

WAVE ENERGY POTENTIAL AND WEC PERFORMANCE ALONG THE ROMANIAN BLACK SEA COAST

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This paper provides a detailed analysis of the wave energy potential at three locations in the Black Sea, evaluating the performance of various WEC technologies. The paper highlights the difficulties of implementing WEC as well as a series of financial data on the electricity produced. In this regard, the paper may be useful for operators in coastal areas to assess the possibilities of practical use of wave energy.

Keywords: Black Sea, wave energy, wave energy converter (WEC), WEC power performance

1. Introduction

Often overlooked, wave energy represents a high-density energy source that can contribute to achieving the ambitious target set by the EU environmental programs, as well as Romania's Energy Strategy for the period 2020-2030, with a perspective towards 2050. This target stipulates that 30.7% of energy production should come from renewable sources, which implies an additional energy capacity of 7 GWh/year. Europe is at the forefront of wave energy research due to its extensive network of specialized research centers, numerous testing facilities, and high volume of scientific publications related to wave energy assessment and harnessing.

Wave energy is characterized by substantial global availability, offers greater predictability compared to other renewable intermittent sources, and is associated with minimal environmental impact. Harnessing of wave energy is still not fully developed in terms of mass production, grid integration, and commercialization.

At the present moment, the wave energy sector is still in early stages of development, with a few examples of WECs reaching commercial versions such as CorPower Ocean and Eco Wave Power, although research has been concerned about wave energy converters (WECs) since 1799 when French Pierre-Simon Girard patented the first wave energy converter concept. The current situation is

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due to many reasons, such as: high initial cost, large number of concepts, failure due to environmental factors - storms, low efficiency, and limitation to a narrow sea state [1].

The production costs of electricity from wave energy conversion systems range between 0.28-0.52 €/kWh, making it currently an expensive solution for generating electricity from renewable sources [8]. Through its renewable energy implementation plan, the EU aims to develop marine power plants (wave energy conversion plants, etc.) with production cost of 0.15 €/kWh in 2030 and 0.1 €/kWh by 2035 [23].

According to data provided in EU-SCORES [11], it can be observed that wave energy within the context of offshore renewable energy sources is beginning to become competitive, with production costs ranging between 260 and 600 €/MWh, depending on the system employed. Currently, the harnessing of the wave energy is more cost-effective in certain regions when using specific systems, compared to energy derived from offshore floating photovoltaic panels, which have a production cost of 354 €/MWh.

Evaluating energy production based on local sea state conditions is a key aspect of determining the feasibility of deploying WECs at specific locations. This study focuses solely on the initial assessment phase, without addressing cost factors or environmental impacts.

The purpose of the presented study is to investigate the power performance of several WECs that are representative of the wave energy industry in three study sites across the Romanian coast of the Black Sea. A total of 15 WECs were considered, namely: CorPower, AquaBuoy, AWS, OEBuoy, Pontoon, Langlee, CETO, Oyster, Oyster 2, Sea Based, BFHB, Oceanec, WaveStar, PWEC, Pelamis, WaveBoB, Wave Dragon.

2. Methodology

This study characterizes the wave energy conversion process at the technical potential stage, inspired by the classification used in [2], referred to as Level 3 in some studies. The technical potential of wave energy is primarily determined by the performance of the WEC and the efficiency of the energy transmission system to shore. It is important to note that not all WEC technologies are equally suitable for every sea state, as their effectiveness depends on site-specific sea state conditions. The ability of a WEC to convert the available wave power into usable electrical output is characterized by its power matrix and rated power. These parameters are influenced by the interaction between the prevailing sea state and the device's physical dimensions, operational principle, and power take-off (PTO) system.

The efficiency of wave energy conversion technologies has been evaluated based on oceanographic data obtained through mathematical modeling of sea state

agitation, provided by the Copernicus Marine Environment Monitoring Service (CMEMS) via the ERA5 reanalysis dataset. The data supplied by CMEMS through the ERA5 reanalysis dataset [24] has a spatial resolution of 1° and a temporal resolution of 1 hour, covering the period from 1990 to 2024.

Developers often present the power matrix either in terms of electrical output (kW) or conversion efficiency (%) across a range of sea states. At this stage of assessment, the most widely used metric to quantify the resource is the Power Output, which reflects the energy the WEC is capable of capturing and converting under given wave conditions. However, if a WEC is designed with a rated power that significantly exceeds the energy levels commonly encountered at a site, it may result in disproportionate capital investment relative to the actual energy yield, thereby undermining the economic viability of the project.

In order to determine the energy production, it is necessary to know both the sea state at the evaluation site (either derived from mathematical wave models or obtained through in situ measurements) as well as the power matrix of the system under consideration. The power matrix represents the electrical power output of a specific WEC corresponding to various discrete combinations of significant wave height and energy period.

The Annual Energy Production (*AEP*), measured in MWh, is estimated by bilinear interpolation of the *WECs* power matrix with the characteristic sea state matrix corresponding to the analyzed region. This can be calculated using the following formula [21]:

$$AEP = \sum_{i=1}^{nT} \sum_{j=1}^{nH} p_{ij} \cdot P_{ij} \quad (1)$$

where, nT represents the number of bins on horizontal axis, corresponding to wave period discretization; nH represents the number of bins on the vertical axis, corresponding to wave height discretization; p_{ij} – describes the sea state at a given site, defined by line i (corresponding to wave period T_e) and column j (corresponding to wave height H_s) in accordance to the bin in the sea state matrix and P_{ij} represents the power output of the WEC corresponding to the bin defined by a specific combination of wave period (defined by line i) and wave height (defined by column j).

The power outputs and capacity factors of the analyzed *WECs* could be considered to be relatively low compared to *WECs* deployed in more energetic sea states. This issue could be solved by rescaling the *WECs* to a dominant sea state expected for particular sites.

2.1. Site selection and wave resource assessment

Efforts to identify optimal deployment sites for wave energy systems aim to minimize environmental impacts while maximizing socio-economic benefits. However, it is important to acknowledge that significant uncertainties remain in the quantification of social and economic parameters associated with wave energy harnessing. These uncertainties are largely attributed to the limited availability of full-scale demonstration projects and the consequent lack of empirical data [2].

Identifying optimal locations for wave energy exploitation is a complex task that involves the consideration of a wide range of technical, environmental, and socio-economic factors. Site-specific aspects, such as local geomorphology, are crucial in the design and implementation of mooring and foundation systems [3]. Potential deployment areas may conflict with existing maritime uses or designated protected zones, such as traffic routes, ecologically sensitive regions, and aquaculture sites.

Despite offshore regions exhibiting higher wave energy potential, they are often inappropriate for harnessing wave energy due to the limited survivability of *WECs*.

Assessing energy production based on local sea state conditions constitutes a critical component of the feasibility analysis for the deployment of *WECs* at specific sites. This study concentrates on the preliminary evaluation phase, excluding considerations related to costs and environmental impact.

Predominantly, global wave energy resource assessments are based on reanalysis data services outcoming from water simulation models, usually validated with in-situ data, such as in the case of the ERA5 reanalysis dataset from the European Center for Medium-Range Weather Forecasts (ECMWF).

The lowest global wave energy values are typically observed in semi-enclosed or enclosed basins such as the Black Sea, where power density estimates range from approximately 2 to 13 kW/m [2].

In the coastal zone of the Romanian Black Sea, climatic conditions are strongly influenced by the thermal and dynamic interactions with the marine basin. These influences lead to significant variability in atmospheric circulation, with wind patterns exhibiting a high degree of instability in both speed and direction. As wave formation is closely driven by wind characteristics, the resulting wave regime is similarly variable. This variability presents both challenges and opportunities for the assessment and exploitation of marine energy resources, particularly wave and wind energy, in the region [17].

The study sites were selected based on multiple criteria imposed by the maritime spatial planning framework, as well as the availability of in-situ data necessary for validating sea state measurements over the period 1990–2024. The primary factors considered in the selection process were: wave height, wave period, proximity to the shore (to minimize the connection distance to the National Energy

System and cost regarding maintenance and operation), and absence of obstacles in accordance with the maritime spatial plan.

This paper provides an overview of the power performance of 15 WECs in 3 specific study sites presented in Table 1. The wave conditions of the selected sites were evaluated by processing wave data spanning from 1990-2024, 35 years, collected from the CMEMS ERA5 reanalysis dataset, a fifth-generation atmospheric reanalysis. The dataset provided hourly modeled estimates of a wide range of sea state and atmospheric variables within the boundaries of large domains relevant to the study sites.

Table 1

Information regarding the study sites

Location	Coordinates	Depth (m)	Distance from shore (km)	Wave resource potential (kW/m)	Wave height H_s (m)		Wave energy period T_e (s)	
					Mean	Max	Mean	Max
P1	44°04'28"N 29°57'24"E	70	109	3.44	0.93	7.04	4.26	9.68
P2	44°18'31"N 30°17'05"E	87	130	3.62	0.95	7.15	4.29	9.71
P3	44°14'08"N 28°39'45"E	13	1.8	2.06	0.74	5.6	4.06	9.42

For determining the wave resource potential, the following equation was used [22]:

$$P = \frac{\rho g H_s^2 T_e}{64\pi} \quad (2)$$

where, ρ represents water density (in the case of the Romanian coast of the Black Sea it is between 1001-1010 kg/m³), g represents gravity acceleration, H_s represents the significant wave height, measured from the wave crest to the trough, expressed in m and T_e represents wave energy period measured in s.

According to the data from the CMEMS ERA5 reanalysis dataset and bathymetric data from the General Bathymetric Chart of the Oceans (GEBCO) [24], the identified study sites exhibit the following characteristics:

- P1 (44°04'28"N, 29°57'24"E): In proximity of the ANA oil platform at a water depth of approximately 70 m, approximately 109 km offshore. The mean wave height is 0.93 m, with a recorded maximum of 7.04 m on November 19, 2023. The mean wave period is 4.26 s, with a maximum of 9.68 s recorded on December 8, 2012. The long-term average wave power at this site is 3.44 kW/m.
- P2 (44°18'31"N, 30°17'05"E): Situated near the location of a former oil platform in proximity of the 87 m isobath, approximately 130 km from the shore. The mean wave height is 0.95 m, with a maximum of 7.15 m recorded

on February 7, 2012. The mean wave period is 4.29 s, with a maximum of 9.71 s on February 8, 2012. The site's multiannual wave power averages 3.62 kW/m, being the study site with the most energetic sea state.

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

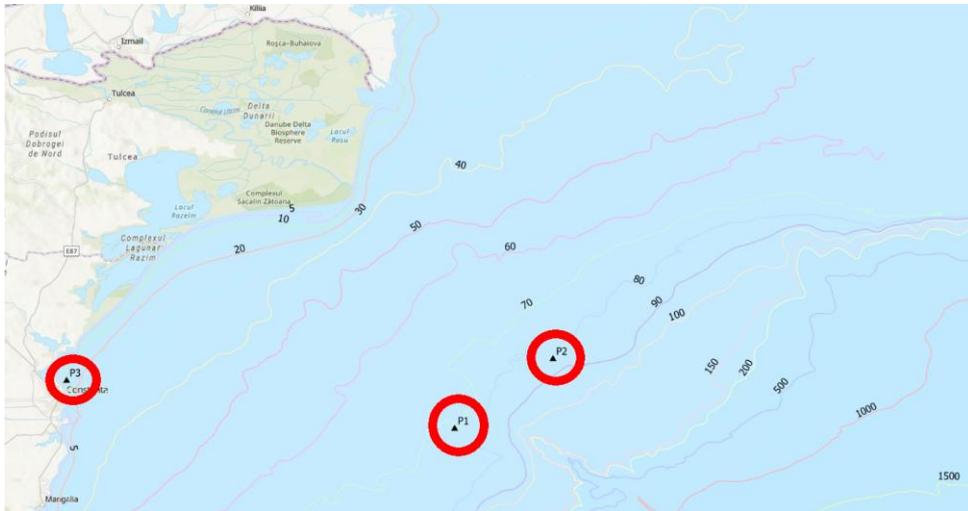


Fig. 1. Location of the selected study sites

2.2. WEC systems

Wave Energy Converters (*WECs*) encounter significant technical challenges due to the complexity of the conversion process, which involves energy absorption, transmission and generation.

Despite the development and testing of numerous *WEC* prototypes, the technology has yet to achieve convergence toward commercially viable solutions. The integration of *WECs* into the global energy sector remains slow, primarily due to several technical and economic challenges. These include the lack of consensus on optimal system configurations and power take-off (PTO) mechanisms, limited technological maturity, challenges related to energy storage and onshore grid integration, and high levels of economic uncertainty [5].

Although high wave power levels may initially appear advantageous for energy extraction, extreme meteorological events, such as high-energy storms, often lead to *WEC* conservation state, in which the system does not generate power,

and structural fatigue [7]. Also, *WECs* installed in high-energy sea states have higher costs associated with installation, maintenance, and survivability.

Given the existence of numerous *WECs*, sorting was based on the following criteria:

- Availability of performance data, including power matrices, etc. (Unfortunately, comprehensive data for all wave energy conversion systems is currently not available);
- Systems specifically designed to harness waves with heights ranging from 0-2 m and periods of 0-5 s, requiring a maximum installation depth of 100 m and capable of withstanding waves of up to 10 m, or systems that can capture more energetic waves, with the possibility of rescaling;
- Advanced technological maturity, nearing commercial readiness;
- Proven resilience in environments subject to significant seasonal variation;
- Low estimated installation and maintenance costs under conditions of limited marine infrastructure.

According to the European Marine Energy Centre (EMEC) classification, the 15 *WECs* considered comprise of 12 point absorbers, one oscillating wave surge converter (OWSC), one attenuator and one overtopping device. The rated power (P_e) of the *WECs* range from 15 kW to 7000 kW with hydraulic motor being the most used power of take-off (PTO) system.

Table 2

Characteristics of the considered *WECs*

<i>WEC</i>	<i>WEC</i> type	PTO	Rated power/unit P_e [kW]	EMEC Classification
CorPower Ocean	Point absorber	Hydraulic pump	400	Point Absorber
Aqua Buoy	Point absorber	High head water turbine	250	Point Absorber
AWS	Wave swing floating platform	Linear generator	2470	Point Absorber
Pontoon	Multi-point absorber	Multi-body floating structure	3619	Point Absorber
Oyster 2	Shallow water oscillating flap	Hydraulic pump	290	Point Absorber
Langlee	Oscillating flap converter	Hydraulic motor	1665	OWSC
CETO	Submerged buoy with pump	Hydraulic motor	260	Point Absorber
Seabased AB	Small point absorber	Linear generator	15	Point Absorber
Heave buoy (BFHB)	Bottom fixed	Linear generator	2192	Point Absorber

Oceantec	Modern floating buoy	Linear generator	500	Point Absorber
Wave Star	Multi-float system	Linear generator	2709	Point Absorber
PWEC	Pendulum wave energy converter	Pendulum	479	Point Absorber
Pelamis	Articulated attenuator	Hydraulic motor	750	Attenuator
Wave Bob	Large point absorber	Hydraulic motor	1000	Point Absorber
Wave Dragon	Overtopping device	Hydraulic turbine	7000	Overtopping/Terminator

Most WECs can achieve satisfactory performance along the Romanian Black Sea coast if appropriately rescaled according to the specific hydrographic conditions. Studies have indicated that the optimal scaling ratio is not directly dependent on the system rated power output. For technological reasons, it is possible to rescale wave WECs by up to 40% of the original model's dimensions [5].

3. Results and discussions

The study results detail the power output and capacity factors of the analyzed WECs over 35 years (1990–2024), based on ERA5 reanalysis data from ECMWF.

Fig. 2 illustrates the power output of the selected WECs across the three study sites: P1, P2, and P3. Among all devices, the Wave Dragon consistently demonstrated the highest performance, with an average annual power output of 2809 MWh/year at P1, 2887 MWh/year at P2, and a lower power output of 2287 MWh/year at P3 due to the site's lower wave energy potential. Significant differences in power output were observed among the selected WECs, largely due to limitations imposed by the rated power of each device. Only two technologies—Wave Dragon and Pontoon—produced more than 1500 MWh/year across all sites. Intermediate outputs (500–1500 MWh/year) were recorded by Oceantec, BFHB, WaveStar, and PWEC, while the remaining WECs generated less than 500 MWh/year per unit at all locations.

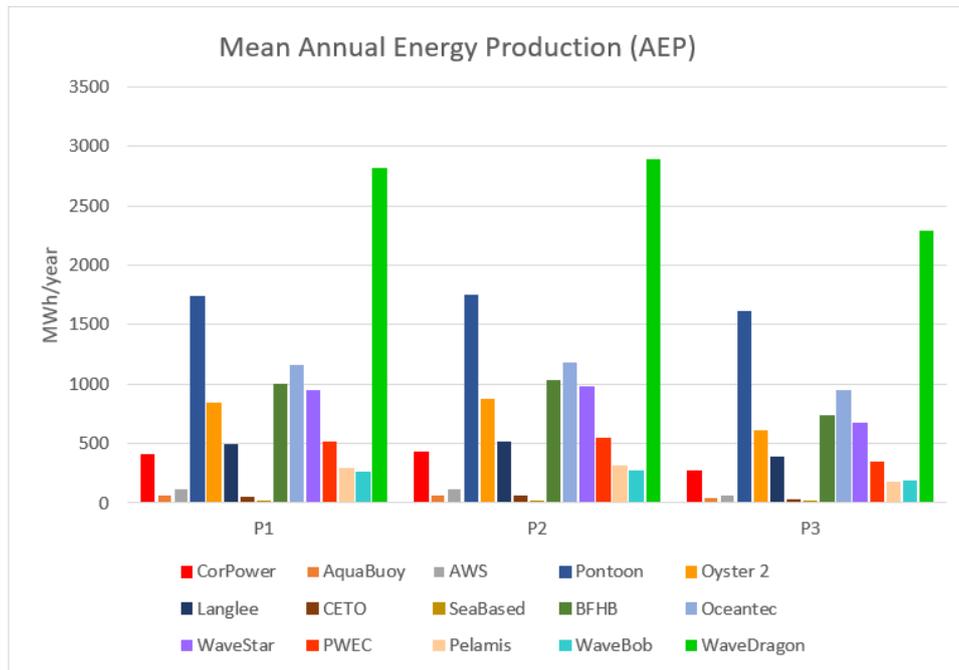


Fig. 2. Mean annual energy production of the selected WEC

Interannual variability in power output AEP , driven by fluctuations in sea state conditions, is clearly observed, with certain years exhibiting significantly increased power outputs relative to others. Among the period analyzed, 1992 notably recorded the highest mean AEP across all evaluated sites.

Average multiannual timeframe from 1990 to 2024, power production of the selected WECs at the three study sites is presented in Fig. 3. The findings clearly show that the Wave Dragon consistently achieved the highest performance across all locations, followed by the Pontoon and Oceantec technologies. In contrast, the lowest power output was recorded for the SeaBased device, which aligns with its low rated power of 15 kW—the smallest among the evaluated technologies. Among the high-capacity devices (rated above 2000 kW), AWS exhibited the lowest energy production. Overall, as expected given the relatively low variability in wave energy resources across the sites, power output differences among technologies were not substantial.

It is noteworthy that the year 1992 was the most energetic within the study period, recording a maximum significant wave height of 7.15 m and a wave energy period of 9.71 s at study site P2.

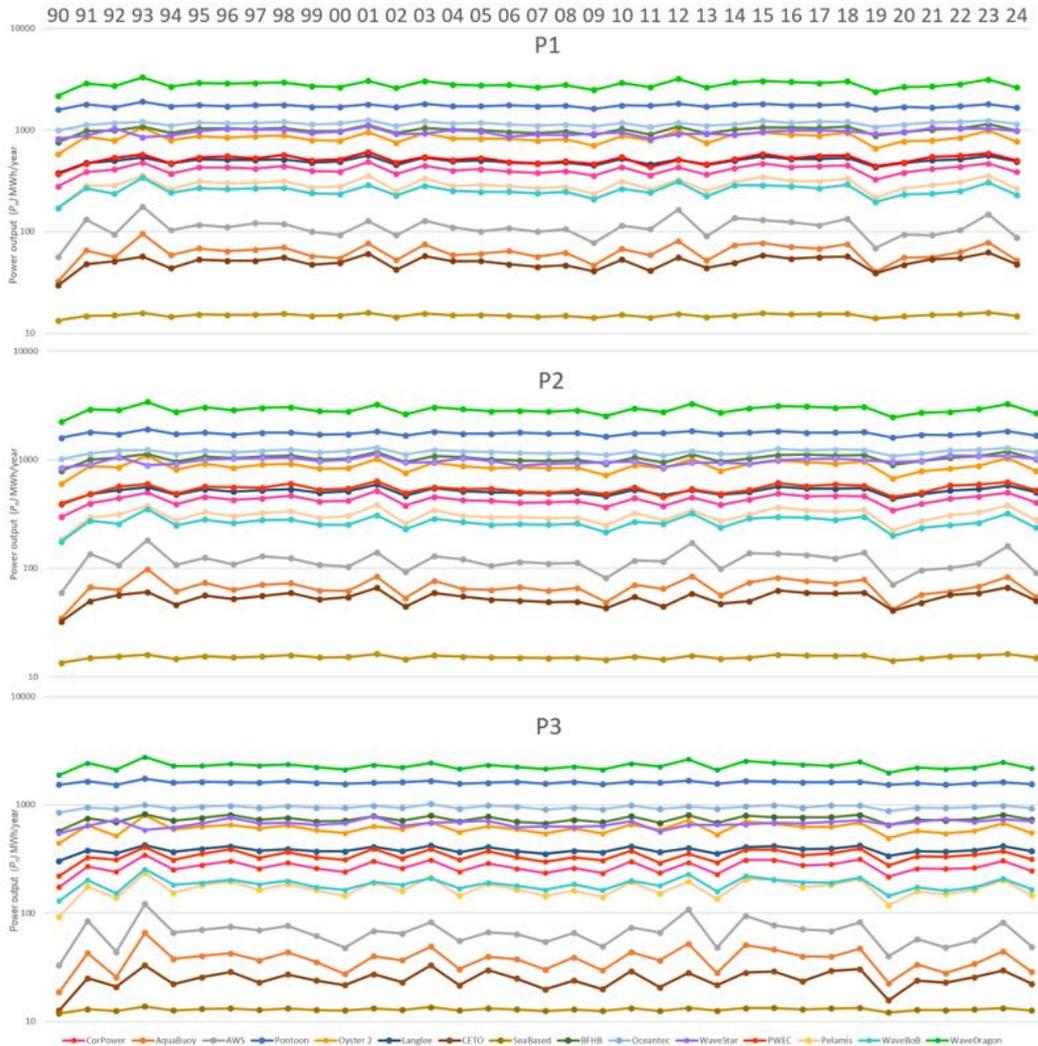


Fig. 3. Annual production of the selected WECs in P1, P2 P3 study sites

The extreme values of AEP , as indicated by the monthly maxima and minima in Fig. 4, demonstrate significant variability both within individual years and across the entire multi-year dataset at all study sites. December consistently registers the highest monthly mean AEP , whereas June persistently records the lowest monthly mean AEP across all sites.

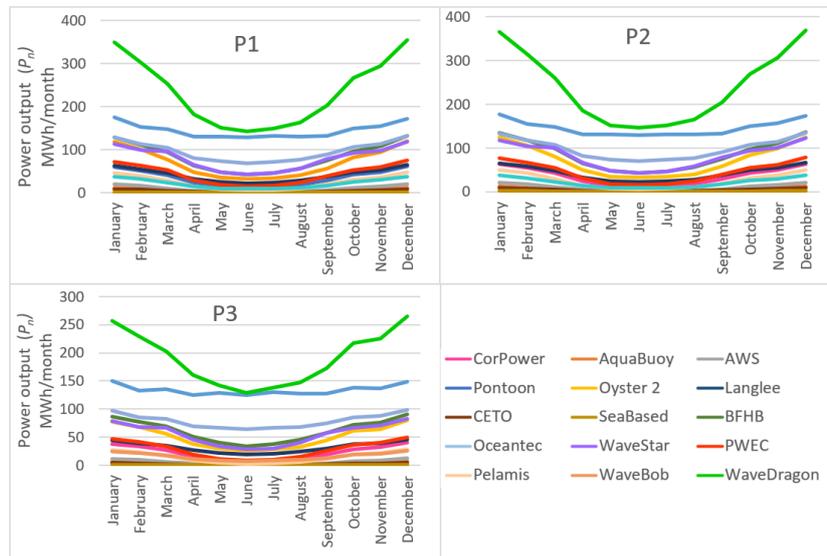


Fig. 4. Monthly variations in energy production in study sites

The observed variation is primarily attributed to seasonal fluctuations in sea state conditions at the study sites. High wind speeds, which contribute to increased wave activity, are typically recorded during December and January along the Romanian coast of the Black Sea, whereas lower wind intensities are generally observed between May and July. It can be observed in Fig. 5. a uniform seasonal trend in power generation across all study sites and WEC technologies, with peak energy production occurring during the winter months. The lowest output is consistently observed during the summer, reflecting the seasonal variability of wave energy availability in the region.

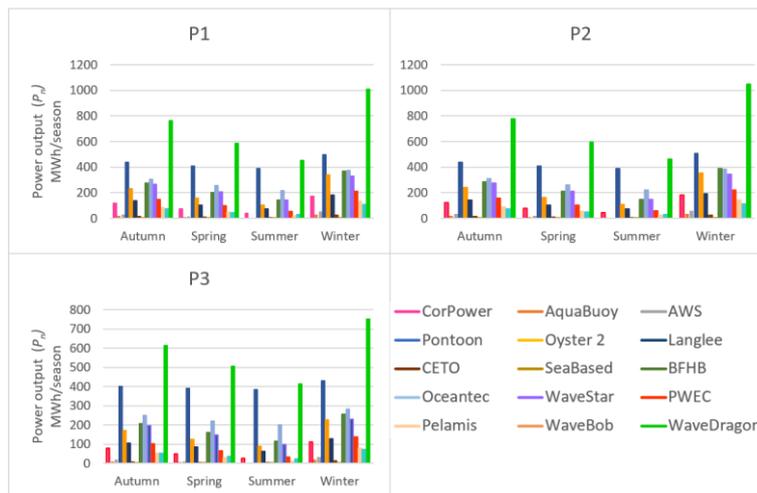


Fig. 5. Seasonal variation

The simulation results indicate that, across all evaluated sites in the Black Sea, the Wave Dragon system achieves an AEP of less than 3000 MWh, with the mean AEP not exceeding 2800 MWh. This performance aligns with the anticipated energy potential of low-energy marine environments characteristic of the Black Sea region [5].

4. Conclusion

Wave energy represents a valuable and underutilized resource with the potential to enhance the diversification of renewable energy systems, contributing to the development of a more sustainable, flexible, and resilient energy future. Its integration into national energy strategies could help reduce dependence on conventional energy sources and improve grid stability, particularly in coastal regions. However, the intra-annual variability of wave energy production remains a critical challenge, influenced not only by seasonal fluctuations but also by the dynamic interactions between site-specific sea states and WEC operational characteristics.

Furthermore, the efficiency and reliability of energy conversion systems are highly dependent on their ability to adapt to the unique wave regimes of the Black Sea. As such, the successful deployment of wave energy requires targeted research into site-specific wave dynamics, advanced modeling techniques, and the selection or development of technologies optimized for low energy environments. Although each location displays distinct characteristics and variability in wave power production, consistent patterns, including seasonal fluctuations and interannual trends, are clearly observable across all sites. A comprehensive understanding of these patterns is essential for effective coastal management, the design and operation of offshore engineering structures, and the optimization of WECs.

All of the evaluated WECs show parallelism in power output at all of the study sites. It can be observed that the Wave Dragon technology had excellent power performance across all sites, aligning with results previously reported by E. Rusu in other coastal areas [18]. Overall, the Wave Dragon and Pontoon technologies present promising results, outperforming other technologies considered in this study.

This investigation highlights the significance of assessing the power performance of wave energy converters, a key parameter in determining their technical feasibility. Nonetheless, it must be taken into account that power performance does not inherently translate to favorable economic performance, as comprehensive techno-economic analyses are necessary to evaluate the overall viability of wave energy projects.

This study seeks to support the advancement of the industry as a viable marine renewable energy solution for harnessing wave energy across the Romanian

Black Sea coast. The findings demonstrate that, despite the Black Sea being classified as a low-energy sea, there exists considerable potential for the effective exploitation of wave energy resources in the region. These results underscore the importance of continued research and technology optimization to realize the practical deployment of wave energy converters along this coastline.

The intermittent and variable nature of marine energy can lead to grid imbalances resulting in additional cost of implementation. Further research should be done regarding the aspects of WEC grid integration following the daily production curve and the possibilities to compensate for the power grid imbalances.

In conclusion, further detailed research is essential to identify wave energy conversion systems optimized for the unique wave dynamics of the Black Sea along the Romanian coast. The development of such systems must prioritize both high conversion efficiency and robust techno-economic performance to ensure practical implementation and long-term viability.

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