Techno-economic analysis of marine hybrid clusters in two potential Latin American markets

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Abstract—[1] **Contemporary communities require innovative solutions to cope with projected increases in demand for natural resources. Diversification and modernization of the energy mix through the affordable and efficient harnessing of marine renewable energies (MRE) are possible means to mitigate the vulnerability of coastal communities and climate change. While the offshore wind sector has reached sufficient maturity to compete in the energy market, other MREs, such as wave energy, are still in the development phase, which limits their financing and commercial deployment. This study aims to evaluate the techno-economic feasibility of maritime hybrid clusters (MHC) powered by wave energy converters (WEC) and offshore wind turbines (OWT) to electrify households and the marine aquaculture sector, where electricity surpluses can be stored in lithium-ion batteries or for green hydrogen production. Different scenarios for WaveDragon (WD) and Pelamis (PEL) WEC farms were studied in two coastal communities, Coquimbo (Chile) and Ensenada (Mexico). The mean annual wave power availability at Coquimbo is high (26.05 kW/m) and of Ensenada, moderate (13.8 kW/m). The wave energy shows less inter- and intra-annual variability in Coquimbo than in Ensenada. The hybridization between WECs and OWT covers the total electricity consumption, where the PEL-OWT system is the cost-effective option in Ensenada and WD-OWT in Coquimbo. Ensenada demonstrated a higher electricity surplus than Coquimbo, profitable result of storing it for sale in the electricity market or for hydrogen production. For both selected WECs, the seaweed aquaculture integration in a blue economy framework generates higher returns than households, higher in Coquimbo than Ensenada.**

Keywords— **Marine renewable energy, green hydrogen, renewable hybrid systems, blue economy.**

I. INTRODUCTION

The search for innovative solutions to improve the capacity of the power sector, mitigating impending climate change and the pressure on ecosystem services created by population growth, has driven the development of the renewable energy (RE) sector [1]. 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 [2]. However, RE technologies have reached uneven commercially viability, so their cost-effectiveness still needs to be improved to accelerate their deployment and contribution to climate quotas [3].

Diversification and modernization of the energy mix through the affordable, secure, and sustainable harvesting of Marine renewable energies (MRE) are possible ways to mitigate the vulnerability of coastal communities [4]. MRE includes ocean currents, tides, thermal and salinity gradients, 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 [5]. Driven by the learning level and experience accumulated from long-term exploitation by onshore wind technologies, with a global total of 56 GW of capacity installed in 2021, offshore wind is weighted as the most competitive MRE [6].

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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 [7]. It has been estimated that the energy contained in ocean swell is of the same order of magnitude as the world electricity consumption [8]. However, most wave energy converter (WEC) projects are in the development phase. Uncertainty in their commercial-scale performances and the wide range of Levelized Cost of Energy (LCoE) values, ranging from 75 to 500 USD/MWh, pose difficulties in securing financing and facilitating their commercial deployment [9], [10].

The co-location and integration of multiple renewable energy sources, known as hybridization, offers several advantages to RE systems. Hybrid RE systems (RHS) can increase overall system performance by balancing the variability of RE sources and increasing annual energy production (AEP), which can reduce the need for energy storage. In turn, it can reduce costs and increase the competitiveness of RE, improve reliability, increase flexibility, minimize greenhouse gas emissions, provide a more sustainable and reliable energy supply, or even incentivize a blue economy through the use of RHS in established coastal industries, such as marine aquaculture production [11].

Several MRE studies, have demonstrated the technical and economic advantages of RHS. Naderipour et al. developed a hybrid photovoltaic, wind, tidal, and fuel cell system, considering hydrogen energy storage. The study evaluated three sites where energy costs were compared as a function of RE potential, showing that MREs have a greater contribution in two of the three study sites [12]. F. Mousavi developed a hybrid system of wind and tidal microturbines with battery storage, where based on genetic algorithms, the minimum annual cost of the system was obtained from the optimal sizing and economic analysis of the MRE [13].

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, integration of battery storage and hydrogen generation in RHS can improve stability, reliability, and sustainability of energy production and distribution, although it can increase the investment, operation, and maintenance costs [14], [15]. Different works, such as Sanchez-Dirzo et al., have demonstrated the technical feasibility of hydrogen generation using wave energy. Through the Blow-Jet device, which converts wave energy into electricity using an impulse turbine with an electric generator, it is possible to feed electricity to produce hydrogen in an electrolyzer with a current efficiency of 90.58% [16].

Marine hybrid clusters (MHC) are multipurpose coupled systems integrated by MREs and consolidated coastal industries, which may prove to be a sustainable strategy to accelerate the viability and competitiveness of emerging MREs [17], [18]. They can provide high commercial value by-products, developing the blue economy and the resilience of coastal communities [19], [20]. In addition, MHC units co-located in RHS with WEC and offshore wind turbines (OWT) arrays and marine aquaculture modules emerge as a potential solution that can strengthen energy and food security [21]. Marine aquaculture is considered one of the principal sustainable food production systems, which has presented the highest growth in the last decade [22]. With an annual production of ~32.4 million tons (wet weight) in 2018 valued at $11.8 billion, it is expected to increase by $22.13 billion by 2024 [23].

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 MHC deployment in a blue economy framework at two potential sites in the Latin American region.

II. METHODOLOGY

A techno-economic analysis was developed for two wave-wind hybrid renewable systems (WWHRS) using Pelamis (PEL) and WaveDragon (WD) WECs in two locations: Coquimbo (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 (Table I) 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).

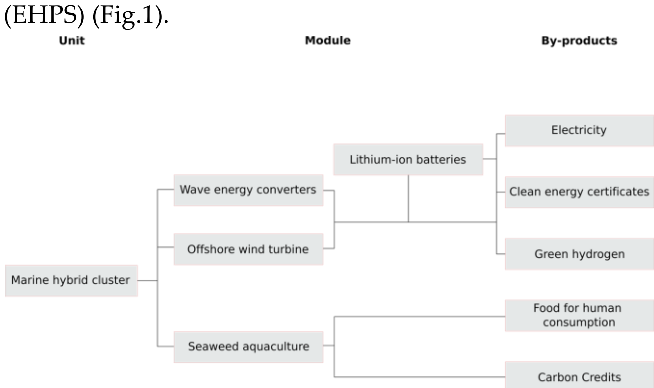

Fig. 1. Marine hybrid cluster components and by-products.

Coquimbo household consumption profile was obtained from EnergíaRegión, while for Ensenada, it was obtained from the Baja California INEGI statistical yearbook [24], [25]. The consumption profile for aquaculture for both sites was based on information from the Productos Marinos de las Californias S. de R.L. de C.V., making an equivalence according to the seasons for each month [26].

The performance of the WEC and OWT technologies was evaluated at Coquimbo and Ensenada regions based on numerical simulations. The third-generation wave model SWAN Cycle IV version 41.20AB [27] 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 [28]. 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 numerical results were validated using available wave data from GlobalWavedata satellite data for Coquimbo and Acoustic Doppler Current Profilers (ADCPs) for Ensenada. Details of wave model implementation and validation can be found in [7], [29].

Based on the previous studies by Gorr Pozzi et al. [7] and Selman-Caro [29], the WECs PEL and WD were used to quantify harvestable wave power HP as [7], [30],

$$HP = \sum\sum HR(H_s, T_p) \cdot PWEC(H_s, T_p), \tag{1}$$

where HR is the wave resource scattermatrix, 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 [31], [32], respectively, and PWEC for WEC farms was computed as in [7].

Wind power was evaluated using wind speed from the ERA5 reanalysis [33]. 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,

$$P_w = \frac{1}{2}\rho U^3, \tag{2}$$

where U is wind speed and ρ is air density. Mean extractable wind power $P_{w_{ext}}$ was computed as,

$$P_{w_{ext}} = \sum nC_p, \tag{3}$$

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 α=0.14 [34],

$$\left(\frac{U_z}{U_{100}}\right) = \left(\frac{z}{100}\right)^{\alpha}. \tag{4}$$

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 Coquimbo 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. In the rest of the main scenarios, a WWHRS consisting of a 3.3 MW OWT and a different number of PEL (0.75 MW) or WD (7 MW) was calculated to complete the electricity consumption required by the microgrid or the APH. The sizing of the WWHRS was developed for the eight main scenarios through an energy balance between electricity consumption and generation profiles, taking as design criteria the supply of the maximum monthly electricity consumption for each one. A generation efficiency of 90% and an electricity transmission efficiency of 78% were considered [35]. The degree of hybridization (DH) is considered as the percentage of energy supplied by the WECs.

The contribution of each co-located module to the profitability of the MHC unit was analyzed by adapting the methodology of Vega & Michaelis [36]. 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 [9]. As the OpEx of WECs, depends on CapEx, it was calculated as 8% of CapEx, as suggested in several studies [30], [37]. The PEL and WD pre-operating costs were adapted from [9], [38], the individual cost from [9], the mooring system cost from [38], [39], the underwater cable cost from [40], the electrical the substation from [9], the cost of underground cable from [41], and the decommissioning costs from [42]. 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) [43].

The lifecycle cost of MHC was estimated through LCoE as [44]. A cash flow model was used, and financial indicators were estimated to provide a first-order approximation of the profitability of MHCs under each scenario. The cash flow model includes the incomes generated by the sale of the products (electricity, electricity stored in lithium-ion batteries, clean energy certificates (CEC), dried seaweed, carbon credits, and green hydrogen) (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. [45]–[48]. 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 [49]), 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 [19].

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 [50]. 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 [51], [52]. The selling price of hydrogen was set at 8 USD/kg [53].

A. Field site

The study analyzes and compares two coastal regions in the southern and northern hemispheres of the eastern Pacific (Fig. 2). Coquimbo 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 [54], [55]. Coquimbo is exposed to energetic swell propagating from the extratropical South Pacific region during the winter season (June-August) and from the North Pacific region in the summer months (December-January) [56]. The most energetic swell reaching Ensenada is propagated from the extratropical region of the North Pacific during the winter and from the South Pacific in the summer. Both zones present the incidence of storms produced by wind-driven seas, associated with low-level coastal atmospheric jets off the coast throughout the year.

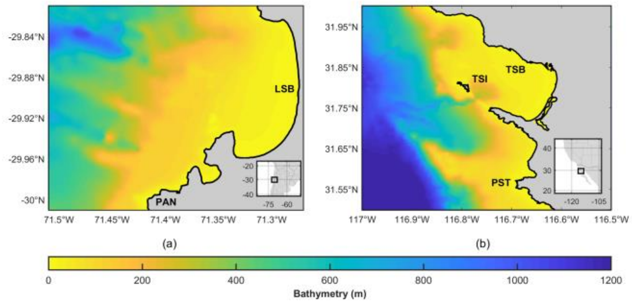

Fig. 2. Study areas in Coquimbo (Chile, panel a) and Ensenada (Mexico, panel b). The color scale expresses bathymetry with values in meters. Panul (PAN) and Punta Santo Tomás (PST) are the selected test sites that overlap with the highest wave energy availability hotspot.

The region of Ensenada exhibits a moderate mean wave power availability ($\bar{P}$), with a mean value close to 10 kWm^{-1} [7]. 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}) [7]. Coquimbo has a high $\bar{P}$, close to 24 kWm^{-1} [29]. The intra- and inter-annual variability of the resource is medium-moderate, with a maximum of $\bar{P}$ during winter (27 kWm^{-1}) and a minimum during summer (19.5 kWm^{-1}). 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 [57]. Coquimbo is located within the most suitable zone for offshore wind exploitation, with an average annual wind density of 730 W m^{-2} and

TABLE I
CHARACTERIZATION OF THE SCENARIOS

Site	WWHRS	Main scenarios	Sub-scenarios
Ensenada	PEL-OWT	Aquaculture	without energy storage
			USBES
			EHPS
		Household	without energy storage
			USBES
			EHPS
	WD-OWT	Aquaculture	without energy storage
			USBES
			EHPS
		Household	without energy storage
			USBES
			EHPS
Coquimbo	PEL-OWT	Aquaculture	without energy storage
			USBES
			EHPS
		Household	without energy storage
			USBES
			EHPS
	WD*	Aquaculture	without energy storage
			USBES
			EHPS
		Household	without energy storage
			USBES
			EHPS

capacity factor of 45% [58]. 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 Coquimbo 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 produce a shadow effect in incoming swell from the extratropical North Pacific [7], [59]. Comparing panels Fig.3(c) and Fig.3(d), an almost inverse trend in the mean monthly availability of wave power is observed, with more energetic months during the winter season from June to August (Coquimbo, Southern Hemisphere) and from December to February (Ensenada, Northern Hemisphere). The most energetic month in PAN is July (32.44 kW/m), and in PST, January (20.68 kW/m). The lowest average energy month in PAN is January (17.78 kW/m), and in PST, August (8.17 kW/m).

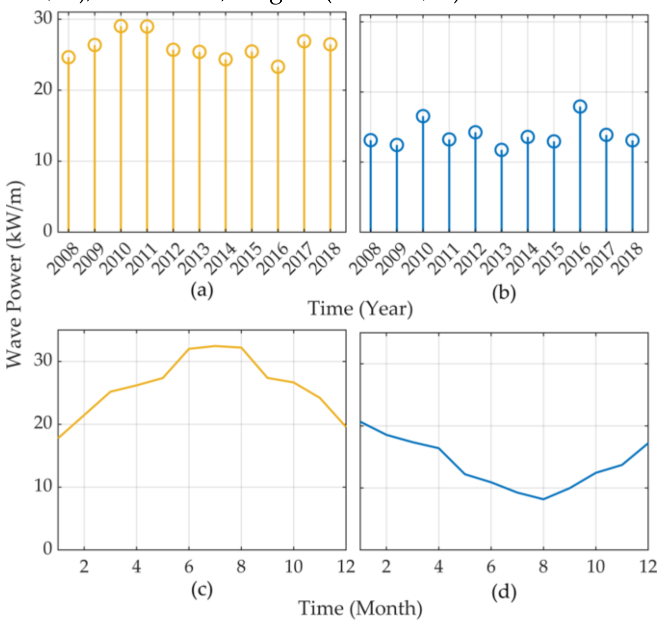

Fig. 3. Mean annual and monthly availability of wave power in the selected PAN (Coquimbo, panels (a) and (c)) and PST (Ensenada, panels (b) and (d)) sites over the full hindcast period.

A relevant aspect of the hybrid renewable system (RHS) design is to evaluate the behavior between generation and consumption. Fig. 4 shows the electricity generation profiles for individual WEC and OWT devices for Coquimbo (panel (a)) and Ensenada (panel (b)). The results show that WECs of the same technology present different performances in the two sites analyzed. For the PEL device, it develops a maximum monthly generation of 730 MWh (146 MWh per device) in Ensenada, while in Coquimbo, it is 391 MWh (65.2 MWh per device), equivalent to 124% more generation in Ensenada than in Coquimbo. On the other hand, the WD device generates 875 MWh (292 MWh per device) in Ensenada, and in Coquimbo, it reaches 875 MWh per device, equivalent to 200% more generation per device than in Ensenada. It can be observed that the highest annual energy production is generated by the WEC WD in Coquimbo, equal to 8990 MWh. Both WECs and OWTs develop lower intra-annual variability in electricity generation in Coquimbo than in Ensenada. The monthly electricity consumption profiles of households and aquaculture in Coquimbo (panel (c)) and Ensenada (panel (d)) are depicted in Fig. 4. 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. Notably, the average annual electricity consumption of households surpasses that of aquaculture in both sites. Furthermore, upon comparing the average monthly variability, it becomes evident that aquaculture consumption displays greater fluctuations than that of households.

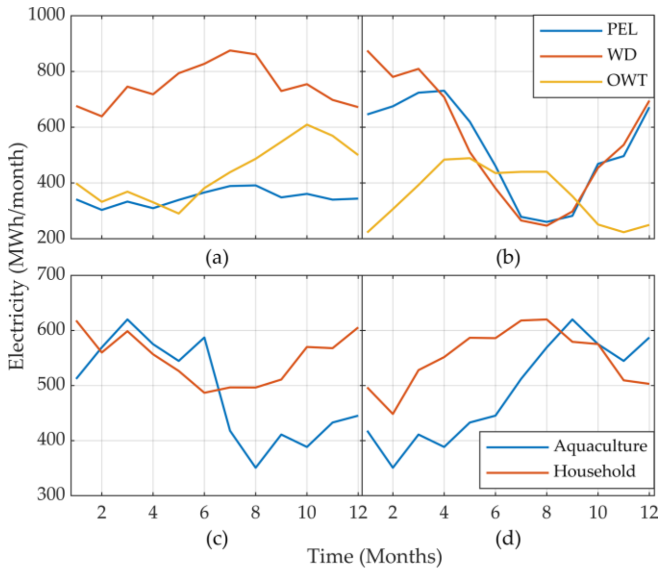

Fig. 4. Electricity generation and consumption profiles in Coquimbo (panels (a) and panel (c)) and in Ensenada (panels (b) and (d)).

Table II summarized the DH of WWHRS, the number of WECs (PEL and WD), and OWT for each of the eight main scenarios analyzed in Ensenada and Coquimbo. The four main scenarios in Coquimbo show that 44.23% DH is required for the Pelamis-OWT system and 100% for the WD-OWT system. The latter scenario allows comparing the need for hybridization from a technical and economic perspective. The four main scenarios in Ensenada require 59.56 % DH for the PEL-OWT system and 60.48 % for the WD-OWT system. The main Coquimbo scenarios require a lower DH than Ensenada. The PEL arrays require a higher number of devices than WD. Except for the base scenario WD Household in Coquimbo, the remaining scenarios only require one OWT device in the WWHRS.

TABLE II
DESIGN PARAMETERS FOR WAVE-WIND HYBRID RENEWABLE SYSTEMS (WWHRS) IN THE MAIN SCENARIOS

<table>
<tr><th>Main scenarios</th><th>Hybridization</th><th>Number of WEC</th><th>Number of OWT</th></tr>
<tr><td>Coquimbo-PEL-OWT Aquaculture</td><td rowspan="2">44.23%</td><td rowspan="2">6</td><td rowspan="2">1</td></tr>
<tr><td>Coquimbo PEL-OWT Household</td></tr>
<tr><td>Coquimbo WD-OWT Aquaculture</td><td rowspan="2">N/A</td><td rowspan="2">1</td><td rowspan="2">0</td></tr>
<tr><td>Coquimbo WD Household</td></tr>
<tr><td>Ensenada PEL-OWT Aquaculture</td><td rowspan="2">59.56%</td><td rowspan="2">5</td><td rowspan="2">1</td></tr>
<tr><td>Ensenada PEL-OWT Household</td></tr>
<tr><td>Ensenada WD-OWT Aquaculture</td><td rowspan="2">60.48%</td><td rowspan="2">3</td><td rowspan="2">1</td></tr>
<tr><td>Ensenada WD-OWT Household</td></tr>
</table>

Fig. 5 illustrates the energy balance between electricity consumption and generation profiles for the WWHRS in Coquimbo. The findings reveal that the month of February poses a challenge for Aquaculture in terms of meeting maximum monthly consumption, as there is relatively lower generation by the WWHRS. Conversely, higher generation occurs during the spring and winter months. Similarly, in domestic scenarios, the summer month of February exhibits the highest consumption paired with the lowest generation, while electricity consumption is lowest during the winter months. It is worth emphasizing that the integration of OWT in the hybrid system enables the WWHRS, equipped with PEL devices, to meet 50% of the annual electricity consumption for aquaculture scenarios, even with a configuration of six WECs. In the case of domestic scenarios, this figure rises to 75% of the year. In contrast, the WWHRS with the WD device requires only a single WEC to provide 100% of the electricity required every month throughout the year.

The energy balance between electricity consumption and generation profiles for the WWHRS in Ensenada are shown in Fig. 6. As in the Coquimbo scenarios, the results indicate that to cover the maximum monthly consumption (September) for the aquaculture scenarios, the WWHRS presents the lowest generation, which implies energy surpluses for the months of lower consumption and higher electricity generation, such as in the winter and spring time. Likewise, for the domestic scenarios, July presents the highest consumption and the lowest generation, while winter presents the lowest

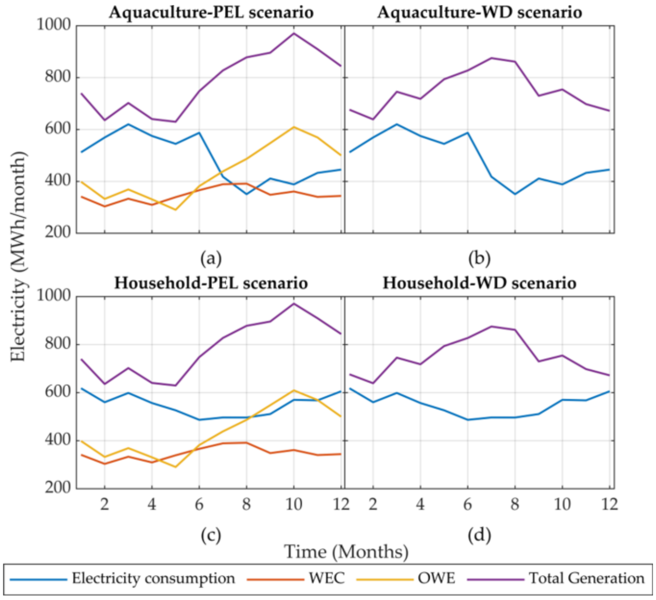

Fig. 5. Electricity generation-consumption profiles in Coquimbo, a) PEL-OWT system for aquaculture scenario, b) WD-OWT system for aquaculture scenario, c) PEL-OWT system for the household scenario, d) WD-OWT system for the household scenario.

electricity consumption. As a result, surplus energy can be used in various secondary applications. The influence of hybridization with OWT allows the WWHRS system with five PEL devices to satisfy the electricity consumption for the aquaculture and domestic scenarios in 41.6% of the months of the year. On the other hand, the hybrid systems with three WD, OWT devices allow supplying the electricity consumption for aquaculture scenarios in 41.6% of the year and for domestic scenarios in 50%.

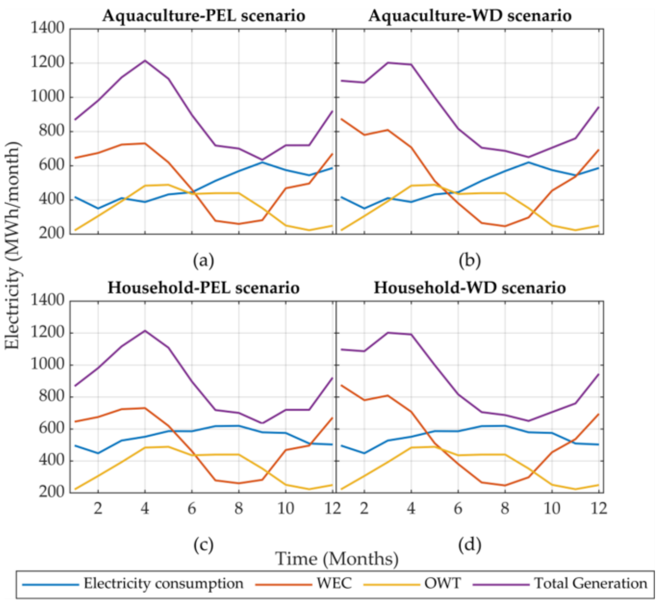

Fig. 6. Electricity generation-consumption profiles in Ensenada, (a) PEL-OWT system for the aquaculture scenario, (b) WD-OWT system for the aquaculture scenario, (c) PEL-OWT system for the household scenario, and (d) WD-OWT system household scenario.

Due to the energy surpluses of the eight main scenarios, the energy surpluses that would be stored for the sale of electricity to the electrical grid (USBES) and to produce hydrogen by alkaline electrolysis (EHPS) were calculated, as shown in Figure 7. It can be observed how the aquaculture and household scenarios generate higher energy storage and annual hydrogen production in Ensenada (panels (b) and (d)) than in Coquimbo (panels (a) and (c)). In addition, the intra-annual variability of both systems is also higher in Ensenada than in Coquimbo. Since the months of a maximum generation tend to coincide with those of lowest electricity consumption, for the eight main scenarios, surpluses of up to 980 and 600 MWh/month are observed in the spring months, while the summer and autumn months generate minimum surpluses of around 50 and 80 MWh/month, respectively. Due to the energy storage efficiency in the EHPS being 68% while the USBES is 90%, it is energetically more convenient to choose to store surplus energy in the USBS. However, the deciding factor may depend on the costs of the system, which may be related to the additional electricity demand from the electricity grid and the green hydrogen market at the study sites.

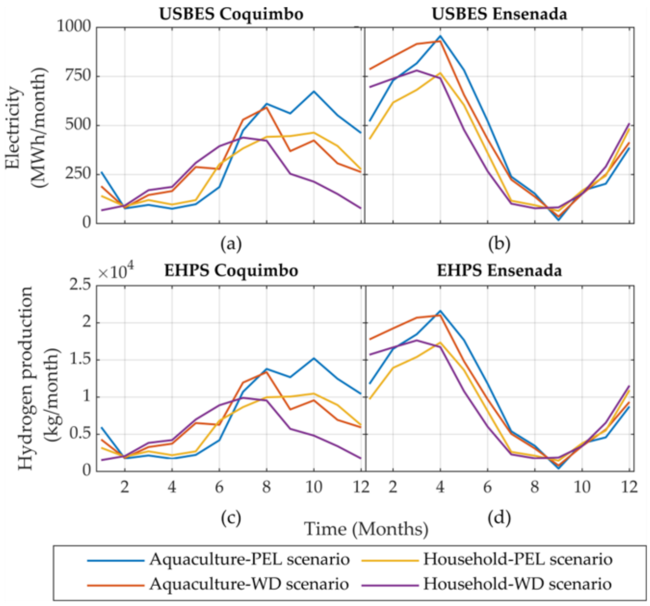

Fig. 7. Surplus energy used in utility-scale battery energy storage systems (USBES) and hydrogen production by electrolysis (EHPS) for aquaculture and household use in Coquimbo (panels (a) and (c)) and Ensenada (panels (b) and (d)).

Fig. 8 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 Coquimbo, 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 Coquimbo. This suggests that Coquimbo offers a more favorable production cost of a unit of energy for the WD-OWT system. While the AEP at Ensenada generated by the PEL and WD WEC farms is similar (Fig.4), the lower LCoE developed by the WWHRS with the PEL device is associated with lower CapEx and a higher performance than WD. However, in Coquimbo, the higher AEP and the lower devices required per WEC farm (Table II) generate a lower LCoE with the WD device than the PEL.

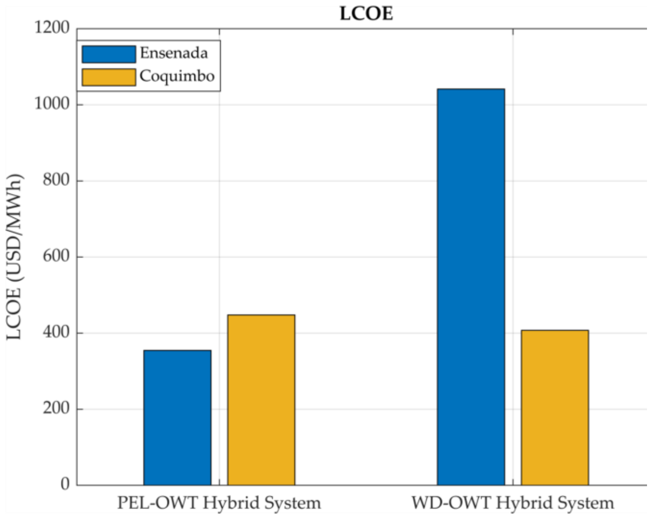

Fig. 8. Levelized cost of energy (LCoE) of the wave-wind hybrid renewable systems (WWHRS) in Coquimbo and Ensenada according to the degrees of hybridization proposed.

The net present value (NPV) of by-products produced by the different scenarios in Coquimbo and Ensenada is presented in Fig. 9. It can be seen how, regardless of the both WEC's type used and the energy surplus, the inclusion of Seaweed aquaculture in a blue economy framework generates higher returns than households, higher in Coquimbo than Ensenada. WD-Aquaculture follows a similar pattern to PEL-Aquaculture in Coquimbo, 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. In contrast, the EHPS sub-scenario produces the lowest NPV in Ensenada, while the reference sub-scenario is the worst in Coquimbo. The PEL-household scenario shows significantly lower NPV values in all sub-scenarios compared to PEL-Aquaculture. Among the available options, the EHPS sub-scenario offers the highest NPV for both Ensenada and Coquimbo. Finally, WD's domestic scenario in Ensenada is not profitable with the proposed electricity sales prices.

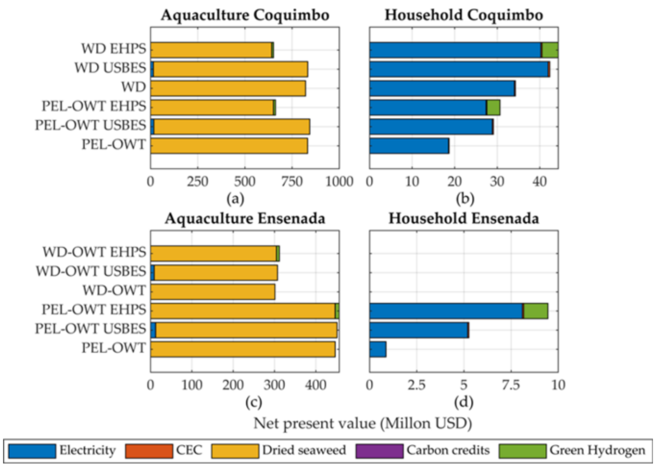

Fig. 9. Contribution of the sale of each by-product to the Net present value (NPV) for the different scenarios in Coquimbo and Ensenada. It can be seen how only positive NPV values are exposed that do not generate losses in the systems investment.

The Internal Rate of Return (IRR) generated by the different main scenarios and sub-scenarios in Coquimbo and Ensenada is shown in Fig. 10. As Fig. 9, 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 Coquimbo 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.

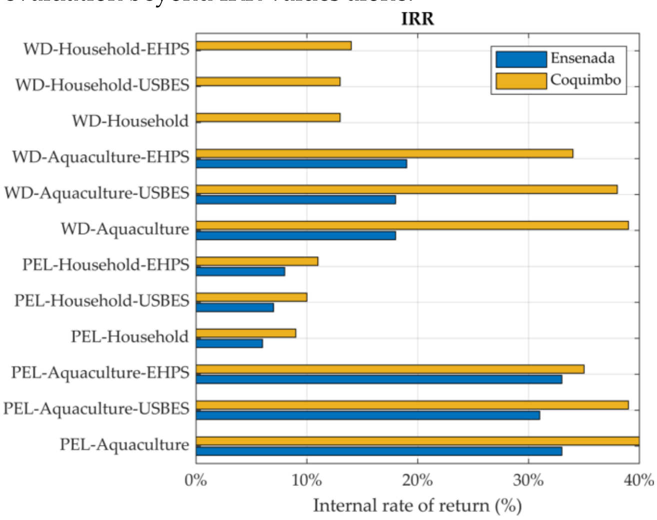

Fig. 10. Internal Rate of Return (IRR) for the different scenarios in Coquimbo and Ensenada.

IV. CONCLUSIONS

The geolocation and proximity to the extratropical generation zones of the Pacific generate differences in the availability of annual and monthly mean wave power in the selected sites. The PAN site has an annual mean wave power approximately 87.6% higher than in PST, equal to 26.05 kW/m and 13.88 kW/m, respectively. The same individual classes of WECs generate different yields at the two sites analyzed. The PEL device produces 120% more mean annual electricity in Ensenada than in Coquimbo, while the WD generates 200% more in Coquimbo. The latter area has a lower mean inter- and intra-annual variability in electricity generated by the WECs and OWT than Ensenada.

Annual household electricity consumption is higher and less variable than aquaculture. The electricity generation profiles for domestic and aquaculture scenarios in both sites exhibited seasonal variations despite a DH of 50% with OWT in most of these. However, hybridization has allowed the required electricity consumption to be met in at least five months throughout the year, both in Ensenada and Coquimbo, except for the WWHRS with WD in Coquimbo. Hybridization with OWT allowed the WECs in the WWHRS to meet a significant portion of the electricity consumption. The need for hybridization varied between scenarios, with the PEL-OWT system requiring less hybridization than the WD-OWT system.

The hybrid approach has successfully met the required electricity demand for a minimum of five months per year at both Ensenada and Coquimbo, except in the case of the WWHRS with WD at Coquimbo, which is year-round. The integration of OWT into the WWHRSs allowed the WECs to contribute significantly to electricity consumption. DH varied between scenarios. The PEL-OWT system required less hybridization than the WD-OWT system.

The results highlight the profitability benefits of a blue economy framework. The seaweed aquaculture module fosters profitability in all scenarios. Regardless of the WEC nature used and the energy surplus, the Seaweed aquaculture integration in a blue economy framework generates higher returns than households, higher in Coquimbo than Ensenada. The coupling of PEL-WHRS with Aquaculture generates higher returns than WD in Ensenada. The analysis highlights the potential benefits of using batteries for energy storage and the value of green hydrogen as an energy source. The PEL device, followed by the WD in the battery-powered aquaculture scenario (USBES), produces the highest NPV and IRR values, indicating a potentially favorable return on investment. However, the EHPS sub-scenario yields consistently lower IRR values at both sites analyzed.

All the proposed reference sub-scenarios present, in general, better investment prospects. It is advisable to consider in future analyses for complete and sound decision-making the availability of ecosystem resources, project feasibility, operating costs, and environmental aspects.

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