Wave Energy Integration for Sustainable Port Development: The Case of Castellammare del Golfo, Sicily

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***Abstract*—Wave energy harvesting represents a promising opportunity to supply small islands and coastal areas with sustainable energy. Although numerous concepts have been proposed in recent years, most wave energy technologies still require further development. In this context, the manuscript investigates the feasibility of installing a Wave Energy Converter (WEC) within the existing harbor infrastructure of Castellammare del Golfo, located in Sicily, Italy. This approach aims to harness renewable energy from wave motion to support the energy needs of harbor users. The manuscript also presents the conceptual design of a prototype currently under development to demonstrate the technical viability of this solution.**

Keywords— Wave energy; Power Take-Off; Renewable energies; Port infrastructure

I. INTRODUCTION

Marine wave energy represents one of the most promising yet underexploited forms of renewable energy sources (RES). Recent advancements in Wave Energy Converters (WECs) have paved the way for practical applications in coastal areas, especially small islands [1].

Many technologies have been developed in the last decades; however, the state of art is not yet as consolidated or advanced as in other renewable energy fields [2].

Even the operating principles are not consistent across projects and pilot plants. Some commonly explored approaches include [3]:

- **Oscillating Water Column (OWC)**, where waves enter a chamber causing the alternative compression and the decompression of the air inside, activating an air turbine.
- **Wave Activated Bodies (WAB)**, that typically consist of multiple floating segments connected by joints or hinges. Wave action induces relative motion between the segments, actuating hydraulic cylinders or mechanical linkages, which then convert the motion into pressurized fluid or mechanical energy.
- **Overtopping Device**, where waves overtop a ramp structure, filling a raised reservoir situated above mean sea level. The stored water is subsequently used to drive a low-head hydro turbine.

Compared to other RES [4], wave energy could effectively meet the energy demands of small islands and coastal areas by offering a predictable and continuous renewable resource, low visual impact and high energy density per square meter [5], [6].

II. RECENT TECHNOLOGIES

Integrating WECs into existing maritime infrastructures [7]—such as breakwaters and piers—can significantly reduce installation costs and environmental footprint, making this solution particularly suitable for space-constrained or protected coastal zones [8], [9]. Moreover, wave energy complements variable renewable sources like solar and wind, enhancing grid stability and enabling hybrid energy systems with improved reliability [10], [11] However, wave energy deployment still faces challenges, including high capital expenditures (CAPEX), limited commercial maturity, and vulnerability to extreme sea conditions [12]. Despite these hurdles, recent technological advancements, particularly in nearshore and modular WEC designs, are gradually overcoming these limitations, improving wave energy’s viability as a sustainable and resilient energy source for insular and coastal communities.

This section presents a brief review of pilot and commercial-scale installations of near-shore WECs, highlighting the technological diversity and geographical breadth of these systems.

A. Mutriku OWC Plant

The Mutriku power plant, located in the Basque Country of northern Spain, represents the first grid-connected wave energy installation integrated into a harbor breakwater [13], [14]. Commissioned in 2011, the system is composed of 16 oscillating water column (OWC) chambers, each equipped with Wells turbines and 18.5 kW generators, for a total installed capacity of 296 kW. Since its commissioning, the plant has supplied over 2.4 GWh of electricity to the Spanish grid and has served as a valuable testbed for turbine optimization and control systems.

B. OBREC – Port of Naples

The OBREC (Overtopping Breakwater for Energy Conversion) device, developed by the University of Campania and EPF Elettrotecnica S.rl., was implemented in 2015 within a low-head hydropower dam structure in the Port of Naples.

OBREC uses overtopping technology to channel incoming wave energy into a reservoir placed above sea level [15]. This innovative structure demonstrates high synergy between coastal protection and renewable energy generation, with minimal visual and environmental impact.

C. *REWEC3 – Port of Civitavecchia*

In 2016, the Port of Civitavecchia became home to the first full-scale REWEC3 (Resonant Wave Energy Converter 3), a U-shaped oscillating water column integrated into a traditional breakwater structure [16], [17]. The installation spans 524 meters and includes 124 air chambers, each with an estimated capacity of 18–20 kW, totaling up to 2.5 MW of potential output. Unlike classical OWCs, REWEC3 allows for frequency tuning to match local wave spectra, improving efficiency under Mediterranean wave conditions.

D. *MARMOK-A5 – BiMEP*

The MARMOK-A5, a floating OWC device developed by IDOM and initially supported by the OPERA project, was first installed in 2016 at the BiMEP test site in northern Spain [18]. The spar buoy-type WEC, with a diameter of 5 meters and a height of 42 meters, operated in 90-meter-deep waters and survived wave heights of up to 14 meters. The system's robust design, zero moving parts in water, and optimized mooring reduce maintenance costs and enhance survivability. A new power take-off (PTO) turbine was tested in 2025 in preparation for redeployment.

E. *WaveRoller – Peniche*

Developed by AW-Energy, the WaveRoller is a bottom-fixed oscillating wave surge converter installed between 0.3 and 2 km from the coast, at depths of 8–20 m [19]. The first commercial-scale 350 kW unit was installed in 2019 and underwent two years of operation. The system uses a hinged panel driven by surge forces to power a hydraulic PTO and generator. As part of the EU-funded ONDEP project, four units will be deployed by 2026 off the coast of Peniche.

F. *Eco Wave Power – Port of Los Angeles*

Scheduled for completion in early 2025, the Eco Wave Power (EWP) system in the Port of Los Angeles represents a new generation of onshore WECs. Floats are attached to existing marine structures (piers, breakwaters) and convert wave-induced vertical motion into hydraulic pressure. The onshore conversion unit, housed in shipping containers, reduces operational and maintenance risks associated with offshore deployments. This modular and insurable design has also been tested in Israel and Gibraltar [7].

G. *ISWEC – Island of Pantelleria*

The ISWEC (Inertial Sea Wave Energy Converter) was developed by ENI in collaboration with Politecnico di Torino and Wave for Energy. The site test is located 800 meters offshore from the island of Pantelleria [20]. The system includes a steel hull containing gyroscopic PTO units optimized via genetic algorithms. With a rated power of 260 kW, the ISWEC supplies renewable electricity to the island grid while minimizing visual impact.

H. *ZOEX Power – Port of Aberdeen*

In 2024, ZOEX Power deployed a 100 kW WEC at the Port of Aberdeen [21]. The device, tested in tank facilities and built with aerospace-grade components, uses a dual-linkage arm to drive a ball-screw PTO. It can be installed on breakwaters or floating barges to supply clean electricity to port operations and off-grid communities. ZOEX emphasizes rapid deployability and reduced operational risk.

III. CASE STUDY: CASTELLAMMARE DEL GOLFO

In this context, the manuscript proposes a project focused on the implementing a wave energy harvesting system at the Port of Castellammare del Golfo. This small town is located along the northern coastline of Sicily (Italy), between the cities of Palermo and Trapani (see Fig. 1).

Fig. 1. Location of Castellammare del Golfo (Sicily)

Leveraging existing coastal infrastructure and minimizing interference with recreational boating, the proposed solution is tailored to local wave conditions, as characterized by bathymetric and wave exposure analyses (see Fig. 2).

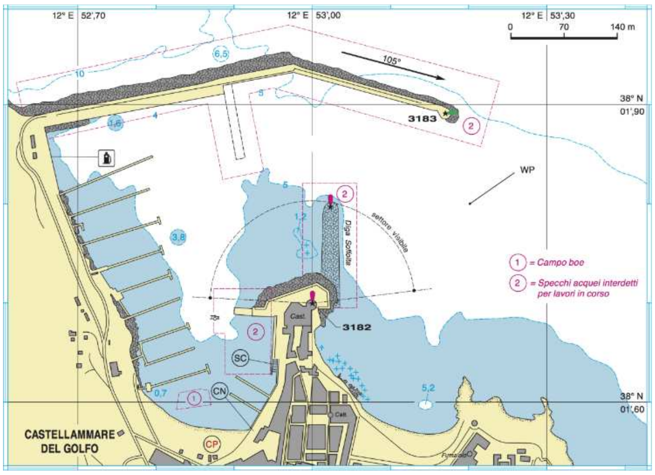


Fig. 2. Layout of the harbor of Castellammare del Golfo

The harbor consists of a pier and a wharf built at the foot of the Norman Castle (Punta Castello) to the aest, and a rocky pier (Molo Nord), anchored at Punta dell'Acqua with an adjacent wharf to the west. Between these structures lies a stretch of natural coastline composed of beaches or rocky areas.

A nature reserve (Riserva dello Zingaro) is located nearby, encompassing a stretch of sea extending from approximately 0.6 nautical miles south of Torre dell'Impiso to about 0.6 nautical miles northwest of Torre Scopello.

A prototype is currently under development at the University of Palermo. The proposed solution involves a floating buoy connected via pulleys and cables to the electrical generators (see Fig. 3) [22].

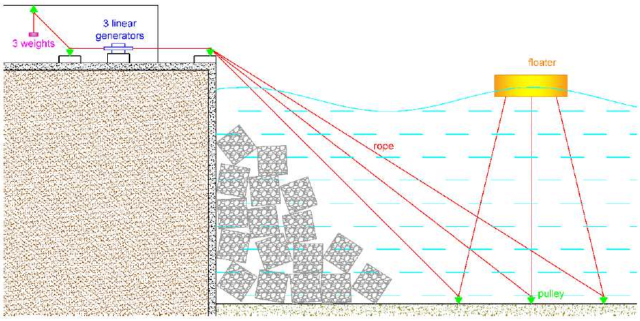


Fig. 3. Position of the pilot plant in the harbor of Castellammare del Golfo

Specifically, linear generators have been chosen for this application (see Fig. 4), due to their capability to convert the alternating motion of the ropes directly into electrical energy [23], [24]. In this configuration, magnets are installed on the movable part (the shifter), while coils are placed on the stationary part (the stator).

The entire system is currently being developed in order to achieve a rated power of approximately 30 kW.

Fig. 4. Prototypes of linear generators

A buoy is used to harvest mechanical energy from wave motion. The floater's movement pulls ropes connected to the mainland via pulleys, activating linear generators. The buoyancy level is calibrated during construction by counterweights installed at the opposite side of the rope inside the technical room. This design allows a reduction in the buoy's weight. Additionally, the proposed configuration enables the buoy to be fully submerged during adverse weather conditions, providing a critical safety feature for the system.

The floater is intended to be installed at a distance between 50 and 80 meters from the breakwaters, where sea depths exceed 10 meters. The pulleys will be mounted on a base positioned on the seabed directly beneath the floater. Energy conversion into electricity occurs within the technical room located on the breakwater. This approach significantly reduces installation complexity and maintenance costs.

IV. WAVE CLIMATE

Over the past two decades, the marine climate along the Italian coast has been assessed through the Italian Wave Measurement Network (RON), helping identify the most promising areas for wave energy harvesting [25].

The RON project, initiated in 1989, is still operational. Initially, only eight measurement buoys were deployed; however, over the years, both the buoys and their instrumentation have been progressively upgraded and replaced. Currently, the network comprises 16 measurement buoys installed along the Italian coastline, as depicted in Fig. 5.

Each 30 minutes, the following parameters are measured and published on the ISPRA webpage:

- Air and water temperature
- Relative humidity and atmospheric pressure
- Wind direction and wind speed
- Mean period and peak period of waves
- Significant wave height
- Average wave direction
- Maximum wave height
- Mean solar radiation
- Total precipitation
- Current speed and current direction

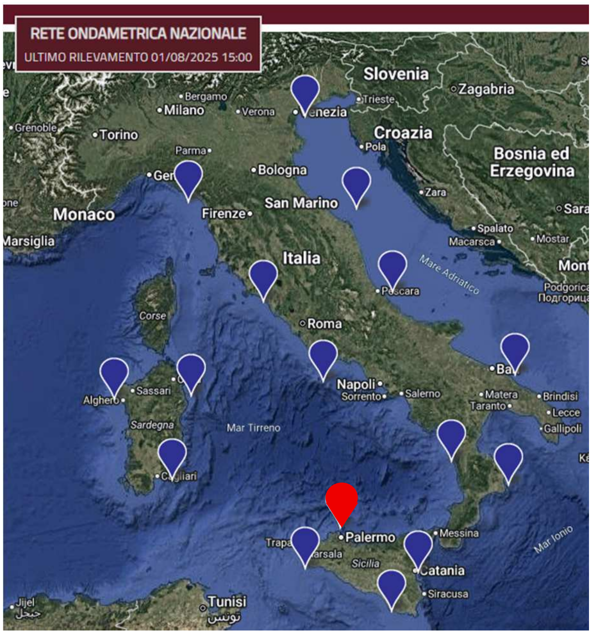
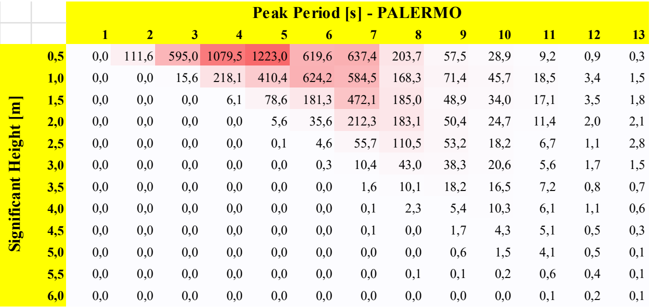


Fig. 5. Position of RON measuring buoys

The closest measurement buoy to the Castellammare del Golfo site is located near Capo Gallo, close to Palermo (marked in red in Fig. 5), where the sea depth is approximately 145 m.

Data was collected from April 2002 to October 2014, although this period included several extended interruptions. The buoy resumed operation in November 2024 and is currently active.

As shown in Fig. 6, the significant wave height typically remains below 3 meters, while the peak period ranges between 2 and 10 seconds.



		Peak Period [s] - PALERMO												
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Significant Height [m]	**0,5**	0,0	111,6	595,0	1079,5	1223,0	619,6	637,4	203,7	57,5	28,9	9,2	0,9	0,3
	1,0	0,0	0,0	15,6	218,1	410,4	624,2	584,5	168,3	71,4	45,7	18,5	3,4	1,5
	1,5	0,0	0,0	0,0	6,1	78,6	181,3	472,1	185,0	48,9	34,0	17,1	3,5	1,8
	2,0	0,0	0,0	0,0	0,0	5,6	35,6	212,3	183,1	50,4	24,7	11,4	2,0	2,1
	2,5	0,0	0,0	0,0	0,0	0,1	4,6	55,7	110,5	53,2	18,2	6,7	1,1	2,8
	3,0	0,0	0,0	0,0	0,0	0,0	0,3	10,4	43,0	38,3	20,6	5,6	1,7	1,5
	3,5	0,0	0,0	0,0	0,0	0,0	0,0	1,6	10,1	18,2	16,5	7,2	0,8	0,7
	4,0	0,0	0,0	0,0	0,0	0,0	0,0	0,1	2,3	5,4	10,3	6,1	1,1	0,6
	4,5	0,0	0,0	0,0	0,0	0,0	0,0	0,1	0,0	1,7	4,3	5,1	0,5	0,3
	5,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,6	1,5	4,1	0,5	0,1
	5,5	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,1	0,1	0,2	0,6	0,4	0,1
	6,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,1	0,2	0,1

Fig. 6. Occurrence of sea state in Palermo

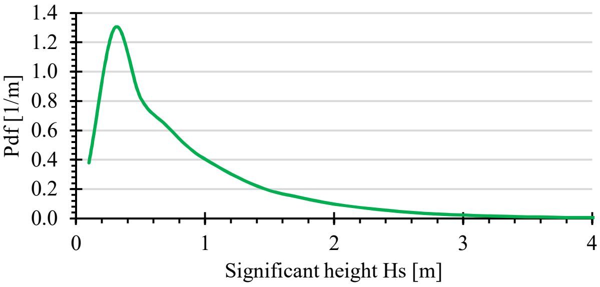


Fig. 7. Probability density function of Significant Height in Palermo

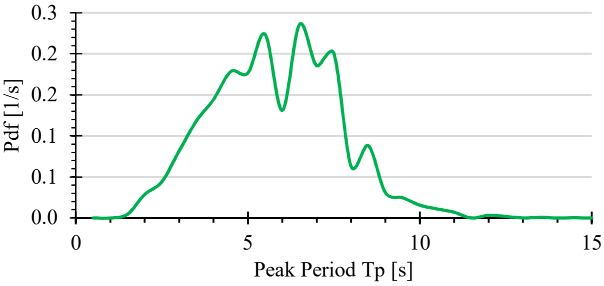


Fig. 8. Probability density function of Peak Period in Palermo

Using the data reported above, a preliminary analysis was conducted with Ansys Aqwa. Results indicate that the proposed prototype could generate between 75 and 100 MWh/year.

V. CONCLUSION

The integration of Wave Energy Converters into existing infrastructure, such as harbor breakwaters, represents an attractive opportunity to reduce the costs associated with developing this technology.

The brief review of the state of art reveals a variety of solutions for wave energy harvesting. In this context, the authors have presented a novel concept currently under development, intended for installation at the harbor of Castellammare del Golfo.

Preliminary analyses suggest that the prototype has the potential to produce between 75 and 100 MWh/year. Future steps will include laboratory tests aimed at optimizing the control system, followed by on-site testing.

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REFERENCES

[1] R. Cascajo, E. García, E. Quiles, A. Correcher, and F. Morant, "Integration of marine wave energy converters into seaports: A case study in the port of Valencia," *Energies (Basel)*, vol. 12, no. 5, 2019, doi: 10.3390/en12050787.

[2] D. Curto, V. Franzitta, and A. Guercio, "Sea Wave Energy. A Review of the Current Technologies and Perspectives," *Energies (Basel)*, vol. 14, no. 20, p. 6604, Oct. 2021, doi: 10.3390/en14206604.

[3] S. Foteinis, "Wave energy converters in low energy seas: Current state and opportunities," *Renewable and Sustainable Energy Reviews*, vol. 162, no. April, p. 112448, Jul. 2022, doi: 10.1016/j.rser.2022.112448.

[4] M. Trapanese, V. Franzitta, and A. Viola, "Design and Performance of a High Temperature Superconducting Axial Flux Generator," *IEEE Trans Magn*, vol. 49, no. 7, pp. 4113–4115, Jul. 2013, doi: 10.1109/TMAG.2013.2250934.

[5] A. F. de O. Falcão, "Wave energy utilization: A review of the technologies," *Renewable and Sustainable Energy Reviews*, vol. 14, no. 3, pp. 899–918, Apr. 2010, doi: 10.1016/j.rser.2009.11.003.

[6] Joao Cruz, *Ocean Wave Energy. Current Status and Future Prespectives*. in Green Energy and Technology(Virtual Series). Berlin, Heidelberg: Springer Berlin Heidelberg, 2008. doi: 10.1007/978-3-540-74895-3.

[7] T. Calheiros-Cabral, P. Rosa-Santos, F. Taveira-Pinto, and J. L. Lara, "Harnessing wave energy through breakwater integration: A review of technologies, deployment strategies and an open-access database," Nov. 01, 2025, *Elsevier Ltd*. doi: 10.1016/j.rser.2025.115975.

[8] X. L. Zhao, D. Z. Ning, Q. P. Zou, D. S. Qiao, and S. Q. Cai, "Hybrid floating breakwater-WEC system: A review," *Ocean Engineering*, vol. 186, no. August, 2019, doi: 10.1016/j.oceaneng.2019.106126.

[9] M. C. Lacasa, M. D. Esteban, J. S. López-Gutiérrez, V. Negro, and Z. Zang, "Feasibility study of the installation of wave energy converters in existing breakwaters in the north of Spain," *Applied Sciences (Switzerland)*, vol. 9, no. 23, 2019, doi: 10.3390/app9235225.

[10] D. Curto *et al.*, "Introduction of Offshore Wave, Wind and Solar Energies in Vietnam," *2020 Global Oceans 2020: Singapore - U.S. Gulf Coast*, 2020, doi: 10.1109/IEEECONF38699.2020.9389219.

[11] D. Curto *et al.*, "Wave energy systems in the Vietnamese context: Proposal for onshore and offshore integration based on a techno-economic analysis," *Sustainable Energy Technologies and Assessments*, vol. 77, May 2025, doi: 10.1016/j.seta.2025.104268.

[12] Y. Zhang, D. Zhang, and H. Jiang, "A Review of Offshore Wind and Wave Installations in Some Areas with an Eye towards Generating Economic Benefits and Offering Commercial Inspiration," May 01, 2023, *MDPI*. doi: 10.3390/su15108429.

[13] J. Lopez-Mendia, A. Aristondo, P. Ricci, J. Lekube, S. Ceballos, and E. Robles, "Improving the power production of Mutriku Wave Power Plant throughout tuning the actual generator and damping valve limits," *Ocean Engineering*, vol. 315, Jan. 2025, doi: 10.1016/j.oceaneng.2024.119917.

[14] Y. Torre-Enciso, I. Ortubia, L. I. López de Aguileta, and J. Marqués, "Mutriku Wave Power Plant: from the thinking out to the reality," *8th European Wave and Tidal Energy Conference (EWTEC 2009)*, pp. 319–328, 2009, [Online]. Available: http://tethys.pnnl.gov/sites/default/files/publications/Torre-Enciso_et_al_2009.pdf

[15] P. Contestabile, G. Crispino, E. Di Lauro, V. Ferrante, C. Gisonni, and D. Vicinanza, "Overtopping breakwater for wave Energy

Conversion: Review of state of art, recent advancements and what lies ahead," *Renew Energy*, vol. 147, pp. 705–718, Mar. 2020, doi: 10.1016/j.renene.2019.08.115.

[16] D. H. Yacob, S. Sarip, H. M. Kaidi, J. A. Ardila-Rey, and F. Muhammad-Sukki, "Oscillating Water Column Geometrical Factors and System Performance: A Review," 2022, *Institute of Electrical and Electronics Engineers Inc.* doi: 10.1109/ACCESS.2022.3160713.

[17] F. Arena, G. Malara, G. Musolino, C. Rindone, A. Romolo, and A. Vitetta, "From green-energy to green-logistics: A pilot study in an Italian port area," in *Transportation Research Procedia*, Elsevier B.V., 2018, pp. 111–118. doi: 10.1016/j.trpro.2018.09.013.

[18] A. A. D. Carrelhas, L. M. C. Gato, J. C. C. Henriques, A. F. O. Falcão, and J. Varandas, "Test results of a 30 kW self-rectifying biradial air turbine-generator prototype," *Renewable and Sustainable Energy Reviews*, vol. 109, pp. 187–198, Jul. 2019, doi: 10.1016/j.rser.2019.04.008.

[19] D. Clemente, V. Ramos, F. Teixeira-Duarte, F. V. C. Taveira-Pinto, P. Rosa-Santos, and F. Taveira-Pinto, "Assessment of electricity production and coastal protection of a nearshore 500 MW wave farm in the north-western Portuguese coast," *Appl Energy*, vol. 379, Feb. 2025, doi: 10.1016/j.apenergy.2024.124950.

[20] S. A. Sirigu *et al.*, "ISWEC design tool," *International Journal of Marine Energy*, vol. 15, pp. 201–213, Sep. 2016, doi: 10.1016/j.ijome.2016.04.011.

[21] Zerina Maksumić, "ZOEX Power completes installation of wave energy device at Port of Aberdeen," *Offshore Energy*, Jul. 01, 2024. Accessed: Aug. 01, 2025. [Online]. Available: https://www.offshore-energy.biz/zoex-power-completes-installation-of-wave-energy-device-at-port-of-aberdeen/

[22] V. Franzitta, A. Viola, and M. Trapanese, "Design of a transverse flux machine for power generation from seawaves," *J Appl Phys*, vol. 115, no. 17, p. 17E712, May 2014, doi: 10.1063/1.4865883.

[23] D. Curto, V. Franzitta, A. Guercio, and M. Trapanese, "Testing a linear ironless generator for the sea wave energy harvesting," in *Oceans Conference Record (IEEE)*, Institute of Electrical and Electronics Engineers Inc., 2022. doi: 10.1109/OCEANSChennai45887.2022.9775494.

[24] M. Trapanese, D. Curto, V. Franzitta, Z. Liu, L. Mcnabb, and X. Wang, "A Planar Generator for a Wave Energy Converter," *IEEE Trans Magn*, vol. 55, no. 12, pp. 1–7, Dec. 2019, doi: 10.1109/TMAG.2019.2933701.

[25] M. Bencivenga, G. Nardone, F. Ruggiero, and D. Calore, "The Italian Data Buoy Network (RON)," *WIT Transactions on Engineering Sciences*, vol. 74, pp. 321–332, doi: 10.2495/AFM120291.