# Hybrid marine eco-parks. Techno-economic analysis in potential Latin America markets

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## I. INTRODUCTION

THE global weighted-average increase in technology readiness levels, installed capacity, and the reduction of new commissioning costs of commercial-scale renewable installations have been the main factors in achieving a competitive levelized cost of energy (LCoE) in the electricity pool, even below the fossil fuel cost range [1].

Diversification and modernization of the energy matrix through the affordable, safe, and sustainable harvester of Marine renewable energies (MRE) are possible ways to mitigate the vulnerability of coastal communities and climate change [2]. MRE includes ocean currents, tides, thermal and salinity gradients, wind waves, and offshore wind.

Several countries have considered offshore wind energy a crucial resource to drive the energy transition. It has some advantages over onshore wind energy, such as higher wind power, availability of large areas for the installation of wind farms, and lower resource variability [3]. Driven by the learning level and experience accumulated from long-term exploitation by onshore wind technologies, with a global total of 56 MW of nameplate capacity in 2021, offshore wind is weighted as the most competitive MRE [4].

Wave energy resource is another promising MRE with vast reserves available to be exploited on a large scale in the near future due to its high energy density per unit area, predictability, and that it naturally flows to coastal zones where its extraction is more cost-effective [5]. However, most wave energy converter (WEC) projects remain in the development phase of commercial scale performance reliability, and the broad range of LCoEs, between 75 and 500 USD/MWh, hamper their funding and commercial deployment [6], [7].

The integration of multiple RE sources, known as hybridization, offers several advantages in RE systems. By combining different energy sources, renewable hybrid systems (RHS) can improve reliability, increase efficiency, reduce costs, provide environmental benefits, and increase flexibility. RHS can balance the variability of RE sources, reduce the need for energy storage, and minimize greenhouse gas emissions. Hybridization can make renewables more competitive than traditional energy sources and provide a more sustainable and reliable energy supply [8].

Batteries and hydrogen are two relevant energy storage technologies that can be integrated into RHS, offering a range of advantages. Batteries can store excess energy generated by renewable sources, providing a more stable and reliable power supply. The stored energy can be used during low RE production or periods of high demand. On the other hand, green hydrogen can be produced and stored as fuel to satisfy the transportation, heating, and power generation markets. Overall, the batteries and hydrogen integration in RHS can improve stability, reliability, and sustainability of energy production and distribution, although investment, operation, and maintenance costs can be high [9], [10].

Marine hybrid Ecoparks (MHE) are multipurpose coupled systems integrated in clusters by MREs and consolidated coastal industries, which may prove to be a sustainable strategy to accelerate the viability and competitiveness of emerging MREs [11], [12]. They can provide high commercial value by-products, developing the blue economy and the resilience of coastal communities [13], [14]. In addition, MHE units co-located with WEC and offshore wind turbines (OWT) arrays and marine aquaculture modules emerge as a potential solution that can strengthen energy and food security [15].

This study aims to understand the techno-economic feasibility of implementing coupled WEC and OWT systems by exploring hybridization and by-products to increase the cost-effectiveness of MHE deployment in a blue economy framework at two potential sites in the Latin American region.

## II. METHODS

A techno-economic analysis was developed for two wave-wind hybrid renewable systems (WWHRS) using Pelamis (PEL) and WaveDragon (WD) WECs in two locations: La Serena (Chile) and Ensenada (Mexico). A microgrid interconnected electrical scheme was used to supply electricity to approximately 5,000 households or 68 hectares of aquaculture production (APH), representing the maximum monthly electricity consumption of 620 MWh for both purposes. Eight main scenarios were evaluated for surplus energy to supply electricity to the interconnected grid based on a utility-scale battery energy storage system (USBES) and compared to an electrolysis hydrogen production system (EHPS) (Fig.1).

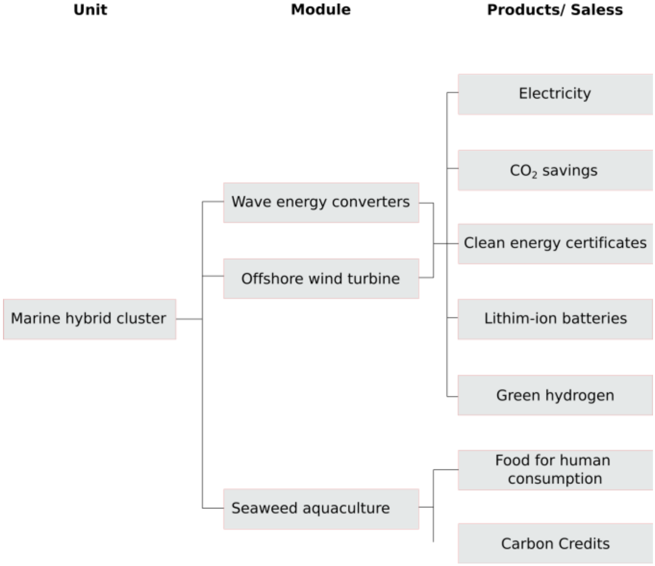

Fig. 1. Marine hybrid cluster components and by-products.

The performance of the WEC and OWT technologies was evaluated at La Serena and Ensenada regions based on numerical simulations. The third-generation wave model SWAN Cycle IV version 41.20AB [16] was implemented to determine wave characteristics and to evaluate wave energy availability and extraction capacity. The SWAN model was forced at the boundaries with directional waves spectra from the IOWAGA wave hindcast [17]. The numerical results were validated using available wave data from GlobalWavedata satellite data for La Serena and Acoustic Doppler Current Profilers (ADCPs) for Ensenada. Details of wave model implementation and validation can be found in [5], [18].

Based on the previous studies by Gorr Pozzi et al. [5] and Selman-Caro [18], the WECs PEL and WD were used to quantify harvestable wave power $HP$ as [5], [19],

$$HP = \sum\sum HR(H \quad) \qquad C(H \quad), \tag{1}$$

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 using the hourly significant wave height ($H_s$) and spectral peak period ($T_p$), $PWEC$ is the power matrix of PEL and WD devices. Power matrices for PEL and WD were obtained from [20], [21], respectively, and PWEC for WEC farms was computed as in [5].

Wind power was evaluated using wind speed from the ERA5 reanalysis [22]. ERA5 has a global coverage from 1940 to date with a spatial resolution around 30 km. Here we use hourly data for 2000 to 2019 from the closest node to each site. Available wind power, $P_w$, was estimated as,

$$- \quad , \tag{2}$$

where is wind speed and is air density. Mean extractable wind power was computed as,

$$\sum n \quad , \tag{3}$$

where $n$ is the wind speed distribution ($Uz$) at the turbine height ($z$), and $C_p$ is the wind turbine power curve. Several $P_{w_{ext}}$ estimates were obtained using diverse wind turbines with nominal capacities between 225kW and 4MW. The wind turbines $C_p$ where obtained from the NREL wind power curve archive. $Uz$ was estimated from ERA5-wind speed at 100 meters height, assuming a wind profile power law with an exponent $\alpha$=0.14 [23],

$$\left(\frac{}{}\right) = \left(\frac{}{}\right) \tag{4}$$

The power generation profiles were obtained after processing the wave power extracted from the two WECs analyzed and the wind power profile. Since the WD in La Serena is the device that generates the highest electricity production, its maximum monthly production (875 MWh) was taken as a baseline to size the WWHRS in the eight main scenarios.

The contribution of each co-located module to the profitability of the MHE unit was analyzed by adapting the methodology of Vega & Michaelis [24]. Capital (CapEx) and operating (OpEx) expenditures for each module were adjusted and updated to the value of the 2023 U.S. dollar based on similar projects and economic data available in the literature. A projected useful life of 20 years was considered for the project, with expenses corresponding to cash flow from CapEx and OpEx, and revenues from product sales. To generate an accurate cash flow model, Chile, and Mexico -specific employee participation, benefits, and deductions, such as profit sharing (PTU) and income taxes (ISR), were also considered. CapEx of WEC farms was calculated from Astariz & Iglesias [6]. As the OpEx of WECs, depends on CapEx, it was calculated as 8% of CapEx, as suggested in several studies [19], [25]. The PEL and WD pre-operating costs were adapted from [6], [26], the individual cost from

[6], the mooring system cost from [26], [27], the underwater cable cost from [28], the electrical the substation from [6], the cost of underground cable from [29], and the decommissioning costs from [30]. The CapEx and OpEx of the OWT module were taken and adapted from the Annual Technology Baseline of the National Renewable Energy Laboratory's (NREL's) [31].

The lifecycle cost of MHE was estimated through LCoE as [32]. A cash flow model was used, and financial indicators were estimated to provide a first-order approximation of the profitability of MHEs under each scenario. The cash flow model includes the incomes generated by the sale of the products (electricity, clean energy certificates, lithium-ion batteries, green hydrogen, dried seaweed, and carbon credits) (Fig. 1) and the expenses associated with the operating and financial costs, depreciation, and taxes. The analysis included the financial indicators' Net Present Value (NPV) and the Internal Rate of Return (IRR).

Electricity selling prices were set at 0.8 USD/kWh for the microgrid and 0.22 USD/kWh for electricity to the grid, based on the selling prices in the two study areas. Renewable energy certificates were priced at USD 7/MWh. [33]–[36]. The annual seaweed crop of one effective hectare (or 10,000 m$^{-3}$) generates a dry weight production of 63.6 ton ha$^{-1}$ yr$^{-1}$ and carbon sequestration of 19 ton ha$^{-1}$ yr$^{-1}$ (assuming a 30% C content [37]), with an energy consumption of 85.1 MWh ha$^{-1}$ yr$^{-1}$. The annual sales of seaweed *Ulva sp*. for human consumption were set at 10,000 USD/ton and the carbon credits at 12 USD/ton [13].

Monthly energy surpluses were obtained through the monthly energy balance and the power balance between electricity generation and consumption profiles. The USBES and EHPS systems to exploit the energy surpluses were sized for each main scenario. The USBES was dimensioned considering lithium-ion batteries with a storage efficiency of 90%, a CAPEX of 2800 USD/kW, and an OPEX of 70 USD/kW per year [38]. The EHPS was dimensioned considering an alkaline electrolyzer with an efficiency of 68%, a CAPEX of 1,460 USD/kW, and an OPEX of 21.9 USD/kW per year. A seawater reverse osmosis system to supply water to the electrolyzer was considered in the EHPS electricity requirements and costs [39], [40]. The selling price of hydrogen was set at 8 USD/kg [41].

### A. Field site

The study analyzes and compares two coastal regions in the southern and northern hemispheres of the eastern Pacific (Fig. 2). La Serena is located in northern Chile, and Ensenada is on the northwestern coast of the Baja California peninsula in Mexico. Both sites are characterized by presenting different wave systems coexisting simultaneously [42], [43].

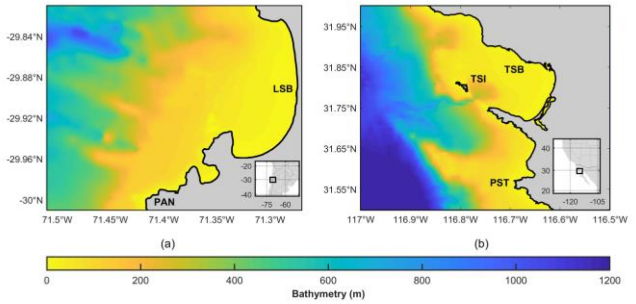

Fig. 2. Study areas in Coquimbo (Chile, panel a) and Ensenada (Mexico, panel b). The color scale expresses bathymetry with values in meters. Panul (PAN) and Punta Santo Tomás (PST) are the selected test sites that overlap with the highest wave energy availability hotspot.

The region of Ensenada and La Serena exhibit a moderate and high mean wave power availability ($\bar{P}$), close to 10 kWm$^{-1}$ and 24 kWm$^{-1}$, respectively [5]. A marked seasonal $\bar{P}$ trend was observed in Ensenada, while in La Serena has a medium-moderate. Mean annual offshore wind speed at Ensenada is close to 3.5 m/s, with a predominant northwest direction and a marked seasonality with higher speeds in spring-summer and lower in autumn-winter [44]. La Serena is located within the most suitable zone for offshore wind exploitation, with an average annual wind density of 730 W m$^{-2}$ and capacity factor of 45% [45]. It presents a marked seasonality, with maximum wind speeds in November (12.8 m/s) and lower in May (1.15 m/s).

## III. RESULTS

The inter- and intra-annual mean wave powers in the selected sites are shown in Fig. 3. The $\bar{P}$ in PAN is 26.05 kW/m (panel Fig. 3(a)), approximately 87.6% higher than in PST, equal to 13.88 kW/m (panel Fig. 3(b)). This is due to the geolocation of both regions studied. The La Serena coast is more exposed and closer to the extratropical South Pacific generation zone, while in Ensenada, the Southern California Bight (SCB), the California Channel Islands, and the Coronado Islands of Baja California

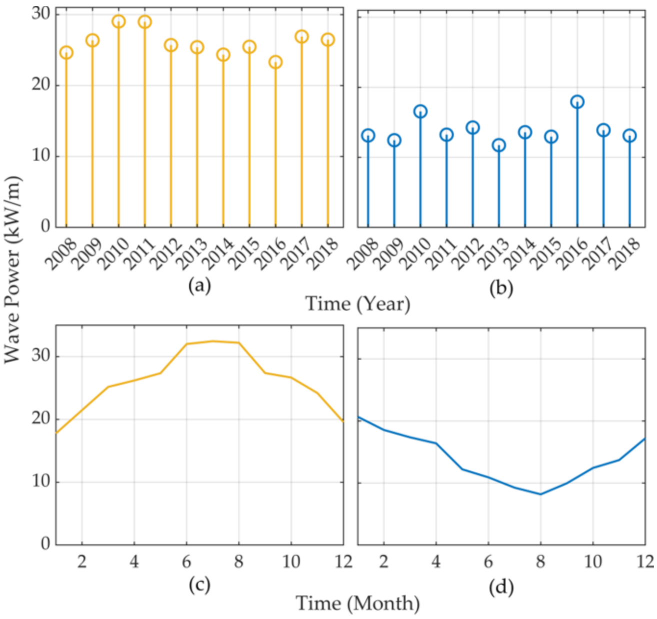

Fig. 3. Mean annual and monthly availability of wave power in the selected PAN (La Serena, panels (a) and (c)) and PST (Ensenada, panels (b) and (d)) sites over the full hindcast period.

produce a shadow effect in incoming swell from the extratropical North Pacific [5], [46].

A relevant aspect of the hybrid renewable system (RHS) design is to evaluate the behavior between generation and consumption. Fig. 4a shows the electricity generation profiles for individual WEC and OWT devices for Ensenada and La Serena. The results show that WECs of the same technology present different performances in the two sites analyzed. The monthly electricity consumption profiles of households and aquaculture in La Serena and Ensenada are depicted in Fig. 4b. The electricity consumption patterns for households in both locations reveal that winter months witness lower consumption levels, whereas summer months experience higher consumption rates. In contrast, the electricity consumption profiles for aquaculture operations demonstrate that autumn months exhibit the highest electricity usage, while winter months display the lowest consumption levels.

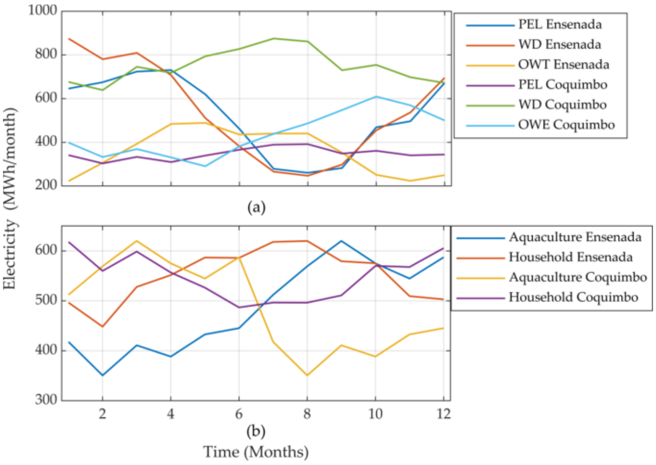

Fig. 4. Electricity generation (panel (a)) and consumption profiles for aquaculture and household (panel (b)) in La Serena and Ensenada.

Fig. 5 shows the LCoE values generated by WWHRS. By comparing both regions analyzed, it is possible to distinguish how the PEL-OWT system in Ensenada shows a slightly lower LCoE than in La Serena, which indicates a more competitive and profitable electricity generation option in Ensenada. On the other hand, the WD-OWT system in Ensenada shows a considerably higher LCoE compared to La Serena. This suggests that La Serena offers a more favourable production cost of a unit of energy for the WD-OWT system.

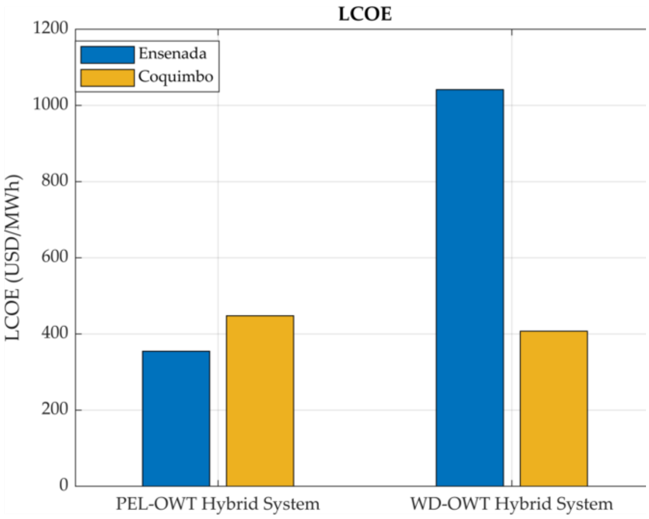

Fig. 5. Levelized cost of energy (LCoE) of the wave-wind hybrid renewable systems (WWHRS) in La Serena and Ensenada according to the degrees of hybridization proposed.

The net present value (NPV) produced by the different scenarios in La Serena and Ensenada is presented in Fig. 6. It can be seen how, regardless of the WEC nature used and the energy surplus, the inclusion of Seaweed aquaculture in a blue economy framework generates higher returns than households, higher in La Serena than Ensenada. WD-Aquaculture follows a similar pattern to PEL-Aquaculture in La Serena, with the USBES sub-scenario producing the highest NPV values. To satisfy Seaweed aquaculture PEL device generates higher returns than WD in Ensenada. The PEL-Aquaculture scenario, the use of batteries (USBES) yields the highest NPV values for both locations. Among the available options, the EHPS sub-scenario offers the highest NPV for both Ensenada and La Serena. Finally, WD's domestic scenario in Ensenada is not profitable with the proposed electricity sales prices.

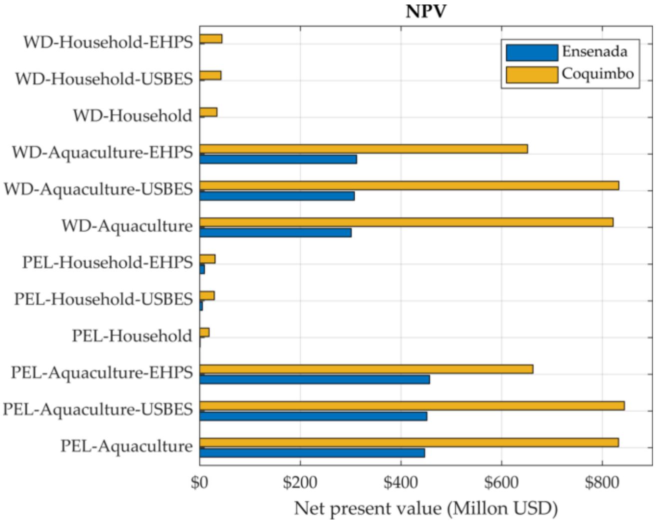

Fig. 6. Net present value (NPV) for the different scenarios in La Serena and Ensenada. It can be seen how only positive NPV values are exposed that do not generate losses in the systems investment.

The Internal Rate of Return (IRR) generated by the different main scenarios and sub-scenarios in La Serena and Ensenada is shown in Fig. 7. As Fig. 6, it can be seen that seaweed aquaculture generates the highest IRR values. In the PEL aquaculture scenario, the reference sub-scenario shows the highest IRR values, indicating a potentially favorable return on investment, while the EHPS sub-scenario yields consistently lower IRR values. Similarly, in the WD Aquaculture scenario, the Reference and USBES sub-scenarios show comparable IRR values, while the EHPS sub-scenario has a slightly lower IRR value. In contrast, the household PEL scenario exhibits lower IRR values, with the reference sub-scenario being the least attractive. The WD household scenario in

Ensenada is unfeasible but shows modest IRR values in La Serena for the Reference and USBES sub-scenarios. It is important to note that the reference sub-scenario generally presents better investment prospects in all scenarios, emphasizing the importance of careful evaluation beyond IRR values alone.

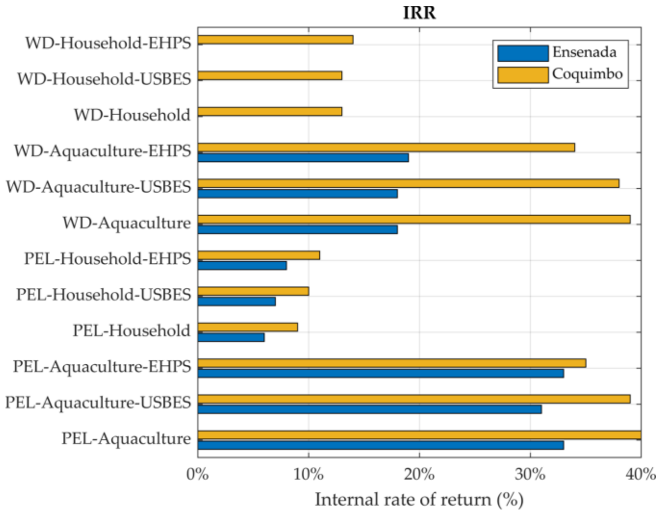

Fig. 7. Internal Rate of Return (IRR) for the different scenarios in La Serena and Ensenada.

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