UNIVERSIDAD AUTÓNOMA DE BAJA CALIFORNIA
INSTITUTO DE INVESTIGACIONES OCEANOLÓGICAS
FACULTAD DE CIENCIAS MARINAS

TESIS

VIABILIDAD DEL APROVECHAMIENTO DEL OLEAJE COMO ENERGÍA RENOVABLE EN BAJA CALIFORNIA

FEASIBILITY OF HARNESSING WAVE ENERGY AS A RENEWABLE ENERGY SOURCE IN BAJA CALIFORNIA

TESIS QUE PARA OBTERNER EL GRADO DE

DOCTOR EN MEDIO AMBIENTE Y DESARROLLO

PRESENTA

EMILIANO GORR POZZI

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RESUMEN de la tesis presentada por **EMILIANO GORR POZZI**, presentada en cumplimiento parcial de los requisitos para obtener el grado de DOCTOR EN CIENCIA en MEDIO AMBIENTE Y DESARROLLO. Ensenada, Baja California, 01 de Junio de 2023.

VIABILIDAD DEL APROVECHAMIENTO DEL OLEAJE COMO ENERGÍA RENOVABLE EN BAJA CALIFORNIA

Resumen aprobado por:

Dr. Héctor García Nava
Director del Comité

El contexto geopolítico contemporáneo, enmarcado por el inminente cambio climático y la creciente demanda de recursos naturales, crea la necesidad de considerar soluciones innovadoras que mejoren la capacidad de adaptación y el desarrollo sostenible. El aprovechamiento de la energía del oleaje se ha convertido en una opción prometedora capaz de generar importantes beneficios para reducir la vulnerabilidad de las costas y las emisiones de carbono. Sin embargo, la mayoría de los proyectos de convertidores de energía del oleaje (CEO) siguen enfrentándose a diferentes retos tecno-económicos que limitan su financiación y despliegue comercial. El presente estudio evalúa la viabilidad del aprovechamiento de la energía del oleaje en Baja California, considerada una de las regiones más energéticas del Pacífico mexicano. El estudio, se centra en el uso de la energía del oleaje en la región desde una perspectiva de generación de electricidad en un esquema energético descentralizado y en Eco-parques Marinos (EPM) impulsados por granjas de CEOs y que incluyen submodulos de producción de agua desalinizada y acuacultura marina. La región estudiada dispone de una cantidad moderada de energía del oleaje con una marcada estacionalidad y baja variabilidad interanual. De los diferentes CEOs analizados, Pelamis genera el mayor rendimiento y la mejor relación técnico-económica, con promedios mensuales del factor de capacidad de hasta el 40% y un coste nivelado de la energía (LCoE) de 480 $/MWh. Si bien el emplazamiento individual de CEO no es rentable, la economía de escala en las granjas CEOs aumenta la rentabilidad del EPM. El submódulo de acuacultura de algas marinas genera la mayor rentabilidad de EPM, mientras que la desalinización de agua de mar no es económicamente viable. Se observa una reducción en las estimaciones de

LCoE previstas para el 2030 en todos los sitios seleccionados. Sin embargo, es necesario continuar innovando y desarrollando de dispositivos más económicos y eficientes que generen una mayor competitividad en el mercado eléctrico frente a otras tecnologías tradicionales de generación de energía. Se espera que la metodología empleada en este estudio pueda ser útil en otras regiones costeras con necesidades y condiciones climáticas similares.

Palabras Clave: energía del oleaje; esquema energético descentralizado; sistemas complejos; eco-parques marinos; economía azul; desarrollo sostenible.

ABSTRACT of the thesis presented by **EMILIANO GORR POZZI**, submitted in partial fulfillment of the requirements for the degree of DOCTOR OF SCIENCE in ENVIRONMENT AND DEVELOPMENT, Baja California, Jun 01, 2023.

FEASIBILITY OF HARNESSING WAVE ENERGY AS A RENEWABLE ENERGY SOURCE IN BAJA CALIFORNIA

Abstract approved by:

Dr. Héctor García Nava
Committee Director

The contemporary geopolitical context, framed by the impending climate change and increasing demand for natural resources, is creating the need to consider innovative solutions that enhance resilience and sustainable development. Harnessing wave energy has emerged as a promising marine renewable option to reduce coastal vulnerability and carbon emissions. However, most Wave Energy Converter (WEC) projects still face different techno-economic challenges that limit their financing and commercial deployment. The present study evaluates the feasibility of harnessing wave energy in Baja California, considered one of the most energetic regions of the Mexican Pacific. The study focuses on wave energy extraction for electricity generation and supply, with a decentralized energy scheme perspective, to Marine Eco-parks (MEP). These are driven by WEC farms coupled with seawater desalination and marine aquaculture sub-modules. The studied region has moderate wave energy with a marked seasonality and low interannual variability. From the different WECs analyzed, Pelamis showed the highest performance and the best technical-economic ratio, with maximum monthly average capacity factors close to 40% and a Levelized Cost of Energy (LCoE) equal to $480/MWh. While individual WEC siting is not profitable, the economy of scale in WEC farms increases the profitability of the MEP. The coupled seaweed aquaculture sub-module generates the highest MEP profitability, while seawater desalination is not economically viable. A reduction in the projected LCoE estimates for 2030 is observed for all selected sites. However, it is necessary to continue innovating and developing more economical and efficient devices that generate greater competitiveness in the electricity market against other traditional power generation technologies. It is expected that the methodology used in this study could be applicable in other coastal regions with similar needs and climatic conditions.

Keywords: wave power; decentralized energy scheme; marine eco-parks; complex systems; blue economy; sustainable development.

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PRESENTA

EMILIANO GORR POZZI

Aprobada por:

Dr. Héctor García Nava
Director

Dra. Cristina Garza-Lagler
Sinodal

Dr. Rafael Hernandez-Walls
Sinodal

Dr. Luis Malpica-Cruz
Sinodal

Dr. Manuel Gerardo Verduzco-Zapata
Sinodal

Declaración de autoría original

El trabajo contenido en esta tesis no ha sido presentado con anterioridad para cumplir los requisitos de obtención de un grado en esta u otra institución de enseñanza superior. A mi leal saber y entender, la tesis no contiene material previamente publicado o escrito por otra persona, excepto cuando se hace la debida referencia.

Firma: Emiliano Gorr

Fecha: 01 de Junio de 2023

DEDICATORIA

A la familia heredada,

los que están y los que se han ido, a pesar de la distancia, siempre están presentes en mi corazón.

A la familia elegida,

gracias por dejarme formar parte de ustedes, por su apoyo en la ruta del doctorado. Sin ustedes, NADA de esto hubiera sido posible.

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Y por último, pero no menos importante, quiero agradecerle al CONACYT por el apoyo financiero y recomendaciones para la realización de esta tesis.

“And no one should be the least bit interested
in the unique outcome of this comedy”.
Friedrich Nietzsche

ÍNDICE

Página

Lista de Figuras

Lista de Tablas

Chapter 1: INTRODUCTION

The scarcity of resources, population growth, and prevention against catastrophic meteorological events in a changing climate places developing countries in a vulnerable position, and therefore, their adaptation to climate change is particularly relevant [1,2].

Ambitious targets have been agreed upon worldwide to reduce carbon or greenhouse gas emissions. In particular, the electricity sector accounts for the largest share of annual anthropogenic CO_2 emissions from fossil fuel combustion, making it a focal point for climate change mitigation, environmental protection, and sustainable development [3]. Among the different contributors, coal-fired thermal power plants are responsible for 30% of global emissions of that pollutant gas. The Mexican government has enacted the Energy Transition Law that establishes a legal framework for clean energy production, energy efficiency, and the reduction of greenhouse gas emissions [4]. This law promotes generating at least 35 and 50% of its electricity from renewable sources by 2024 and 2050, respectively.

Renewable energies have become indispensable resources to promote the energy transition and mitigate global warming in modern societies [5]. The energy transition gained momentum in 2021, with a 38% contribution of renewables to the global installed capacity, almost 257 GW that avoided the emission of 1.08 $GtCO_2$ into the atmosphere [6,7]. The global objective is that, by 2050, renewable energy sources can satisfy 86% of the energy demand [8]. To this end, various resources are being explored to produce sustainable energy. Although the Mexican Energy Transition Law [4] has encouraged the proportion of installed clean energy capacity in the national energy matrix, it is necessary to continue adding efforts to achieve the climate proposals agreed upon in the Paris Agreement [9,10].

These actions encourage the consideration and evaluation of Marine Renewable Energies (MRE) as promising energy resources that have high power availability and have not yet been exploited to their maximum capacity [11]. With a global deployment potential of 337 GW and a generation capacity of over 885 TWh/year [12], harvesting MRE emerges as an alternative to strengthen energy security and boost sustainable development in Mexican coastal areas [13,14]. There are five principal MRE sources: ocean currents-tides, salinity gradients, thermal gradients, offshore wind generation, and wind-waves [14,15].

Wave energy is envisioned as one of the most promising renewable resources to be exploited on a larger scale in the future due to its high energy density per unit area and its intrinsic characteristics that allow transforming it into clean energy [16–18]. Worldwide, wave energy is estimated to be between 1 TW and 10 TW, the same order of magnitude as global electricity demand. Although estimated in enormous quantities, the spatial distribution of wave energy limits its exploitation in areas of the planet where current technologies allow viable extraction. The extratropical regions of both hemispheres have the highest wave power ($\geq$ 60 kWm^{-1}) it decreases latitudinally towards the equatorial region where the lowest values are present ($\leq$ 10 kWm^{-1}) [18]. Wave power in the Mexican Pacific coast (Figure 1) is within the resource's exploitable range, with availability of up to ~10 kWm^{-1} at least 50% of the time [14]. The Baja California peninsula is within these areas, has the highest wave energy availability in Mexico coasts, with maximum values close to 20 kWm^{-1} [14,17].

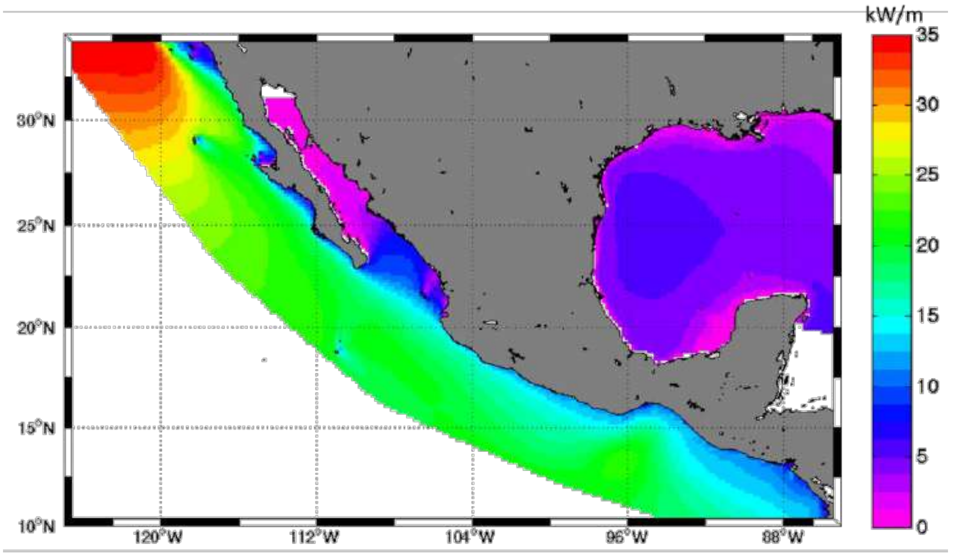

Figure 1. Mean Wave Power availability in México for 1994 to 2018 [19].

Wave energy has the advantage of being predictable and flowing naturally from generation zones to coastal areas, where it can be captured and harnessed through wave energy converters (WECs). Wave Energy Converters principles of operation are based on oscillatory motion or pressure fluctuations under the free surface of the ocean [18]. In recent years, many WEC prototypes that extract the energy transported by sea waves into electricity have been proposed and investigated [e.g. 21–24]. These devices can be grouped in five categories: point absorbers, overtopping devices, oscillating water columns, terminators, and attenuators.

Point dampers are WECs that move in heave, pitch, surge, or some combination thereof. The main characteristic of these devices is that they are relatively small compared with the wavelength of the incident wave. Examples of single-point absorbers are CETO [24], Oyster [25], AquaBuOY [26], or other WEC designs that use an array of point absorbers as WaveStar [27]. The first two WECs pump water at high pressure to an onshore power plant, where power is converted through hydraulic turbines in a power plant. The main difference between these converters is that CETO is a heaving point absorber submerged (Figure 2), Oyster is a surging point absorber fixed at the sea bed (Figure 3), and AquaBuOY (Figure 4) is a surface buoy that is designed to operate in nearshore and offshore regions between 20-50 m depth.

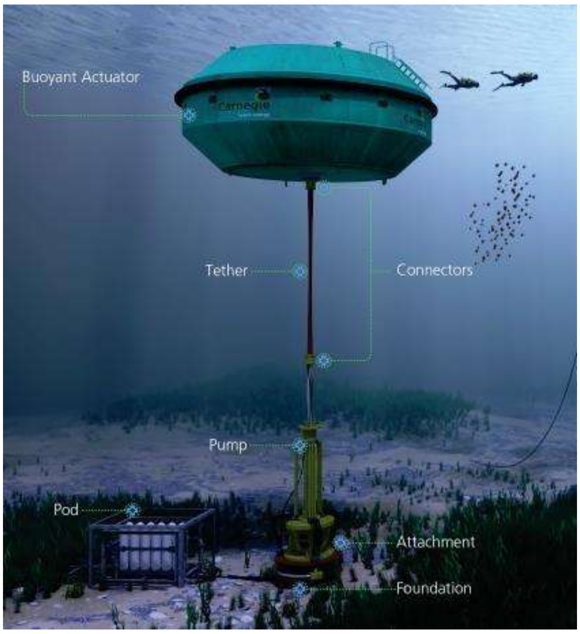

Figure 2. CETO wave energy converter [28].

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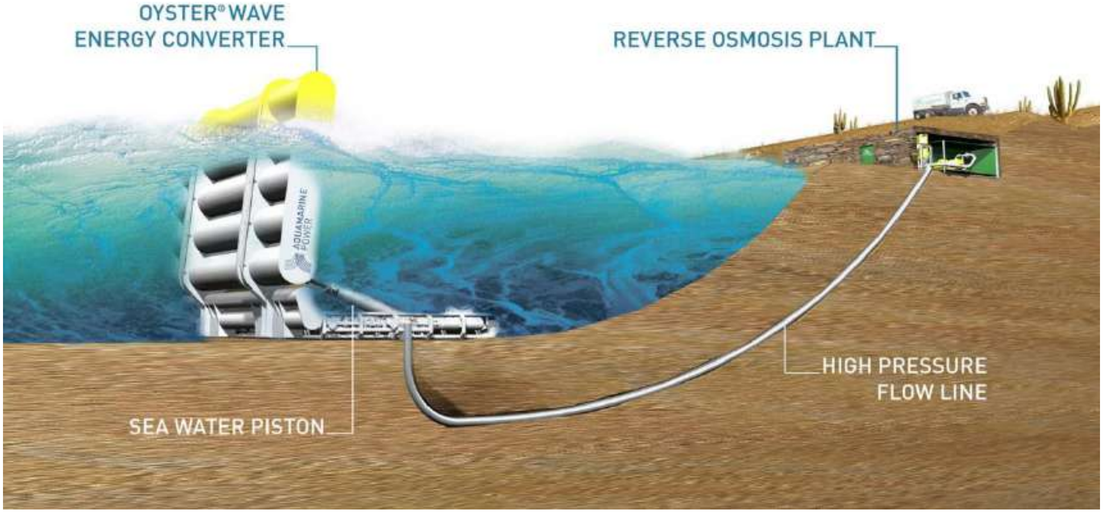

Figure 3. Oyster oscillating wave surge converter [29].

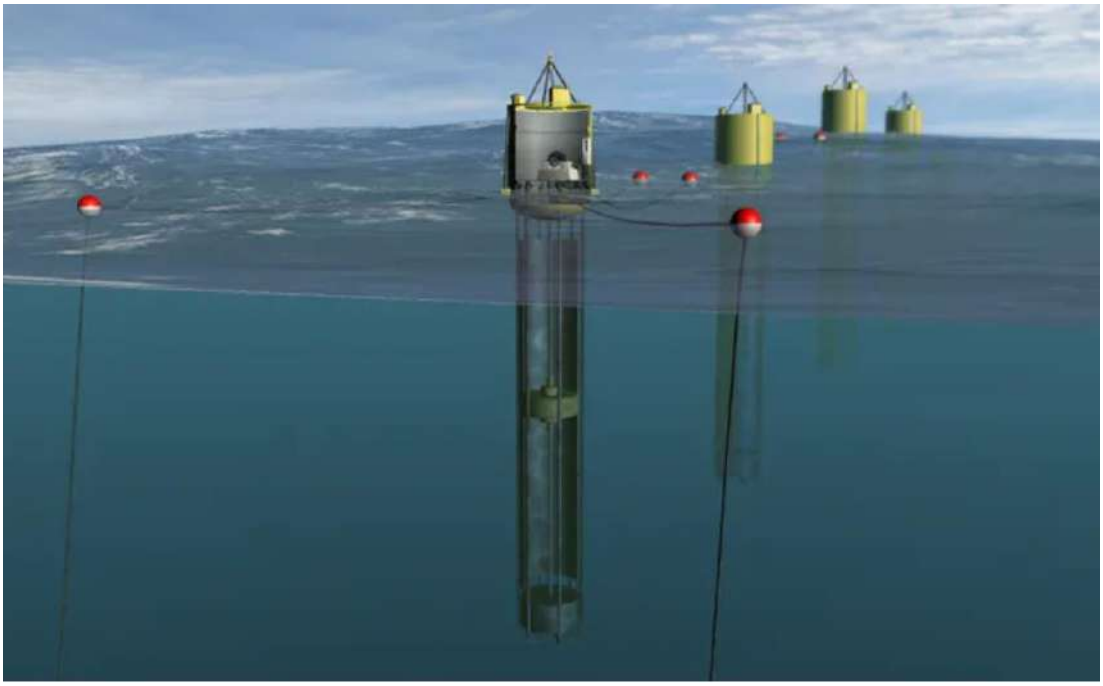

Figure 4. AquaBuOY point absorber devices [26].

WaveStar has a fixed support structure with an array of heaving floats (Figure 5). Its power take-off is based on hydraulic actuators, as described by Hansen *et al.* [30].

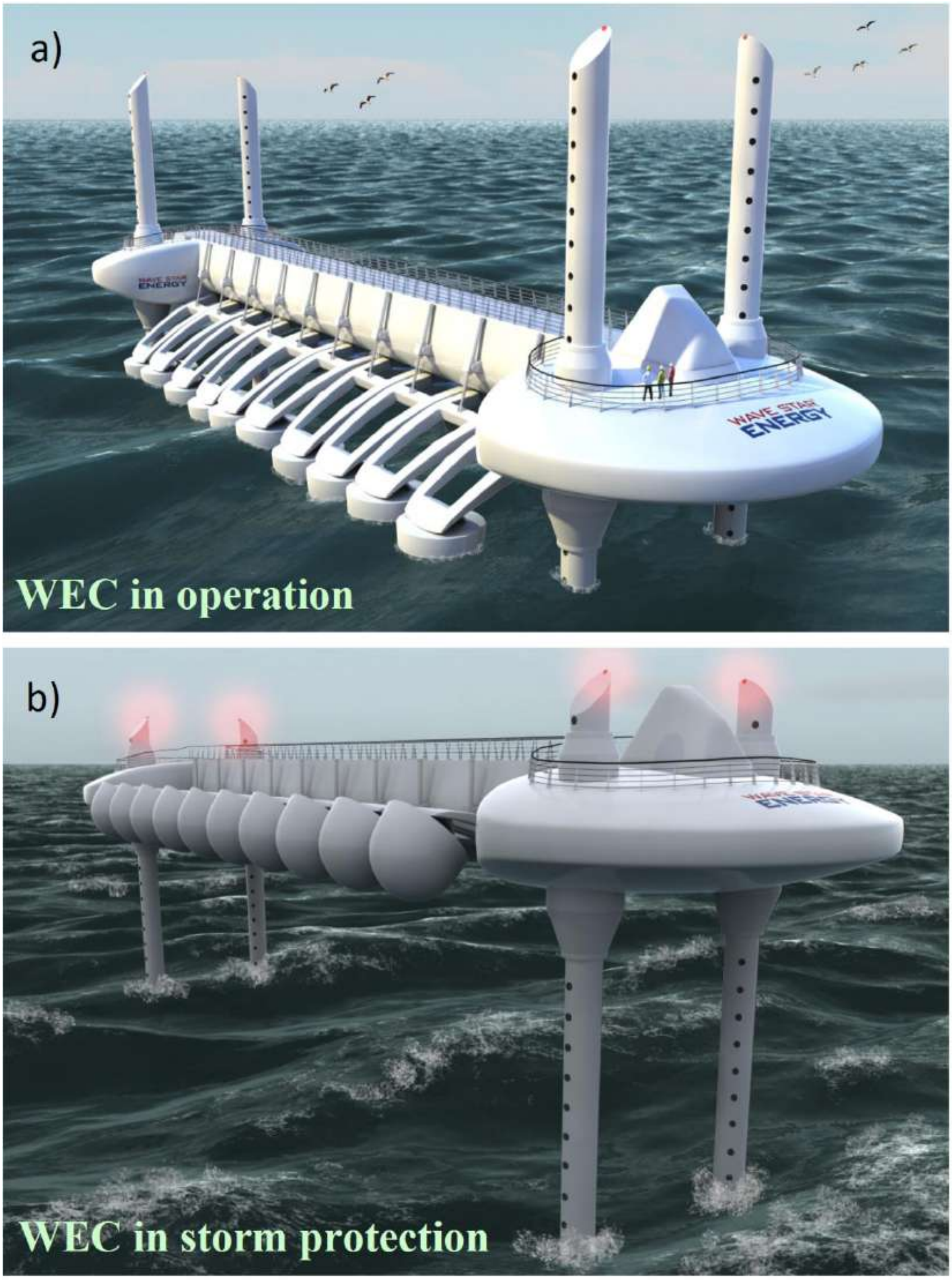

Figure 5. WaveStar point absorber converter [31].

The overtopping devices have a curved ramp where the incoming waves propagate until they drop vertically into a reservoir. The stored water is drained through conduits, where hydraulic turbines transform the kinetic energy into electricity. Several WEC designs using the overtopping principle have been proposed, such as the WaveDragon (Figure 6) [32].

Figure 6. The WaveDragon overtopping device [33].

An oscillating water column (OWC) consists of a partially submerged structure that forms a chamber with an opening. The pressure generated by ocean waves oscillates the enclosed water and trapped air through an orifice containing a Wells turbine and generator. This turbine rotates in the same direction regardless of the airflow direction. OWCs were widely investigated in the early stage of ocean wave energy due to their easy accessibility offshore. An example of this technology is LIMPET [34] (Figure 7), with a rated capacity of 250 kW.

Figure 7. LIMPET, an oscillating water column system [34].

Terminators, these converters have the principal axis perpendicular to the incident wave direction (Figure 8). An example of this type is Salter's Duck [35], comprised of a finite number of asymmetric rotating segments facing the incoming waves to produce the output power. The work of Joao Cruz [36] shows a complete description of this converter.

Figure 8. Salter´s nodding-duck shaped bodies, performing pitch oscillation, with different phases [35].

Attenuators (also called line absorbers) are WECs with a predominant dimension aligned with the incident wave direction, such as Pelamis [37] , developed by

Pelamis Wave Power. This device is a floating converter composed of five cylindrical segments that produce energy through the relative pitching motion between them (Figure 9). A single unit of Pelamis has a rated capacity of 750 kW. Pelamis Wave Power is the most researched project yet and was the first WEC design to generate electricity for a national grid.

Figure 9. Pelamis Wave Power, an example of an attenuator device [38].

Although research, development, innovative components, and demonstration and validation in marine environments of WEC designs have led to significant progress in the technological maturity levels (TRL) and present extensive possibilities for the future energy supply [39], the wave power industry still faces significant hurdles to accelerate their viability and commercial deployment [40–42]. Some of these challenges include a lack of investors for development and generation projects, the existence of a broad diversity of prototypes that dilutes efforts, and a high levelized cost of electricity (LCoE) [43] due to the high structural installation and maintenance costs [44,45], the moderate capacity factors (CF) of current WEC technologies [16,46,47], and the lack of energy policy mechanisms [13,48] to promote wave power investment.

For wave power generation to be economically viable, the installation of arrays of multiple WECs,also called wave energy farms, has been proposed according to economies of scale [38,46,49] and to seek alternative electrical interconnection options that make the designed installed capacity viable In this context, decentralized electricity schemes (DES) match the electrical needs of WEC sites and, in addition, generate multiple benefits by empowering isolated communities without electrical connections and increasing the cost-effectiveness of renewable projects by reducing the need for costly energy storage systems, and supporting the achievement of both socio-economic and global climate ambitions [50,51]. The DES consists of an autonomous energy supply through low-capacity plants close to the consumers [52]. Thus, access to energy services can be expanded by tapping into locally available renewable energy sources [51]. In this way, wave energy can be part of a DES to provide power services near the end-user in remote areas with low load requirements. Concerning their harnessing, the selection of such electrical systems depends mainly on the TRL and technology performance level (TPL) of WEC devices and the desired installed capacity of the wave energy farms.

As investor decisions are mainly based on the economic performance of technologies, an innovative strategies are required to open up other niche markets and leverage the commercial deployment of the emerging MRE sectors [46,53]. Marine Ecoparks (MEP) are multi-purpose coupled systems that could offer a sustainable option to accelerate the viability of the pre-commercial MRE stage and leverage the development of the blue economy oriented projects in coastal areas [42,54–59]. The symbiosis and the multiple use of space makes efficient use of the available area combining industries can increase their profitability and competitiveness and optimize the management of marine space, reducing CapEx and Opex associated with shared space, infrastructure and construction, and plant operating costs [46,50,55,58,60]. MEPs coupled with WEC arrays, seawater desalination, and marine aquaculture emerge as a possible sustainable solution that could drive symbiotically boost energy, water, and food security in coastal areas [42,56–58].

The transition to clean energy requires the search for new scientific approaches that allow glimpsing the complexity of renewable energy systems [61]. Bringing together and increasing the link between the capabilities of academia, industry, and other stakeholders requires a paradigm shift in how renewable energies are conceived [48]. Complex Systems is a perspective that allows us to explore how two or more subsystems are integrated and interdependent [62]. These conceptual frameworks offer a powerful means to understand and articulate the systemic structure from a holistic perspective to ensure better functionality of the low-carbon energy system [63,64]. Such a management strategy, approached from co-management, encapsulates and regulates sectors related to government, law, and society [65]. The inclusion and monitoring of the different actors, from a local vision extrapolated to national and international levels, will generate better management and adaptability of the wave energy system in the Mexican context.

The main goal of this study is to assess the feasibility of harnessing wave energy in Baja California, one of the most energetic regions of the Mexican Pacific. For this purpose, the thesis is organized into four chapters: the first one **¡Error! No se encuentra el origen de la referencia.** introduces and contextualizes wave energy through a literature review. Chapter 2: determines the available and extractable wave power in a Baja California region and analyzes electricity generation with WECs in a decentralized energy scheme. Chapter 3: evaluates the techno-economic feasibility of 0.5 MW Marine Eco-parks (MEPs) as marine clusters driven by WEC farms to energize a blue economy, including sub-modules of seawater desalination and marine aquaculture. Finally, Chapter 4:, with a systemic perspective, identifies the different actors, interactions, emergent properties, and processes that would potentially constitute wave energy system in the Mexican context.

Most of the information presented in this paper is found in several published articles or at some stage of the publication process: [17,59,66].

Chapter 2: WAVE ENERGY RESOURCE HARNESSING ASSESSMENT IN A SUBTROPICAL COASTAL REGION OF THE PACIFIC

Most Wave Energy Converters (WECs) are designed to operate in high-latitude energetic seas, limiting their performance in regions usually dominated by milder conditions. The present study assesses the performance of complete test-stage WECs in farms that satisfy a decentralized Energy Scheme (DES) on the coast of Baja California, which is considerate one of the most energetic region along the Mexican Pacific. A high-resolution 11-year nearshore wave hindcast was performed and validated with Acoustic Doppler Current Profilers (ADCPs) data to characterize the wave energy resource in the study area. Two hotspots were identified from the wave power climatology. In these sites, the extractive capacities of seven well-known WEC technologies were determined based on their power matrices. Finally, the power extracted by small WEC farms, with the minimum number of devices required to satisfy a DES, was estimated. The studied region has moderate wave power availability with marked seasonality and low inter-annual variability. Out of all the evaluated devices, WaveDragon extracts the highest wave power; however, Pelamis has the best performance with maximum monthly mean capacity factors up to 40%. Coupling WEC farms with storage modules or hybrid renewable systems are recommended to satisfy a continuous DES during the less energetic summer months.

Keywords: numerical wave modeling; marine renewable energy; wave energy resource; decentralized energy scheme

2.1 Introduction

Electricity is essential to the development of modern economies. The electricity sector accounts for the largest share of annual anthropogenicCO_2 emissions from fossil fuel combustion globally. This makes it a focal point for climate change mitigation, environmental protection, and sustainable development[3].

Harnessing renewable energies to generate electricity creates new horizons regarding technological development and innovation worldwide, and is becoming a viable alternative for building resilient electrical systems that satisfy the growing energy demand of industrialized societies [67,68]. The global objective is that, by 2050, renewable energy sources satisfy 86% of energy demand [8]. To this end, various sources are being explored to produce sustainable energy. The most common are hydroelectric, biomass, wind, geothermal, and solar energy. However, marine renewable energies (MRE is an abundant and essential resource for achieving this goal [69].

There are five main MRE sources: ocean currents and tides, salinity gradients, thermal gradients, offshore wind generation, and wind and waves [14,15]. Wave energy is one of the most promising MRE sources to be exploited on a large scale due to its high energy density per unit area and the feasibility of its capture [70]. In addition, wave energy has the second highest availability among all MRE sources [71].

It is estimated that the worldwide wave energy availability is around 29,500 TWh yr^{-1} and that, on average, each wave front could transmit between 10 and 15 kWm^{-1} [72,73]. The extratropical regions of both hemispheres have the highest wave power, exceeding 60 kWm^{-1}; this decreases with latitude towards the equatorial region, where values are lower than 10 kWm^{-1} [18]. Wave power in the Mexican Pacific coast is within the resource's exploitable range, with available power of up to ~10 kWm^{-1} at least 50% of the time [14]. In particular, the Baja California peninsula has the highest wave power availability on the Mexican coast, with maximum mean values close to 20 kWm^{-1} [74].

Ocean waves carry part of the energy transferred from the atmosphere to the ocean over long distances. An advantage of wave energy is that it is predictable and flows naturally from generation areas to the coast, where it can then be harvested and transformed into electricity via wave energy converters (WECs). Its operating principle is based on oscillatory movements or pressure fluctuations under the free surface of the ocean[18]. In this way, kinetic or potential wave energy can be transformed into usable electrical energy. The WEC performances are heavily dependent on the dominant sea-state and its temporal and spatial variability [75]. The type of WEC selected depends mainly on the wave conditions, the physical characteristics of the area of interest, and the device's operating principle and associated costs[20,74].

Many studies [21–24] have shown how different WEC technologies can optimally and efficiently harvest wave energy. These can be classified by various methods, such as location, structure, principle of operation, size and orientation, and power take-off systems [45]. WEC devices are typically designed to operate in coastal regions or on the open sea [76]. Onshore and nearshore systems have the advantage of easy installation and maintenance This is because they generally do not require an underwater power cable to connect to the power grid or expensive anchors in deep waters. However, these nearshore systems usually operate under lower energy wave regimes, which may be subject to potentially dangerous loads due to wave breaking[21]. On the other hand, offshore systems are usually floating devices operating in water depths greater than 40 m [69].

However, due to different challenges, there is currently no WEC technology that is mature enough to harness the resource efficiently and reliably [45]. Some of these challenges include a lack of investors and a broad diversity of prototypes, as well as high structural installation and maintenance costs[44,45].

For power generation to be economically viable, arrays of multiple WECs –also called wave energy farms– must be installed in the marine environment [38,46,49]. The number of WECs per farm depends on at least four factors: 1) local wave conditions, 2) the technology readiness level (TRL) of the selected devices, 3) the technology performance level (TPL), and 4) the electrical marketing scheme to be supplied. It is necessary to understand the possible implications that the WEC facility could have on the coastal ecosystem to achieve sustainable development [77]. The magnitude and impact of wave energy farms depend on their design and location, as well as the incident wave conditions [78,79].

The centralized electricity system is the traditional management scheme used to transport energy that is generated at a few large power plants and then distributed to consumers. However, global economic and demographic development, as well as the lack of local electrical infrastructure (e.g., isolated non-electrified areas), have generated the need to seek innovative solutions that adapt to local needs and to ever-increasing electrical demand [80].

Decentralized energy schemes (DES) consists of an autonomous energy supply through low-capacity plants close to the consumers [52]. Thus, access to energy services can be expanded by exploiting locally available renewable energy sources [51]. In this way, wave energy can be part of a DES to provide power services near the end-user in remote areas with low load requirements. Concerning their harnessing, the selection of such electrical systems depends mainly on the TRL and TPL of the WEC devices and the desired installed capacity of the wave energy farms.

There are several DES options: systems directly connected to the distribution grid, systems where electricity production is isolated from the grid (fully decentralized), and hybrid systems where a centralized grid and a local DES coexist [51,80]. This results in new requirements for energy management and grid operation, as well as the need for responsive economic, social, political, and regulatory environments [81]. Particularly, the DES regulations in Mexico are defined for generation systems with capacities of less than 0.5 MW [82].

DES offer a wealth of environmental, economic, technical, and social advantages for consumers. The use of on-site renewable energy generates environmental benefits in terms of system efficiency and reduction of greenhouse gas emissions. By allowing energy production to be closer to the consumer, DES offers promising opportunities for project feasibility and benefits associated with capital cost-saving, due to reducing the need for transmission and distribution lines, reducing transmission and distribution inefficiencies, and creating electricity independence, flexibility, and strengthened national energy security [51,80]. The creation of MRE prosumers, such as self-consumption cooperatives, could help meet different needs in communities by promoting their resilience in the short term [83,84]. This, in turn, could generate indirect benefits that help stimulate the local economy through the integration and development of new local opportunities that improve the welfare of coastal communities with deficient or non-existent electricity in Mexico [85].

The main goal of this chapter is to assess the performance of WEC farms that satisfy a DES in the region of Todos Santos Bay (TSB) in Baja California, Mexico. For this purpose, the wave energy availability is evaluated according to the spatial and temporal variability of the resource. In addition, the extractive capacity of the WEC devices is quantified. Finally, the power extracted with WEC farms is estimated, according to a DES scheme.

2.2 Materials and Methods

The study was carried out in three stages to assess the performance of the different WEC farms with numerical wave model simulations. First, the climatology and the variability of wave power were determined (sections 2.2.2 and 2.2.3). Then, the extractive capacity of different WECs was evaluated based on their response to local wave conditions (section 2.2.4). Lastly, the wave power extracted by WEC farms that satisfy a decentralized energy scheme (section **¡Error! No se encuentra el origen de la referencia.** was estimated.

2.2.1 Study Area

Todos Santos Bay is located on the northwestern coast of the Baja California peninsula in Mexico (Figure 10). It is a semi-sheltered bay delimited by Punta San Miguel (PSM) in the North and Punta Banda (PB) in the South.

The sea state around TSB is commonly composed of different wave systems co-existingat the same time. The main sources of swells arriving at the area are the extratropical North and South Pacific regions. The North Pacific swells occurs mainly in autumn and winter, while the South Pacific swells is more energetic in summer, but occurs all year round.

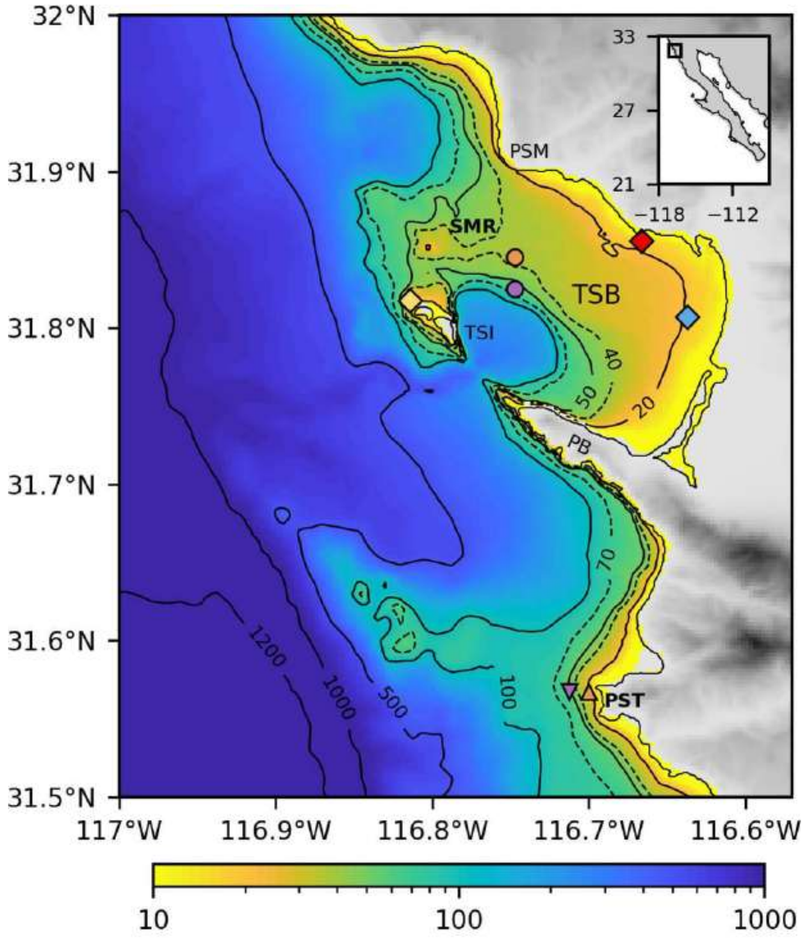

Figure 10. Bathymetry and location of the study area in the Baja California peninsula. The triangles and circles are the deep (purple) and shallow (orange) test sites in the hotspots areas of Punta Santo Tomas (PST) and San Miguel Reef (SMR), respectively. The diamonds are the ADCP measuring sites. The text legends are Punta San Miguel (PSM), Todos Santos Bay (TSB), Todos Santos Islands (TBI), and Punta Banda (PB). The solid and dashed lines are the isobaths with values expressed in meters.

Significant wave height (H_s) has a markedly annual cycle, with higher waves in winter and lower waves in summer [86]. Outside the bay, the mean H_s of the winter months is between 1.5 m and 2 m, while in summer, it decreases to values around 1

m. The mean monthly peak period (T_P) is between 13 s and 15 s. The inner section of the bay is partially protected from the South Pacific swells by the Todos Santos Islands (TSI). Within the bay, H_s is smaller than in the outer section and has a somewhat more pronounced annual cycle, with around 1.3 m in winter and 0.7 m in summer, and an overall average of about 1 m. The incidence of storms in the area increases between October and April, with a maximum H_s of 3 m to 4 m.

2.2.2 Wave Model Setup

Numerical wave simulations were performed to characterize the spatio-temporal distribution of wave characteristics and available wave power within TSB and its surroundings. The third-generation wave model SWAN Cycle IV version 41.20AB [87] was implemented in an area of 0.5° by 0.5°, from 31°30' to 32° N and from 117° to 116°30' W. The model was run in a non-stationary two-dimensional mode from January 1st, 2008 to December 31st, 2018 with hourly output data. The domain was discretized in a regular grid with a spatial resolution of 0.0025° (approximately 280 m), with an equal logarithmic spaced frequency resolution with 41 frequencies, from 0.04 Hz to 0.7 Hz, and a directional resolution of 5°.

The SWAN model was forced at the boundaries with directional waves spectra from the IOWAGA wave hindcast [88]. IOWAGA data used here are from the PACE subgrid with a 1/6° resolution and forced with global winds from the ECMWF.

The SWAN numerical results were validated using available wave data from ADCPs deployed at three locations (Figure 1) within the TSB.

2.2.3 Wave Energy Resource Assessment

The available wave power density (P), or wave energy flux, was computed from simulated directional spectra (E) as,

$$\mathrm{P} = \rho g \int\int c_g(f) E(f,\theta) df d\theta, \qquad (1)$$

where ρ is the water density of water, g is the gravitational acceleration, c_g is the group velocity, and f and θ are wave frequency and direction, respectively. The seasonal climatology was computed considering winter (January to March), spring (April to June), summer (July to September), and autumn (October to December).

Temporal variability of wave power is a relevant factor to consider when selecting WEC locations. Sites with a more regular and uniform wave power are preferable to those with highly variable wave conditions, as they might be more reliable for extraction of the energy resource. The temporal variability of wave power, at different time scales, was characterized by the coefficient of variation (CoV), the annual variability index (AVI), the seasonal (SVI) and monthly (MVI) variability indexes, computed as [89],

$$\mathrm{CoV} = \frac{\sigma_P}{\bar{P}}, \tag{2}$$

$$\mathrm{AVI} = \frac{\bar{P}_{A1} - \bar{P}_{A2}}{\bar{P}_{year}}, \tag{3}$$

$$\mathrm{SVI} = \frac{\bar{P}_{S1} - \bar{P}_{S2}}{\bar{P}_{year}}, \tag{4}$$

$$\mathrm{MVI} = \frac{\bar{P}_{M1} - \bar{P}_{M2}}{\bar{P}_{year}}, \tag{5}$$

where σ_P is the standard deviation of wave power, $\bar{P}$ is the overall average wave power, $\bar{P}_{year}$ the yearly mean available wave power; and $\bar{P}_{A1}$, $\bar{P}_{A2}$, $\bar{P}_{S1}$, $\bar{P}_{S2}$, $\bar{P}_{M1}$, $\bar{P}_{M2}$ are the mean values for the most (subindex 1) and the least (subindex 2) energetic years (subindex A), seasons (subindex S) or months (subindex M), respectively. Therefore, these indices determine which areas receive a more regular and constant wave power and which are more variable. The CoV calculates the variability concerning the mean value during the period considered and is based on hourly wave power values, which are more sensitive to extreme values. In contrast, AVI, SVI, and MVI indexes rely on annual, seasonal, and monthly averages, respectively, being more sensitive to the large time scale variability.

2.2.4 Extractable Wave Power

Seven well-known WECs with different designs and operational principles were evaluated to quantify harvestable wave energy. These were the AquaBuOY, WaveStar, Oyster315, Oyster800, WaveDragon, OWCFloating, and Pelamis [22,26,90–93]. From the point of view of their operability, these technologies cover the whole range of existing WEC types that have reached the full test stages. The first two are point absorbers, the third and fourth are oscillating wave surge converters, and the following, overtopping, oscillating water column, and attenuator devices, respectively [45]. Since the WECs are designed to operate in different water depths, two regions were defined: a shallow one (between 10 m and 40 m water depth) and a deep one (between 40 to 70 m water depth) [76]. Pelamis was designed to work optimally at depths between 50-70 m (offshore region), AquaBuOY between 20-50 m (nearshore and offshore regions). At the same time, the rest devices can be installed in shallow coastal locations (nearshore regions), generally between 10 m and 40 m water deep.

The harvestable wave power (HP) was computed as [94],

$$\mathrm{HP} = \sum \sum HR(H_s, T_p) \cdot PWEC(H_s, T_p), \tag{6}$$

where HR is the availability matrix, which represents the probability of occurrences of the different sea states expressed as a fraction from the total number of observations and $PWEC$ is the corresponding WEC power matrices, obtained from publicly available technical data of the seven devices considered [22,26,90–92].

To facilitate the comparison between WECs, their efficiencies were determined by normalizing HP with the physical width of each device [93]. Their performances were evaluated considering the fraction of time that the WECs operate at full capacity [22], according to the capacity factors (C_f) as [95].

2.2.5 Wave Power Extracted by a WEC Farms to Satisfy a DES

The harvestable wave power of different WEC farms was evaluated at the selected sites through numerical simulations of WEC arrays with the SNL-SWAN model. This spectral numerical model is a version of SWAN, developed by Sandia National Laboratories, which incorporates a module for WEC analysis and performance studies [96,97]. The number of WECs per site was chosen to get a mean generation capacity of around 0.5 MW to satisfy the regulations of a DES scheme [82].

The numerical model SNL-SWAN was implemented at the selected sites in 2 x 2 km areas with a spatial resolution of 20 m. The boundary conditions were established as the regional SWAN runs described previously. Only WaveDragon and Pelamis were considered for this analysis, as they showed the best overall performance in the selected sites. WECs were included in the model as obstacles using their corresponding $PWECs$, obtained from [22,90].

The SWAN-SNL model was run in a stationary mode using the availability matrix at the offshore boundary as a reference. A stationary run with spatially varying boundaries was made for each combination of H_s and T_p of the reference availability matrix. The boundary's spatial variability was included using its means H_s, T_p, at each node, and the directional peak (D_p) computed for the exact times as those included in the reference combination.

The model results included the wave power extracted by each WEC in the array for each stationary run. All runs performed for the same WEC farm were used to compute an *in-site* $PWEC$ matrix. The extractable power by each WEC in the array was computed using (6) replacing $PWEC$ with its corresponding *in-site* $PWEC$ and were HR is the reference availability matrix at the boundary.

2.3 Results

2.3.1 Wave Model Validation

The comparison between the observed and the modeled wave characteristic is summarized in Table 1. In general, there is good agreement between the simulations and the wave measurements at the three ADCP locations. The linear correlation coefficients are higher than 0.92 and 0.55 for H_s and T_p, respectively. The mean bias of H_s and T_p are lower than 0.1 m and 0.8 s, respectively, showing a slight over-prediction of H_s and T_p for ADCP 1 and ADCP 2, while for ADCP 3 H_s is under-predicted. The RMSE for H_s is of the order of 0.22 m and for T_p is 2.78 s. The low bias ranges and high correlation values between observed and modeled results provide confidence in our dataset.

Table 1. Comparison of modeled and observed wave characteristics at three different locations within BTS.

ADCPs	No. Observations	Wave Parameters	Bias	RMSE	SI	r
ADCP $_1$	7985	H_s	0.05 m	0.23 m	0.18	0.92
		T_p	0.25 s	2.74 s	0.22	0.63
ADCP $_2$	4557	H_s	0.11 m	0.22 m	0.25	0.95
		T_p	0.80 s	3.18 s	0.30	0.55
ADCP $_3$	26719	H_s	-0.11 m	0.23 m	0.23	0.93
		T_p	0.11 s	2.42 s	0.23	0.72

Statistical values of Bias, Root mean square error (RMSE), Scatter index (SI), and linear correlation coefficient (r) from the comparison of the numerical results and observations when estimating the integral parameters of the wave energy, H_s in meters and T_p in seconds, for the three different ADCP locations within BTS.

Figure 11 shows a scatter diagram of observed and simulated comparisons of H_s at the three ADCP locations. Relatively satisfactory agreement between simulations and measurements is observed. There is a good representation of the most common swell arriving at the area with H_s between 0.75 and 1.25 m ranges for ADCP 1 (**¡Error! No se encuentra el origen de la referencia.**a), 0.5–0.8 m for ADCP 2 (**¡Error! No se encuentra el origen de la referencia.**b) and 0.5–1.2 m for ADCP 3 (**¡Error! No se encuentra el origen de la referencia.**c). ADCP 3 has the best correlation of the most common waves in the area where the highest H_s percentages align along the line of perfect agreement (black line in **¡Error! No se encuentra el origen de la referencia.**), whereas in ADCP 1 and ADCP 2, the most common waves are slightly overestimated by the model. The best representation of extreme values occurs at ADCP 1, while extreme values at ADCP 2 and ADCP 3 are overestimated and underestimated by the wave hindcast, respectively.

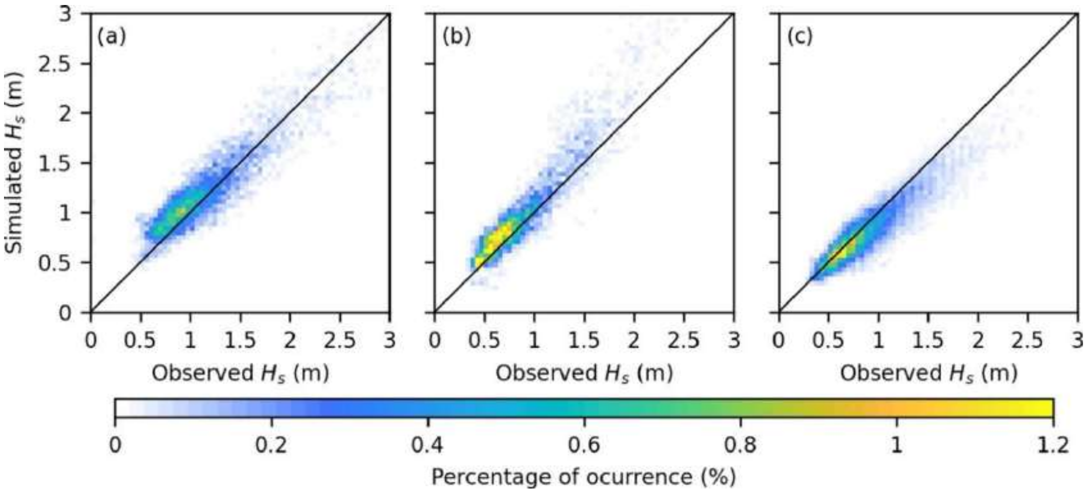

Figure 11. Comparison of the significant wave height (H_s) simulated and observed at ADCP 1 (a), ADCP 2 (b) and ADCP 3 (c) measuring locations.

2.3.2 Wave Power Available

The mean wave power and the coefficient of variation in the study area are shown in Figure 12a and Figure 12b, respectively. The region has a moderate $\bar{P}$ (Figure 12a) with an average value close to 10 kWm^{-1}. The $\bar{P}$ varies spatially, with higher values outside than inside TSB. Outside the bay, the $\bar{P}$ is around 12 kWm^{-1} and increases from north to south; with a maximum of 14 kWm^{-1} in the southern region, where the 10 kWm^{-1} isoline is found closer to shore than in the northern region. The PST is the site outside of TSB with the highest $\bar{P}$ of the study area occurs at PST, outside the TSB, with values between 13 kWm^{-1} and 15 kWm^{-1}. Within the bay, the $\bar{P}$ is around 8 kWm^{-1} increasing from south to north, with a range of values from 5 kWm^{-1} to 11 kWm^{-1}. The SMR is the TSB site with the highest $\bar{P}$, with values of 11 kWm^{-1} for shallow and 9 kWm^{-1} for deep locations. As shown in **¡Error! No se encuentra el origen de la referencia.**b, the domain shows a CoV trend similar to the $\bar{P}$ availability; with a marked average temporal variability of wave power close to 1.15. Outside the TSB, both the northern and southern regions have the highest CoV values, close to 1.2. Particularly at the PST site, the shallow and deep locations have values of 1.2 and 1.17, respectively. Within the TSB, the northern region has a 50% higher $\bar{P}$ variability than the southern region, with the highest CoV value observed at the SMR site of 1.35. On this site, the shallow and deep locations have CoV values of 1.48 and 1.22, respectively.

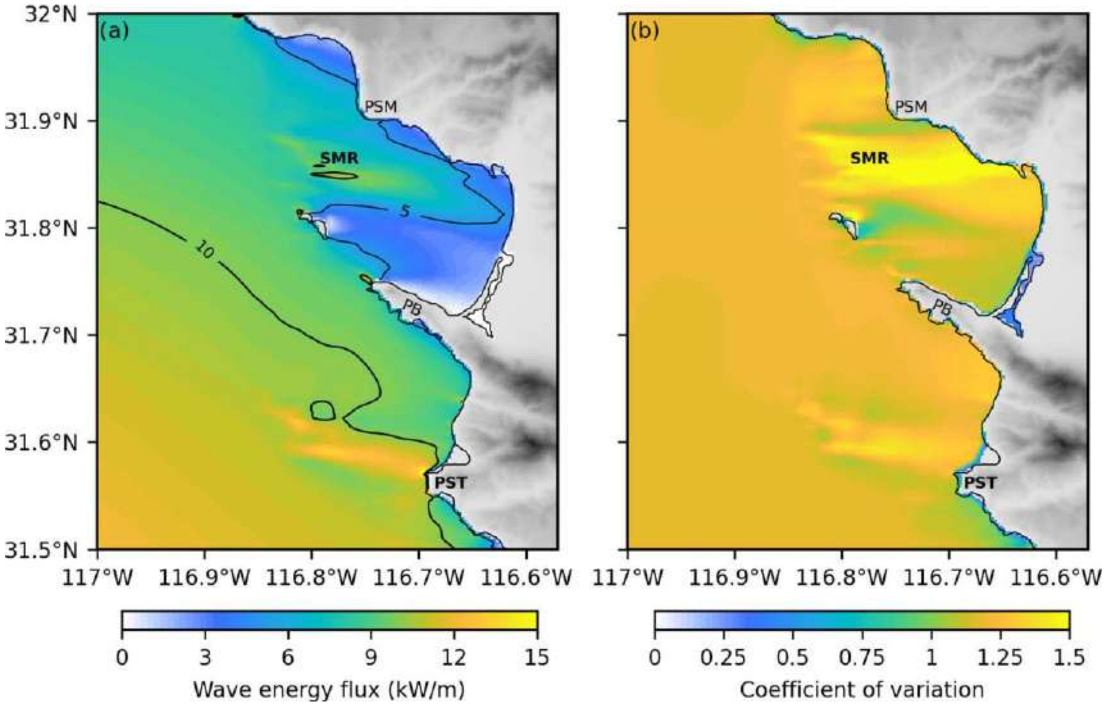

Figure 12. Mean available wave power (a) and CoV (b) over the full hindcast period. The selected sites, Punta Santo Tomas (PST) and San Miguel Reef (SMR), are in bold. The solid black lines in panel a represent wave power isolines, expressed in kWm^{-1}.

PST and SMR are the best sites to harvest wave power in terms of resource availability. The HR of their respective locations are presented in Figure 13. All test sites show a similar pattern of wave occurrence, with a higher range of T_p than H_s, from 4.5 s to 19.5 s and 0.5 m to 3.75 m, respectively. The most common wave power concentrates between H_s of 0.75 m and 1.5 m and T_p of 10 s and 16 s. Two wave trains are distinguished. The first train is related to short waves with a lower HR, H_s ranges of 0.75—1.5 m and T_p of 4.5—12 s. The second train is a long waves with H_s between 0.5 and 1.75 m and a T_p of 9 to 18 s. The outer TSB locations (Figure 13c,d) have higher wave power ranges (isolines of 5 to 20 kWm^{-1}) than the inner locations (Figure 13a,b), with values from 2 to 11 kWm^{-1}. In addition, locations outside TSB show a higher H_s range and frequency of extreme wave power events (H_s > 3 m and wave power > 50 kWm^{-1}) than inner TSB locations. Both deep and shallow SMR locations show a higher HR in the range of H_s 0.75—1 m and T_p 12—14 s than the PST locations. The PST and SMR shallow locations present the highest and lowest dispersion of peak energy, respectively, with a maximum energy concentration with H_s 0.75-1 m and T_p 12.5 s.

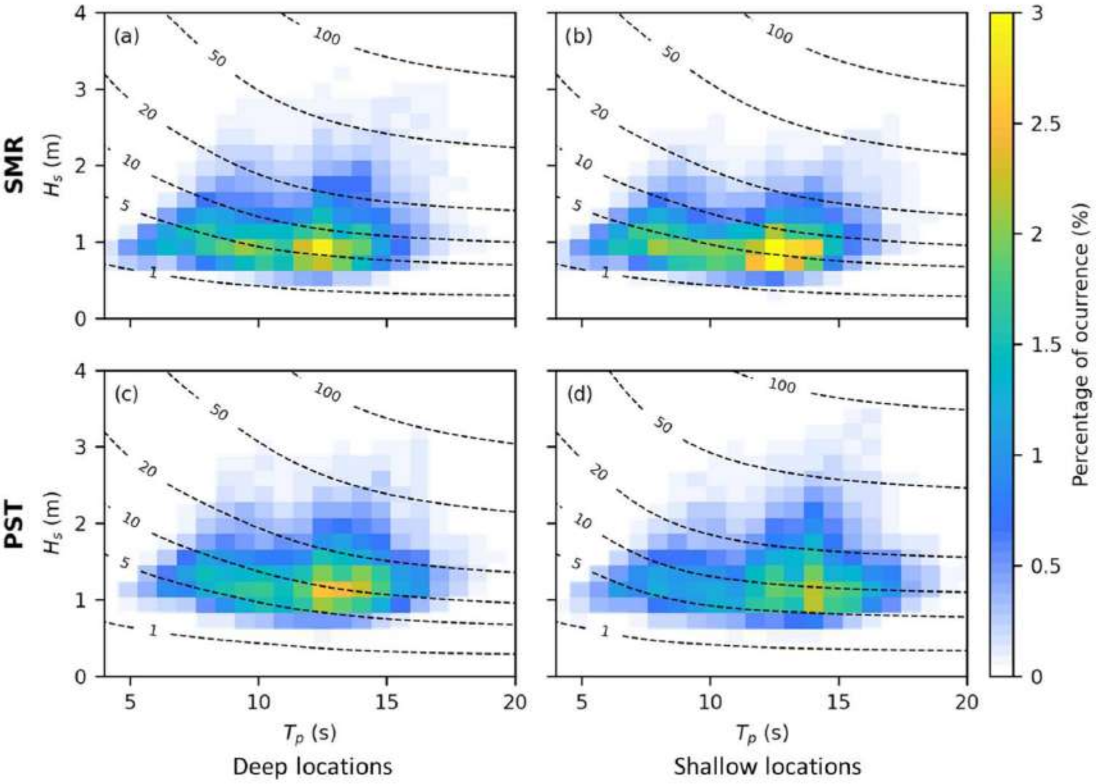

Figure 13. Joint distribution of significant wave height H_s and peak period T_p at the deep (a and c) and shallow (b and d) locations of the hotspots in PST (c and d) and SMR (a and b). The color bar represents the percentage of HR, colored by the total wave power contribution, for each sea state. The dashed lines are isolines of constant wave power in kWm^{-1}.

The seasonal mean wave power availability is presented in Figure 14. A marked seasonal trend can be observed, with maximum $\bar{P}$ during the winter and minimum during summer. A $\bar{P}$ about three times higher is observed during winter (16 kWm^{-1}, Figure 14a) than in summer (5.3 kWm^{-1}, Figure 14c). The spring and fall times have an intermediate $\bar{P}$ availability between winter and summer, with spring being higher (10.5 kWm^{-1}, Figure 14b) than fall (7.5 kWm^{-1}, Figure 14d). During all seasons, higher $\bar{P}$ availability occurs outside TSB. In winter, the PST site presents the highest resource availability, with a maximum mean value close to 25 kWm^{-1}, while the SMR site shows a maximum mean of 17.5 kWm^{-1}.

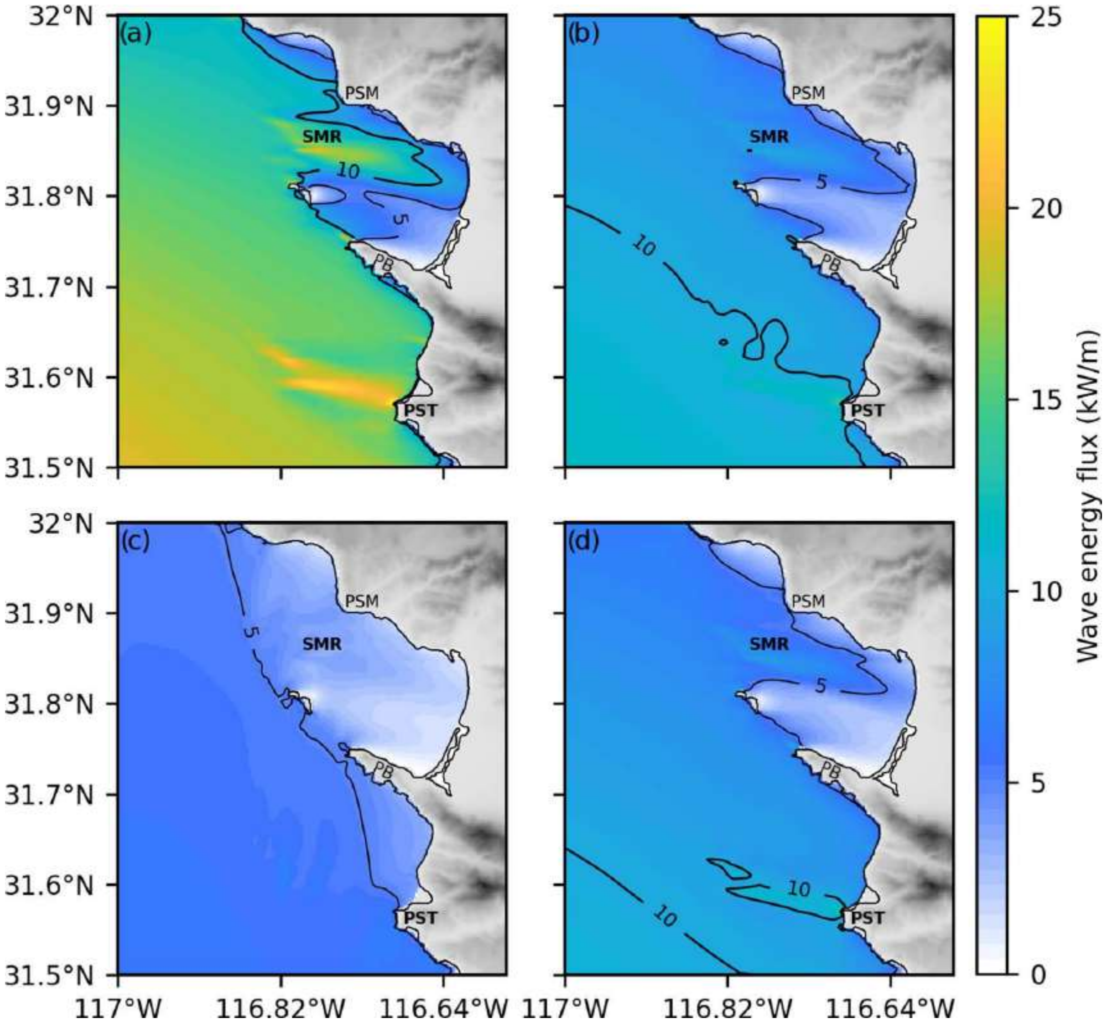

Figure 14. Seasonal mean wave power for the 2008-2018 period. Panel (a) winter season (January to March), (b) spring season (April to June), (c) summer season (July to September), and (d) fall season (October to December). San Miguel Reef (SMR) and Punta Santo Tomas (PST) sites are indicated in bold. The solid lines represent the 5 and 10 kWm^{-1} isolines.

Table 2. $\bar{P}$ and variability indeces at sallow and deep locations of PST and SMR sites. presents the overall mean wave power and its variability indices for the selected sites. The PST site has, on average, a 40 % higher $\bar{P}$ than the SMR site. The PST deep location is 15.3% more energetic than the shallow one, while the SMR shallow location is 22.2% more energetic than the deep one. When comparing the shallow and deep locations between sites, the four variability indices are lower at the PST than at

SMR sites. In addition, the deep PST location has the lowest values of the four indices quantified, while the shallow SMR location has the highest value. Both sites presented smaller values of AVI, followed by CoV, SVI, and MVI.

Table 2. $\bar{P}$ and variability indeces at sallow and deep locations of PST and SMR sites.

	PST		SMR	
	Shallow	Deep	Shallow	Deep
$\bar{P}$	13	15	11	9
CoV	1.2	1.17	1.48	1.22
AVI	0.6	0.58	0.66	0.59
SVI	2.2	2.08	2.9	2.16
MVI	3.74	3.55	5.01	3.61

$\bar{P}$ in kWm^{-1}. CoV, MVI, SVI, and AVI are the coefficient of variation and the annual, seasonal, and monthly variability indexes, respectively.

2.3.3 Wave Power Harvestable

The mean monthly wave power harvested with the analyzed WECs shows a marked seasonality at both selected sites, with the highest extractive capacities during winter and the lowest in summer (Figure 15. Monthly mean power harvested by the analyzed WECs at the deep (a and c) and shallow (b and d) locations of the PST (c and d) and SMR (a and b) sites.). Outside TSB, at the PST site (Figure 15c,d), the WEC devices show a higher wave power extraction capacity than inside the bay at the SMR site (Figure 15a,b). Furthermore, among all the evaluated devices, Pelamis and WaveDragon harvest the greatest wave power at the deep and shallow locations, respectively, of both hotspot sites. At the PST site, the maximum mean monthly wave power extracted by Pelamis is 216.4 kW in April. There, twice as much wave power is extracted in winter as in summer. At the SMR site, the maximum wave power harvest with Pelamis occurs in February (155.4 kW), with four times more extraction capacity in winter than in summer. The WaveDragon device extracts a higher mean wave power at the PST site equal to 375 kW, and the SMR site of 204 kW. The PST site has 2.6 times more extraction capacity in winter than in summer, with a maximum in January, while the SMR site presents an inter-seasonal ratio of 3.1, with a maximum in February.

In terms of its performance, Pelamis has an average monthly capacity factor of 28.9% at the PST site, with a maximum C_f of 40.6% and a difference of 18.3% between the winter and summer seasons. While at the SMR site it is 20.7% and 23.6%, respectively. In contrast, WaveDragon has a lower capacity factor at both sites with a mean monthly C_f value of 5.4%, maximum of 8.3%, and a seasonal C_f difference of 4.9% for the PST site. At the SMR site it is 2.9%, 4.4%, and 2.9%, respectively.

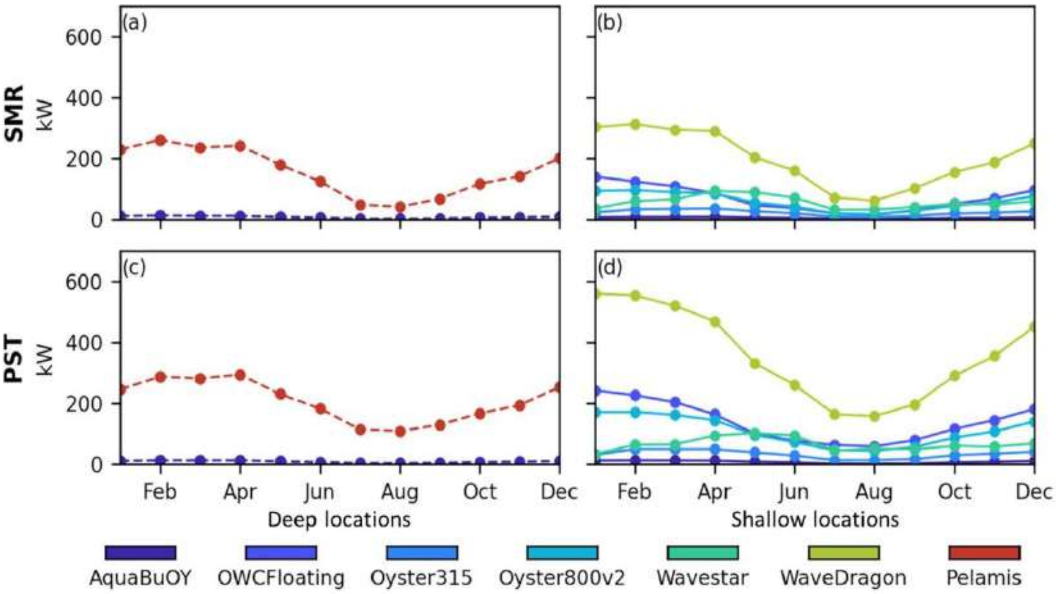

Figure 15. Monthly mean power harvested by the analyzed WECs at the deep (a and c) and shallow (b and d) locations of the PST (c and d) and SMR (a and b) sites.

Figure 16 shows the mean efficiency of Pelamis (a) and WaveDragon (b) throughout the studied region. In this analysis we focus on Pelamis and WaveDragon because they have the highest extractive capacities in the region. As expected, both devices have a higher extractive capacity at the PST site compared to the SMR. Pelamis is 40% more efficient at the PST site than at SMR, while WaveDragon is 82%. In turn, Pelamis is 10.4 times more efficient than WaveDragon at the PST site and 13.7 at the SMR.

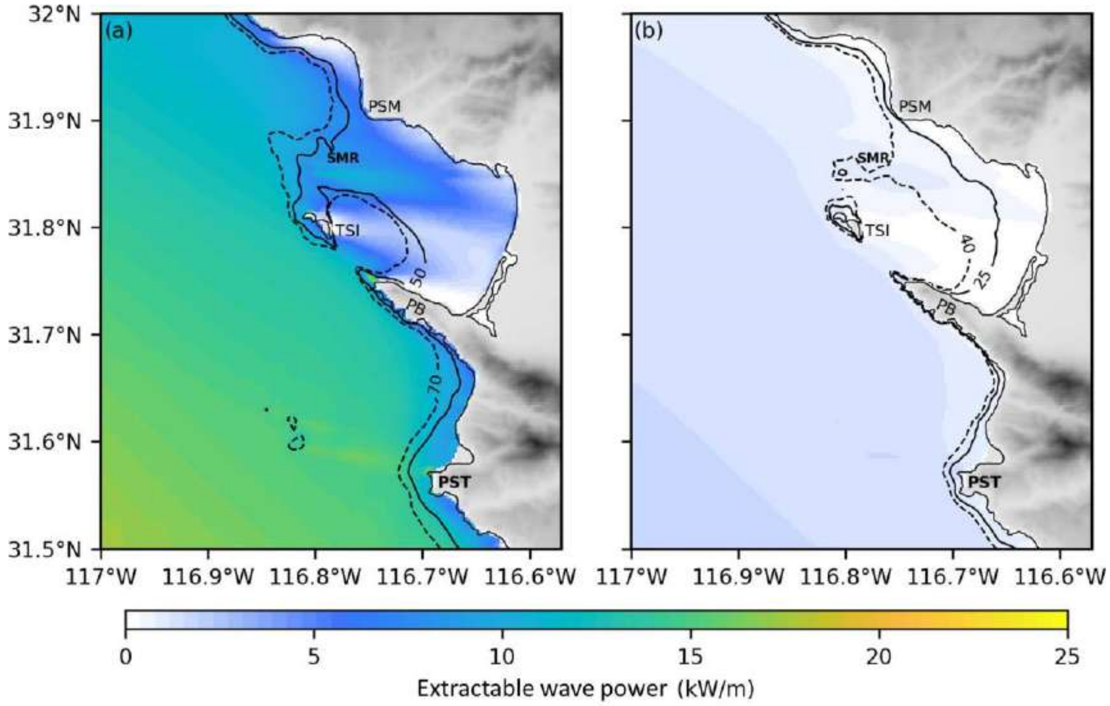

Figure 16. Mean efficiency of Pelamis (a) and WaveDragon (b), in terms of the wave power extracted by their respective dimensional widths. Punta Santo Tomas (PST) and San Miguel Reef (SMR) sites are indicated in bold. The solid and dashed lines represent isobaths in meters; the area between isobaths is the area with the optimal operating depth range for each WEC.

2.3.4 Wave Power Extracted by WEC Farms Based on a Decentralized Energy Scheme

From previous results, it was determined that to satisfice the regulations of the Decentralized Energy Scheme in Mexico, at the PST site a WEC farm should be composed of two Pelamis or one WaveDragon, while at the SMR site WEC arrays should have four Pelamis or two WaveDragons.

The monthly climatology of wave power extracted by the minimum number of WECs required to satisfy a DES at the SMR and PST sites is shown in Figure 17. At the PST site, the mean monthly wave power harvested by two Pelamis arrays is 0.5 MW, while a single WaveDragon device produces 0.62 MW. At the SMR site, four Pelamis arrays extract a mean wave power of 0.59 MW, and two WaveDragon arrays harvest 0.78 MW. The extractive capacity of the WEC farms presents a marked seasonality, higher in winter than in summer, which is a consequence of the seasonality of the available wave power. The PST site has lower intra-annual wave power extraction variability than the SMR site. At the PST site, the Pelamis device extracts 148% more power during winter than in summer and WaveDragon 79%. While at the SMR site, the difference is about 181% for the Pelamis device and 73% for WaveDragon.

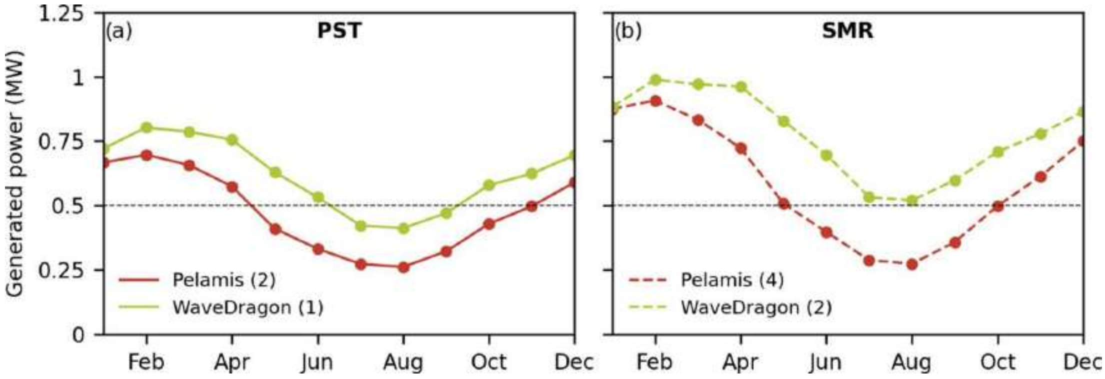

Figure 17. Monthly mean power extracted by a WEC arrays at the PST (a) and SMR (b) sites, based on a DES. The number of devices used in each array is shown in parenthesis. The dashed line of 0.5 MW represents the generation capacity required to satisfy a DES.

2.4 Discussion

In the study area, the wave power availability (Figure 12a) has values close to 10 kWm^{-1}, the minimum needed for commercial-scale wave energy projects [97]. The computed $\bar{P}$ availability agrees with the values reported by Ahn et al. [98] for southern California. The moderate wave power of the region is mainly due to its geolocation and the shadowing effect generated by the Southern California Bight (SCB), the California Channel Islands, and the Coronado Islands of Baja California over the incoming swell from the extratropical North Pacific. The highest $\bar{P}$ values in the southern area, outside the TSB, are due to the more exposed shoreline to rougher sea conditions. These increase from south to north because of the effect of the SCB and the groups of islands on the incoming swell. The lower $\bar{P}$ values inside the TSB are associated with the shadowing effect produced by Todos Santos Island. The high wave power that occurs in the PST and SMR hotspots are the result of bathymetric irregularities. These induce refraction processes that cause convergence of orthogonal wave rays in caustic zones where wave energy is focused, resulting in localized amplification of wave energy and power [99,100]. In the PST, wave focusing is associated with the presence of an offshore shallow ridge and a headland, whereas at the SMR site, it occurs in the leeward side of the offshore reef. The high-resolution bathymetry used in the wave model at a local scale of approximately 280 m allows to observing coastal formations that induce wave processes and characterize the specific locations where wave energy is focused. The wave power observed outside the TSB is in substantial agreement with those described by Hernández-Fontes et al. [14], who reported an available $\bar{P}$ between 10-20 kWm^{-1} in northwestern Baja California offshore waters. It is worth mentioning that their estimate was computed with a global wave model with a spatial resolution of 1/8° and, therefore, does not include the wave power spatial variability induced by bathymetric features smaller than 10 km, which are very important in coastal areas, as observed in the present work.

Regarding resource persistence, in agreement with Guillou et al. [101], the most energetic PST and SMR sites are characterized by higher CoV values than the rest of the analyzed domain (Figure 12b), which generates a marked variability of the wave power that may affect the extractive capacity and performance of the WECs. Due to the focusing effect of the wave energy, the CoV will be higher at those sites than in the surrounding environment where no focusing effect occurs. However, although the SMR site has lower $\bar{P}$ than the PST site, the SMR shallow has the highest CoV value in the domain (Table 2). This is associated with the combination of lower $\bar{P}$ within TSB than in the rest of the area and the focusing effect induced by the offshore reef in the SMR site as the PST site. The lower temporal variability of $\bar{P}$ within TSB is associated with the shading effect generated by TSI. Thus, the southern region of TSB has a lower and more constant $\bar{P}$ than the northern region of TSB.

The wave characterization in the TSB area by Ruiz de Alegría-Arzaburu et al. [86] is consistent with the results of the joint distribution diagrams (**¡Error! No se encuentra el origen de la referencia.**). The presence of short wave trains is associated with local wave generation and the long wave trains are related to the occurrence of swell arriving from extratropical regions. As expected, the PST site (Figure 13c,d) has more occurrences of higher waves than the SMR site (Figure 5 4a,b). This is because the PST site is in a relatively more exposed area, and the shadow effect generated by TSI over the TSB site.

The seasonal wave regime that predominates in this area has a yearly trend with higher wave power during the winter due to the presence of North Pacific swells and low wave power during summer when the sea state is dominated by swell originated from the extratropical South Pacific region [102,103]. This marked seasonal trend of the wave resource could affect the WEC performances, resulting in low long-term capacity factors [104].

The PST and SMR locations has a mean wave power higher than 10 kWm^{-1} with higher values at the PST site than at the SMR site (Figure 12a), making them suitable for energy extraction [97]. Although, in a global context, the PST and SMR locations have a moderate resource availability, its seasonal variability is lower than that observed north of the studied area, in the U.S. Pacific Northwest coastal regions [98]. Thus, the identified hotspots provide a relatively more consistent energy supply that might enhance opportunities for wave energy extraction. However, both PST and BSM sites have CoV values close to or above 1.2, indicating a significant variability [105,106], and reflects the occurrence of extreme wave power values [101] in the area which are enhanced at PST and SMR due to wave energy focusing. Low AVI values indicate low inter-annual resource variability and relative regularity in the total $\bar{P}$ extracted between years at the selected sites [98]. However, the high SVI values and, to a greater extent, VMI denote a high monthly and intra-annual $\bar{P}$ variability and reflect the sensitivity of wave characteristics to these longer time scales [101]. Based on variability indices, the deep PST location has the most regular $\bar{P}$. In contrast, the shallow location of the SMR has the highest variability indices, indicating higher variability of the resource at all time scales.

The mean extracted power shows a clear seasonal pattern, higher in winter and lower in summer (Figure 15) that reflects the bimodal nature of the wave energy annual cycle in the study area. Although the wave resource has a higher variability at SMR than the PST site (Table 2), in general, the mean monthly extracted wave power of all evaluated WECs varies in a smaller range at the SMR site than at the PST site (Figure 15). This is associated with higher resource availability and the WECs specific extractive capacity at the PST site during the more energetic winter months. Among all the WEC evaluated, Pelamis and WaveDragon devices developed the highest extractive capacity at the two selected sites (Figure 15), due to a better response of these devices to the local wave conditions. Likewise, the highest wave power extracted by Pelamis at the PST site is generated in April (Figure 15c) and not during the most energetic months of winter (Figure 14a), as would be expected.

As well as the extractive capacity, the WEC capacity factors follow the evolution of the available wave power (not shown). It has been pointed out, that the inter-annual variability of the resource can induce changes in the C_f between different years [95]. However, the studied region has a low inter-annual resource variability (Table 2); thus, WEC performances are expected to have relatively low fluctuations between the years considered. Although WaveDragon appears to be the most attractive technology for deployment because it generates the highest mean extracted wave power (Figure 15), Pelamis has more than ten times higher efficiency at the PST and SMR sites (Figure 16). Despite the reduced WaveDragon efficiency, it has a more consistent C_f between the winter and summer seasons than Pelamis, which could be of interest to reduce the electricity intermittency generated at both selected sites. This demonstrates the need to continue the design and adaptation of new generations of WECs that are more efficient under moderate wave conditions [16].

To contextualize the results obtained with other regions of potential interest, Table 3 presents a comparative summary of the wave resource availability and the productivity (expressed in their performances) of Pelamis and WaveDragon. C_f is used as a measure of the technical feasibility for deployment of WECs [101]. at three regions with different $\bar{P}$: the Aegean Sea (Greek region, GR), British Columbia (Canada, CAN), and western Brittany (France, FR) [90,95,107]. It can be observed that, despite the fact that the selected sites in Baja California possess lower $\bar{P}$ than the Canadian and French regions, Pelamis has higher C_f values than the rest of the analyzed regions. This may be associated with greater intra-annual, seasonal and monthly variability at GR, CAN, and FR. This is related to an improved use of the Pelamis device, in terms of energy production, in PST and SMR. In contrast, it can be observed that, regardless of $\bar{P}$, WaveDragon has a higher C_f in GR, CAN, and FR, as compared with the selected sites in Baja California. This demonstrates that WaveDragon is an unsuitable technology to be implemented in the study area. It is a device designed to extract power from highly energetic swell, which reduces its performance in regions with moderate resources. From a technical perspective, the high C_f of Pelamis in the study area, especially at the PST site, denote greater adaptability of this technology to the local climatology than in other analyzed regions. This creates an opportunity area for installing Pelamis devices to harness wave energy in the Baja California peninsula.

Table 3. Wave resource availability and productivity generated individually by Pelamis and WaveDragon in Baja California and other well-known places in the world.

WECs	Sites						
	Baja California Study Site				Other Places in the World		
	PST		SMR				
	$\bar{P}$	C_f	$\bar{P}$	C_f	$\bar{P}$	C_f	$Ref.$
Pelamis	15	28.9	9	20.7	10.1	11.3	GR [90]
					12.3	16.3	CAN [107]
					24.6	14.1	FR [95]
WaveDragon	13	5.4	11	2.9	10.1	13.2	GR [90]
					12.3	23.9	CAN [107]
					17.9	25.2	FR [95]

Pelamis and WaveDragon are the selected WECs. $\bar{P}$ is the average wave power in kWm^{-1}, C_f is the capacity factor in %, and $Ref.$ are the references of the well-known places in the world.

Although a complete analysis of techno-economic feasibility is beyond the scope of this chapter, a preliminary economic comparison between WECs can inferred using C_f as a proxy for the Levelized Cost of Energy (LCoE) [101]. The LCoE relates the total project cost capital expenditures (CapEx, such as cost of construction, mooring lines, underwater and underground power cable, electrical substation) and operating and maintenance (OpEx) (expressed in \$/MWh), and annual energy production (AEP), all values being expressed in present values [47]. Since the annual energy production is a major parameter that determines the LCoE behavior and, in turn, is related to it, it can be inferred that the devices most adapted to the local climatology (generates higher productivity) will be those that obtain lower LCOE [16]. Therefore, considering cost capital expenditures and OpEx of similar ranges between devices and sites, it can be preliminarily determined that the Pelamis device will generate the lowest LCoE values in the selected sites. However, it is recommended to strengthen the analysis with techno-economic feasibility studies that include CapEx and OpEx, adapted to local needs and conditions, to continue promoting the opportunity to install Pelamis devices to harness wave energy in the Baja California peninsula. However, future robust techno-economic feasibility studies that include CapEx and OpEx, adapted to local needs and conditions, are recommended.

Ensuring the leap to commercial scale and higher penetrability in the domestic electricity market requires that the techno-economic feasibility of WEC projects be addressed equally in terms of their commercial readiness and economic viability [48]. Innovation and adaptation of WECs to local wave climatology (higher TPL) will generate a higher stage of development (higher TRL). Achieving project commercialization will lead to a reduction in associated costs and LCOE [47]. Consequently, wave energy will experience a higher level of competition and inclusion within the Electricity Market that will be reflected by a higher installed capacity within the national renewable pool. Public policies are a crucial instrument to meet the requirements of stakeholders [108].

In terms of resource availability, the WEC arrays must be configured with a higher number of devices at the SMR site than at the PST to supply energy through a DES (Figure 17). Also, in terms of extractive capacity developed per device (Figure 15), WEC farms are composed of a higher number of Pelamis devices than WaveDragon. This could be an economic advantage for WaveDragon farms, as fewer devices are needed to satisfy the same range of electrical demand however, we are not considering the cost of each device nor the operational costs which are different for WaveDragon and Pelamis. In addition, the placement of nearshore devices, such as WaveDragon, generates a cost reduction associated with a shorter length of underwater transmission cables required for interconnection with the local power grid [94].

The low-moderate extractive capacity developed by individual devices (see Figure 15) or WEC farms (see Figure 17) creates the need to look for alternative electrical schemes that allow greater technical-economic feasibility for the electrical supply in Baja California. Opting for the traditional centralized system requires further scaling up and increasing the installed capacity of the WEC farms and a more robust local power grid [109,110]. While this could reduce the cost of electricity generation over its lifetime, it would also be associated with increased investment expenditures (requiring a higher number of WECs per farm) and high electrical infrastructure investment in off-grid areas [111,112]. In addition, the increase in production could exceed the local demand required during the winter months of higher wave energy availability, while the summer months would also generate a low electricity supply due to the low availability of the resource [113]. Therefore, the DES requirements in Mexico are an attractive option for WEC farms, with small-scale installed capacities (less than 0.5 MW), to satisfy the electricity needs in the coastal zone [82,108].

As shown in Figure 17 and the AVI (Table 2), the expected electrical power to be supplied by each WEC farm is less variable at the PST site than at the SMR. However, the seasonal variability of wave power may generate problems in supplying consistent ability to operate smoothly and safely in the local power grids [114].

As can be seen in Figure 17, for the DES generation capacity of 0.5 MW, the Pelamis farm at the PST site extracts an average power surplus equal to 0.22 MW in winter and a power deficiency of 0.21 MW in summer. In comparison, the SMR site extracts a mean power surplus of 0.37 MW in winter and a deficit of 0.19 MW in summer. The WaveDragon at the PST and SMR sites extracts a mean wave power surplus equal to 0.27 MW and 0.45 MW respectively during the winter season, while the PST site only has a power deficiency equal to 0.07 MW during summer. Exceeding 0.5 MW of power on a high percentage of days may indicate that it is more appropriate for WEC farms to require another electricity scheme, such as the Wholesale Electricity Market that accepts plants from 0.5MW and above [110]. On the other hand, if the average daily generation is well below 0.5 MW, it will be a relevant factor in determining other sites for WEC farms. Coupling WECs with hybrid systems using conventional renewable energy sources and including energy storage support could be suitable complements to meet a constant electricity supply all year long [115]. This would provide greater flexibility to the power system and help to increase the economic feasibility of the WEC farm project [116–119]. It is worth noting that the extracted power with the WEC farms computed here does not consider the electrical losses due to transmission nor the electrical consumption of the farm facilities. It is recommended in future works to include in the analysis the daily and seasonal demand profile of the selected sites to strengthen the demand side management.

Regarding the energy needs of the selected sites, the PST rural area lacks grid interconnection, while the SMR site is relatively close to an electrical substation in the city [112,113]. Thus, the PST site has greater electrical infrastructure deficiencies and needs than the BSM area. Therefore the deployment of a DES projects could generate more noticeable benefits at the PST site than at SMR. The development of wave energy prosumer enterprises, through a DES scheme, could meet the energy needs of the PST site and, in turn, foster the development of new local opportunities that would improve the welfare of this remote coastal community [42,120,121]. However, in the absence of a robust power grid, the construction of new transmission lines in the PST area can be costly and plagued by siting issues and delays. BSM, on the other hand, could take advantage of existing power lines, which would reduce associated capital costs. In addition, DES deployment could guarantee power supply at both sites when the conventional power grid goes down.

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According to the wave power extracted by the different WEC farms (Figure 17), the Pelamis device could satisfy a daily energy demand of approximately 93 households (313 people) at the PST site and 114 houses (383 people) at the SMR site. WaveDragon could support the electrical needs of 120 homes (405 people) at the PST site and 151 households (509 people) at the SMR site considering an average daily consumption of 4.05 kWh and 3.4 persons per household in the city of Ensenada, Baja California [113].

Local autonomy efforts are related to active community participation [51]. Therefore, energy autonomy is considered an effective tool on the way to the sustainable development of communities. This is especially reflected in the rural area of the PST, which could foster its local development. In turn, harnessing renewable wave energy through DES offer a green and sustainable answer that reduces greenhouse gas emissions to the atmosphere. On the other hand, the siting of DES requires decentralized companies to build, operate and maintain the facilities, which creates opportunities for job creation and economic benefit for local businesses. This would help increase access to better quality electricity services and electricity independence, improve coastal community resilience, reduce energy poverty, and strengthen national energy security [112,122]. Therefore, the concept of energy autonomy could be considered an effective tool to promote sustainable development in the communities of both selected sites [81].

While DES is capable of offering several potential benefits, it also presents different challenges. The management of Mexico's electricity market by the State can generate institutional, legal, and administrative barriers that hinder the development of DES by supporting traditional centralized electricity generation schemes. The increase in the number of DES projects requires a degree of energy market diversification with policies that support the participation of local governments, community cooperatives, and private companies in the production and distribution of electricity [80]. Strategies that incentivize the use of renewable sources should be promoted through electricity tariffs that take into account not only the cost of electricity production from the unit or system but also the capacity and willingness of users to pay [51]. Concerning the technical challenges, adequate planning is necessary to ensure that the deployment of DES does not cause instability in the voltage profile of electricity demand and its quality supply. In addition, power system operation criteria must be redesigned and modernized to facilitate the development of emerging technologies such as smart grids, renewable energies, and energy storage. The financial challenges are associated with a higher capital cost per kW than large plants. In addition, due to the stability problems that DES systems can present, increased grid integration and operation costs must be considered [52].

Considering the potential conflicts that the WEC facility could cause by coexisting with the diverse economic activities, human uses, and existing exclusion zones in the coastal zone, PST appears to be the most suitable site for the WEC facility, since it is located in a remote rural area, where only agricultural and fishing activities occur. On the contrary, the SMR site is located in a highly populated coastal area inside the TSB (Figure 10), where a higher number of activities and coastal uses coexist such as port, shipping, industrial, tourism, agriculture, fishing, and aquaculture; which may hinder the placement of the WEC within the bay and, in turn, could affect the welfare of local communities and cause conflicts between stakeholders [94,123].

Wave energy extraction projects should determine the possible effects of WEC farm facilities on the marine environment. The farm design should minimize their potential impact on coastal circulation, morphodynamics [78], and biota [77]. These studies are far beyond the scope of the present work but are being undertaken as a next step along with a complete economic feasibility study.

2.5 Summary and Conclusions

This chapter presents a characterization of the wave energy resource and an assessment of WEC farms' performance that satisfies a DES in the coastal region of Baja California, México. The wave power availability is determined using 11 years of a high-resolution wave hindcast made with the SWAN spectral model. Wave simulations have been validated with ADCP measurements, showing good agreement and increasing confidence in the results. Based on the results, the study area has several sites suitable for wave energy extraction. The domain presents a moderate $\bar{P}$ availability with a mean annual value close to 10 kWm^{-1}.

Hotspots in the studied region are due to wave focusing caused by wave refraction over bathymetric features such as reefs, ridges and headlands. These results further shows the importance of using numerical wave simulations and bathymetric data with high resolution, as those used in this study, for wave energy assessment in coastal seas. The most appropriate locations for wave energy extraction are identified through hotspots of maximum availability and lower temporal variability of the resource. The PST and SMR sites present the highest mean availability of the wave resource, the former being higher than the latter. At both sites, the most common waves have H_s between 0.75 m and 1.25 m, and T_p of 12—14 s, with a higher occurrence of extreme events in the outer TSB locations. Although, as expected, the deep PST location is more energetic than the shallow location, the shadowing effect of the TSI and the focusing effect of the reef cause the shallow SMR location to have higher $\bar{P}$ than the deeper SMR location. There is considerable temporal P variability in the analyzed domain, where both selected sites have lesser inter-annual than intra-annual variability. The highest wave power occurs during winter and the lowest in the summer months. The maximum wave power at PST and SMR sites are close to 25 kWm^{-1} and 17.5 kWm^{-1}, respectively. Considering the higher availability and lower temporal variability of the resource, the deep location of PST is the most suitable for extracting wave power and developing, preliminarily, the WEC project in the analyzed domain.

In addition to determining the wave conditions, numerical wave models allow estimating the wave power extracted and WECs performance at specific locations. The generation capacities of the analyzed WECs show a similar trend to $\bar{P}$, higher at the PST site than at BSM during the winter season. Among all the devices evaluated, WaveDragon and Pelamis extract the highest wave power at the selected shallow and deep locations, respectively. WaveDragon extracts more energy than Pelamis. However, Pelamis is 10.4 times more efficient at the PST site and 13.7 at the SMR site. Thus, Pelamis appears to be the most attractive technology to implement in WEC development because it is the best adapted to the local wave climatology, producing the highest capacity factors at the selected sites. Although Pelamis generates a maximum C_f of 40.6%, its lower annual average value reflects the need to continue the development, and innovation on a new generation of WECs that better adapt to wave conditions with moderate wave power availability, such as those found in the subtropical region of Baja California, Mexico.

WEC farms, designed to satisfy a DES, require fewer devices at the PST site than at the SMR site. Given the seasonal variability of the wave power extracted by WEC farms in the region, coupling with energy storage modules or support with hybrid renewable systems could be suitable complements to satisfy a constant power supply during the less energetic summer months. The WEC farm facility may produce a significant impact on nearshore wave characteristics and on the environment. Detailed studies are required to assess the effects of WEC farms on the near-field and nearshore wave climate, currents, and sediment transport, as well as the possible conflict with other activities existing in the marine-coastal zone.

Chapter 3: TECHNO-ECONOMIC FEASIBILITY OF MARINE ECO-PARKS DRIVEN BY WAVE ENERGY: A CASE STUDY AT THE COASTAL ARID REGION OF MEXICO

Coastal arid regions face significant challenges to ensure energy, water, food security. Given the urgency of meeting these demands, it is necessary to consider innovative solutions that enhance the adaptive capacity and sustainable development of coastal zones. Harnessing wave energy has become a promising marine renewable option that can provide significant benefits in reducing coastal vulnerability and mitigating climate change. However, most wave energy converter (WEC) projects still face different challenges that limit their financing and commercial deployment. Symbiotic integration between emerging WEC facilities and consolidated coastal industries is proposed as a potential blue growth pathway to accelerate the viability of the emerging wave energy sector and generate multiple sustainable benefits. This chapter aims to evaluate the techno-economic feasibility of 0.5 MW Marine Eco-parks (MEP) as maritime clusters coupled with complete test-stages Pelamis and WaveDragon WECs, seawater desalination, and marine aquaculture industries to satisfy through a decentralized energy scheme with electricity, freshwater, and food resources to energize the blue economy in of arid coastal communities of Baja California, a Mexican Pacific region with a mild wave power resource. Based on technical and economic data available in the literature, the cost estimates and the contribution of each coupled unit to the MEP's profitability were carried out and compared against other forms of energy generation using different current and projected 2030 market scenarios. All the cases analyzed show that the Pelamis device generates higher techno-economic performance than the WaveDragon. While individual WEC siting is not profitable, economic scal-

ing in WEC farms increases MEP's profitability. Optimally selected Pelamis facilities attain capacity factors over 40% and Levelized Cost of Energy (LCOE) of 480 $/MWh. The coupled seaweed aquaculture submodule generates the highest MEP's profitability, while seawater desalination is not economically viable. The annual production of 321 tons of dried *Ulva sp.* can generate a net present value of 23.8 M$ and an internal rate of return of 28%, which determines an amortization of the system in 5 years, concerning the 20 MEP's lifespan. A reduction in the projected 2030 LCOE estimates is observed in all the WEC farms analyzed. However, it is necessary to continue innovating and developing more economical and efficient devices to achieve greater competitiveness in the electricity market against other traditional power generation technologies. It is hoped that the methodology employed in this case study, with site-specific adaptations, could be useful in other coastal regions with similar needs and climatic conditions.

Keywords: marine renewable energy; wave energy resource; blue economy; low pressure reverse osmosis; seaweed aquaculture.

3.1 Introduction

Population growth and recurrent weather events in a changing climate increase the pressure and vulnerability of arid coastal areas in developing countries, making it paramount to consider better sustainable options to support their management and adaptive capacity [3,124].

One-third of Mexican coastal municipalities have arid and semi-arid climates; its population is expected to increase by 26.8% by 2030, with 60 million inhabitants [125,126]. Increased demand for natural resources to meet their basic needs and sustain their quality of life intensifies pressure on biodiversity and the health of ecosystem services, limiting socioeconomic development in arid coastal zones [127].

Ensuring access for everyone to affordable, safe, sustainable, and modern ways of harnessing resources is a vital issue for countries [128]. The geopolitical condition of Mexico's arid zones undermines energy and water security, which conditions the sustainability and development of other productive sectors, such as food [127,129]. The drought-prone climate, dependence on the United States, and growing resources demand create uncertainties in Baja California's energy, hydrological, and food future [5].

Renewable energies have become indispensable resources to promote the energy transition and mitigate global warming in modern societies [5]. Although Mexico's Energy Transition Law [4] has encouraged the proportion of installed clean energy capacity in the national energy matrix, it is important to continue adding efforts to achieve the climate proposals agreed upon in the Paris Agreement [9,10]. With a global deployment potential of 337 GW and a generation capacity of over 885 TWh/year [12], harvesting MRE emerges as an alternative to strengthen energy security and boost sustainable development in Mexico's coastal areas [13,14].

The arid coasts of Mexico offer a variety of MREs, such as thermal gradient energy, ocean currents, tides, and water waves [17,130,131]. The latter is considered one of the most promising marine renewable resources to be harnessed due to its high energy density per unit area, its reliable short-term predictability, and persistence, as well as the fact that it flows naturally to the coast, where it can be harvested by WECs. In particular, the Baja California peninsula has the highest availability of resources in the Mexican Pacific [16,17].

The study of Gorr-Pozzi et al. [17] have shown that the extractive capacity generated by WEC arrays in locations with moderate resource availability creates the need to seek alternative electrical interconnection options that make the designed installed capacity viable. DES match the electrical needs of WEC sites and, in addition, generate multiple benefits by empowering isolated communities without electrical connections and increasing the cost-effectiveness of renewable projects by reducing the need for costly energy storage systems, and supporting the achievement of both socioeconomic and global climate ambitions [50,51].

Although research, development, innovative components, and demonstration and validation in marine environments of WEC farms have led to significant progress in the TRL and present extensive possibilities for the future energy supply [39], the industry still faces significant hurdles to accelerate their viability and commercial deployment [40–42]. The uncertainties associated with the large and diverse portfolio of WEC prototypes [69,74,104], commercial-scale performance [39], potential environmental impacts of WEC farms [38,77,132], high LCoE [43] related to higher capital (CapEx) and operation, maintenance, repair, replacement costs, plus administrative expenses (OpEx) costs and moderate CF [16,46,47], and the lack of energy policy sensitivity and mechanisms to push/pull the market inhibit the lack of confidence of potential investors and competitiveness in the energy market [13,48].

The LCoE is one of the most important indicators to determine whether an energy technology can become competitive and commercialized [46]. The diversity of WEC, wave power availability, and location-specific aspects have led several studies to expose a broad range of LCoEs with values between 75-500 USD/MWh [41,133,134]. Oliveira et al. [135] estimate that Pelamis and Wave Dragon devices in regions with moderate wave power availability in Brazil generate LCoE of 163 and 138 USD/MWh, respectively. MacGillivray et al., 2014 [136] expose that the uncertainties involved in learning rate analyses of various WEC TRLs generate a wide range of costs (in million USD) per MW installed (MUSD/MW) from 3 to 10 MUSD/MW, concluding that commercial prospects depend on substantial learning and cost reduction. De Andres et al. [12] analyzed several devices and found lower cost ranges between 2.5 to 7.6 MUSD/MW. Furthermore, Chozas [47] identify that differences in cost estimates, pre-commercial wave energy technologies, and resource availability at the project site have a huge impact on the LCoE, with a range between 240 and 840 USD/MWh, and concludes that the LCoE should only be compared to other energy technologies once the wave energy technology is mature, reliable and commercial. Lavidas and Book [16] determine the techno-economic feasibility of selected converters in areas with mild resource availability, revealing that low variability locations can provide high energy production and achieve better WEC survival, reaching CF higher than 30%, with average LCoE values of 167 to 279 USD/MWh and a minimum of 67 USD/MWh.

As investor decisions are mainly based on the economic performance of technologies, an innovative strategies are required to open up other niche markets and leverage the commercial deployment of the emerging MRE sectors [46,53]. Sustainable human uses of the ocean, particularly associated with economic benefit, have recently been reformulated under the term Blue Economy [137]. It encompasses activities that explore, develop and utilize ocean resources to generate economic development, improve human welfare and social equity, and reduce potential environmental impacts [138]. It offers diversified opportunities for sustainable, clean, and equitable progress in traditional and emerging sectors, promoting better management of food security, nutrition, renewable energy use, maritime trade, job creation, ecosystem health and biodiversity, and carbon emissions mitigation with resource efficiency. The blue ocean economy is expected to double to $3 trillion in the next decade [139].

MEP are multi-purpose coupled systems that could offer a sustainable option to accelerate the viability of the pre-commercial MRE stage and leverage the development of the blue economy and resilience in coastal areas [42,54–59]. Such integrated marine clusters create a symbiotic ecosystem capable of producing a range of products and services beneficial to coastal communities [56,137]. The symbiosis and the multiple use of space makes efficient use of the available area combining industries can increase their profitability and competitiveness and optimize the management of marine space, reducing CapEx and Opex associated with shared space, infrastructure and construction, and plant operating costs [46,50,55,58,60]. In addition, harnessing MRE enables local green energy production to power the coupled functionalities, resulting in less dependence on grid-supplied fossil energy and lower electricity costs in the medium and long term [42,59]. This allows the sectors to insert themselves into the Clean Energy Certificates (CEL) and Carbon Credits (CC) markets [140], which increases their coastal communities acceptance by increasing their environmental and socially responsible commitment [55]. This trend, within an energy market that facilitates the deployment of renewable projects could foster greater cumulative installed capacity by increasing the number of sites adopting these technologies, learning and R&D opportunities, the creation of new jobs and associated industries, and progress in the quality of life of local communities [54]. MEPs coupled with WEC arrays, seawater desalination, and marine aquaculture emerge as a possible sustainable solution that could drive symbiotically boost energy, water, and food security in coastal areas [42,56–58].

Scarcity and access to water resources are global problems that affect the sustainable development of modern societies [141]. Projections estimate that they will reach critical levels within the first half of this century [142]. 386,000 Mexicans lack access to safe water, and more than half of households that have access to running water have this intermittently, particularly in smaller settlements and in poorer areas [143]. Therefore, either new sources of water or measures to limit groundwater extraction are needed [144]. Seawater desalination and wastewater recovery process have become promising options to mitigate water shortages and reach well-being in arid coastal regions by providing water both in quality and quantity [145,146]. Among the different techniques used to remove certain minerals and dissolved salts for freshwater production, the rise of seawater reverse osmosis (SWRO) is attributed to its lower energy consumption and large improvements in performance [145,147]. However, still, the desalination process faces certain hurdles associated with high energy consumption that generates relevant amounts of greenhouse gas emissions [42,148]. A conventional SWRO system consumes between 2.5 and 4 kWhm^{-3}, and energy costs per cubic meter can be as high as 30%-60%, remains the main component of the costs of these systems [146,149]. Kalogirou [150] estimated that the production of 1,000 m^{3} of fresh water per day requires 10,000 tons of fossil fuels. Due to the inextricable nexus between electricity and water generation processes, several studies have demonstrated the benefit of synergistic coupling between renewable technologies and desalination [68,120,146,151–155]. Examples of seawater desalination project driven by wave energy include the pilot plant installed on Garden Island, Western Australia, which uses a 5 MW CETO WEC farm [156] to produce a nominal capacity of up to 150 m^{3}day^{-1} of potable water from SWRO desalination facility; Viola et al [148] explore the use of 80 kW WEC point absorbers to satisfy desalinated water treatment in Sicily, Italy and Fernandez-Prieto et al [157] evaluate the use of wave energy to power existing seawater desalination plants, determining that it is a viable alternative to promote the use of renewable energy, reduce the high dependence on fossil fuels and mitigate the shortage of fresh water in the Canary Island, Spain.

In certain regions —particularly in developing countries that rely on small-scale local resources— threats to food security are worsening due to pressures from rapid population growth, economic growth, environmental degradation, and climate change. The Regional Overview Food Security and Nutrition 2021 [158] reveal a bleak scenario for the region's food future. Four in ten Latin Americans (267 M) experienced moderate or severe food insecurity in 2020, 60 M more than in 2019, an increase of 9%, the steepest relative to other world regions. The challenge of strengthening food systems creates the need to seek innovative solutions that contribute to reducing their vulnerability, increasing their sustainability, and ensuring the well-being of communities. Aquaculture is considered one of the principal food production systems, which has presented the highest growth in the last decade [159]. It is also a pivotal activity for adding resilience to the global food system [160]. It allows for a more stable, sustainable, and predictable food supply, generating jobs, mainly in developing countries

[161,162]. In particular, seaweed farming has become an important sector within the blue economy. With an annual production of ~32.4 M tons (wet weight) in 2018, valued at 13,300 M USD, it is expected to increase to 22,130 M USD by 2024 [163]. Coupling seaweed farms with WEC farms can generate synergies that reduce costs and benefit their deployments by sharing some infrastructure, transportation, and labor costs, as well as addressing fossil fuel dependence [53,60]. Some integrative solutions are described by Stuiver et al. [121], who explores the application of governance frameworks for better marine spatial planning of the location of new sustainable economic activities through the development of multiple platforms in four case studies in different European sea basins; Fletcher [57] in the MUSICA project, which proposes a multipurpose platform to provide synergistically support services to aquaculture and thus reduce operating costs associated with operation and maintenance on the island of Oinousses, Greece and Zanuttigh et al [55] that preliminarily examine the possible synergies that can produce a multipurpose solution by combining wind and wave energy farms, aquaculture, and transport facilities in the temperate climate zone of the Mediterranean Sea in the northern Adriatic. They determine that the most promising solution is the stand-alone scheme integrated with fixed wave energy devices that offers local removable energy and protection to aquaculture farms and significantly optimizes the use of marine resources and space, driving more sustainable blue growth.

The main goal of this study is to assess the opportunities and challenges that may lie in the development of MEPs to boost sustainable development in a coastal-arid region of TSB in Baja California, México. For this purpose, the techno-economic feasibility of MEP integrated by WEC farms, seawater desalination, and seaweed aquaculture was evaluated. In addition, the MEP profitability is determined to meet the energy, water, and food needs of coastal communities based on different market scenarios. Finally, the projected LCoE values is calculated and compared with other energy resources.

3.2 Materials and Methods

The study was carried out in six scenarios that determine the techno-economic feasibility developed by the complete test-stages Pelamis and WaveDragon WECs to power the 0.5 MW MEP. The developments were sited in maximum wave energy availability hot spots to meet the energy, water, and food needs and energize the local blue economy of coastal communities. Based on technical and economic data available in the literature, the cost estimates and the contribution of each coupled unit to the MEP's profitability was calculated using: (1) electricity from each single WEC device; (2) electricity produced by WEC arrays; (3) electricity from WEC arrays and clean energy certificates (CEL); (4) electricity from WEC arrays, CEL, and seawater desalinated; and (5) electricity from WEC arrays, CEL, dry seaweed, and carbon credits. Finally, in scenario (6), the LCoE WEC arrays were estimated and compared with other power generation options based on the current and projected 2030 roadmap.

3.2.1 Study Area

Todos Santos Bay is located on the northwest coast of the Baja California peninsula in Mexico (**¡Error! No se encuentra el origen de la referencia.**). This is a semi-enclosed bay protected from the Pacific swell by Todos Santos Island (TSI). The TSB sea state is commonly composed of different wave systems coexisting simultaneously. It presents throughout the year mainly a bimodal swell character. The swell over the North Pacific region occurs mainly during the winter season, while that of the South Pacific region, during the summer months [86].

The region exhibits moderate $\bar{P}$, with a mean value close to 10 kWm^{-1}. The most common wave power is concentrated between H_S of 0.75 m and 1.5 m and the 10 s and 16 s spectral peak. A marked seasonal trend was observed, with a maximum of $\bar{P}$ during winter (16 kWm^{-1}) and a minimum during summer (5.3 kWm^{-1}). The exposed area outside the bay has a higher $\bar{P}$ than the inner area due to the shading ITS effect over TSB [17]. Outside the bay, $\bar{P}$ is close to 12 kWm^{-1}, with the highest $\bar{P}$ in the study area is PST close to 14 kWm^{-1} (**¡Error! No se encuentra el origen de**

la referencia.). Within the bay, $\bar{P}$ is 8 kWm^{-1}, with the highest value at the SMR site, around 11 kWm^{-1}.

3.2.2 Market Description

This section describes the market opportunities for an MEP. Each of its by-products (energy, desalinated water, and algae) is analyzed based on how they would meet unmet needs in the study area.

The state's accelerated economic growth and dependence on fossil fuel use create the need to increase installed renewable energy and freshwater capacity to foster sustainable development and coastal resilience by satisfying the water, energy, and food demands [164,165]. The PRODESEN 2020-2034 [166] indicates that the Baja California peninsula needs to increase its installed capacity of electric energy. However, the peninsula is isolated from the national electricity system (SEN), so the uninterrupted supply of electricity depends on the interconnection to the electricity grid of the Western Electricity Coordinating Council (WECC) of the United States [167]. Therefore, encouraging the development of innovative solutions that take advantage of locally available MRE can help minimize the vulnerability of national electricity security and reduce local energy poverty. These sustainable projects can in turn help meet other basic needs, such as access to fresh water and food security.

Also, the BTS region is dependent on groundwater as a source of drinking water. According to estimates by the local water utility (CESPE), the estimated water demand has ceased to be met, on a sustainable basis, since 2006 [168]. To meet the current and future water demand of BTS, the National Water Commission (Conagua) has considered SWRO systems as a possible alternative to provide access to freshwater [144]. However, the use of energy continues to be the main component in the costs of these systems, which has repercussions on their economic feasibility [149,169]. Likewise, the insufficiency of electricity in Baja California generates an additional limitation for its location. In this sense, the supply of electricity to SWRO systems, based on the harvest of local renewable sources, emerges as an attractive and innovative option for accessing freshwater, both in quality and quantity [146].

Likewise, energy and water have become indispensable resources for ensuring food security and eradicating poverty [162]. The accelerated development of seaweed aquaculture is mainly driven by its versatility and use in industries that include food, biofuel, chemical, nutraceutical, pharmaceutical and cosmetic industries, as well as environmental bioremediation [170]. Likewise, their intrinsic characteristics allow them to have a rapid increase in biomass and contribute to climate change adaptation by acting as highly efficient carbon sinks [171] by capturing and mitigating atmospheric CO_2, protecting the seashore from erosion, raising pH, supplying oxygen to the aquatic ecosystem, and locally reducing the effects of ocean acidification and deoxygenation [172,173]. The ideal seaweed species for culture development are those that can grow vegetatively and their morphology or size is not compromised by the "tumbling" movement in the ponds. In this paper, green seaweed *Ulva sp.* (sea lettuce) was selected as the cultivated seaweed in the MEP, as large quantities of biomass with a high commercial value could be produced [59]. This genus has proven to be very productive and the method of continuous resuspension in a pond is adapted [174]. Among other seaweeds, *Ulva sp.* is recognized as a valuable marine resource due to its multiple uses as food for human consumption, animal feed, biofilter, pharmaceuticals, and even as biomass for biofuels [170,174]. It would also capture atmospheric carbon, reducing the carbon footprint and create carbon credits [37]. The amount of carbon sequestered by *Ulva sp.* was calculated, using the conversion factor of Chung et al. [171], which considers 30% of the dry biomass, and 7.6% of sea-salt [174].

3.2.3 Techno-economic Design

Data and methodologies for designing and determining unit costs and production rates of each couple MEP sub-modules were obtained from the scientific literature reviews (**Table 4**) since there is no existing design on the market that considers all of the components of our design. The amount of energy extracted, and desalinated water and biomass produced, as well as the ton/day of carbon sequestration, via the cultivation of *Ulva sp.*, were calculated.

Table 4. Methodology used for the MEP design.

Submodule	Methodology	Reference
Energy production	0.5 MW WEC farms	Adapted from Gorr-Pozzi et al. [17]
Desalinated water production	Desalinated water	Sensitivity analysis adapted from [145,149]
	Seaweed aquaculture	Adapted from the *Ulva sp.* ponds of Zertuche-González et al. [174]
Seaweed production	*Ulva sp.* nutrient demand and net yield per m^2	Hanisak [175]
	CO_2 capture capacity of *Ulva sp.*	Chung et al. [171]and Zertuche-González et al. [48]

The MEP consists of a 0.5 MW wave DES farm that produces energy to satisfy desalinated water and seaweed aquaculture coupled submodules, the last one considered the main advantage of the plant in terms of financial feasibility (Figure 18).

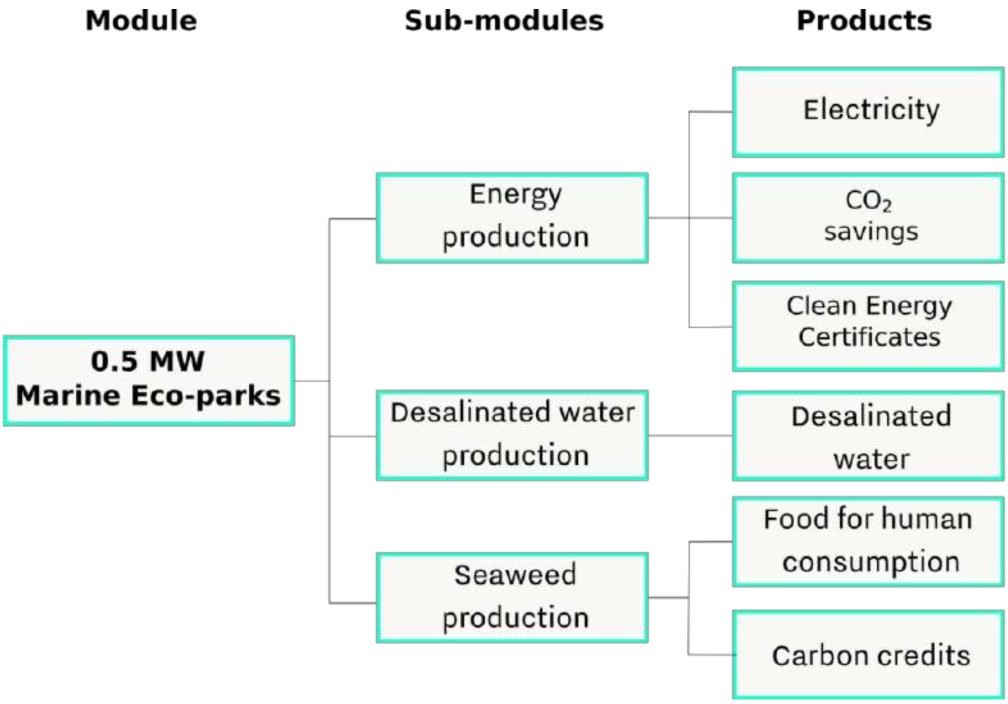

Figure 18. Components of the Marine Eco-parks adapted from Tobal-Cupul et al. [59].

The size and characteristics of the MEP components were designed for the WEC farms to satisfy a DES adapted from Gorr-Pozzi et al. [17] concerning the number of devices per WEC farms (N), the installed power (I_P), depth (Z), distance from the shoreline (D_{OFF}), length of mooring system (l_{ML}), length of underwater electric cable (l_{UW}), length of underground electric cable (l_{UG}) (Table 5).

Table 5. Summary of the technical characteristics of the WEC farms at the selected sites.

	PST		BSM		Reference
	Pelamis	**WaveDragon**	**Pelamis**	**WaveDragon**	
l_{ML}	2	1	4	2	[17]
I_P [MW]	1.5	7	3	14	[22,90]
Z [m]	52	26	61	38	[17]
D_{OFF} [km]	1.87	0.75	8.72	6.6	[17]
l_{ML} [km]	0.86	1.59	1.68	3.2	[17,176]
l_{UW} [km]	2.41	1.08	10.49	8.35	[17,46]
l_{UG} [km]	5.20	5.20	1.52	1.52	[17,177]

is the length of mooring system, I_P is the installed power, Z is the depth at the WEC location, D_{OFF} is the distance from the coastline to the WEC sites, l_{ML} is length of mooring system, l_{UW} length of underwater electric cable, l_{UG} is the length of underground electric cable. Pelamis and WaveDragon are the selected WEC at PST and SMR test sites.

The desalination submodule was coupled based on the art studies of Valladares et al. [149] and Li et al. [151] as summarized in Table 6.

Table 6. Desalination Assumptions.

Energy consumption SWRO (MWh/m^3)	0.0035
Daily flowrate (m^3/d)	11,110

The seaweed aquaculture was adapted from Zertuche-Gonzalez et al. [174] based on the results of pond culture in a commercial pilot facility on the temperate Pacific coast of Mexico (Table 7).

Table 7. Readjustment of the production of *Ulva sp.* plant.

	25%	**50%**	**75%**	**100%**
Plant surface (ha)	2.38	4.75	7.13	9.51
Effective area (ha)	1.06	2.13	3.19	4.26
Production units	16.63	33.27	49.90	66.54
Energy consumption (MWh)	127.59	155.69	183.79	211.89

Dry weight production (ton/ yrs)	80.22	160.44	240.66	320.88
Carbon sequestered (ton/ yrs)	24.07	48.13	72.20	96.26

The percentages represent the seaweed produced as a function of the annual energy production by the WEC farms.

To determine the contribution of each co-located submodule to the MEP's profitability the study was carried out in six sale scenarios in the market of: (1) electricity produced from individual Pelamis and WaveDragon devices within the optimal operating depth range [76] across the entire domain; (2) electricity produced by WEC arrays based on DES as Gorr-Pozzi et al. [17]; (3) electricity from WEC arrays and clean energy certificates (CEL); (4) electricity from WEC arrays, CEL, and seawater desalinated; and (5) electricity from WEC arrays, CEL, dry seaweed, and carbon credits. Finally, in scenario (6), the LCoE (see Equation (11) WEC arrays were estimated and compared with other power generation options based on the current and projected 2030 roadmap.

3.2.4 Wave power, Water and Seaweed Resources Assessment

3.2.4.1 Wave Power Availability and Conversion

The third-generation wave model SWAN Cycle IV version 41.20AB [87] was implemented to characterize the spatio-temporal distribution of wave characteristics and available wave power within TSB and its surroundings. The SWAN model was forced at the boundaries with directional waves spectra from the IOWAGA wave hindcast [88]. The model was run in a non-stationary two-dimensional mode from January 1st, 2008 to December 31st, 2018 with hourly output data. The domain was discretized in a regular grid with a spatial resolution of 0.0025° (approximately 280 m), with an equal logarithmic spaced frequency resolution with 41 frequencies, from 0.04 Hz to 0.7 Hz, and a directional resolution of 5°. The SWAN numerical results were validated using available wave data from Acoustic Doppler Current Profilers (ADCPs) deployed at three locations (Figure 1) within the TSB.

Two well-known WEC with different designs and operational principles, Pelamis and WaveDragon, were evaluated to quantify harvestable wave energy since in previous studies by Gorr Pozzi et al. [17] they have shown to generate the highest overall extracted power capacity in the study area.

The annual energy production (AEP) was computed as [16,17],

$$AEP = \sum_{i=1}^{n} \sum HR(H_s, T_p) \cdot PWEC(H_s, T_p), \tag{7}$$

$$CF = \frac{AEP}{P \cdot \Delta T}, \tag{8}$$

where n is the expected lifetime of a WEC site, HR is the availability matrix, which represents the probability of occurrences of the different sea states expressed as a fraction from the total number of observations computed using the hourly H_s and T_p obtained from the SWAN model [87] simulations. Also, $PWEC$ is the corresponding power matrix of each considered device as characterized in cartesian coordinates (i,j), obtained from publicly available technical data of the Pelamis and WaveDragon devices [22,90]. P is the available wave power density, computed from simulated directional spectra, and ΔT being the hours in a year for the gathered probabilities. Since the highest availability of $\bar{P}$ in the study area is in the SMR and PST hotspots. In the PST, wave focusing is associated with the presence of an offshore shallow ridge and a headland, whereas at the SMR site, it occurs in the leeward side of the offshore reef [17]. We chose these locations to analyze the techno-economic feasibility of the MEP site.

3.2.4.2 Desalinated Water Production

Based on the AEP generated by the Pelamis and WaveDragon devices at the selected PST and SMR sites, the amount of water desalinated by SWRO was calculated according to a detailed study of the art made by of Valladares et al. [149] and Li et al. [151] (shown in Table 5).

3.2.4.3 Seaweed Aquaculture Production

Conceptually, the development of cultureis proposed is based on practiced in macroalgae culture farms by Zertuche et al [174]. For this purpose, the amount of biomass produced by offshore *Ulva sp.* cultures is calculated. *Ulva sp.* cultivation typically involves an initial seeding of 3 kgm^{-3}. If there is no nutrient limitation and the temperature is adequate, the biomass doubles over a period of approximately 21 days. When the crop reaches 6 kgm^{-3}, the surplus is harvested. Thus, it is reasonable to assume a net yield per m^2 of 3 kg (wet weight, equivalent to 300 g dry weight) over a three-week period. The critical nitrogen, defined by the concentration below which the seaweed would be N_2-limited for an alga such as *Ulva sp.* is 2 % [175]. In other words, the N_2 demand would be equivalent to 2% of the new biomass. In the above case, the N_2 demand would be 60 g per m^3 in 21 days or 2.85 g per day. According to the concentrations reported in the study region, 1 m^3 would have enough N_2 to satisfy the calculated demand [178]. If a water renewal capacity of 1 m^3 per m^2 of crop area is considered, the production capacity would be given by the number of m^3 available to renew the same number of m^2.

3.2.5 Economy Analisys

The economic feasibility of WEC farms was analyzed by adapting the methodology of Vega & Michaelis [179]. The costs used were updated according to projects similar to the value of the US dollar in 2022. A projected useful life (n) of 20 years was considered, with outflows corresponding to cash flow from CapEx, OpEx, and revenues from product sales. The initial net investment of the scenarios is financed 45% by the partners and 55% by government loans at a fixed annual rate of 11.84%, paid over eight years with a 12.5% loan amortization each year. To generate an accurate cash flow model, specific PTU (workers' statutory profit sharing) and ISR (income tax) Mexican taxes are mainly considered.

CapEx of WEC farms was calculated from Astariz & Iglesias [46] as,

$$CapEx = c_{PRE} + (N\ x\ N_P\ x\ c_{WEC}) + (c_{ML}\ x\ l_{ML}) + [(c_{UW} + c_{VI})\ x\ l_{UW}] + c_{SUB} + (c_{UG}\ x\ l_{UG}) + c_{DS}, \tag{9}$$

where c_{PRE} is the pre-operating costs, N is the number of devices, N_P is nameplate for an individual WEC, c_{WEC} is an individual WEC cost and its installation, c_{ML} is the mooring system cost and its installation, l_{ML} is the mooring system length, c_{UW} is the cost per unit length of underwater cable, c_{VI} is costs of the required vessel and installation of the underwater cable, l_{UW} is the underwater electric cable lenght, c_{SUB} is the substation and electrical installation costs, c_{UG} is the cost per unit length of underground cable, l_{UG} is the length of undergrown electric cable, and c_{DS} is the decommissioning costs. The WEC farms infraestructure costs are shown in Table 8.

Table 8. CapEx assumptions for WEC farms made on the economic modelling.

	Pelamis	**WaveDragon**	**Reference**
c_{PRE} [$/MW]	10% of CapEx		[46,180]
c_{WEC} [M$/MW]	3.89	2.8	[46]
c_{ML} [$/km]	10% of c_{WEC}		[180,181]
c_{UW} [M$/km]	0.43		[181,182]
c_{VI} [M$/km]	0.0028		[183]
c_{SUB} [M$]	1.64		[46]
c_{UG} [M$/km]	0.117		[107,177]
c_{DS} [M$/MW]	0.068		[184]

c correspond to costs, associated to: pre-operating (c_{PRE}), individual device and its installation (c_{WEC}), mooring system and its installation (c_{ML}), length of underwater electric cable (c_{UW}), required vessel and installation of the underwater cable (c_{VI}), substation and electrical installation (c_{SUB}), length of underground cable (c_{UG}), decommissioning (c_{DS}). Pelamis and WaveDragon are the selected WEC.

Due $OpEx$ is dependent on CapEx [16], the costs relating to the operation, maintenance, repair, replacement, and administrative WEC expenses was calculated as sugest in several studies [16,185],

$$OpEx = 8\% \, of \, CapEx, \tag{10}$$

OpEx increases every life span year due to the inflation generated by the annual increase in the cost of services, such as workers' salaries.

Regarding coupling costs, the desalination module costs were adapted from a review of actual running desalination plants as Valladares et al. [149] and Candela & Breyer [145] with a CapEx of 1176.47 ($/m^3) and an OpEx of 0.59 ($/m^3). Seaweed aquaculture submodule costs were taken from the literature [60,186] and include installation, harvesting, transportation, materials, and maintenance costs for a 20-year lifetime (Table 9). It is assumed that there will be cooperation between seaweed modules and WEC farms by sharing part of the infrastructure, logistics, and labor costs.

As the literature on the economics of commercial seaweed culture is scarseand covers diverse production methods and environmental conditions, this information should be treated with caution.

Table 9. Production cost of *Ulva sp.*

	25%	50%	75%	100%
CapEx (M$)	2.29	2.67	3.04	3.41
OpEx (M$)	0.09	0.11	0.12	0.13

CapEx and OpEx are in 2022 US dollars, and the percentages represent the seaweed produced as a function of the annual energy production by the WEC farms.

To conceptually determine the lifecycle cost associated with different scenarios and compare WEC farms with other power generation technologies, the method was applied and estimated as [47],

$$LCOE = \frac{CapEx_{t=0} + \sum_{t=1}^{n} \frac{OpEx_n}{(1+r)^n}}{\sum_{t=1}^{n} \frac{AEP_n}{(1+r)^n}}, \tag{11}$$

where t is the time elapsed since the start of the project, and r is the discount rate (5.40%) taken form EIA [187]. (11 can be extended on both the cost and revenue sides by considering the financial costs, taxes, and system degradation components [59]. The NPV and a cash flow model were estimated to provide a first-order approximation of the project's economic viability. The cash flow model includes the income generated by the sale of the products (electric power, freshwater, dried algae, CELs, and CCs) and the expenses associated with the project's operating and financial costs, depreciation, expenses and taxes.

Concerning the financial indicators, which show the viability of the project, the return on investment (ROI), the payback period (PP), and the present value factor (PWF) were considered and determined as shown in the following equations:

$$NPV = -C_0 + \sum_{1}^{n} \frac{F_n}{(1+r)^n}, \tag{12}$$

$$ROI = \frac{R_n - C_n}{C_n}, \tag{13}$$

$$PP = \frac{C_0}{C_n}, \tag{14}$$

$$PWF = \frac{1 + ER}{1 - ER} * \left(1 - \left(\frac{1 + ER}{1 + r}\right)^n\right), \tag{15}$$

where, F_n is the net cash flow for year n, R_n is the net income, ER refers to inflation (3.15%), taquen form the annual rate of Mexico inflation [188], C_0 and C_n are the initial and year n capital and construction cost, respectively.

Revenues include the sale of electricity, freshwater, dry seaweed, CELs, and CCs. Expenses include salaries, administrative costs, seaweed, social security (35% in Mexico), accumulated investment, maintenance and replacement, PTU, and ISR.

3.3 Results and Discussions

3.3.1 Single Pelamis and WaveDragon WEC profitability

Figure 19 shows the LCOE produced by Pelamis and WaveDragon. Throughout the domain, the Pelamis device generates a lower mean LCoE values than WaveDragon. This is associated with a lower cost and higher performance of the Pelamis device than WaveDragon. The latter has an average CapEx value of M$ 28.82 and OpEx of M$ 2.31 higher than the M$ 8.98 and M$ 0.72 of Pelamis (not shown). Although WaveDragon produces an average AEP of 4693 MWh higher than the 1661 MWh of Pelamis, the latter has an average CF of 25.3% higher than WaveDragon's 7.7%. On the other hand, it can be observed that Pelamis produces higher LCoE ranges (589-3954 $/MWh) than WaveDragon (679-3031 $/MWh).

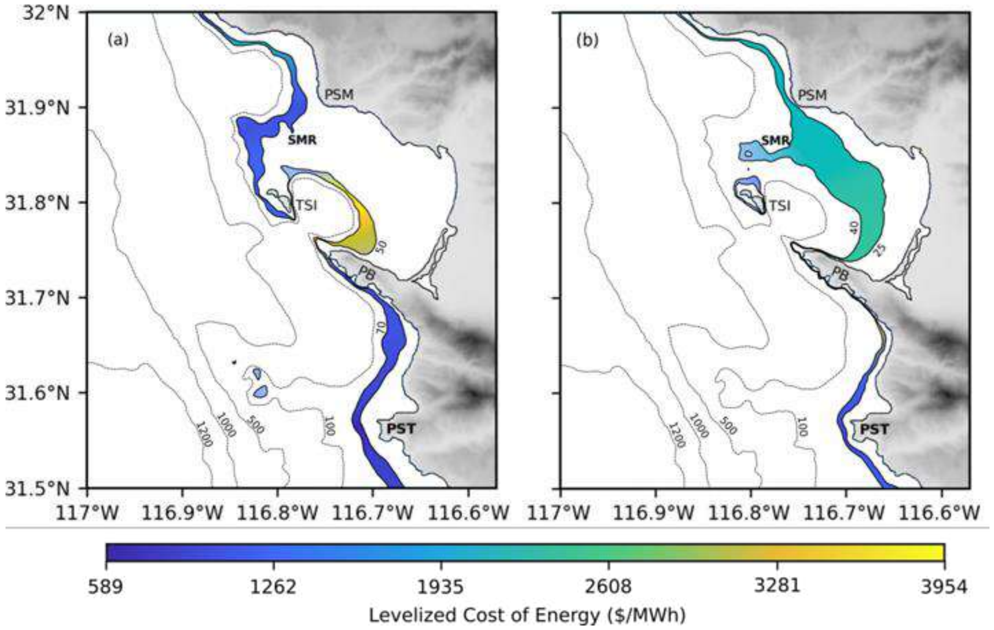

Figure 19. Comparison of the Levelized costs of energy developed by a single Pelamis (a) and WaveDragon (b) devices in their performance ranges throughout the domain. Gray lines represent isolines of equal depth in meters.

The lowest LCoE values are located in areas of higher $\bar{P}$ availability. Acording to Gorr-Pozzi et al. [17], it is observed that the SMR and PST sites are characterized by the lowest LCOE values in the study area (Table 10). The lower extractive capacity of both devices inside the TSB, is associated with the shadowing effect produced by TSI over the TSB area [17]. Lavidas & Bloke [16] determined that the AEP is a major parameter that determines the LCoE behavior. For this reason, it can be observed in Figure 19a, how Pelamis produces in the southern location of TSB the highest LCOE value, associated with the lowest AEP of 526 MWh. While WaveDragon produces 2365 MWh, although it generates higher CapEx and OpEx values, its LCOE in the southern region of TSB is lower.

Table 10. Summary of techno-economic analysis of individual Pelamis and WaveDragon devices for the sale of electricity at the selected PST and BSM sites. Scenario 1.

	PST		**BSM**	
	Pelamis	**WaveDragon**	**Pelamis**	**WaveDragon**
N	1	1	1	1
I_P [MW]	0.75	7	0.75	7
CF [%]	34	8.84	28	13.5

AEP [MWh]	2233.8	5421.9	1839.6	8278.2
CapEx [M$]	6.94	28.21	9.50	29.62
OpEx [M$]	0.56	2.26	0.76	2.37
LCOE [$/MWh]	589.34	986.91	979.31	678.62
NPV [M$]	-2.77	-25.59	-9.58	-14.20

N is the number of devices per WEC farm, I_P is the nominal capacity, CF is the capacity factor, AEP is the annual energy production, CapEx and OpEx are the investment, maintenance, and operating costs, LCoE is the Levelized cost of energy, and NPV is the net present value of the investment. AEP and average CF were calculated by Gorr-Pozzi et al. [17]. PST and SMR are the selected sites.

The net present value produced by Pelamis and WaveDragon is presented in Figure 20. As can be seen, the placement of both WECs along the domain generates negative NPV values, which investment project produces losses. Furthermore, a trend directly proportional to the availability of $\bar{P}$ is observed, with the highest NPV values found outside the TSB and the lowest in the areas protected from incident waves inside the bay. Since no positive NPV values are observed, ROI and PP values are not shown.

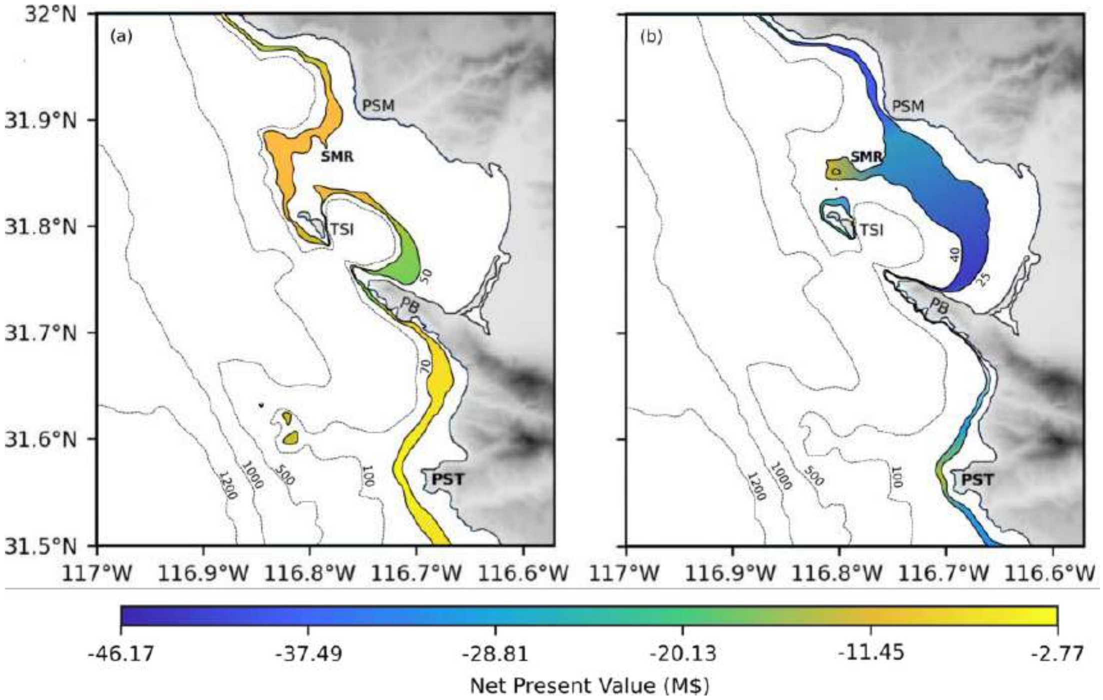

Figure 20. Comparison of Net Present Value generated by a single Pelamis (a) and WaveDragon (b) devices in their performance ranges throughout the domain. Gray lines represent isolines of equal depth in meters.

3.3.2 Pelamis and WaveDragon farms profitability

Table 11 presents the techno-economic summary produced by the sale of energy produced by Pelamis and WaveDragon farms at the selected PST and SMR sites. It can be seen how the increase in the installed capacity of the WEC farms generates a reduction in LCOE and higher profitability. This is due to the economy of scale where CapEx and OpEx-related expenses are reduced by leveraging and sharing existing infrastructure (e.g., electrical wiring or electrical substation), and generating a higher AEP per plant. The Pelamis farm at the PST site is the only site that performs profit (NPV = 0.34), with a return of 6% and a payback period of 19.23 years. This is attributed to the fact that Pelamis at PST generates the highest CF in the entire domain analyzed [17]. This is because the location involves wave focusing processes associated with the presence of an offshore shallow ridge and a headland.

Table 11. Summary of techno-economic analysis of WEC farms for electricity sales. Scenario 2.

	PST		**SMR**	
	Pelamis	**WaveDragon**	**Pelamis**	**WaveDragon**
N	2	1	4	2
I_P [MW]	1.5	7	3	14
CF [%]	31.87	8.84	19.51	5.55
AEP [MWh]	4187.2	5421.9	5127.5	6811.7
CapEx [M$]	10.59	28.21	18.81	54.36
OpEx [M$]	0.85	2.26	1.51	4.35
LCOE [$/MWh]	479.68	986.91	695.92	1513.59
NPV [M$]	0.34	-25.59	-9.91	-66.59
ROI [%]	0.06	-	-	-
PP [yrs.]	19.23	-	-	-

N is the number of devices per WEC farm, I_P is the nominal capacity, CF is the capacity factor, AEP is the annual energy production, CapEx and OpEx are the investment, maintenance, and operating costs, LCoE is the Levelized cost of energy, NPV is the net present value of the investment, ROI is return on investment, and PP is the payback period. AEP and average CF were calculated by Gorr-Pozzi et al. [17]. PST and SMR are the selected sites.

3.3.3 Sale of electricity and CEL from Pelamis and WaveDragon farms

The summary of the benefits produced by the sale of energy and clean energy certificates from the Pelamis and WaveDragon farms at the selected PST and SMR sites is presented in Table 12. Since the I_P's of the farms considered are maintained as the previous scenario 2, the CF and LCOE are also the same, so they are not specified. It is observed that the CEL instrument improves the investment in all the cases analyzed. However, only the Pelamis Park at the PST site generates a positive NPV. Compared to the previous scenario, this farm shows an increase in NPV of 162%. There is also an improvement in ROI of 16.6% and a payback of 1.1 years earlier.

Table 12. Summary of techno-economic analysis of the WEC farm for the sale of electricity and CELs. Scenario 3.

	PST		**BSM**	
	Pelamis	**WaveDragon**	**Pelamis**	**WaveDragon**
I_P [MW]	1.5	7	3	14
NPV [M$]	0.89	-24.88	-9.25	-65.70
ROI [%]	7	-	-	-

PP [yrs.]	18.13	-	-	-

I_P is the nominal capacity, CF is the capacity factor, NPV is the net present value of the investment, ROI is return on investment, and PP is the payback period. PST and SMR are the selected sites.

3.3.4 MEP profitability from the sale of electricity from WEC farms, CEL, and seawater desalination

Table 13 presents the techno-economic results of the coupling of a desalination sub-module to the WEC farms at the selected locations. As can be seen, in no case where energy is supplied for SWRO production (≥ 25%), the NPV values produced are positive, so the investment project is expected to generate losses and should be rejected. This is due to the high costs associated with the CapEx of the desalination sub-module. They range from \$38.9 million for the Pelamis farm site at PST to \$1099 million for the WaveDragon farm at SMR (not shown). Thus, the proceeds from the sale of SWRO do not generate profits and do not allow recovering the investment made for the MEP site. Also, as in scenario three, it is observed that only the sale of energy and CEL produced by the Pelamis farm at the PST site generates NPV equal to 0.89, which indicates that the investment can be accepted.

Table 13. Net present value for MEP coupling by WEC farms de desalination submodules. Scenario 4.

	0%	**25%**	**50%**	**75%**	**100%**
Pelamis farm at SMR	-2.62	-43.74	-154.65	-335.35	-591.15
WaveDragon farm at SMR	-65.70	-132.11	-321.81	-634.79	-1071.06
Pelamis farm at PST	0.89	-25.51	-98.49	-218.05	-384.18
WaveDragon farm at PST	-24.68	-75.04	-218.57	-455.28	-785.17

The percentages represent the energy supply to produce SWRO concerning the AEP produced by each WEC farm at the PST and SMR selected sites.

3.3.5 MEP profitability from the sale of electricity from WEC farms, CEL, dry seaweed, and carbon credits

The net present values of MEP produced by the coupling between WEC farms and a seawater aquaculture sub-module for energy sales, CEL, *Ulva sp.*, and carbon credits, at the selected PST and SMR sites, are presented in Table 14. It is observed that the sale of seaweed generates profits in all the cases analyzed. The higher the percentage of *ulva sp.* produced and sold, the higher the NPV of the MEPs. However, only the Pelamis device generates a positive NPV at the PST site and from ≥ 50% at SMR. Concerning scenario 3, the sale of seaweed and CC, driven by Pelamis farms at the PST site, increases NPV between 321- 2582% and profitability between 28.6-271%, with a decrease in PP between 3.4-12.8 years (not shown). At the SMR site, NPV increases between 43.8-271.1%, profitability between 7-14%, and reaches a PP between 18.02 and 9.8 years. MEPs composed of WaveDragon farms do not recoup the investment made over the projected lifetime due, in large part, to their associated high CapEx.

Table 14. Net present values of the coupling of WEC farms with different production percentages of the *Ulva sp.* culture. Scenario 5.

	0%	**25%**	**50%**	**75%**	**100%**
Pelamis farm at SMR	-9.10	-5.11	1.78	8.67	15.57
WaveDragon farm at SMR	-76.23	-61.71	-54.82	-47.93	-41.03
Pelamis farm at PST	0.89	3.75	10.45	17.16	23.87
WaveDragon farm at PST	-24.68	-20.71	-13.82	-6.94	-0.05

The percentages represent the seaweed produced as a function of the annual energy production by each WEC farm at the PST and SMR selected sites.

3.3.6 Projected LCoE and profitability for the deployment of the WEC farms based on the 2030 roadmap

Table 15 shows the techno-economic estimates obtained from the WEC farms based on the projected 2030 roadmap. Concerning scenario three, it is observed in the 2030 projection that CapEx and OpEx decreased by an average of 23.2% and 13.8%, respectively. Likewise, the AEP increases by a mean of 72.9%, which generates a reduction in the mean LCoE of 52.4%. This can be mainly associated with the learning and cost reduction produced by the increase in projected installed capacity and the performance generated by the new generations of more efficient WECs *adapted to* the local moderate $\overline{\mathrm{P}}$ [16].

Table 15. Summary of techno-economic analysis of the WEC farm based on the 2030 roadmap. Scenario 6.

	PST		**BSM**	
	Pelamis	**WaveDragon**	**Pelamis**	**WaveDragon**
I_P [MW]	1.5	7	3	14
CF [%]	55.1	15.3	33.7	9.6
AEP [MWh]	7237	9385	8862	11773
CapEx [M$]	8.13	21.67	14.45	41.74
OpEx [M$]	0.73	1.95	1.30	3.77
LCOE [$/MWh]	228.42	469.97	331.40	720.77
NPV [M$]	18.96	3.04	14.03	-25.75
ROI [%]	33%	7%	17%	-
PP [yrs.]	3.64	17.01	8.02	-

I_P is the nominal capacity, CF is the capacity factor, AEP is the annual energy production, CapEx and OpEx are the investment, maintenance, and operating costs, LCoE is the levelized cost of energy, NPV is the net present value of the investment, ROI is the return on investment, and PP is the payback period. CF, CapEx, and OpEx are projected from [39,47,189] and adapted to AEP determined by Gorr-Pozzi et al. [17]. PST and SMR are the selected sites.

The net present value generated by the different WEC arrays based on the actual and projected 2030 CF *is* shown in Figure 21. Except for the WaveDragon device at the SMR site, the rest of the WEC farms projected through 2030 show a positive NPV, denoting a higher return on future investments. Among all the sites, the Pelamis farm at the PST site produces a positive NPV both in the present and in 2030. In addition, this WEC farm generates the highest projected NPV, equal to 18.96 M$, with an ROI of 33% and a PP of 3.64 years. This can be associated, mainly, with the fact that the Pelamis farm at the PST site presents the highest increase in CF, equal to 23%.

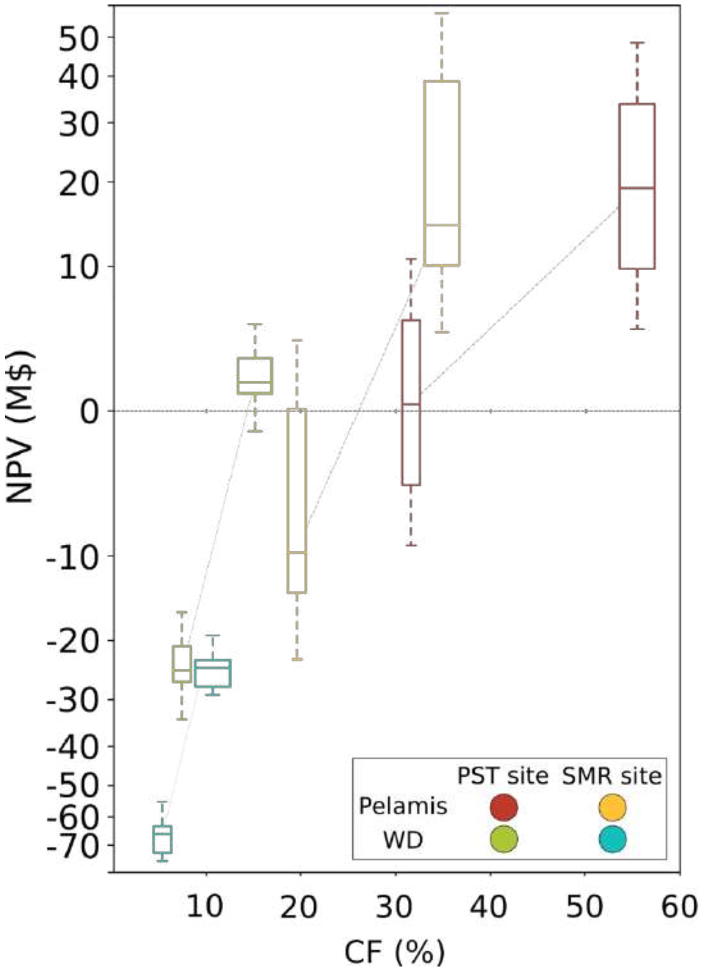

Figure 21. Net present values as a function of capacity factor generated by Pelamis and WaveDragon devices (WD) at PST and SMR sites in 2022 (thin boxes) and 2030 (thick boxes). Each WEC site is represented by a different color.

The comparison between the current and projected 2030 LCoE and CF produced by the WEC farms agains other power generation options is shown in the Figure 22. As can be seen, all the WEC farms show a higher reduction in projected LCoE to 2030 than the rest of the power generation technologies. This can be associated with the usual behavior described by emerging technologies through an exponential learning curve with a cost reduction as their installed capacity increases [47]. Although it is observed that the projection to 2030 generates a LCOE reduction and an increase in CF in all the WEC farms analyzed, no proposed WEC site is able to place in the cost range of traditional renewable and fossil technologies. Although the Pelamis device at the PST site, for example, is estimated to produce a CF close to onshore wind, offshore wind, and concentrated solar technologies (between 53 and

56%) in 2030, the high CapEx and OpEx associated with the WEC farms generate a large LCoE. Although the electricity costs from WEC farms are expected to continue to decline over the next decade, continued innovation and development of new, more cost-effective generations of WECs that are increasingly competitive with other power generation technologies are necessary.

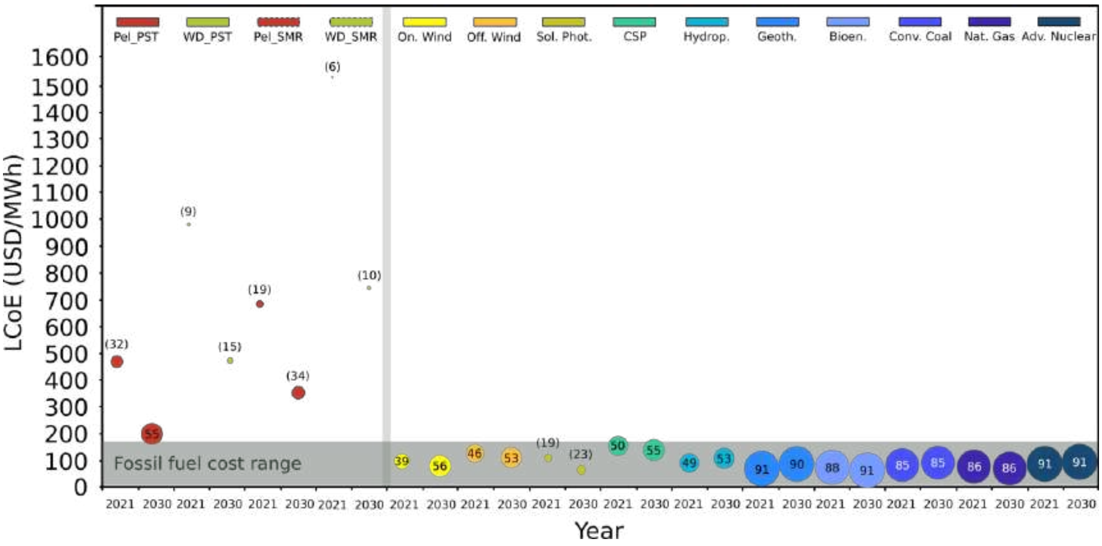

Figure 22. Levelized cost of energy and capacity factors generated by different energy options at present (2022) and projected (2030) adapted from [17,39,47,189]. Each technology is specified with different colors. Pelamis (Pel) and WaveDragon (WD) farms are represented in red and green colors, respectively. The diameter of the circles is a function of their respective CF (expressed as a percentage inside and in parentheses above the circles). The shaded area represents the cost range of fossil fuel technologies.

It should be noted that the analysis does not monetize the benefits obtained from the use of electricity, freshwater or the increase in the quality of life of coastal populations. In future work, it is recommended that these benefits be included so that financial indicators can be more attractive to promote investment in these sustainable solutions.

3.4 Summary and Conclusions

This study presents the techno-economic feasibility of Marine Ecoparks powered by wave energy converters to satisfy a DES and produce different services from the coupling with desalination and seaweed aquaculture sub-modules, such as freshwater, food, clean energy certificates, and carbon credits in the arid coastal region of Baja California, Mexico. For this purpose, the contribution per coupled unit to MEP profitability is calculated through six proposed scenarios using a financial model based on technical and economic cost data available in the literature and on WEC performances obtained from wave simulations results, to determine the LCoE, NPV, ROI and PP indicators.

It is observed in all cases that Pelamis device generates higher techno-economic benefits with lower mean LCoE and higher profits values than WaveDragon at the selected sites. This is associated with lower CapEx and OpEx, and higher throughput generated by the Pelamis device than WaveDragon. In addition, it is observed that CF and AEP condition LCoE and economic profitability to a greater extent than CapEx and OpEx, so that areas with higher $\overline{\mathsf{P}}$ availability generate the lowest LCoE and maximum profits from MEP plants.

The financial evaluation showed that the MEP is economically viable, based on using WECs in arrays and CEL. The economy of scale, the reduction of CapEx and OpEx, the higher AEP per plant, and the CEL instrument improve the investment in all the cases analyzed. However, only the Pelamis farm at the PST site generates a positive NPV. This plant produces a CAPEX of \$10.59 M, an OPEX of \$0.85 M, and an AEP of 4187.2 MWh generating an LCoE of \$479.68/MWh. These values should be considered indicative of the economic viability of this system with an NPV of 0.89, an ROI of 7%, and a PP in 18.23 years.

In no case would seawater desalination be profitable. This is due to the high CapEx and OpEx costs associated with SWRO production, which do not allow recovering the investment made in the MEP project. However, seaweed aquaculture was the most profitable product, followed by electricity. The sale of energy, CEL, *Ulva sp.*, and carbon credits generates benefits in all the cases analyzed. The higher the percentage of seaweed sold, the higher the NPV of the MEPs. However, only the Pelamis device generates returns on investment. The sale of *Ulva sp.* and CC, driven by the

Pelamis farms, generates higher profitability at the PST site with an NPV between 0.89-23.87%, an ROI between 7-26%, and a PP between 5.27-18.11 years.

Based on the projected estimates for the 2030 roadmap, a reduction in CapEx and OpEx is observed in all the WEC farms analyzed. This is associated with high learning and competitiveness developed by the deployment of installed capacity and AEP by the new generations of more efficient and adapted to moderate $\overline{\mathsf{P}}$ WEC, resulting in a reduction of average LCoE and increased competitiveness in the electricity pool. Except for the WaveDragon device at the SMR site, the rest of the WEC farms show positive NPVs. The Pelamis farm at the PST site produces the highest projected NPV since this WEC farm has the highest CF increase, equal to 55.08%.

Comparison against other power generation technologies shows that WEC farms develop the highest reduction in LCoE projected for 2030. Despite this, no proposed WEC site is capable of falling within the cost range of traditional renewable and fossil technologies, which disqualifies them competitively. It is necessary to continue with the innovation and development of new generations of cost-effective WECs that leverage the higher percentage of financing and increase competitiveness with other energy generation technologies, thus improving the adaptive capacity and sustainable development of arid coastal regions.

Chapter 4: ADAPTABILITY OF THE MEXICAN ENERGY SYSTEM TO CLIMATE CHANGE

The extraction of energy from renewable sources is conceived as a possible solution to mitigate the impending global climate crisis. In particular, wave energy is considered one of the most promising marine renewable resources to be harnessed thereby promoting climate change mitigation and fostering the sustainability of coastal systems. The challenge of the transition to low-carbon technologies creates the need to seek new scientific approaches that recognize the complexity of renewable energy systems. This chapter aims to address, from a systemic perspective, the challenges to wave energy generation in the current Mexican socioeconomic context. Based on a holistic and interdisciplinary vision, integrating environmental, social, and economic dimensions, the diversity of actors involved in the wave energy system is identified. It is also determined how they relate, interact and define themselves interdependently. This generates, in turn, emergent properties, feedback, adaptation, management, and learning processes. Some synergies and interactions must be articulated and reconstructed to achieve better functionality and progress of the wave energy system. Co-management, follow-up, and joint work among all stakeholders will lead to better management and increase the adaptability and resilience of the system. Achieving a successful energy transition in Mexico requires a paradigm shift that guarantees environmental protection for sustainable development.

4.1 Introduction

Electric power is one of the driving forces for a country's development, economic growth, and social well-being. The continuous increase in world energy demand, as a consequence of the expansion of a globalized economy and demographic growth, has generated a scenario that demands a paradigm shift in the energy system. The energy transition towards new renewable technologies capable of taking advantage of clean energy sources, which do not produce greenhouse gases or polluting emissions, contribute to mitigating climate change and promoting sustainable development [190].

On a global scale, energy systems produce ~60% of total anthropogenic greenhouse gas emissions and therefore constitute a central focus for urgent action to combat climate change and its environmental impacts [3]. Global CO_2 emissions related to electricity and heat generation grew by 1.7% in 2018, reaching an all-time high of 33.1 Gt CO_2 [68]. Among the different contributors, coal-fired thermal power plants are responsible for 30% of global emissions of that pollutant gas. Climate change adaptation is particularly relevant for developing countries, as they are the most affected by climate effects [1]. The capacity and potential of human adaptation are distributed unevenly across regions and populations, with developing countries generally having a lower adaptive capacity [2].

In 2015, the 193 member states of the United Nations adopted a new agenda for Sustainable Development Goals (SDG) [191]. The 2030 SDG succeeds the UN Millennium Development Goals (MDGs) and includes 17 Sustainable Development Goals and 169 Targets that UN member states have committed to implement by 2030. Prior to the SDG, energy was not explicitly mentioned within the MDGs and came to be referred to as "missing" [192]. During the operational period of the MDGs and the negotiation of the 2030 Agenda, energy was emphasized as the basis for social and economic development, dependent on the sustainable management of our planet's natural resources. This inclusion in the SDG –goal number 7 (SDG7): "affordable and clean energy"– highlighted sustainable energy as one of the central themes of the 2030

Agenda. SDG7 is composed of five goals: ensure universal access to affordable, reliable, and modern energy services (7.1); increase the share of renewable energy in the global energy mix (7.2); double the global rate of improvement in energy efficiency (7.3); strengthen international cooperation to facilitate access to clean energy research and technology (7.4), and promote investment in energy infrastructure and clean energy technologies (7.5).

In this international context, Mexico's Energy Transition Law establishes a legal framework for clean energy, energy efficiency, and the reduction of greenhouse gas emissions [4]. This law stipulates that, by 2024, 35% of electricity generation should come from clean sources.

Recent technological advances indicate a clear intention to take advantage of natural resources cleanly and efficiently. Transforming primary energy sources into electricity creates new horizons in terms of technological development and innovation worldwide [67]. Currently, renewable energies have become a viable alternative to fossil fuels to meet the growing energy demand of industrialized societies [190]. The energy transition gained momentum in 2021, with a 38% contribution of renewables to global installed capacity amounting to almost 257 GW that avoided the emission of 1.076 $GtCO_2$ into the atmosphere [6,7].

Conventional renewable energy sources include hydroelectric, biomass, wind, geothermal and solar. Marine Renewable Energy (MRE), however, has a high availability that has not yet been fully exploited [11]. Among the different MRE sources, wave energy is one of the most promising to be harvested on a larger scale shortly due to its high energy density per unit area and feasibility of extraction [18]. Globally, wave power is estimated to be between 1 TW and 10 TW, the same order of magnitude as the world's energy demand. Locally, their extraction and conversion into electrical energy depend on the characteristics of the waves, the technology available for their harness, and the particular site characteristics [17].

Although estimated in enormous quantities, the spatial distribution of wave energy is limited to those areas of the planet where current technology allows viable extraction. The extratropical regions of both hemispheres have the highest amount of wave power ($\geq$ 60 kWm^{-1}), which decreases latitudinally towards the equatorial region where the lowest values are present ($\leq$ 10 kWm^{-1}) [18]. This crudely suggests that the marine platform of Western Europe, the North coast of England, the Pacific coast of South America and North America, as well as Africa, Australia, and New Zealand, are potential areas to take advantage of this energy resource [69]. The Baja California peninsula is within these potential areas and has the highest wave energy availability along the Mexico coast, with maximum values close to 20 kWm^{-1} [14,17].

The idea of converting wave energy into usable energy forms is not new. The first patented techniques date back to 1799 [193]. However, the boom in research and development associated with wave energy conversion became more pronounced after the dramatic increase in oil prices in 1973. Compared with other sources, wave energy has the advantage of being predictable and flowing naturally from generation zones to coastal areas, where it can be harnessed through WECs.

Promoting national economic development based on energy security and human and environmental well-being requires innovative ways to reduce dependence on fossil fuel sources, reduce greenhouse gas emissions and foster sustainable growth. Bringing together and increasing the link between the capabilities of academia, industry, and other stakeholders requires a paradigm shift in how renewable energy is conceived [48]. Complex systems is a perspective that allows us to explore how two or more subsystems are integrated and interdependent [62]. This chapter presents a proposal towards a systemic perspective as a tool to address and make the development and implementation of wave energy generation processes more efficient.

4.2 Problem Statement

MRE development is held back by industry downturns and a shortage of investors due to their unwillingness to assume the high economic risks present in the early stage of development. For example, ten WEC technology developers raised more than \$500 million between 2005-15, prior to the financial market crisis associated with rising capital costs and low annual energy production, making the technologies less affordable [32]. Furthermore, the diversity of WEC prototypes that put investors in uncertainty, the lack of development of new and more efficient WEC generations, and the high construction, installation, and maintenance cost negatively interfere with the wave energy industry progress. In recent years, the increased efficiency and reduced installation costs of conventional renewable technologies have led to a significant decrease in the Levelized cost of energy (LCoE) and increased competitiveness in the electricity pool (mainly onshore wind, followed by solar PV and offshore wind) [194]. As a result, an increase in installed capacity and a number of increasingly profitable renewable developments have been observed, even in the face of hydrocarbon options. However, the incipient stage of emerging MREs still generates low viability for their development competitiveness and installed capacity. This, in turn, leads to less consideration and operational need in the power grid to adapt to their technical needs in coastal areas [195,196]. In turn, it could have indirect repercussions on the public policy domains, with the non-compliance of the Energy Transition Law and international treaties, and promotes a lower use and availability of clean energy by consumers (socio-economic sphere and local community) and a higher environmental impact since no alternatives to cut down on emissions of polluting gases are pursued. Under this scenario, the feedback mechanisms generate a low resilience of the wave energy system.

4.2.1 Toward a systemic perspective of the wave energy system

The epistemology of the academic sciences that investigate and address clean energy has been changing from disciplinary and multidisciplinary approaches to interdisciplinary research frameworks that incorporate integral concepts in the environment, such as culture, landscape, and aesthetics, among others [197,198]. The integration and articulation of multiple academic disciplines under the same perspective generates a helpful tool when addressing a specific problem [127,199,200]. Participatory and dynamic multidisciplinary strategic alliances create a new object of study that nourishes the resulting synergies to overcome the scientific-technological barriers and challenges required for a functional Mexican Energy Transition.

Since the second half of the 20th century, complexity has been explicitly and systematically investigated and addressed from various conceptual and experimental perspectives [62,201,202]. The imminent transition to clean energy requires the search for new scientific approaches that allow glimpsing of the complexity of renewable energy systems [61]. Complexity techniques and tools offer a powerful avenue to understand and articulate the systemic structure from a holistic perspective to ensure better functionality of the low-carbon energy system [63,64]. Such a management strategy, approached from co-management, encapsulates and regulates sectors related to government, law, and society [65]. The inclusion and monitoring of the different actors, from a local vision extrapolated to national and international levels, will generate better management and adaptability of the wave energy system in the Mexican context.

Feedback, prediction, and synchronization exist in living beings, nature, society, and machines. These principles are essential to maintaining an effective and balanced organization for nonlinear and complex dynamic systems [203]. Thus, the Mexican wave energy system must be autonomous, and its self-organization must promote interaction among its components as feedback for adaptation towards a sustainable energy transition that meets the needs of society.

From a complex systems perspective, the structure of the wave energy system is defined by the boundaries and the components or subsystems. The latter may be present at different organizational levels and are differentiated by their own "semi-autonomous" dynamics that cannot be studied independently since each modulates the activity of the adjacent components (Figure 23). The boundary condition does not necessarily determine the processes occurring in the core part of the system but can influence the entire system, including its foundation. Boundary conditions are defined as the third level and include international policies (e.g., the Paris Agreement [9,191]) related to climate change [68]. In addition, it shares some components with the second level – such as decision makers and public policies– which are also present in the first level. The first level, the core level, is defined by the four components of the wave energy system: decision-makers, public policy, socio-economic and environmental.

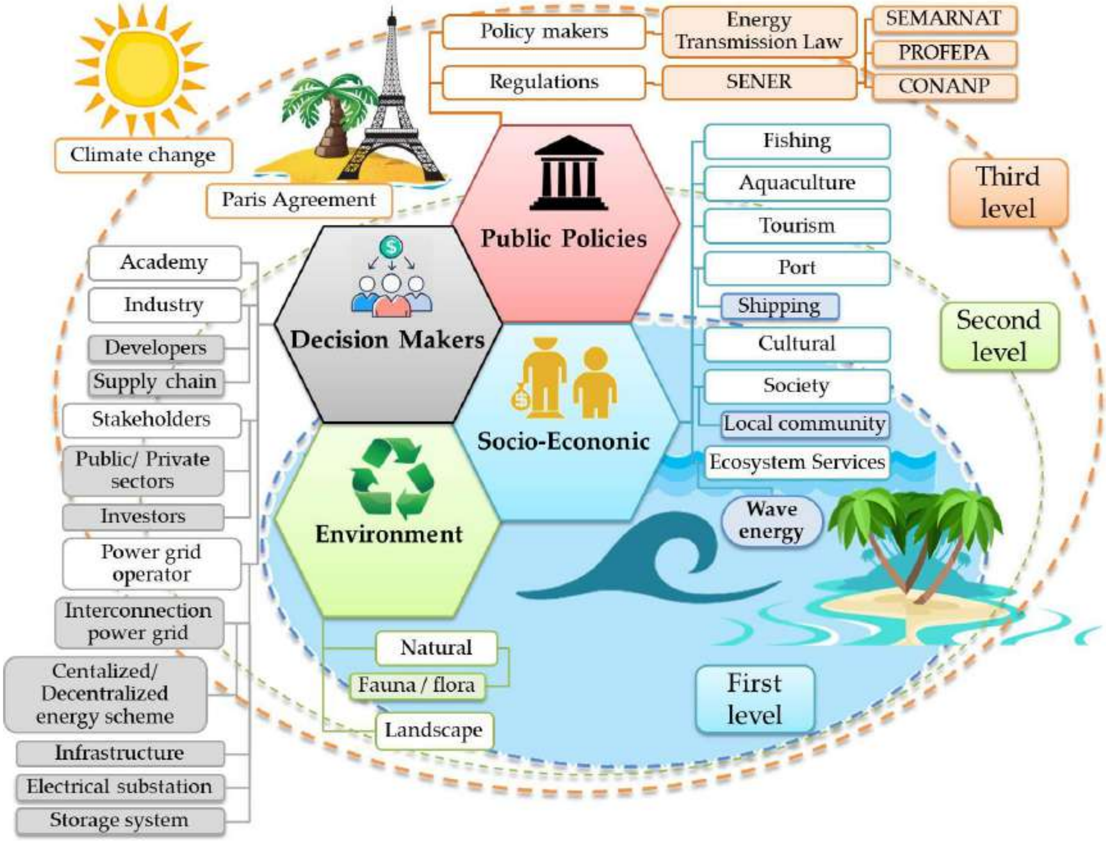

Figure 23. Structure of the complex wave energy system in Mexico.

The elements of the complex system proposed here are conceptualized and integrated within each component in an interdependent and interdefined manner, so their analysis requires an interdisciplinary vision. The Decision Makers component integrates the elements: academia, industry, developers, private sector, investors, grid operators, infrastructure, distribution, electric substation, and storage system (Figure 23). Public Policy integrates regulations, policymakers, Energy Transmission Law, SENER, SEMARNAT, PROFEPA, and CONANP. The Environmental is composed of the natural fauna, flora, and landscape, while socioeconomic for fishing, aquaculture, tourism, port sector, transportation, culture, local community, ecosystem services, and the renewable resource under study, waves.

As a result of the relationships between the elements constituting the wave energy system, different articulation functions or processes are generated. For example, the processes involved in third-level climate change, on an international and global scale, will become progressively more recurrent for local and national environmental issues [204]. Some synergies and interactions limit or impose severe constraints on the development and progress of the wave energy system [39,44]. Therefore, processes must be rearticulated to achieve better functionality and deployment of the wave energy system.

4.3 Summary and Conclusions

This chapter proposes the need to articulate certain elements that play an essential role in the functionality of the wave energy system. Within the realm of decision makers, by increasing cooperation, contribution, and synergy between established developers, academia, and government, it is expected to foster the development of new generations of more efficient WECs with a lower price in the market, which will also boost the deployment of WEC industries. The production of more efficient and lower-cost devices is likely to attract the attention of stakeholders, enabling more investment to drive WEC development. This momentum will generate pressure on industries related to the operation of the electricity grid, encouraging interconnection and the development of infrastructure that facilitates electricity distribution. In the public policy domain, this will promote compliance with the Energy Transition Law and other international treaties. Furthermore, because sustainable energy systems are complex socio-technical systems with a social network where a variety of players jointly develop, operate and maintain the technical infrastructure, the success of the energy system depends –in addition to market dynamics, regulations, and support from different stakeholders– on social acceptance [205]. The co-management tool would allow the incorporation of local communities from the very beginning and provide them with adequate opportunities to participate in the decision-making process. In this way, furthermore, in addition to increasing the acceptance of MRE projects, in the socio-environmental sphere, communities will be able to have clean energy, which will reduce polluting emissions, promoting environmental protection (environmental sphere) and sustainable development. In this way, it can be seen how through local co-management and the articulation of certain key elements, it is possible to promote the increase of the resilience of the Mexican wave energy system and, in turn, contribute to mitigating climate change on a global scale.

The wave energy system is composed of interdependent elements that cannot be analyzed separately. Addressing this problem from a holistic perspective that can explain the system's complexity and the incorporation and integration of different academic disciplines and concepts under an interdisciplinary vision are required. The precise articulation of all the actors involved, grouped within the decision-making, socio-economic, public policy, and environmental components, guarantees a better functionality of the system. Thus, complexity techniques and tools offer a powerful means to understand the complex decision-making processes needed to implement a low-carbon system. The applicability of a complex systems approach as a management tool could ensure better management of renewable resource and foster the viability of wave-based renewable energy development in Mexico.

Co-management, follow-up, and networking among all the actors involved will generate better management and increase the adaptability and resilience of the system. Achieving a successful energy transition in Mexico requires a paradigm shift to ensure sustainable development and the sustainable use of energy.

Chapter 5: SUMMARY

This study presents a characterization of the wave energy resource and an assessment of WEC farms' performance that satisfy a DES in the coastal region of Baja California, México. In addition, the techno-economic feasibility of Marine Ecoparks powered by WECs are evaluated to produce different services such as freshwater, food, clean energy certificates, and carbon credits. Finally, the elements that conform the wave energy system are identified from a theoretical framework of complex systems.

For this purpose, the wave power availability is determined using 11 years of high-resolution wave hindcast made with the SWAN spectral model. Wave simulations have been validated with ADCP measurements, showing good agreement and increasing confidence in the results. Furthermore, the contribution per coupled unit to MEP profitability is calculated through six proposed scenarios using a financial model based on technical and economic cost data available in the literature and on WEC performances obtained from wave simulations results, to determine the LCoE, NPV, ROI and PP indicators. Complexity techniques and tools offer a powerful means to understand the complex decision-making processes needed to implement a low-carbon system. The applicability of a complex systems approach as a management tool will ensure better management of the renewable resource, which will foster the viability of wave-based renewable energy development in Baja California.

The wave power availability in Todos Santos Bay and its surroundings was determined using 11 years of high-resolution wave hindcast made with the SWAN spectral model. Wave simulations were validated with ADCP measurements, showing good agreement and increasing confidence in the results. Based on the results, it is found that the study area has several sites suitable for wave energy extraction. The area presents moderate wave power availability with a mean annual value close to 10 kWm−1. Best sites identified for wave energy extraction are associated with bathymetric features that concentrate wave energy through refraction processes. These results also demonstrate the importance of using high resolution numerical wave simulations and bathymetric data for wave energy assessment in coastal seas. The most appropriate locations for wave energy extraction are identified through hotspots of maximum availability and lower temporal variability of the resource. The PST and SMR sites present the highest mean availability of the wave resource in the studied region, the former having a higher wave power than the latter. Wave power has a considerable temporal variability in the analyzed domain, and both selected sites have a lower interannual variability than intra-annual variability. Considering only the availability and temporal variability of the resource, the deep location of PST is the most suitable for extracting wave power in the analyzed domain.

Numerical wave models allow the estimation of the extractable wave power and WEC performance at specific locations. The generation capacities of the analyzed WECs show a similar trend to that of $\bar{P}$, higher at the PST site than at SMR during the winter season. Among all the evaluated devices, WaveDragon and Pelamis extract the highest wave power at the selected shallow and deep locations, respectively. Pelamis appears to be the most attractive WEC technology to implement because it is the best adapted to the local wave climate, producing the highest capacity factors at the selected sites. Due to the high seasonal variability of the extracted wave power by WEC farms in the region, energy storage modules or support with hybrid renewable systems could be suitable complements to satisfy a constant power supply during the less energetic summer months.

The facility of the WEC farm may have a significant impact on nearshore wave characteristics and the environment. Detailed studies are required to assess the effects of WEC farms on the near-field and nearshore wave climate, currents, and sediment transport, as well as possible conflicts with other activities existing in the marine coastal zone.

From the techno-economic analysis of WEC farms and Marine Eco-parks, it is observed that the Pelamis device generates higher benefits than Wave Dragon in all cases, with a lower mean LCoE and higher profit values in the selected sites. This is associated with lower CapEx and OpEx, and higher throughput generated by the

Pelamis device than WaveDragon. In addition, the CF and AEP condition LCoE and economic profitability to a greater extent than CapEx and OpEx, so areas with higher wave power availability generate the lowest LCoE and maximum profits from MEP plants. The financial evaluation showed that the MEP is economically viable, using the WECs in arrays and CEL. The economy of scale, the reduction of CapEx and OpEx, the higher AEP per plant, and the CEL instrument improve the investment in all the cases analyzed. However, only the Pelamis farm at the PST site generates a positive NPV. In no case seawater desalination powered with wave energy is profitable. This is due to the high CapEx and OpEx associated with the SWRO system, which does not allow for recovering the investment made in the MEP project. Instead, seaweed aquaculture was the most profitable product, followed by electricity. The sale of energy, CEL, *Ulva sp.*, and carbon credits generates benefits in all the cases analyzed. The higher the percentage of seaweed sold, the higher the NPV of the MEP. However, only the Pelamis device generates returns on investment. The sale of *Ulva sp.* and CC, driven by the Pelamis farms, generates higher profitability at the PST site with an NPV between 0.89-23.87%, an ROI between 7-26%, and a PP between 5.27-18.11 years. Based on the projected estimates for the 2030 roadmap, a reduction in CapEx and OpEx is observed in all the WEC farms analyzed. This is associated with high learning and competitiveness gained by the deployment of installed capacity and with an increase in energy production due to the new generations of more efficient WECs developed for low to moderate wave energy conditions, resulting in a reduction of average LCoE and increased competitiveness in the electricity pool. Comparison against other power generation technologies shows that WEC farms have the highest LCoE reduction projected by 2030. Despite this, none of the proposed WEC farms fall below the cost range of traditional renewables or fossil technologies, which makes them less competitive.

Cooperation, contribution and synergy between established developers, academia and government are expected to foster the deployment of a new generation of more efficient and lower cost WECs in the market. This is likely to capture the attention of stakeholders, accompanied by a higher number of investors willing to step in and drive the deployment of the WEC industry in Mexico. These players could generate pressure on other sectors related to the operation of the electricity grid, encouraging interconnection and the development of infrastructures that facilitate the transmission and distribution of electricity from renewables. Furthermore, in the socio-environmental sphere, through co-management, communities will intervene as stakeholders and will be able to choose to have access to clean energy, which will reduce polluting emissions, promoting environmental protection (environmental sphere) and sustainable development. In this way, it can be seen how, through the use of management tools and the articulation of certain key elements, it is possible to promote the increase of the resilience of the Mexican wave energy system and, in turn, contribute to mitigating climate change on a global scale. Thus, it is clear that the wave energy system is composed of interdependent elements that cannot be analyzed separately. Addressing this problem from a holistic perspective -that can explain the system complexity- the incorporation and integration of different academic disciplines and concepts under an interdisciplinary vision are required. The precise articulation of all the actors involved, grouped within the decision-making, socio-economic, public policy, and environmental components, guarantees a better functionality of the system.

Co-management, follow-up, and networking among all the actors involved will generate better management and increase the adaptability and resilience of the wave energy system. Achieving a successful energy transition in Mexico requires a paradigm shift to ensure sustainable energy development and harnessing.

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