Annals of the Academy of Romanian Scientists
Series on Engineering Sciences
32 Volume **17**, Number **2**/**2025** ISSN 2066-8570

SCALING WAVE ENERGY CONVERTERS FOR MAXIMUM EFFICIENCY ALONG THE ROMANIAN BLACK SEA COAST

Theo-Andrei TEODOROF[1], Ajab Gul MAJIDI[2], Mihai Octavian POPESCU[3]

Rezumat. *Studiu oferă o evaluare preliminară a fezabilității implementării sistemelor de valorificare a energiei valurilor (WEC – Wave Energy Converter) în zona litoralului românesc al Mării Negre. Acesta explorează ipoteza conform căreia versiuni redimensionate ale acestor sisteme ar conduce la creșterea eficienței în contextul condițiilor locale. Pentru a testa această ipoteză, au fost redimensionate 18 tehnologii reprezentative de WEC, eficiența acestora fiind evaluată în trei puncte de studiu. Rezultatele oferă informații valoroase cu privire la eficiența și compatibilitatea diferitelor tehnologii de energie a valurilor pentru această regiune.*

Abstract. *This study provides a preliminary feasibility assessment for Wave Energy Converters (WECs) deployment along the Romanian Black Sea coast. It investigates the hypothesis that scaled versions of WECs may be better suited for the local conditions. To investigate this, 18 representative WEC technologies were scaled and their performance evaluated at three study sites. The findings offer valuable insights into the efficiency and suitability of different wave energy technologies for the region.*

Keywords: Wave energy technologies; *WEC* performance optimization; Marine renewable energy; Upscaling; Downscaling.

DOI 10.56082/annalsarscieng.2025.2.32

1.Introduction

Wave energy presents significant global availability, offers enhanced predictability compared to other intermittent renewable sources, and is associated with low environmental impact. These attributes have contributed to the growing interest in harnessing waves for electricity generation.

Strong policy frameworks have been introduced, particularly across Europe, to accelerate technological development, reduce investment risks and administrative obstacles. Wave energy harnessing could play a significant role in supporting Romania's efforts to meet its climate and energy goals, including the 30.7% share

[1]PhD. Student, National University of Science and Technology POLITEHNICA Bucharest, Romania, (tetheoan@gmail.com).
[2]Researcher, Interdisciplinary Centre of Marine and Environmental Research of the University of Porto (CIIMAR), Portugal, (ajabgulmajidi@gmail.com).
[3]Prof., National University of Science and Technology POLITEHNICA Bucharest, Romania, (mo.popescu@upb.ro)

of renewable energy in total energy production as outlined in Romania's national energy strategy for 2020–2030, with a long-term outlook extending to 2050 [1].

Wave energy presents significant global availability, with many countries, particularly in Europe, actively exploring its potential. For example, a study assessing Wave Energy Converters (*WEC*s) along the coast of mainland Portugal, one of the largest wave energy resource areas in continental Europe, highlighted Figueira da Foz (Central Portugal) as a promising location for *WEC* deployment, noting high Annual Energy Production (*AEP*) and favorable capacity factor values. This underscores the importance of conducting localized assessments to optimize energy capture efficiency, an approach reflected in this study along the Romanian Black Sea coast [2]. In recent years, wave energy resources have been extensively characterized at various global sites. Some studies [2, 3] have demonstrated that locations with higher energy potential may be less productive than sites with lower potential if the majority of the energy occurs during sea states where *WEC* efficiency is low.

The lowest global wave energy levels are generally recorded in semi-enclosed or enclosed basins, such as the Black Sea, where wave power density is typically estimated to range between 2 and 13 kW/m [5]. This is due to the region's geographical features, which limit wave formation. However, even in such areas, optimized *WEC*s can still harness valuable energy. For instance, a study on the southwestern Black Sea found that two *WEC* technologies: Oceantec at depths of 50, 75, and 100 m, and the Oyster at 5 and 25 m, performed most efficiently, revealing the importance of depth-specific optimization for maximizing energy capture in the region [5].

The vast global potential of wave energy has driven considerable academic and technological interest in developing methods for its conversion into electricity. The wave energy sector is characterized by a multitude of competing technologies designed to harness this energy. Although some technologies, such as those developed by EcoWave and CorPower Ocean, are approaching commercial viability, fundamental issues regarding the resilience of devices and economic affordability remain significant barriers to widespread commercial deployment.

The global variability in wave height and wave period presents significant challenges for the deployment of *WEC*s; most existing *WEC* technologies are optimized for operation in medium to high-energy sea states. Low-energy sea states, such as those present in the Black Sea, may offer higher energy yield potential, as a substantial portion of the total wave energy in high-energy regions often occurs under conditions where *WEC* efficiency is relatively low. There is a significant number of patents for *WEC*s, but only a small number have progressed beyond the prototype stage to reach pre-commercial or near-commercial deployment. Each *WEC* has specific efficiency characteristics and operational limits that vary according to the range of wave heights and periods in which it operates [6].

*WEC*s are typically designed for high-energy sea conditions. Therefore, deploying existing *WEC* technologies along the Romanian coast of the Black Sea may result in low energy yield due to reduced efficiency of the capture and conversion systems under lower-energy conditions. An improvement in capacity factor (C_f) may be achieved by scaling the devices according to the prevailing sea state. To guide the scaling process, the Froude similarity criterion was applied, based on the assumption that gravitational and inertial forces are the dominant factors influencing wave energy extraction.

The evaluated *WEC*s are scaled in relation to the sea conditions at three study sites (P1, P2, P3). By comparing their *AEP* and C_f, the optimal scaling factor for each technology is identified at the evaluated locations.

This study explores the potential for enhanced wave energy harnessing by assessing whether scaled versions of *WEC*s are a more efficient solution for the specific sea conditions along the Romanian Black Sea coast.

2.Methodology

Assessing energy production based on local sea state conditions is a fundamental step in determining the suitability of deploying *WEC*s at specific sites. This study is limited to the preliminary assessment phase and does not incorporate economic considerations or environmental impact analysis.

The scaled performance of a selection of 18 *WEC*s is assessed at 3 points of interest along the Romanian coast of the Black Sea, on the basis of a 35-year hindcast wave dataset (1990–2024) from the ERA5 reanalysis provided by CMEMS alongside publicly available *WEC* performance data.

The Froude scaling law dictates that wave heights scale linearly with λ, wave periods scale with the square root of λ, and power scales with $\lambda^{3.5}$ of the geometric scale [6]. In this study, each selected *WEC* was subjected to a scaling analysis using a scale factor (λ) ranging from 0.69 to 1.31 in increments of 0.01, with λ =1 representing the original scale. Values of λ<1 correspond to a downscaled version, while values of λ>1 indicate an upscaled version of the *WEC*. The upscaling or downscaling process follows the Froude similarity principle, which preserves dynamic similarity between the model and the prototype by maintaining equality of the Froude number [7]:

$$Fr = \frac{\mathrm{U}}{\sqrt{gL}} \quad (1)$$

where U is the characteristic velocity, g is gravitational acceleration, and L is the characteristic length (e.g., device diameter).

For this study, λ was varied between 0.69 and 1.31, corresponding to ±31% size variation around the prototype. Under Froude scaling, the main parameters of the device and the wave field are related as follows [8]:

$$L_{scaled} = L_0 \times \lambda \tag{2}$$

$$T_{scaled} = T_0 \times \sqrt{\lambda} \tag{3}$$

$$P_{scaled} = P_0 \times \lambda^{3.5} \tag{4}$$

The prototype power matrix $P_0(H_s, T_p)$ gives the average power output as a function of significant wave height (H_s) and peak period (T_p). To evaluate scaled devices, the measured sea states are converted to prototype-equivalent conditions [8]:

$$Hs_{proto} = \frac{Hs_{real}}{\lambda} \tag{5}$$

$$T_{proto} = \frac{T_{real}}{\sqrt{\lambda}} \tag{6}$$

The instantaneous power output of the scaled device is then:

$$P_{scaled} = P_0\left(Hs_{proto}, T_{proto}\right) \times \lambda^{3.5} \tag{7}$$

Most *WEC*s can perform satisfactorily along the Romanian Black Sea coast if they are appropriately scaled to align with the specific hydrographic conditions. Research suggests that the optimal scaling ratio is not directly dependent on the system's rated power output. Due to technological constraints, it is possible to rescale wave *WEC*s by up to 40% of the original model's dimensions [5]. For the present study, a rescaling factor of 31% of the original model's dimension was applied.

The Annual Energy Production (*AEP*), expressed in kilowatt-hours (kWh), is determined through time-series evaluation of the scaled WEC power output rather than by a discrete scatter matrix approach. The device performance is obtained by bilinear interpolation of the prototype power matrix $P_0(H_s, T_p)$, which defines the average electrical power (in kW) produced for a given sea state characterized by the significant wave height (H_s) and wave period (T_p, or T_e).

For each sea-state record in the measured time series, the corresponding scaled device power is computed using Froude-based scaling laws, and the total annual energy is derived as the time-average of all instantaneous power values over the simulated period. The *AEP* is therefore expressed as [9]:

$$AEP = \frac{1}{N_{years}} \sum_{t=1}^{N_{steps}} P_{scaled}(t)\Delta t \tag{8}$$

where Δt is the time step (1 h), and N_{years} is the total number of years represented by the time series.

This formulation ensures that all sea-state variations are captured directly from the long-term wave dataset, providing a more accurate representation of annual energy yield than traditional scatter-diagram integration methods.

The capacity factor (C_f) is defined as the ratio of the maximum power output, also known as rated power, of the analyzed *WEC* to the theoretical power available from the wave energy resource over a given period, measured in %. C_f highlights the annual energy delivered by the device with respect to the theoretical maximum it could deliver if operating continuously at its rated power. It is a crucial parameter for assessing the performance of *WEC*s in terms of their power generation capabilities. It can be calculated using the following equation [8]:

$$C_f = 100 \times \frac{P_e}{P_n} \tag{9}$$

where P_e is the maximum power output, also known as rated power, and P_n is the power output of the *WEC* in a specific context (wave height and wave period) for a defined period.

As the analyzed *WEC*s were designed for different wave climates than the ones encountered along the Romanian coast of the Black Sea, scaled devices have been considered – either upscaled or downscaled according to the Froude similarity principle - in order to match the wave conditions. For each study site, the optimum device size was determined by numerical simulation of different scaled versions to identify the scaling factor that maximizes the mean annual C_f and mean *AEP*.

The analysis was performed for a total of 342399960 computations across the three study sites, accounting for 18 *WEC* technologies, 65 scaling factors, and 306810 wave state samples (hourly data for 35 years). All the estimates of *AEP* were normalized with respect to scaled rated power in order to achieve a mean annual C_f.

3.Site and *WEC* selection

When selecting optimal sites for *WEC* deployment, a key objective is to balance environmental protection with socio-economic benefits. However, it's often difficult to accurately measure these social and economic factors. This is mainly due to a shortage of full-scale demonstration projects, which has resulted in a lack of real-world data to draw upon.

Significant wave height (Hs) and mean wave period (Te) were extracted from the ERA5 reanalysis dataset over 35 years, ranging from January 1990 to December 2024. The mean and maximum values of H_s and T_e for the three study sites are presented in Table 1. The wave resource was computed using the following equation [10]:

$$P = \frac{\rho g H_s^2 T_e}{64\pi} \tag{10}$$

where, ρ denotes water density, g is the gravitational acceleration, H_s is the significant wave height, expressed in m, and T_e represents wave period.

Table 1. Information regarding the study sites

Site	Coordinates	Distance from coastline (km)	Depth (m)	*Hs* (m)		*Te* (s)		Wave resource (kW/m)
				Mean	Max	Mean	Max	
P1	44.074444 29.956667	109	70	0.93	7.04	3.44	9.68	3.44
P2	44.308611 30.284722	130	87	0.95	7.15	3.62	9.71	3.62
P3	44.235556 28.6625	1.8	13	0.74	5.6	2.06	9.42	2.06

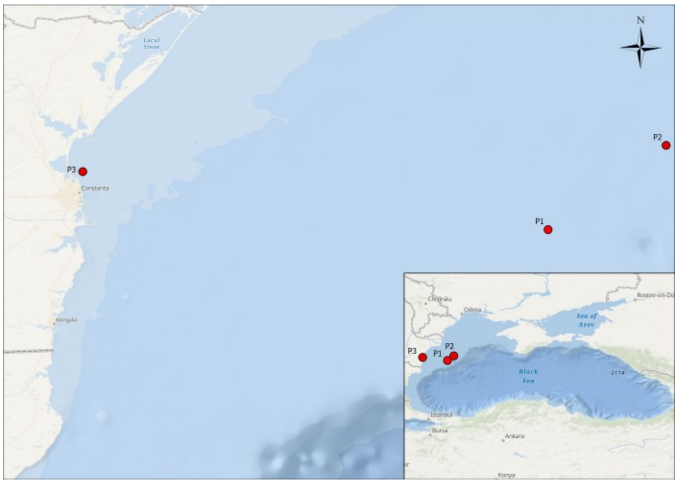

Fig. 1. Location of the selected study sites

As expected, the study sites that present the high values of H_s and T_e, study sites P1 and P2, demonstrate a greater wave energy potential, while study site P3 shows lower values of these parameters.

Based on data derived from the CMEMS ERA5 reanalysis dataset and the General Bathymetric Chart of the Oceans (GEBCO) bathymetry [11], the selected study sites were found to exhibit the following characteristics:

•P1 (44°04'28"N, 29°57'24"E): Located approximately 109 km offshore near the ANA oil platform, at 70 m water depth, the site has a mean wave height of 0.93 m and a mean wave period of 4.26 s. The highest recorded wave was 7.04 m on November 19, 2023, and the longest period was 9.68 s on December 8, 2012. The average wave power at this site is 3.44 kW/m.

•P2 (44°18'31"N, 30°17'05"E): Situated near a former oil platform approximately 130 km offshore, at 87 m water depth. The mean wave height and period are 0.95 m and 4.29 s, respectively. A maximum wave height of 7.15 m was recorded on February 7, 2012, and a maximum period of 9.71 s on February 8, 2012. At 3.62 kW/m, this site has the highest average wave power of all locations examined.

•P3 (44°14'08"N, 28°39'45"E): Located near a Spotter SofarOcean oceanographic buoy, located 1.8 km offshore, adjacent to the 13 m isobath. Daily in situ data have been collected from this site since 2022. The mean wave height is 0.74 m, with a historical maximum of 5.60 m recorded on February 7, 2012. The mean wave period is 4.06 s, and the maximum recorded period was 9.42 s on February 8, 2012. The long-term average wave power at this location is 2.06 kW/m.

Given the wide range of existing *WEC*s, the selection was made considering several key criteria:

•<u>Data Availability:</u> Only *WEC*s with verifiable performance data, such as power matrices, were included. It's important to note that comprehensive, publicly available data is not yet standard across the industry;

•<u>Suitability for Regional Conditions:</u> Systems designed to operate within the specific wave climate of the Black Sea. This included devices optimized for wave heights of 0-2 m and periods of 0-5 s, capable of withstanding extreme wave events up to 10 m, and suitable for installation depths of 100 m or systems that operate in more energetic wave environments, with scalable design features;

•<u>Operational Resilience:</u> Proven resilience in environments subject to significant seasonal variation;

•<u>Economic Feasibility:</u> Minimal expected costs for installation and upkeep in regions lacking extensive marine facilities.

The evaluation of 18 *WEC* technologies: CorPower Ocean [12], Aqua Buoy [13], AWS (Archimedes Wave Swing) [6], OEBuoy [6], Pontoon [6], Langlee (Floating 3 body Oscillating Flap) [14], CETO [15], Oyster [16], Oyster 2 (Bottom Fixed Oscillating Flap Buoy) [17], SeaBased AB [18], SSG (Sea Slot-cone Generator) [19], BFHB (Bottom Fixed Heave Buoy) [14], Oceantec [20], Wave Star [21], PWEC [22], Pelamis [23], Wave Bob [6], Wave Dragon [19] with rated power outputs between 250 kW and 20000 kW, facilitates the selection of the most suitable *WEC* technology for the three designated study sites along the Romanian coast of the Black Sea. Relevant differences can be observed between *WEC* technologies in terms of *AEP* and C_f in Table 2.

Table 2. Characteristics of the considered *WEC* (λ =1 original dimensions)

WEC	Rated power/unit P_e (kW)	Mean *AEP* (MWh/year)			Mean C_f (%)		
		P1	P2	P3	P1	P2	P3
CorPower Ocean	400	410.67	429.79	271.55	11.7	12.2	7.7
Aqua Buoy	250	61.63	65	35.39	2.7	2.9	1.6
AWS	2470	109.90	116.45	67.18	0.5	0.5	0.3
OEBuoy	2880	353.99	375.94	199.26	1.4	1.4	0.7
Pontoon	3619	735.92	771.68	435.87	2.3	2.4	1.3
Langlee	1665	347.15	367.48	196.22	2.3	2.5	1.3
CETO	260	50.50	53.76	25.40	2.1	2.3	1.1
Oyster	290	298.22	314.91	184.74	11.7	12.4	7.2
Oyster 2	3332	640.85	679.28	361.63	2.2	2.3	1.2
Seabased AB	15	8.01	8.41	4.6	6.1	6.4	3.5
SSG	20000	5219	5521	3214	2.9	3.1	1.8
Heave buoy (BFHB)	2192	708.84	747.31	2192	3.7	3.9	2
Oceantec	500	452.34	482.90	266.60	10.3	11	6.1
Wave Star	600	961.60	987.75	691.72	18.2	18.7	13.2
PWEC	479	498.91	479	328.20	11.9	12.5	7.8
Pelamis	750	288	306.51	171.70	4.3	4.6	2.6
Wave Bob	1000	202.55	214.91	116.97	2.3	2.4	1.3
Wave Dragon	7000	1813.3	1924.6	1069.4	2.9	3.1	1.7

4.Results and discussions

For a thorough assessment of each *WEC* at various scale factors, two key performance metrics were utilized: *AEP* and C_f. *AEP* represents the total electrical energy generated by the device over the course of a year, serving as an absolute measure of energy output. The C_f quantifies the efficiency of the device by expressing the ratio of actual energy produced to the maximum possible energy if the device operated at full rated power continuously throughout the year. These indicators together provide a comprehensive evaluation of both the energy yield and operational effectiveness of the *WEC*s under different scaling and environmental conditions.

As part of the performance assessment methodology, the *AEP* and C_f were computed for each selected *WEC* across all study sites (P1, P2, and P3), considering scale factors (λ) ranging from 0.69 to 1.31 with an incremental step of 0.01.

As anticipated, the scaling process had a significant impact on the variation of C_f. Reducing the scale (downscaling λ<1) resulted in an increase in C_f, indicating improved energy capture efficiency. In contrast, upscaling (λ>1) the devices led to a reduction in C_f, suggesting decreased efficiency under the given wave conditions. This trend was observed uniformly across all study sites and with all *WEC* technologies, highlighting the importance of aligning device dimensions with local wave climate for optimal wave energy harnessing.

Downscaling the devices led to an increase in the C_f for all analyzed *WEC* technologies. Among them, the WaveStar device exhibited the most significant improvement, with an increase of approximately 4% across all study sites. The highest C_f values were consistently achieved at the lowest scale factor (λ = 0.69) for all technologies and locations.

Conversely, upscaling led to a decline in C_f, reflecting reduced performance under the prevailing wave conditions. The results indicate that upscaling of *WEC* devices reduces performance, as reflected in the variation of the C_f. All of the analyzed *WECs* exhibited a reduction in performance when subjected to downscaling. This reduction was consistently reflected in the C_f, with the majority of devices experiencing a decrease of approximately 4% across all three study sites (P1, P2, and P3). The consistency of this trend suggests that downsizing the physical dimensions of the converters leads to a mismatch between the device's operational parameters and prevailing wave energy conditions, thereby reducing their energy efficiency.

For each location, the optimal scale was identified by determining the best scaling factor of each technology by finding the scale at which the maximum *AEP* and C_f could be reached. Additionally, the results corresponding to the highest (λ=1.31) and lowest (λ=0.69) scaling factors were reported for comparison.

Table 3 shows the mean C_f for the evaluated *WEC* technologies, at minimum scale factor λ=0.69, at original scale λ=1, and at maximum simulated scale λ=1.31, under the sea state conditions present in the selected study sites P1, P2 and P3. A clear trend can be observed wherein an increase in λ corresponds to a decrease in C_f. The results suggest that the *WEC* designs are, on average, most efficient at a smaller scale.

The analysis demonstrates a consistent and uniform trend across the entire dataset: for all *WEC*s and at all scales, both the C_f and the *AEP* consistently exhibit the ordering P2>P1>P3.

The results show a clear shift in *WEC* leadership based on scale factor. While Oyster (25.29% at P2) and CorPower Ocean (24.78% at P2) excel when downscaled, their performance plummets if upscaled. In contrast, Wave Star proves to be the most scalable and robust, becoming the top performer at both the original scale (18.78% at P2) and upscaled (14.02% at P2). The optimal results regarding C_f were obtained by Oyster (25.29% at P2) at the minimum evaluated scale factor λ=0.69.

Table 3. C_f of the considered *WEC*s at λ =0.69, λ =1 and λ =1.31

WEC	C_f (%) at λ=0.69			C_f (%) at λ=1			C_f (%) at λ=1.31		
	P1	P2	P3	P1	P2	P3	P1	P2	P3
CorPower Ocean	23.86	24.78	16.74	11.71	12.26	7.74	6.19	6.51	3.98
Aqua Buoy	8.41	8.88	5.2	2.79	2.98	1.61	1.03	1.13	0.56
AWS	1.78	1.88	1.13	0.51	0.54	0.31	0.17	1.86	0.11
OEBuoy	3.98	4.21	2.35	1.4	1.49	0.79	0.56	0.59	0.29
Pontoon	5.17	5.4	3.25	2.32	2.43	1.37	1.17	1.24	0.64
Langlee	4.88	5.11	2.99	2.38	2.52	1.34	1.16	1.23	0.62
CETO	4.71	4.95	2.6	2.22	2.36	1.11	1.06	1.13	0.49
Oyster	24.31	25.29	16.63	11.73	12.39	7.27	5.79	6.16	3.37
Oyster 2	5.85	6.16	3.56	2.19	2.33	1.24	0.94	1	0.49
Seabased AB	11.68	12.1	7.58	6.09	6.39	3.5	3.32	3.52	1.71
SSG	7.81	8.19	4.97	2.98	3.15	1.83	1.31	1.39	0.79
BFHB	7.79	8.13	4.78	3.69	3.89	2.05	1.89	2.01	0.96
Oceantec	23.24	24.66	14.21	10.32	11.02	6.08	4.3	4.58	2.51
Wave Star	22.26	22.57	17.19	18.28	18.78	13.15	13.59	14.02	9.36
PWEC	21.76	22.59	15.74	11.88	12.48	7.82	6.43	6.81	3.99
Pelamis	10.5	11.04	6.51	4.39	4.66	2.61	1.9	2.02	1.11
Wave Bob	6.56	6.92	4.03	2.31	2.45	1.33	0.96	1.02	0.52
Wave Dragon	7.67	8.06	4.89	2.96	3.14	1.74	1.32	1.41	0.73

As expected, scaled versions of *WEC*s play a significant role in C_f manipulation. This is because most devices are originally developed to harness waves in a specific sea state. Hence, lower scaling factors generally result in higher C_f values. It is evident that the scale factor required to maximize C_f at a given site depends on the *WEC* technology.

At all study sites in the Black Sea, the capacity factors for the evaluated *WEC*s remain below 26% - a finding that aligns with expectations for low-energy seas like the Black Sea [24]. In contrast, *WEC* deployments in high-energy regions such as those facing the North Atlantic near Ireland, France, or western Britain often achieve capacity factors in the range of 20 % to 40 % [5] for available *WEC* models.

Table 4 provides an overview of the mean *AEP* of the evaluated *WEC*s, at three scale factors λ=0.69, λ=1, and λ=1.31, based on the site-specific sea state conditions at P1, P2, and P3. The results in Table 4 present a contrasting pattern, whereas the previous table, Table 3 regarding C_f, indicated that smaller scales were advantageous, the trends observed here are nearly the opposite. In this assessment, SSG outperforms all other devices in terms of energy production at every scale, peak performance at λ=1.31 (6273 MWh/year at P2), the next-closest competitors being Wave Dragon (2225 MWh at P2 with λ=1.31). However, this result should be interpreted within the context of a key deployment constraint of SSG, it cannot be deployed in nearshore or offshore sites.

The P2>P1> P3 order observed previously is no longer consistent. The relationships now demonstrate significantly greater complexity and appear to be device-specific.

Table 4. *AEP* of the considered *WECs* at λ =0.69, λ =1 and λ =1.31

WEC	*AEP* (MWh/year), λ=0.69			*AEP* (MWh/year), λ=1			*AEP* (MWh/year), λ=1.31		
	P1	P2	P3	P1	P2	P3	P1	P2	P3
CorPower Ocean	228.3	237.1	160.1	410.7	429.8	271.6	559	587.1	359.4
Aqua Buoy	50.3	53.1	31.1	61.4	65.3	35.4	58	62.1	31.4
AWS	105.4	111.2	66.8	109.9	116.5	67.2	97.5	103.9	58.8
OEBuoy	274.2	289.8	162.2	353.9	375.9	199.3	361.7	385.7	193.7
Pontoon	447.5	468.1	281.5	735.9	771.7	435.9	956.9	1010.9	519.2
Langlee	194.4	203.5	118.9	347.2	367.5	196.2	435.4	463.5	231.5
CETO	29.3	30.8	16.2	50.5	53.7	25.4	62	66.5	29.1
Oyster	168.6	175.5	115.4	298.3	314.9	184.8	379	403.2	220.1
Oyster 2	466.5	491.2	284.1	640.9	679.3	361.6	704.6	750.5	371.8
Seabased AB	4.19	4.34	2.72	8.01	8.41	4.6	11.2	11.89	5.78
SSG	3735.3	3919.4	2377.2	5219	5521.8	3214	5908.1	6273.3	3574.5
BFHB	408.6	426.1	250.5	708.8	747.3	393.2	935.3	994.9	474.7
Oceantec	278	294.9	170	452.4	482.9	266.6	485.4	517	282.8
Wave Star	319.5	323.9	246.7	961.6	987.8	691.7	1838.9	1897.9	1266.1
PWEC	249.3	258.9	180.4	498.9	524.1	328.2	695.2	735.9	431.5
Pelamis	188.4	198	116.8	288.9	306.5	171.7	321.4	342	187.4
Wave Bob	157	165.5	96.51	202.6	214.9	116.9	215.8	230	116.9
Wave Dragon	819.6	1348.8	986	1813.3	1925	1069.3	2083.6	2225	1155.8

Table 5. Optimal scale for *AEP* and C_f of the considered *WEC*s

WEC	P1				P2				P3			
	λ	*AEP, MWh*	λ	C_f, %	λ	*AEP, MWh*	λ	C_f, %	λ	*AEP, MWh*	λ	C_f, %
CorPower Ocean	1.31	559	0.69	23.8	1.31	587	0.69	24.8	1.31	359	0.69	16.7
Aqua Buoy	1.07	63.9	0.69	8.41	1.07	65.6	0.69	8.88	0.95	35.4	0.69	5.2
AWS	0.89	110.3	0.69	1.78	0.89	116.8	0.69	1.88	0.84	68.9	0.69	1.13
OEBuoy	1.19	364.1	0.69	3.98	1.20	387.8	0.69	4.21	1.09	200.1	0.69	2.35
Pontoon	1.31	957	0.69	5.17	1.31	1011	0.69	5.41	1.31	519.3	0.69	3.25
Langlee	1.31	435.4	0.69	4.88	1.31	463.5	0.69	5.11	1.31	231.5	0.69	2.99
CETO	1.31	62	0.69	4.71	1.31	66.5	0.69	4.95	1.31	29.1	0.69	2.6
Oyster	1.31	379	0.69	24.3	1.31	403.2	0.69	25.3	1.31	220.1	0.69	16.6
Oyster 2	1.31	704.6	0.69	5.85	1.31	750.5	0.69	6.16	1.31	371.8	0.69	3.56
Seabased AB	1.31	11.2	0.69	11.7	1.31	11.9	0.69	12.1	1.31	5.8	0.69	7.58
SSG	1.30	5914	0.69	7.81	1.31	6273	0.69	8.19	1.29	3577	0.69	4.97
BFHB	1.31	935	0.69	7.79	1.31	995	0.69	8.13	1.31	474.7	0.69	7.78
Oceantec	1.27	494.2	0.69	23.2	1.27	526.4	0.69	24.6	1.27	287	0.69	14.2
Wave Star	1.31	1839	0.69	22.3	1.31	1898	0.69	22.6	1.31	1266	0.69	17.2
PWEC	1.31	695.2	0.69	21.8	1.31	735.9	0.69	22.6	1.31	431.5	0.69	15.7
Pelamis	1.29	321.7	0.69	10.5	1.29	342.2	0.69	10	1.28	187.6	0.69	6.6
Wave Bob	1.31	215.8	0.69	6.56	1.31	230	0.69	6.92	1.12	118.7	0.69	4.03
Wave Dragon	1.30	2084	0.69	7.67	1.30	2225	0.69	8.06	1.28	1159	0.69	4.89

Table 5 shows a comparative analysis of the optimum scale factor identified in relation to *AEP* and C_f, determined by evaluating all scale factors from λ=0.69 to λ=1.31 with a step of 0.01, in the three study sites selected for evaluation, P1, P2, and P3. A consistent performance hierarchy across all technologies can be observed: P2>P1>P3. Both *AEP* and C_f are higher in the P2 study site and lower in the P3 study site. This confirms the assumption that P2 represents the location with the most abundant and effective wave energy resource, while P3 represents the least energetic.

Downscaling appears to have a beneficial effect on C_f, as all evaluated technologies achieved their best results at the minimum scale factor considered λ=0.69. Upscaling of all evaluated *WEC*s associated with the study sites shows a decrease in C_f. Regarding scaling in relation to *AEP*, the optimal scale factor varies by technology, with maximum energy production achievable through either upscaling or downscaling, depending on the specific characteristics of each *WEC*.

Technologies like Oyster (25.3% at P2) and CorPower Ocean (24.8% at P2) appear to be more hydrodynamically efficient, achieving a higher C_f relative to their scale. This indicates they are significantly more effective at converting the available energy resource.

Regarding *AEP* performance, it is clear that large-scale devices are favored. SSG demonstrates by far the highest *AEP* (6273 MWh/year at P2), followed by Wave Dragon (2225 MWh/year) and Wave Star (1898 MWh/year). Devices with low

AEP may still have value in specific applications but are less suitable for large-scale energy generation in this region.

The charts present in Fig. 2, Fig. 3, and Fig. 4 provide a graphic comparative analysis of the selected *WEC* technologies, illustrating the impact of scaling on both *AEP* and C_f at the selected study site: P1, P2, and P3. At all sites, the responses of the devices are similar. For the majority of *WEC* technologies (e.g., CorPower, Wave Dragon, Pelamis, CETO), *AEP* demonstrates a positive correlation with the scaling factor. An increase in the scaling factor, corresponding to the upscaling of the device, results in a corresponding increase in *AEP*. There is a significant variance in *AEP* among the different technologies.

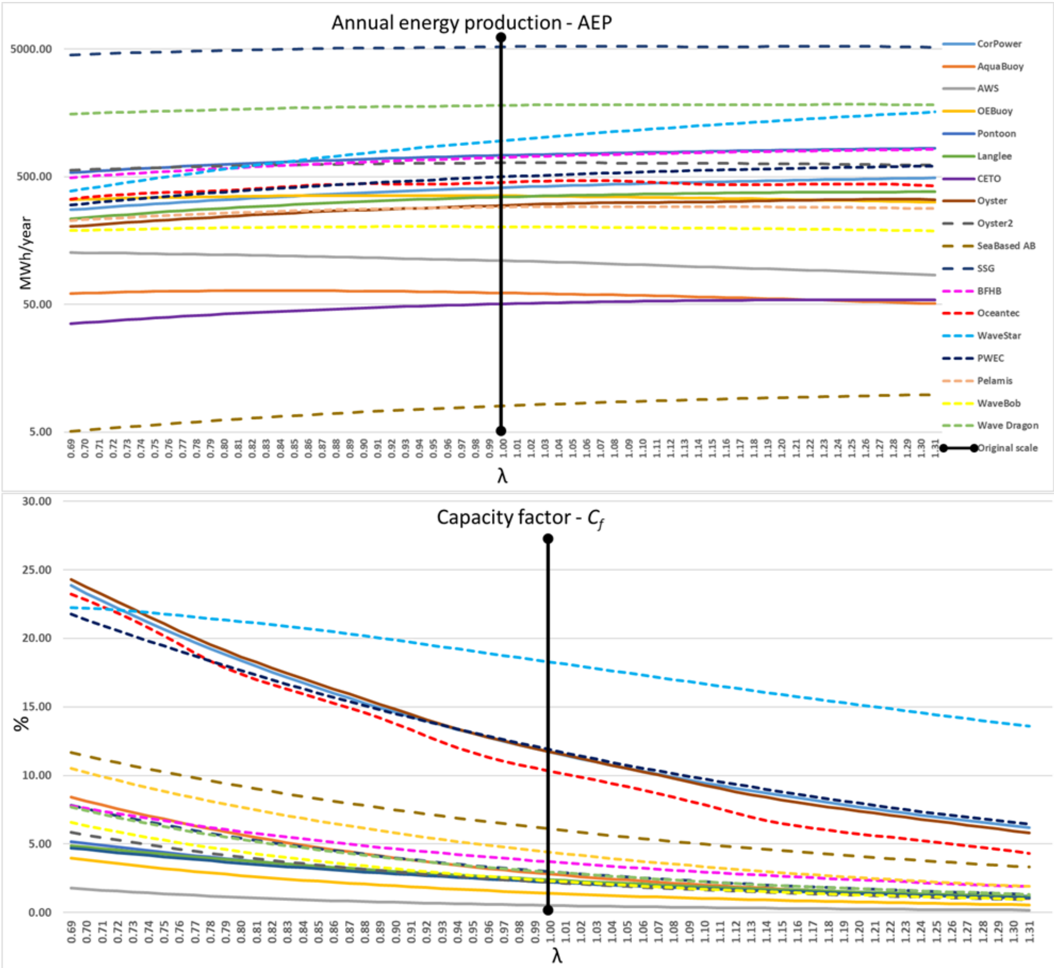

Fig. 2. Scaling results for P1 study site

In direct contrast to *AEP*, the C_f for all technologies shows a clear inverse relationship with the scaling factor. As the scaling factor increases, the C_f decreases.

This trend indicates that while upscaling results in a higher rated power and greater *AEP*, it simultaneously reduces the device's operational efficiency. The device spends more time operating at a lower fraction of its new, larger maximum capacity, thus lowering its C_f. There is a clear divergence between the objectives of maximizing *AEP* and maximizing operational efficiency (C_f). Upscaling benefits *AEP* at the expense of C_f. Different *WEC* designs exhibit varying responses to this compromise between performance metrics. CorPower is optimized for high *AEP*, characteristic of larger-scale devices, but this comes with a low C_f. Conversely, CETO and Oyster show higher C_f values, particularly at smaller scales, but yield significantly less total energy.

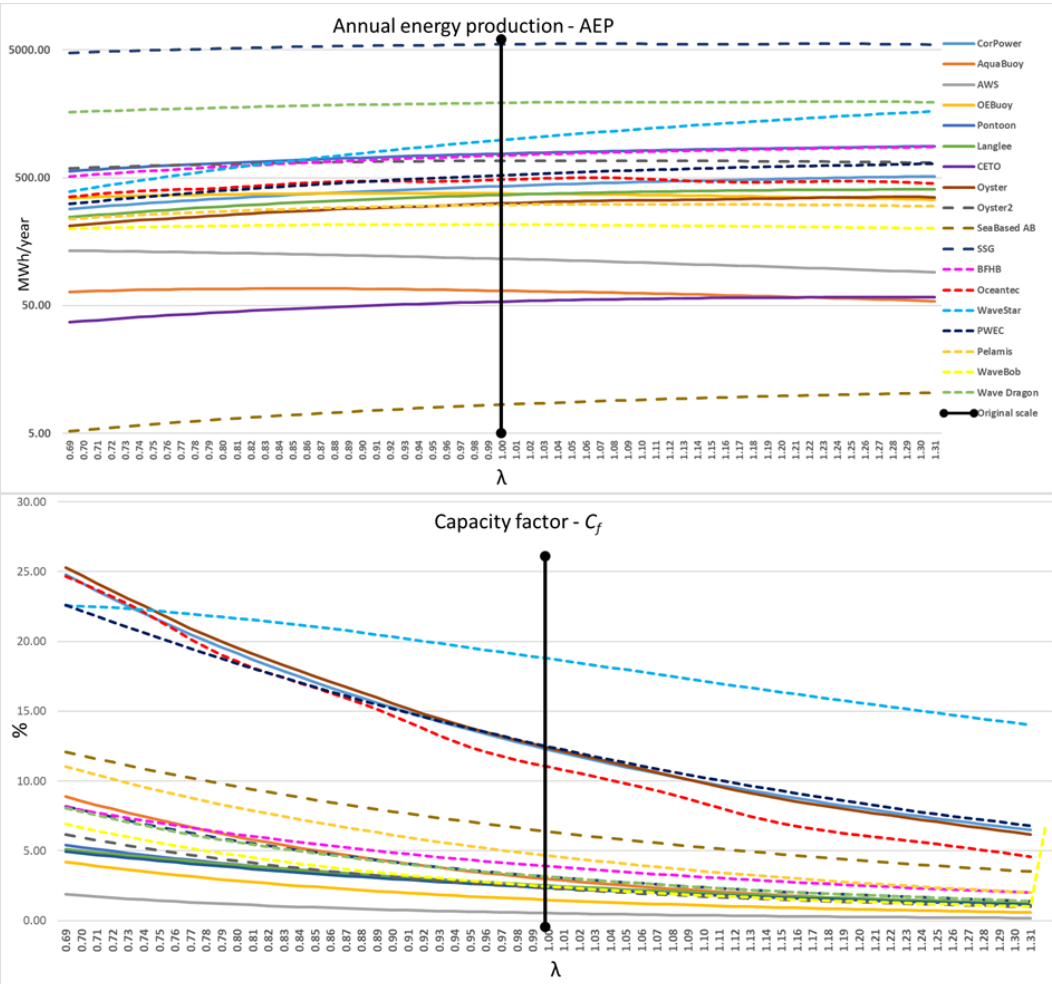

Fig. 3. Scaling results for P2 study site

All of the charts, for the three study sites, confirm that while upscaling leads to increased *AEP*, it often comes at the cost of a lower capacity factor C_f.

Interannual variability in power output, *AEP,* and C_f, driven by fluctuations in sea state conditions, leads to differences in *AEP* and C_f, with specific years exhibiting significantly enhanced energy yields. This highlights the importance of sea state on *WEC* performance.

Upscaling a device yields a higher *AEP* but does so at the cost of diminishing C_f. In contrast, downscaling (λ<1) improves efficiency but sacrifices total energy production. Therefore, the optimal scale for a *WEC* is not one that simply maximizes *AEP*, but rather one that balances *AEP* and C_f, to achieve the lowest possible Levelized Cost of Energy (LCOE).

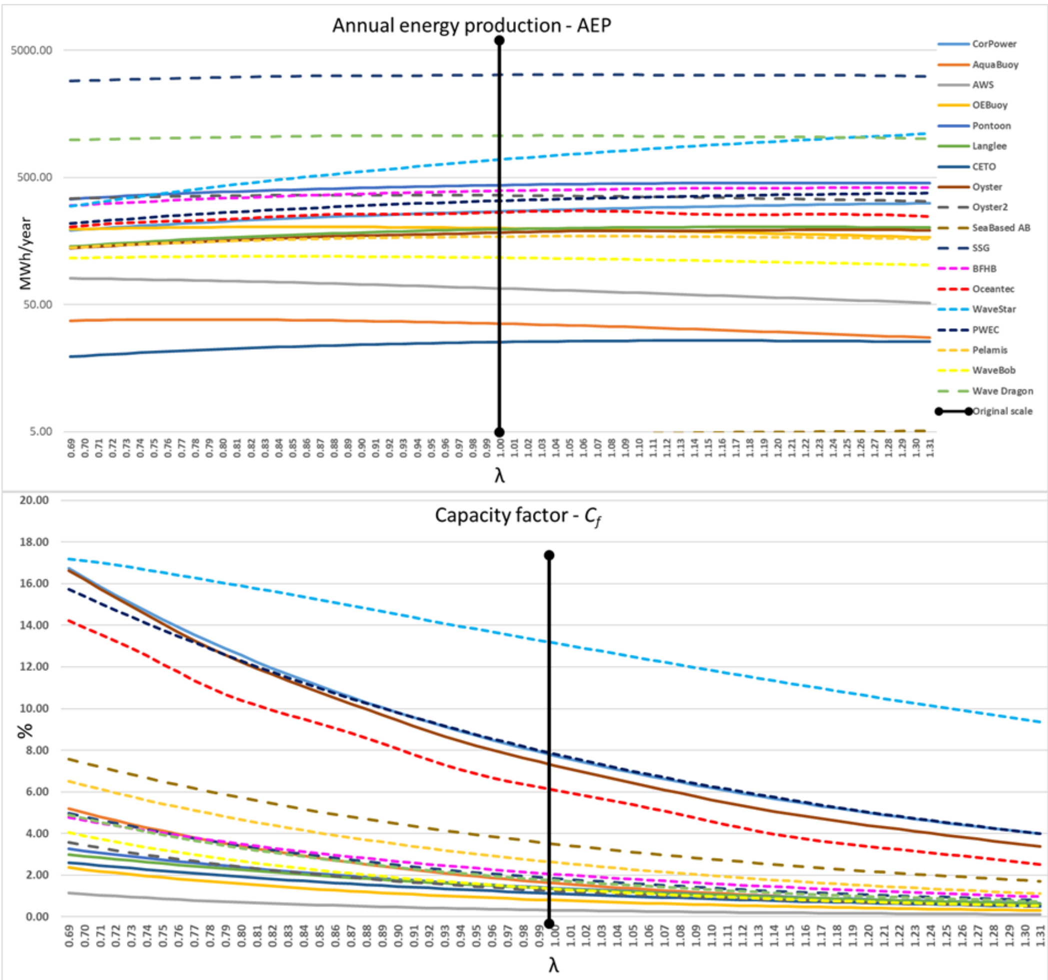

Fig. 4. Scaling results for P3 study site

Among the three selected locations, study site P2 is identified as the optimal site for deployment, as it consistently yields the highest C_f and *AEP* across all evaluated wave energy converters (*WEC*s) and scale levels.

Based on a comprehensive parameter assessment, this study identified P2 as the optimal location among the three sites investigated. At this location, the SSG achieved the highest *AEP* (5378.55 MWh/year) output of 5378.55 MWh/year at the minimum scale factor (λ=0.69), while Oyster demonstrated the best C_f (24.74%) also at the minimum scale factor used for evaluation.

This study focuses on a representative subset of the data rather than a comprehensive overview of all results. Specifically, it presents the *AEP* and C_f only for the scaling ratios that yielded the best and worst performance for each of the 18 *WEC* models across the three designated study sites. A comprehensive analysis of all scaling variations falls outside the scope of this paper.

5.Conclusions

Wave energy is an underutilized, yet valuable, resource that can contribute to the diversification of renewable energy systems. Its development is essential for fostering a more sustainable, flexible and resilient energy infrastructure.

Each *WEC* technology demonstrates a unique capacity to adapt to different environmental conditions and operational scales. Several *WEC* technologies, such as Wave Star, demonstrate a wide range of adaptability in responding to local wave conditions at different scale factors. Some devices perform well compared to others in the context of the evaluated sea state. Low *AEP* devices are unsuitable for large-scale energy production along the Romanian coast of the Black Sea, but they could still be valuable in specific, smaller-scale contexts. Different *WEC* scales were considered, from λ=0.69 to λ=1.31, the original scale defined as λ=1, with steps of 0.01, in order to determine the optimal scale for each *WEC* technology corresponding to the designated study sites: P1, P2, and P3. To estimate the electrical output of the device after scaling, the electrical output of the scaled devices was estimated using Froude similarity, in accordance with established practices in the physical modeling of *WEC*s as reported in previous studies.

The results in this study indicate that downscaling positively impacts the C_f, with all evaluated *WEC*s achieving their highest C_f at the minimum scale factor analyzed λ = 0.69. In contrast, the optimal scale factor for maximizing *AEP* varies among the evaluated technologies, requiring upscaling or downscaling of the device.

This study may serve as a valuable resource for stakeholders, investors, and project developers in identifying the most suitable *WEC* technology for deployment along the Romanian coast of the Black Sea, depending on whether they seek to maximize total energy output or optimize conversion efficiency.

The findings indicate that applying scaled *WEC*s could improve wave energy harvesting along the Romanian Black Sea coast. By optimizing the size of the *WEC*s for specific wave conditions, it's possible to increase the overall energy capture. This strategy could lead to more efficient and reliable energy generation, making better use of this valuable marine resource. They also underscore that the optimal design for a *WEC* is not absolute but depends on the specific project economic drivers, such as whether the goal is to maximize total revenue (favoring *AEP*) or to ensure high, consistent utilization of a rated capacity (favoring C_f).

In conclusion, the optimal scale of a *WEC* cannot be defined solely by the maximization of *AEP*; it requires a balanced consideration of both maximizing total energy output and enhancing techno-economic efficiency, as reflected by the C_f, in order to achieve a competitive Levelized Cost of Energy (LCOE).

This study should be regarded as a preliminary assessment of the technical feasibility of *WEC* deployment on the Romanian Black Sea coast. While this analysis provides a technical foundation, a holistic evaluation to identify optimal deployment sites must also integrate critical economic, social, and political factors.

R E F E R E N C E S

[1] Government of Romania, “Romania’s Energy Strategy 2025–2035, with a 2050 Perspective [Strategia Energetică a României 2025–2035, cu perspectiva anului 2050].” Bucharest, Romania: Ministry of Energy, 2024, 2024. [Online]. Available: https://energie.gov.ro/strategia-energetica-a-romaniei-2025-2035

[2] A. G. Majidi, V. Ramos, P. Rosa-Santos, L. Das Neves, and F. Taveira-Pinto, “Power production assessment of wave energy converters in mainland Portugal,” *Renewable Energy*, vol. 243, p. 122540, Apr. 2025, doi: 10.1016/j.renene.2025.122540.

[3] E. Rusu, “Evaluation of the Wave Energy Conversion Efficiency in Various Coastal Environments,” *Energies*, vol. 7, no. 6, pp. 4002–4018, June 2014, doi: 10.3390/en7064002.

[4] M. Veigas, M. López, and G. Iglesias, “Assessing the optimal location for a shoreline wave energy converter,” *Applied Energy*, vol. 132, pp. 404–411, Nov. 2014, doi: 10.1016/j.apenergy.2014.07.067.

[5] Ajab G. Majidi, Bilal Bingölbali, and Adem Akpınar, “Power Production Performance of Different Wave Energy Converters in the Southwestern Black Sea,” *World Academy of Science, Engineering and TechnologyInternational Journal of Energy and Power Engineering*, vol. 14, no. 7, pp. 191–195, 2020.

[6] S. Bozzi, G. Besio, and G. Passoni, "Wave power technologies for the Mediterranean offshore: Scaling and performance analysis," *Coastal Engineering*, vol. 136, pp. 130–146, June 2018, doi: 10.1016/j.coastaleng.2018.03.001.

[7] G. Giannini *et al.*, "Wave Energy Converter Power Take-Off System Scaling and Physical Modelling," *JMSE*, vol. 8, no. 9, p. 632, Aug. 2020, doi: 10.3390/jmse8090632.

[8] A. Majidi, B. Bingölbali, A. Akpınar, G. Iglesias, and H. Jafali, "Downscaling wave energy converters for optimum performance in low-energy seas," *Renewable Energy*, vol. 168, pp. 705–722, May 2021, doi: 10.1016/j.renene.2020.12.092.

[9] International Electrotechnical Commission, "Marine energy-wave, tidal and other water current converters—part 100: electricity producing wave energy converters-power performance assessment." Geneva: IEC, 62600-100, 2023.

[10] European Commission. Joint Research Centre., *Clean Energy Technology Observatory, Ocean energy in the European Union: status report on technology development, trends, value chains and markets : 2022.* LU: Publications Office, 2022. Accessed: Aug. 28, 2025. [Online]. Available: https://data.europa.eu/doi/10.2760/162254

[11] D. C. Kapoor, "General bathymetric chart of the oceans (GEBCO)," *Marine Geodesy*, vol. 5, no. 1, pp. 73–80, Jan. 1981, doi: 10.1080/15210608109379408.

[12] A. Ulazia, M. Penalba, A. Rabanal, G. Ibarra-Berastegi, J. Ringwood, and J. Sáenz, "Historical Evolution of the Wave Resource and Energy Production off the Chilean Coast over the 20th Century," *Energies*, vol. 11, no. 9, p. 2289, Aug. 2018, doi: 10.3390/en11092289.

[13] L. Castro-Santos, D. Silva, A. R. Bento, N. Salvação, and C. Guedes Soares, "Economic Feasibility of Wave Energy Farms in Portugal," *Energies*, vol. 11, no. 11, p. 3149, Nov. 2018, doi: 10.3390/en11113149.

[14] G. Reikard, B. Robertson, and J.-R. Bidlot, "Combining wave energy with wind and solar: Short-term forecasting," *Renewable Energy*, vol. 81, pp. 442–456, Sept. 2015, doi: 10.1016/j.renene.2015.03.032.

[15] J. Morim, N. Cartwright, M. Hemer, A. Etemad-Shahidi, and D. Strauss, "Inter- and intra-annual variability of potential power production from wave energy converters," *Energy*, vol. 169, pp. 1224–1241, Feb. 2019, doi: 10.1016/j.energy.2018.12.080.

[16] A. Gul Majidi, B. Bingölbali, A. Akpınar, and E. Rusu, "Dimensionless Normalized Wave Power in the Hot-spot Areas of the Black Sea," *E3S Web Conf.*, vol. 173, p. 01001, 2020, doi: 10.1051/e3sconf/202017301001.

[17] A. Babarit, J. Hals, M. J. Muliawan, A. Kurniawan, T. Moan, and J. Krokstad, "Numerical benchmarking study of a selection of wave energy converters," *Renewable Energy*, vol. 41, pp. 44–63, May 2012, doi: 10.1016/j.renene.2011.10.002.

[18] N. Almonacid, "Evaluating a project for wave energy generation at a coastal site in Chile," 2015, *Unpublished*. doi: 10.13140/RG.2.1.2131.5447.

[19] J. C. Pacaldo, P. H. T. Bilgera, and M. L. S. Abundo, "Nearshore Wave Energy Resource Assessment for Off-Grid Islands: A Case Study in Cuyo Island, Palawan, Philippines," *Energies*, vol. 15, no. 22, p. 8637, Nov. 2022, doi: 10.3390/en15228637.

[20] X. Shi, S. Li, B. Liang, J. Zhao, Y. Liu, and Z. Wang, “Numerical study on the impact of wave-current interaction on wave energy resource assessments in Zhoushan sea area, China,” *Renewable Energy*, vol. 215, p. 119017, Oct. 2023, doi: 10.1016/j.renene.2023.119017.

[21] H. R. Ghafari, H. Ghassemi, and A. Neisi, “Power matrix and dynamic response of the hybrid Wavestar-DeepCwind platform under different diameters and regular wave conditions,” *Ocean Engineering*, vol. 247, p. 110734, Mar. 2022, doi: 10.1016/j.oceaneng.2022.110734.

[22] G. Giannini, P. Rosa-Santos, V. Ramos, and F. Taveira-Pinto, “Wave energy converters design combining hydrodynamic performance and structural assessment,” *Energy*, vol. 249, p. 123641, June 2022, doi: 10.1016/j.energy.2022.123641.

[23] D. Silva, E. Rusu, and C. Soares, “Evaluation of Various Technologies for Wave Energy Conversion in the Portuguese Nearshore,” *Energies*, vol. 6, no. 3, pp. 1344–1364, Mar. 2013, doi: 10.3390/en6031344.

[24] A. G. Majidi, V. Ramos, P. Rosa-Santos, A. Akpınar, L. Das Neves, and F. Taveira-Pinto, “Development of a multi-criteria decision-making tool for combined offshore wind and wave energy site selection,” *Applied Energy*, vol. 384, p. 125422, Apr. 2025, doi: 10.1016/j.apenergy.2025.125422.