WEC tank tests. In *Proceedings of the European Wave and Tidal Energy Conference*, 2018.

[32] C. Angulo, P. Estensoro, M. Santos, et al. Design, construction and testing of a hydraulic power take-off for wave energy converters. *Energies*, 5(6):2030–2052, 2012.

[33] D. Clemente, P. Rosa-Santos, T. Ferradosa, and F. Taveira-Pinto. Wave energy conversion energizing offshore aquaculture: Prospects along the portuguese coastline. *Renewable Energy*, 204:347–358, 2023.

[34] M.C. Freeman, L. Garavelli, E. Wilson, M. Hemer, M.L. Abundo, and L.E. Travis. Offshore aquaculture: a market for ocean renewable energy. Report, Ocean Energy Systems (OES), April 2022. Report for Ocean Energy Systems (OES).

[35] Tamaryn Morris, Daniel Rudnick, Janet Sprintall, Juliet Hermes, Gustavo Goni, Justine Parks, Francis Bringas, and Emma Heslop. Monitoring boundary currents using ocean observing infrastructure. *Oceanography*, pages 16–17, December 2021.

[36] Andrea E. Copping, Rebecca E. Green, Robert J. Cavagnaro, Dale S. Jenne, David Greene, Jayson J. Martinez, and Yang Yang. Powering the blue economy - ocean observing use cases report. Technical report, Pacific Northwest National Lab. (PNNL), Richland, WA (United States), February 2020.

[37] Chris Dizon, Robert J. Cavagnaro, Bryson Robertson, and Ted K. Brekken. Modular horizontal pendulum wave energy converter: Exploring feasibility to power ocean observation applications in the u.s. pacific northwest. *IET Renewable Power Generation*, 15(14):3354–3367, August 2021.

[38] Ahmed Alkaisi, Ruth Mossad, and Ahmad Sharifian-Barforoush. A review of the water desalination systems integrated with renewable energy. *Energy Procedia*, 110:268–274, March 2017.

[39] Matt Williams. Harnessing the waves: The ceto wave-power station. HeroX blog, 2025. Publicado en HeroX, "Energy, Environment & Resources", accedido el 28 jul 2025.

[40] World Bank. The role of desalination in an increasingly water-scarce world. Technical report, World Bank, Washington, D.C., 2019. License: CC BY 3.0 IGO.

[41] Jungbin Kim, Kiho Park, Dae Ryook Yang, and Seungkwan Hong. A comprehensive review of energy consumption of seawater reverse osmosis desalination plants. *Applied Energy*, 254:113652, November 2019.

[42] T. Hoshino et al. Lithium recovery from seawater using manganese oxide adsorbents. *Industrial & Engineering Chemistry Research*, 55(30):7930–7936, 2016.

[43] B. Swain. Recovery and recycling of magnesium resources—a review. *Resources, Conservation & Recycling*, 113:35–50, 2016.

[44] J. Kim et al. Uranium extraction from seawater: Energy consumption and economic feasibility. *Chemical Engineering Journal*, 237:204–210, 2014.

[45] Y. Zhao, T. Xu, and G. Chen. Electrodialysis for potassium recovery from seawater. *Journal of Membrane Science*, 599:117857, 2020.

[46] R. Sander. Bromine chemistry in the marine boundary layer. *Chemical Reviews*, 103(12):4783–4822, 2003.