Wave Energy Integration in Harbor Infrastructure: A Case Study in Sicily

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***Abstract*—Coastal communities in the Mediterranean often face, at the same time, a fragile energy supply and a structural shortage of freshwater. This paper assesses the integration of a wave energy converter (WEC) for the direct pumping of pressurized seawater into the harbor infrastructure of Castellammare del Golfo (Sicily, Italy), where the pressurized flow feeds a reverse osmosis unit and a hydraulic turbine, so that freshwater and electricity are produced without any intermediate electrical conversion stage. The hourly wave climate measured by the RON buoy of Capogallo was transferred to the nearshore deployment site through a backward ray-tracing procedure based on refraction-shoaling theory, applied to a composite bathymetric model of the study domain. The resulting nearshore climate was then combined with the production characteristic of a single ExoMare-04 unit. Two operating strategies were compared: combined production of freshwater and electricity, yielding 198 m^3/y of freshwater and 1236 kWh/y, and electricity-only operation, yielding 2229 kWh/y. The results encourage the potential installation on the test site and scale-up of the system.**

Keywords—sea wave energy, water-energy nexus, harbor

I. Introduction

The transition toward low-carbon energy systems is particularly urgent for coastal communities and small islands, where dependence on imported fossil fuels, weak or absent grid interconnection, and — critically — freshwater scarcity often occur simultaneously [1], [2]. Among renewable sources, wave energy presents characteristics that make it especially attractive in these contexts: it exhibits higher energy density and lower short-term intermittency than solar or wind, it is available both day and night, and in the Mediterranean basin it shows a marked seasonal pattern with higher availability in winter, which is complementary to the summer-driven peaks in freshwater and energy demand typical of touristic coastal areas [1], [3], [4]. Despite this potential, wave energy exploitation in the Mediterranean remains at an early stage compared to oceanic basins, owing to its comparatively moderate and fetch-limited wave climate; this has motivated a growing body of research aimed at characterizing the regional resource [3], [4] and at identifying wave energy converter (WEC) archetypes and deployment strategies suited to such moderate conditions [5], [6].

A specific and increasingly investigated application of WECs is the direct mechanical pumping of pressurized seawater, which can be used either to drive an onshore hydraulic turbine for electricity generation or to directly feed a reverse osmosis (RO) desalination unit, avoiding the additional energy-conversion losses associated with an intermediate electrical stage [7]. This coupling is particularly relevant for small islands and coastal towns, where local desalination is often the only practicable solution to freshwater scarcity, but is itself energy-intensive and, when powered by the grid or by diesel generation, carries a significant economic and environmental cost [8].

Several systems based on this principle have been documented in the literature and in pilot deployments. The CETO technology, developed by Carnegie Clean Energy (Australia), couples a submerged buoyant actuator to a seabed-mounted hydraulic pump: the pressurized fluid is conveyed onshore to drive hydraulic motors and generators, and the same architecture has been proposed for direct RO desalination [9], [10]. Three CETO 5 units were grid-connected at Garden Island (Western Australia) as part of the Perth Wave Energy Project, operating over multiple seasons [11]. Similar wave-powered pumping concepts, at smaller scale, have been investigated at the University of New Hampshire for upwelling applications [12], at Uppsala University for combined electricity/desalination generation, and specifically for insular and Mediterranean contexts, including the Canary Islands [13] and, closer to the present case, the Sicilian coast and the minor island of Pantelleria, where the coupling between wave energy converters and desalination plants has been previously investigated by the authors' research group [14], [15].

Harbors represent a particularly favorable setting for this class of devices. Their breakwaters are already designed to intercept and dissipate the incoming wave energy, and they are conceived as purely passive structures: the energy they absorb is entirely lost, while the reflection and the run-up they induce contribute to scour at the toe and to the erosive processes that affect the structure itself and the adjacent shoreline [6].

Installing wave energy converters in front of, or integrated into, these structures allows part of the incident energy to be extracted before it reaches the breakwater, with the twofold benefit of reducing the hydrodynamic solicitation responsible for such erosive phenomena and of converting a share of the dissipated energy into a useful output. In this perspective, the breakwater ceases to be a passive component of the harbor and becomes an active element that contributes to the energy and water self-sufficiency of the port, without requiring additional land occupation.

In this context, the authors assess the possibility of installing a pilot plant at the harbor of Castellammare del Golfo (Sicily, Italy). The site was selected for three reasons. First, the interest expressed by *Lega Navale Italiana sezione di Castellammare del Golfo* in hosting the installation, which provides the local involvement required by a demonstration project. Second, the sheltered sea conditions of the harbor basin, milder than in the open sea, which reduce the extreme loads acting on the device and on its mooring. Third, the shallow water depth of a few meters, which allows the subsea components to be installed, inspected and recovered under safer working conditions. The proposed solution is based on a WEC device able to convert wave energy into pressurized seawater. By coupling the system with a reverse osmosis unit and a hydraulic turbine, the project aims at the combined production of freshwater and electricity. In the following, the expected productivity of the pilot plant is analyzed.

II. Methodology

A. Input data

The assessment of the wave potential available at the deployment site required transferring the long-term wave climate, known at an offshore reference location, to the specific nearshore point of interest adjacent to the Castellammare del Golfo breakwater, accounting for the transformation of the wave field induced by the local bathymetry.

Hourly time series of significant wave height (H_s), peak period (T_p) and mean wave direction were obtained from the Italian National Wave Measurement Network (Rete Ondametrica Nazionale, RON) buoy located off Palermo (Capogallo, close to Palermo 38°15'30''N, 13°20'00''E), the closest operating station to the study area. The Castellammare del Golfo deployment site is located at 38°02'04''N, 12°52'42''E.

Fig. 1. Location of the RON buoy (Capogallo) and test site

A composite bathymetric model of the study domain was built by combining two data sources at different scales: (i) the EMODnet Bathymetry digital terrain model [16], providing regional-scale coverage (~115 m grid resolution) of the stretch of coast between the buoy location and Castellammare del Golfo; and (ii) a high-resolution local dataset, digitized from bathymetric survey isobaths in the immediate vicinity of the harbor breakwater, georeferenced to the UTM WGS84 (zone 33N) reference system. The two datasets were merged into a single composite depth function, with the local high-resolution data prevailing near the structure and a smooth transition (feathering) toward the regional dataset further offshore, so as to avoid discontinuities at the boundary between the two sources.

The transformation of the offshore wave climate to the nearshore point of interest was performed through a backward ray-tracing approach based on linear wave refraction-shoaling theory [17], [18]. For each reference period, wave rays were traced from the target location seaward across the composite bathymetry, solving the classical ray equations for wave direction as a function of the local phase celerity gradient; only rays reaching open-water (deep-water) conditions without intersecting the coastline identify directions effectively exposed to open-sea wave action, thereby defining, without any a priori assumption, the directional exposure window of the site. For each valid direction and period, the shoaling coefficient was derived from the ratio of offshore-to-nearshore group velocities, while the refraction coefficient was estimated from the convergence/divergence of adjacent ray pairs. The resulting transfer coefficients were tabulated as a function of offshore wave direction and period and subsequently applied to the full hourly buoy time series, yielding the transformed H_s, T_p and direction at the point of interest. The wave-ray integration scheme was verified against the analytical solution for shore-parallel, straight bathymetric contours (Snell's law), confirming conservation of the invariant $\sin \psi / c$ along the traced rays.

The resulting nearshore hourly wave climate constitutes the input boundary condition used to evaluate the expected pumped-flow performance of the ExoMare unit and the corresponding desalinated water production potential at the Castellammare del Golfo site.

B. The technology

In this work, the authors considered the potential application of Exowave ExoMare technology—a modular, wave-powered desalination system—to the coastal context of Castellammare del Golfo, a harbor town located along the northern coast of Sicily (Italy). This system is designed for a nearshore application. The subsea components operate at shallow water depths (approx. 3 m), making the technology particularly suitable for protected coastal and harbor areas.

As shown in Fig. 2, the Wave Energy Converter (WEC) exploits the wave-induced oscillatory motion of a floating buoy. The floater is rigidly connected, through a vertical rod, to a positive-displacement seawater pump anchored to the seabed at a water depth of about 3 m. The heave motion imposed on the floater by the incoming waves is transmitted directly to the pump piston: during each stroke, seawater is drawn in through the suction valve, pressurized and delivered through the discharge valve, so that the mechanical energy of the wave is converted into hydraulic energy without any intermediate electrical conversion stage.

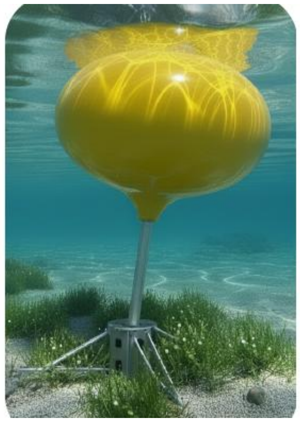

Fig. 2. Exowave desalination unit. Model: ExoMare-04

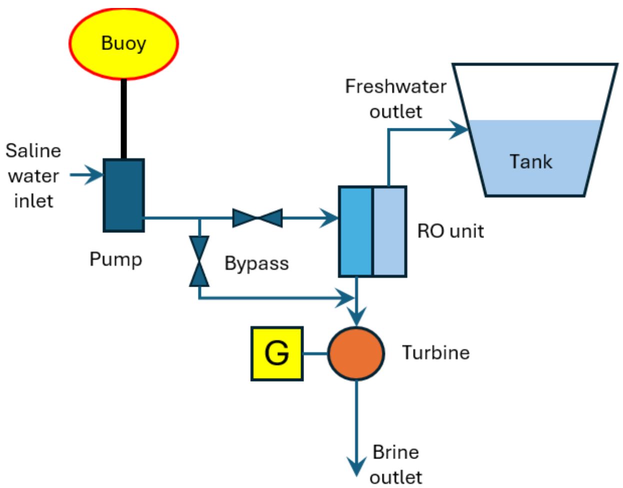

Fig. 3. Working principle of the system

As shown in Fig. 3, the pressurized flow produced is conveyed onshore through a high-pressure pipeline. Seawater is supplied to the RO membrane racks, which are fed directly at the pressure required for permeate production. Brine, still under high pressure, is finally conveyed to a hydraulic turbine, which recovers the residual energy, producing electrical energy for the auxiliaries and small electrical loads. Alternatively, the whole pressurized flow can be delivered directly to the hydraulic turbine, bypassing the RO unit; the two options correspond to the operating cases discussed in Section III. Since the pump is the only moving component exposed to the marine environment and no electrical machinery is installed offshore, the architecture keeps the submerged part of the plant mechanically simple and limits maintenance to periodic inspection of the valves and of the mooring system.

III. Results

The wave climate in Castellammare del Golfo was evaluated, propagating the data of the last available year from the RON measuring buoy in Palermo (Fig. 4) to the test site.

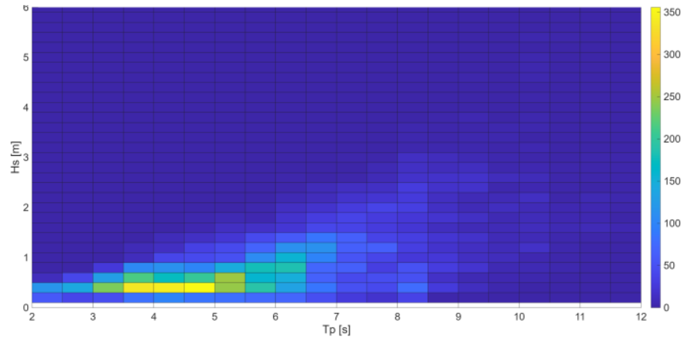

Fig. 4. Wave climate in Capogallo (Palermo).

Fig. 5 reports the scatter table of the evaluated wave climate in Castellammare del Golfo. Wave height rarely exceeds three meters; peak period ranges between 2.5 s and 7.5 s. Winter shows a greater energy potential than summer.

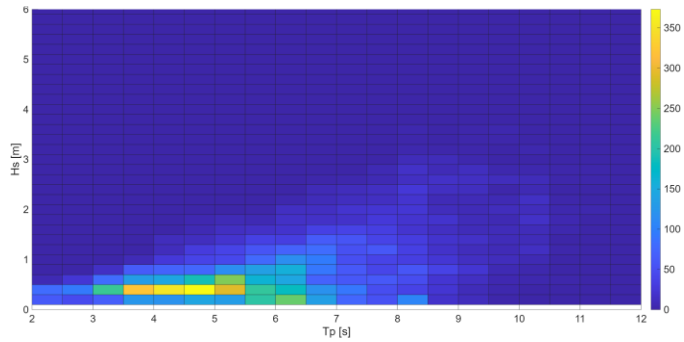

Fig. 5. Wave climate in Castellammare del Golfo

The wave climate was matched with the potential feedwater production. Data, shared by ExoMare, are reported in Fig. 6, where the lines express the feedwater flow rate in liters per second. The system shows feedwater production directly proportional to H_s (thanks to the greater magnitude of the vertical movement) and reciprocally proportional to T_p (since the greater number of cycles that can be realized in a fixed interval). The system is operationally active with significant wave height up to 2 m.

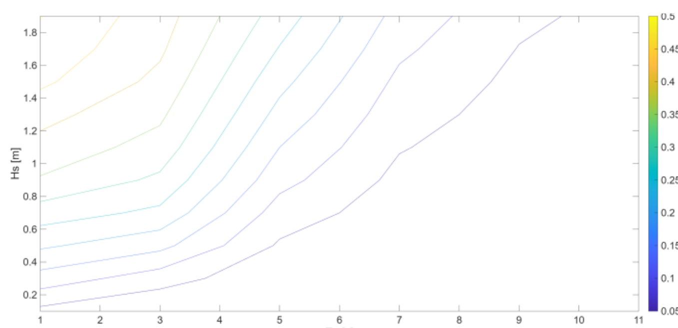

Fig. 6. Feedwater production of ExoMare-04.

In this evaluation the authors considered both scenarios:

- **Case A**: the feedwater produced by the WEC is first conveyed to the RO desalination unit. The permeate recovery ratio of the RO unit is assumed to be equal to 45%, as well known in literature [8]. The remaining amount is used by the hydraulic turbine to produce electrical energy. The authors assumed overall efficiency was equal to 85%.

- **Case B**: the feedwater is entirely conveyed to the hydraulic turbine. In this case, the electrical production is maximized; however, no freshwater is produced.

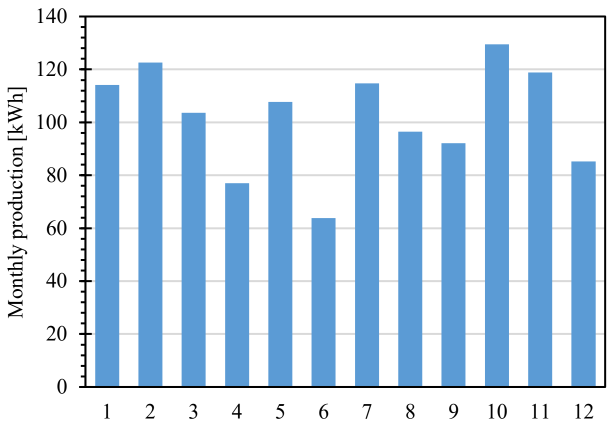

Fig. 7. Energy production in Case A.

In case A, where the WEC system is used to produce freshwater and electrical energy (Fig. 7), the matching between wave climate and WEC data reveals a potential producibility of 1236 kWh/y and 198 m^3/y of freshwater.

In case B, instead, electricity is the only output of the system. In this configuration, an overall electricity production equal to 2229 kWh/y is expected.

As a term of comparison, the same evaluation was performed, considering the original data of Capogallo. In that case, production achieves the following values: 1633 kWh/y and 262 m^3/y of freshwater in case A; 2968 kWh/y in case B.

Thus, the test site reveals annual energy production is about 24% lower than the expected production in the measuring station. This is due to the different exposure to waves. Indeed, the Castellammare del Golfo harbor is a secluded area, where the wave climate is reduced, as shown in Fig. 1.

In any case, the expected output remains modest in absolute terms, consistent with the rated size of a single ExoMare-04 unit: the installation must therefore be interpreted as a demonstrator, whose purpose is to verify the behavior of the technology in a real harbor environment rather than to cover the electrical demand of the neighborhood.

IV. Conclusion

This work assessed the technical feasibility of a wave-powered pilot plant for the combined production of freshwater and electricity at the harbor of Castellammare del Golfo. The offshore wave climate measured at Capogallo was transferred to the near-shore deployment point through a backward ray-tracing procedure applied to a composite bathymetric model, and the resulting hourly climate was combined with the production characteristic of a single ExoMare-04 unit.

The analysis confirms that the site is exploitable, although with a reduced resource: the sheltered position of the harbor implies a production about 24% lower than at the offshore reference point, with 198 m3/y of freshwater and 1236 kWh/y in the combined configuration and 2229 kWh/y when the whole flow is delivered to the hydraulic turbine. The two configurations should not be read as alternatives, but as operating strategies that can be selected according to the prevailing need, favoring freshwater in summer, when demand peaks, and electricity in winter, when the resource is higher.

Several considerations, related to the pilot installation, mitigate the limited absolute output. The sheltered location that penalizes the resource also reduces the extreme design loads on the device and its mooring, allows access for inspection during most of the year, and makes the existing harbor infrastructure—breakwater, onshore space, water and electrical connections—available at marginal cost. Moreover, the plant requires no offshore electrical machinery, which simplifies both authorization and maintenance. For a demonstrator, whose objective is to acquire operational evidence rather than to maximize yield, these aspects are as relevant as the energy figures.

Within the framework of the project supporting this activity, the expected output is compatible with the low power, distributed uses typical of a fishing harbor, such as freshwater for onshore washing operations, lighting and small auxiliary loads, and its modular architecture allows the capacity to be scaled by adding units once the first one has been validated.

Future developments will address the extension of the wave-climate analysis to a multi-year dataset, the definition of the array layout inside the harbor basin, and a techno-economic assessment of the levelized cost of water and electricity, together with the environmental monitoring required by the authorization process.

Above all, the know-how acquired from the operation of the pilot plant will support the assessment of larger-scale prototypes in the near future, to be deployed in other harbors along the Sicilian coast, where the same combination of sheltered conditions, shallow depths and existing infrastructure can be found.

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