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POLITEHNICA BUCHAREST**

DOCTORAL SCHOOL of ELECTRICAL ENGINEERING



EXTENDED ABSTRACT

Ph. D. THESIS

Wave energy conversion on the Black Sea littoral area

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Content

1	Introduction	4
1.1	Presentation of the doctoral thesis domain.....	4
1.2	Scope of the doctoral thesis.....	4
1.3	Content of the doctoral thesis.....	5
2	The Black Sea and sea waves.....	6
2.1	The Black Sea.....	6
2.1.1	Relief.....	7
2.1.2	Climate.....	7
2.2	Romania's maritime space.....	7
2.2.1	Romanian Black Sea littoral	8
2.2.2	Marine Spatial Planning.....	8
2.3	Marine waves	9
2.3.1	Black Sea wave state.....	10
3	Energy sources	11
3.1	Energy	11
3.2	Energy conversion.....	11
3.2.1	Energy machines	11
3.3	Energy storage.....	11
3.3.1	Electrochemical storage systems	12
3.3.2	Mechanical and thermal energy storage	12
3.3.3	Electromagnetic storage systems	12
3.4	Renewable energy sources	12
3.4.1	Offshore renewable energy sources	12
3.4.2	RES in Romania.....	13
3.5	Wave energy.....	13
3.5.1	Harnessing wave energy in low energy in seas	13
4	Wave energy converters.....	14
4.1	History.....	15
4.1.1	Wave energy converters developed in Romania.....	15
4.2	Classification.....	16
4.3	PTO - Power Take-Off systems	17
4.4	Practical methods to store wave energy	17
4.5	Modern systems.....	17
4.5.1	CorPower Ocean	17
4.5.2	AquaBuoy	17
4.5.3	AWS (Archimedes WaveSwing)	18
4.5.4	OEBuoy.....	18
4.5.5	Pontoon	18
4.5.6	Langlee.....	18
4.5.7	CETO	18
4.5.8	Oyster 2	19
4.5.9	Oyster.....	19
4.5.10	SeaBased AB	19
4.5.11	SSG	19
4.5.12	BFHB (Buttom Fixed Heave Buoy)	19
4.5.13	Oceantec.....	20
4.5.14	WaveStar.....	20

4.5.15	PWEC	20
4.5.16	Pelamis.....	20
4.5.17	WaveBob.....	20
4.5.18	Wave Dragon	21
4.5.19	Wave-driven hydropneumatic power plant MV-5.....	21
4.6	Large-scale exploitation	21
5	Harnessing wave energy in the Romanian Black Sea littoral area	22
5.1	Research methodology	22
5.2	Location.....	24
5.3	WECs analyzed in the study.....	25
5.4	Simulation	25
5.5	In-depth study of the CorPower Ocean solution	25
5.6	Results	26
5.6.1	Annual energy production and capacity factor	26
5.6.2	Scaling.....	28
6	Conclusions.....	30
6.1	Obtained results.....	30
6.2	Original contributions	31
6.3	List of original publications	31
6.4	Perspectives for further developments	31
	References.....	32

1 Introduction

Among the oscillatory movements, the most important are waves and tides. Waves are mainly generated by wind and mainly influence the superficial layers of water. Studies started in recent decades aim both to deepen the knowledge and explain these phenomena, as well as to identify methods by which these forms of hydraulic energy can be captured and utilized.

Waves store an immense energy potential, according to researchers the global theoretical potential of waves is approximately 32,000 TWh/year [1] of which the exploitable energy potential of the Black Sea in the most energetic areas (Burgas–Rezovo), based on 31-year simulations, is estimated to be 44 MWh/m/year [2].

The production costs of electricity from wave energy conversion systems vary between 0.28–0.52 €/kWh, which makes this solution an expensive one for generating electricity from renewable sources [3].

1.1 Presentation of the doctoral thesis domain

Research into wave energy conversion systems (WEC - Wave Energy Converter) is essential for transforming the theoretical potential of the oceans into usable energy. The importance of studies addressing wave energy conversion lies in the need to overcome technical and economic barriers.

In Romania, research has focused on assessing the energy potential of waves in the Black Sea and on analyzing the impact of marine energy capture on the marine environment. Only a limited number of studies have investigated the possibility of implementing wave energy capture and conversion systems on the Romanian coastal sector of the Black Sea [4], [5], [6], [7].

Evaluating energy production based on local sea state conditions is a key aspect in determining the feasibility of implementing wave energy systems. This study focuses exclusively on the initial evaluation phase, without addressing cost factors or environmental impacts.

The purpose of the presented study is to investigate the energy efficiency, respectively to identify the optimal size of several representative systems. In this work, 18 WECs were evaluated, over a period of 35 years, in three study points located in Black Sea.

1.2 Scope of the doctoral thesis

The thesis has a multidisciplinary character involving knowledge from multiple fields such as: electrical engineering, energy engineering, mechanical engineering, physics, oceanography and economics. The study proposes and evaluates technological solutions adaptable to the specific conditions of the research area, with the objective of identifying WECs capable of harnessing the energy potential of the Black Sea.

The paper is based on analytical techniques based on systematic searches within a structured analysis framework, oriented towards comparing and selecting the most efficient WEC technologies. The research approach included: extensive consultation of the specialized literature, extraction and systematization of relevant information and development of the analysis framework. The application stage involved processing long-term oceanographic data, mapping optimal locations and performing advanced simulations to determine the energy performance and conversion efficiency of the analyzed systems.

The main objective of this doctoral research is to identify and evaluate wave energy capture and conversion systems for which technical data exist, in order to determine their viability under the specific conditions of the Black Sea.

1.3 Content of the doctoral thesis

The doctoral thesis entitled “Wave energy conversion on the littoral of the Black Sea” is structured in six chapters, as follows:

Chapter 1 highlights the relevance and importance of the research topic, presents a brief history of the field, and defines the central objectives of the thesis.

Chapter 2 analyzes the physical-geographical characteristics of the Black Sea, with increased attention to the climatic regime, bathymetric morphology and specific wave characteristics.

Chapter 3 is a theoretical chapter, which synthesizes basic concepts in the field of energy such as energy conversion and storage.

Chapter 4 summarizes wave energy technologies. The historical evolution of the systems is analyzed, including local contributions, methods of energy capture and conversion, and practical ways of energy storage.

Chapter 5 represents the practical component of the thesis, presenting the targeted research methodology and defining the study area. The chapter addresses the evolution of 18 WEC systems under the conditions of 3 study points over a period of 35 years (1990-2024) tracking their annual production and energy efficiency, investigating the possibility of resizing.

Chapter 6 concludes the thesis by formulating the main conclusions of the research and stating the original contributions of the research.

The references include the main sources of documentation used in the development of the thesis and reflects the current level of knowledge in the field of wave energy utilization.

2 The Black Sea and sea waves

The Black Sea is a semi-enclosed sea, a component of the Mediterranean Sea, connected to the main Mediterranean basin by the Bosphorus and Dardanelles straits, as well as by the Sea of Marmara and the Aegean Sea. Of the well-individualized basins of the Mediterranean Sea, the Black Sea has the largest surface area (approximately 466200 km²). The coastline extends for 4340 km, with Romania's coastal segment being 245 km [8].

The Black Sea Basin has promising natural resources for the development of marine renewable energy infrastructure. The region presents a favorable localized energy potential for the installation of wave energy systems [9]. The wave regime is closely correlated with the wind regime.

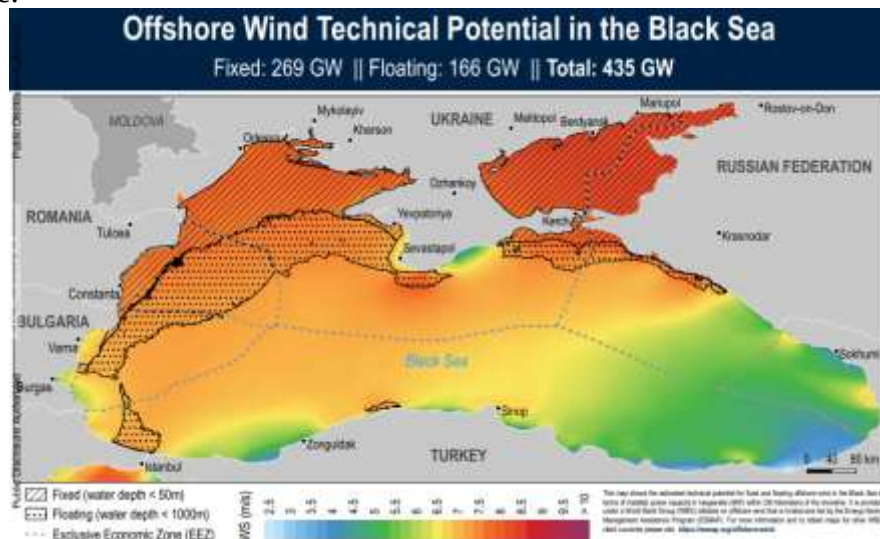


Figure 2.1 Map of wind energy potential in the Black Sea [25]

The wave regime in the Black Sea is more intense offshore than in the coastal area, presenting moderate average dynamic parameters, with a predominance of wind waves in the process of formation.

2.1 The Black Sea

Geographically, the Black Sea is located in eastern Southeastern Europe, between 40°55'–46°32' north latitude and 27°27'–41°42' east longitude. The wide opening to the Pontic steppes in the northern part favors the penetration of cold and dry continental air masses, with significant influences on the processes in the western basin.

Of the total length of the coastline (4340 km), the most extensive sectors belong to Turkey and Ukraine (1400 km each), followed by Russia (475 km), Georgia (310 km) and Bulgaria (300 km) [10], while Romania has an opening of only 245 km.

The analysis of the bathymetric map of the Black Sea highlights the fact that the continental shelf extends under the sea waters to a depth of 180 m. The 180 m isobath is located in the proximity of the shore in the northeastern, southern and southeastern sectors, while in the northwestern part, on the alignment between Sevastopol and Burgas, it is located over 160 km from the coast, outlining a relatively shallow basin. In front of the Romanian coastline, the slope is particularly gentle, and the 180 m isobath reaches a distance of approximately 200 km from the shore [10].

2.1.1 Relief

The continental shelf is the submarine continuation of the continent with depths up to approximately 200 m. The real limit of the continental shelf is not given strictly by depth, but by the change in slope. In the Black Sea, the sharp change in slope occurs between the isobaths of 180 - 200 m [10].

The continental shelf region is made up of three subzones: the prelittoral zone, the littoral zone and the sublittoral zone. The prelittoral zone represents the part of the sea that remains uncovered during low tide, it extends between the maximum limit of wave action and the line to which the waters retreat from the shore towards the sea, under the influence of the winds. The littoral zone includes the sea sector located between the prelittoral zone and the 100 m isobath. The sublittoral zone represents the portion of the sea between the littoral zone and the edge of the continental shelf.

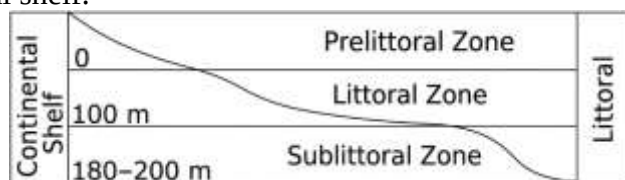


Figure 2.2 Delimitation of littoral areas

The main geodynamic factor of sedimentogenesis in the coastal zone is the action of waves and marine currents. The periodic movement of water generated by waves in shallow regions constitutes an essential mechanism that ensures the redistribution, modification and accumulation of sedimentary material brought into the marine basin.

2.1.2 Climate

The climate above the water area is influenced by the main pressure centers that control the general circulation of the atmosphere in Southeastern Europe, such as the Eurasian continental anticyclone, the Azores subtropical anticyclone, the North Atlantic cyclone, and the Mediterranean cyclone [10].

During the summer, the air temperature is relatively evenly distributed, with differences of the order of tenths of a degree. However, in the cold season, the thermal distribution becomes uneven, with minimum values in the northwestern corner (-0.7°C) and maximum values in the southeastern part of the basin (6.9°C) [10].

The atmospheric circulation regime shows significant variability, with winds being characterized by instability in both speed and direction. Average speeds are generally low, and storms occur relatively rarely. The wave regime is closely correlated with the wind regime. The Black Sea is under the influence of the continental regime of atmospheric circulation.

In the winter season, the temperature distribution at the surface of the Black Sea presents a thermal gradient that increases on the North-South axis: the average is 2°C in the Romanian littoral area (Constanța), 6°C in the center of the basin, 7°C in the Crimean peninsula area (Sevastopol) and reaches 8°C in the southeastern sector, the isotherms closely following the morphological configuration of the shores [11].

2.2 Romania's maritime space

According to Law no. 17/1990 [12], the territorial sea of Romania comprises the strip of sea adjacent to the coast and internal maritime waters, having a width of 22224 km (12 nautical miles). The internal maritime waters, the territorial sea, their soil and subsoil, as well as the airspace above them constitute an integral part of the territory of Romania. In these spaces, the

Romanian state exercises its sovereignty in accordance with national legislation, with the provisions of the international conventions to which it is a party and with the general principles of international law.

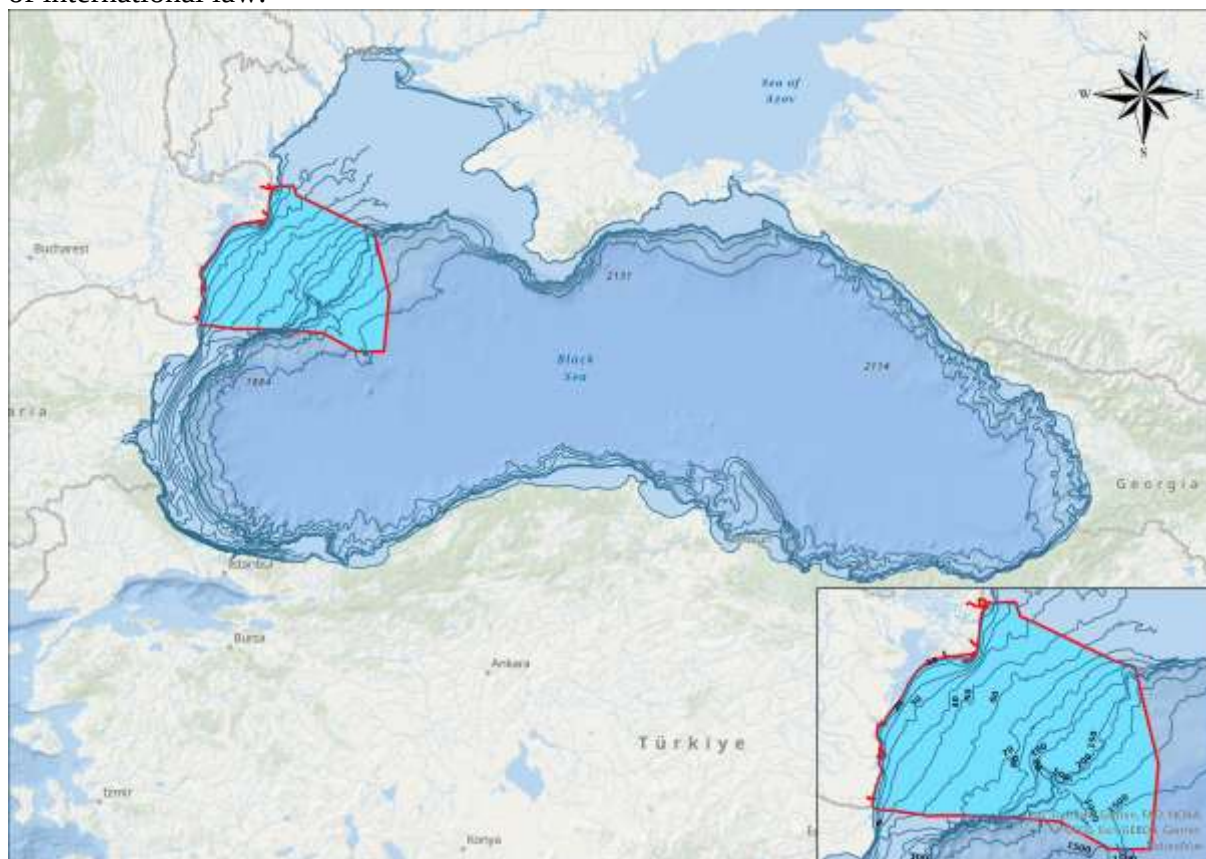


Figure 2.3 Delimitation of Romania's maritime space

Romania's offshore area covers approximately 22,000 km² and reaches depths of over 1,000 m. The area is divided into several perimeters of different sizes, some of which are concessioned to holders for exploration, development and exploitation activities [13].

2.2.1 Romanian Black Sea littoral

The littoral represents the land area located in the vicinity of the sea, whose particularities are shaped by its influence, while the sea is, in turn, influenced by the specifics of the coastline. It extends from the upper limit of the shore and includes the pre-littoral area, as well as the entire marine coastal area, in the case of the Black Sea located between the isobaths of 180 m and 200 m.

The Romanian littoral is located in the eastern part of Dobrogea and extends in the form of a strip in a north–south direction, for approximately 245 km, between the Chilia delta and Vama Veche. From the shoreline to depths of 180–200 m, a relatively uniform and almost flat submarine plain, the continental platform, develops, characterized by a very gentle slope [10].

2.2.2 Marine Spatial Planning

Marine spatial planning aims to coordinate and harmonize the development of maritime activities. Spatial analysis of the use of maritime space highlights the fact that the overlap of protected natural areas with coastal zone protection infrastructure, transport infrastructure, as well as with areas intended for fishing and mineral resource exploration and exploitation activities can be a factor influencing the emergence and evolution of conflicts between the

different types of uses of marine space and the objectives of conservation, respectively protection of biodiversity and marine habitats.

The relationships of compatibility and incompatibility between the various uses of maritime space can be grouped into the following categories [14]:

- exclusive zones intended for the development of activities regulated by special rules;
- areas susceptible to development;
- favorable areas that can be considered for the development of activities in the future.

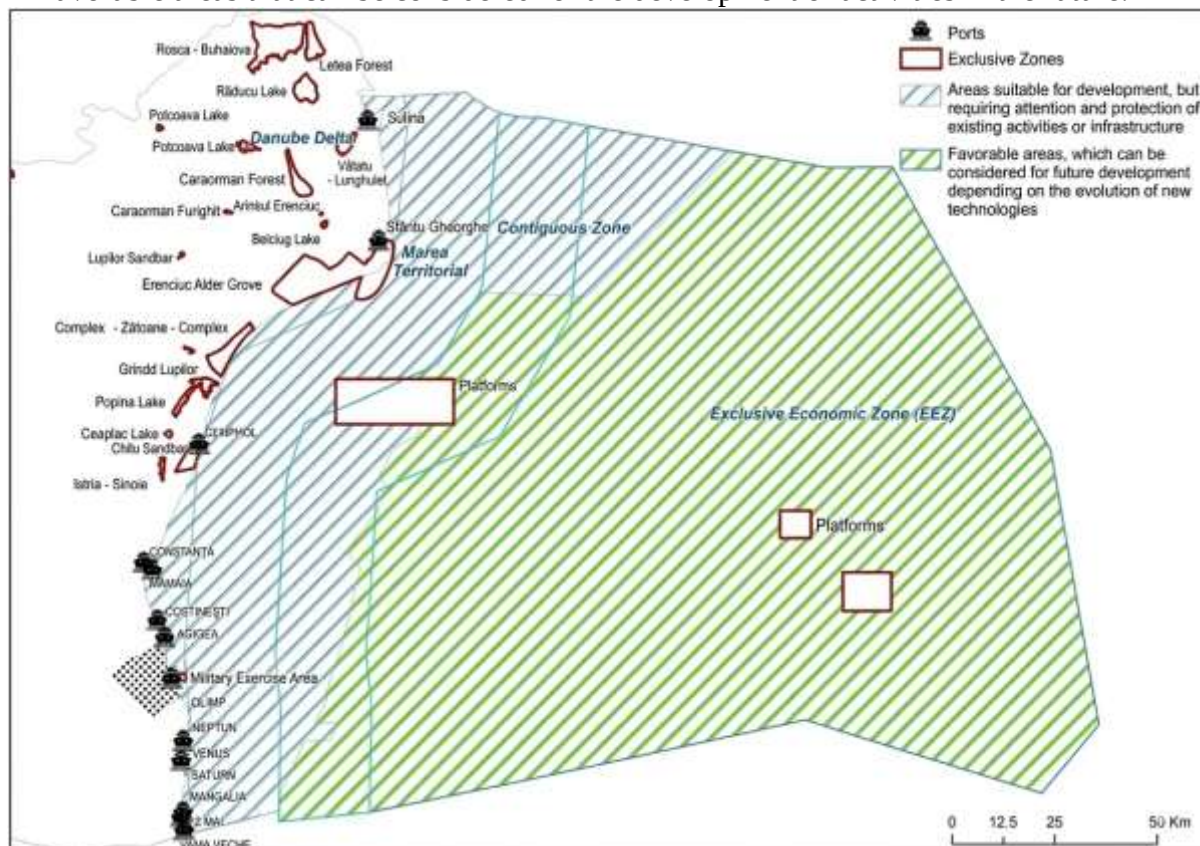


Figure 2.4 Exclusive areas, susceptible to development and suitable areas [48]

2.3 Marine waves

A wave is a temporary physical phenomenon, manifested by the deformation of the surface of a liquid. The energy of the waves is directly proportional to the variation of the displaced water surface. Waves on the surface of the oceans and seas are generated mainly by the action of the wind at the contact between the atmosphere and the water. They tend to increase in height especially when the wind acts in the opposite direction to a current. The length of the waves is determined by the wind speed and is closely correlated with their height. The speed of wave propagation depends on the intensity of the generating winds, the average values being between 11 and 12.5 m/s, and in areas dominated by trade winds they can exceed 14 m/s [15].

Waves can have various origins, but from an energetic point of view, the most relevant category is represented by wind waves, or waves of aeolian origin, which constitute the predominant type of wave in the Planetary Ocean. They are generated and maintained by the action of the wind on the water surface, by the direct transfer of the kinetic energy of air masses to the aquatic environment [16]. The main factors that influence the generation and evolution of waves are: wind speed, duration of action and length of the action path (fetch).

The main parameters of waves are wavelength (λ or L), period (T) and height (h). Wavelength is the horizontal distance between two consecutive troughs or crests of the wave profile. The wave period is the time interval required for two successive troughs or crests to pass the same fixed point. Wave height is defined as the vertical distance between the crest and the trough.

2.3.1 Black Sea wave state

In the Black Sea, the wave state is dominated by wind-generated and tidal waves. Along the coastline, the level of wave energy varies depending on the orientation of the shore, the bathymetric features of the coastal area, and the presence of coastal structures.

The winds in the Black Sea basin directly influence the wave characteristics, namely their height and period, and there is a clear correlation between these parameters [17]. The average dynamic characteristics of the waves are relatively low, with an average height of 1.0 m, a period of 4.5 s and a wavelength of 28.7 m [10]. The maximum height estimated by calculations reached 9.8 m during the exceptional storm of January–February 1962 [18].

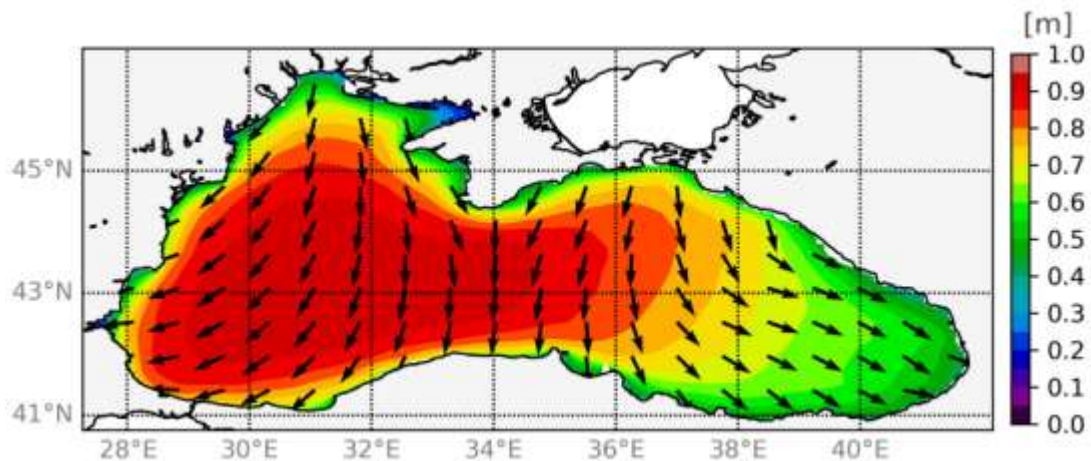


Figure 2.5 Significant wave height in the Black Sea (1988-2021) [63]

2.3.1.1 Wave state in the Romanian coastal area

Estimates for the Romanian Black Sea coast indicate an average gross energy of approximately 12,200 kWh/year for each meter of installed frontage [18], [19]. There are exceptional situations generated by extreme weather phenomena; for example, during a storm in January 2023 a maximum wave height of 9 m was estimated, a value obtained based on mathematical models correlated with wind speed [20].

In the Romanian Black Sea littoral area, the predominance of waves originating from the N–NNE–NE sector is noticeable, as well as a high frequency of waves from the E–SE sector. The distribution highlights the increased exposure of the shore to the action of marine factors, in the context of the N–S orientation of the coastline.

Due to the calm regime of the Black Sea compared to other seas, the energy potential of the Romanian coastal area is relatively small. Research has concluded that for one meter of developed sea front approximately 50 MWh/year can be obtained, correlated with 245 km of coastline, the waves in the territorial waters could produce 10-11.25 TWh/year, assuming a single capture front line with maximum capture and conversion ratio [19].

3 Energy sources

Since the beginning of its existence, humanity has interacted with the natural environment and tried to dominate it. During its evolution, it found that the energy obtained directly through muscular force is insufficient, which generated the need to use external energy sources.

3.1 Energy

The concept of "energy" was introduced into the study of physics in the 18th century, and later, Einstein demonstrated that there is a relationship between the mass of a body and its energy. The main forms of energy include electrical energy, mechanical energy, and thermal energy.

3.2 Energy conversion

The main ways of converting primary energy into useful energy include: converting chemical energy into heat, converting fission energy into thermal energy, converting fusion energy into plasma, converting thermal energy into mechanical energy, converting mechanical energy into electrical energy, as well as converting chemical energy directly into electrical energy.

The most widely used and versatile form of energy today is electrical energy. The energy generated by waves can be stored in various forms: mechanical, electrical and chemical.

3.2.1 Energy machines

A machine is a complex assembly of elements (some moving, others fixed) designed to transform energy into a useful purpose.

3.2.1.1 Hydraulic and pneumatic machines

Hydraulic energy is the energy associated with an incompressible fluid. Hydraulic machines are power machines in which hydraulic energy is converted into mechanical energy and vice versa. Pneumatic machines perform either the transformation of mechanical energy into pneumatic energy or the transformation of pneumatic energy into mechanical energy.

3.2.1.2 Electric machines

An electric machine is an energy converter that converts electrical energy into mechanical energy or mechanical energy into electrical energy.

3.3 Energy storage

A major challenge associated with many renewable sources is their intermittent nature. Photovoltaic panels and wind turbines produce energy only when there is sufficient solar radiation or wind. To compensate for energy intermittency, stored energy can be used during periods of surplus.

3.3.1 Electrochemical storage systems

Electrochemical energy storage systems can be realized using classical or non-classical batteries. The classical category includes acid and alkaline batteries. The most widespread and used type is the lead-acid battery, which can reach, at low discharge rates, an energy density of up to 40 Wh/kg [21].

3.3.2 Mechanical and thermal energy storage

Mechanical and thermal energy storage systems can store energy through various methods, such as: springs, flywheels and gyrostats, inducing defects in the crystal lattices of materials, compressed gas, hydrostatic devices, ceramic materials.

3.3.3 Electromagnetic storage systems

Electromagnetic storage systems store energy in the electric or magnetic field of devices such as capacitors, electrets, permanent magnets, or superconducting coils.

3.4 Renewable energy sources

The concept of renewable energy sources (RES) refers to natural 'inexhaustible' sources of energy such as solar energy, wind energy, hydraulic energy, biomass energy, energy from environments with low thermal potential, including geothermal energy, but also extends to technological systems that allow the conversion of these natural renewable energy sources into useful energy (mainly electrical and thermal) [22].

3.4.1 Offshore renewable energy sources

Offshore renewable energy represents one of the most promising directions for increasing energy production in the coming years, contributing to achieving Europe's decarbonization goals and covering the expected growth in electricity demand.

Renewable energy sources in the marine environment are diverse and include swell, waves, ocean currents, tidal flows, temperature differences between surface and deep waters, and winds [23]. The conversion and capture of energy from offshore renewable sources includes a diverse range of technologies, techniques, and methods specific to the energy sector.

Table 3.1 Offshore RES [24]

Nr. crt	Offshore renewable energy technology	Production cost [€/MWh]
1	Offshore wind turbines	66-106
2	Floating wind turbines	124-194
3	Floating photovoltaic panels	354
4	Wave energy converters	260-600

Studies conducted in areas where waters are protected and closed [25], such as the Black Sea, have confirmed that the use of WEC systems in areas with low energy potential involves significantly lower implementation, operation and maintenance costs. Wave energy systems sized for low waves and areas with low agitation can offer multiple benefits such as: high construction conservation rate, low maintenance costs and low financial risk.

3.4.2 RES in Romania

The energy sector is an essential element in the development of a nation, evolving in line with the development policy of the respective state and with the need to meet the demands of the economy and the population. RES technologies have become competitive with the classic ones, as demonstrated by the continuous decrease in the LCOE indicator below the thresholds recorded by coal or gas-fired power plants.

3.5 Wave energy

Wave energy is condensed solar energy because wind speed and its duration are the determining factors in the process of wind wave formation, and variations in baric potential originate in the energy of unevenly distributed solar radiation [18].

Wave energy is proportional to the variation of the displaced water surface. This is made up of the kinetic energy of the moving water particles and the potential energy due to the weight of the water raised above sea level. Wave energy manifests itself at the water surface, 95% of the wave energy is present between the surface and 1/4 of the wave wavelength.

3.5.1 Harnessing wave energy in low energy in seas

Current systems are designed to harness wave energy with high energy potential. Studies highlight that highly energetic marine environments are highly susceptible to severe weather events. Storm conditions force equipment into conservation mode and directly endanger the structural integrity of WEC systems, generating a major risk of compromising the entire investment [5], [26], [27]. The need to design structures capable of withstanding these exceptional demands exponentially increases capital (CAPEX) and maintenance (OPEX) costs.

3.5.1.1 Harnessing wave energy in the Black Sea

Recent research shows that the northwestern sector of the Black Sea (the Romanian coast and part of the Ukrainian coast) presents the most promising combined potential in the basin. Optimal exploitation is not directed towards individual wave farms, but towards hybrid wind-wave exploitation projects. The location of wave energy systems alongside offshore wind turbines would stabilize production, with wave energy compensating for periods of weak wind [17].

Wave energy systems designed for small waves and low-tide areas can offer several advantages, such as a higher structural preservation rate, lower maintenance costs, and reduced financial risk. The feasibility of wave energy utilization in the Black Sea area has been analyzed in numerous studies, including research by Eugen Rusu, Ajab Gul Majidi, and others [4], [5], [7], [17], [25], [28], [29], [30], [31].

4 Wave energy converters

Exploiting the energy potential of waves is a constant concern worldwide, but implementing efficient technical solutions remains a complex undertaking.

The process of harnessing wave energy includes four main stages: energy capture and extraction, energy conversion, energy storage and final use. In the first stage, wave energy is captured and extracted, obtaining, in most cases, mechanical energy transmitted to the shaft of a turbine, to a pneumatic joint or to a piston attached to a pump. The second stage consists of converting mechanical energy into other forms. The third stage involves storing the energy obtained in the previous stage. This stage can be omitted when the consumer is directly connected to the conversion system but becomes essential to ensure autonomy if the wave energy source is the only source. The last stage consists of using the energy obtained, which can be in the form of alternating or direct electric current, seawater, compressed air, steam, etc. The scheme shows the wide diversity of ways in which wave energy can be transformed and utilized [19].

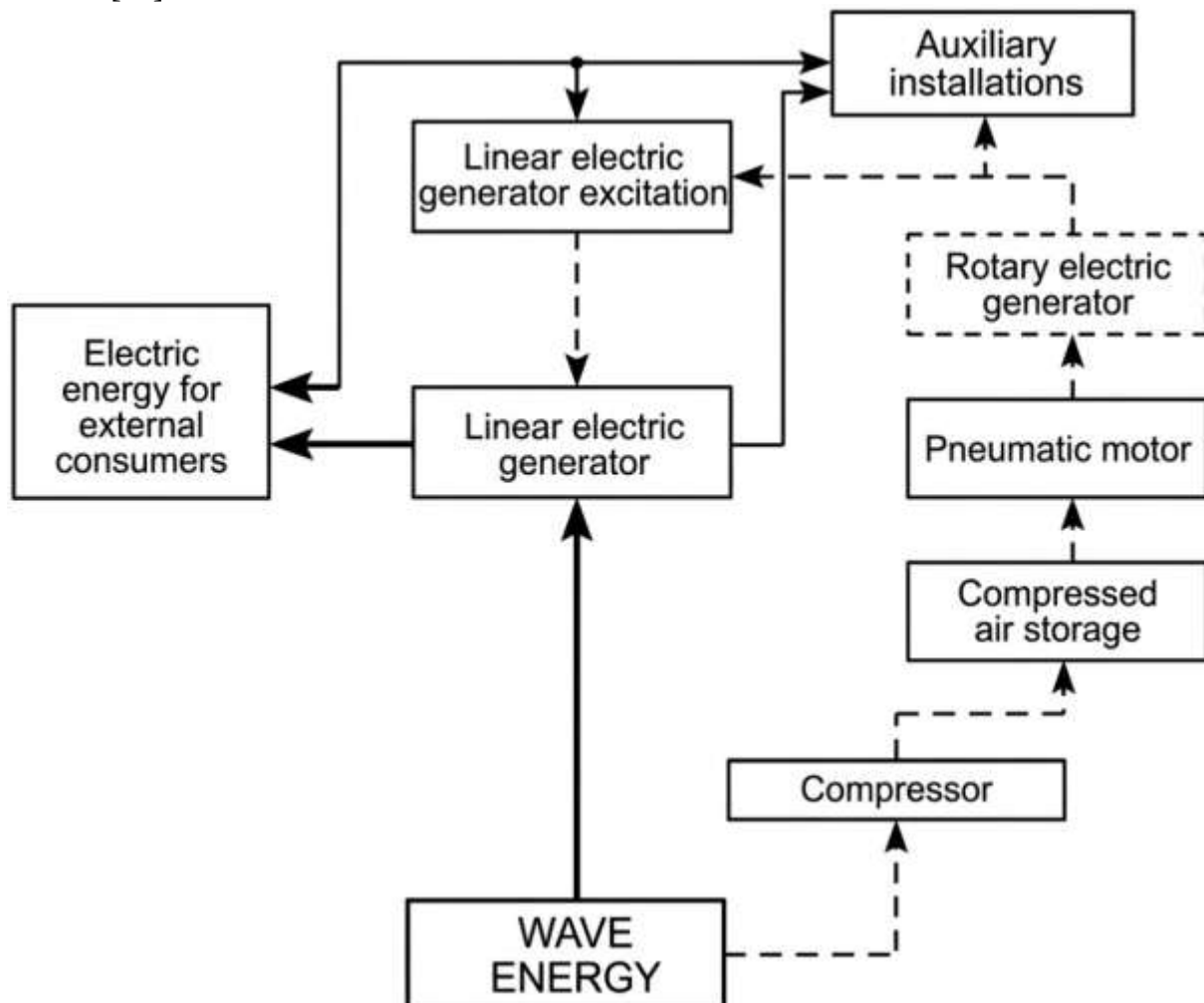


Figure 4.1 Operating principle of a wave energy converters [19]

The biggest challenge of wave energy systems is to capture the low-frequency, random oscillatory motion and convert it into a stable form of energy. The variability of wave characteristics directly influences the power generated. The design of structures for wave energy capture is complex, as they must be able to utilize both small-amplitude and large-amplitude waves.

4.1 History

The issue of harnessing wave energy has been analyzed since ancient times, but is currently being approached through modern methods, with a growing interest in transforming the kinetic energy of waves into electrical energy.

4.1.1 Wave energy converters developed in Romania

In Romania, wave energy research began in the period 1980–1985, being carried out in institutes such as ICH, ISPH, ICPE, as well as in the hydraulics laboratories of the Polytechnic Institute of Bucharest and the Institute of Construction of Bucharest. During this period, extensive studies were carried out on models in wave channels and the possibilities of capturing and converting wave energy in the Black Sea were evaluated. Two experimental models were built, based on the ICPE Patent 79184/1981 “Mașină motrică pentru utilizarea energiei valurilor”, tested in real conditions with promising results: the oscillating buoy with unidirectional turbine G-2 and the hydropneumatic micropower plant MV-1.

4.1.1.1 Buoy type WEC G-1

The device is equipped with a unidirectional turbine, mounted on a frame supported by a float, and the turbine shaft drives the generator through a speed multiplier. The turbine consists of 18 oscillating blades, each equipped with a stop that limits the amplitude of oscillations, mounted on radial axes [19].

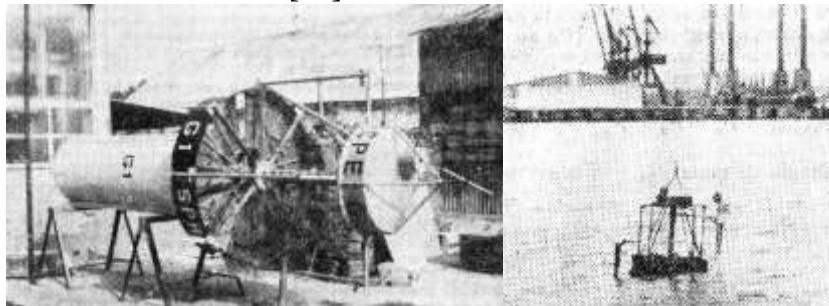


Figure 4.2 Experimental model G-1[19]

4.1.1.2 Buoy type WEC G-2

The system is designed in the form of a buoy and operates on the OWC principle. The main structure consists of a cylinder in which the liquid piston is formed, having a diameter of 1.5 m and a height of 2.5 m, provided at the top with a conical lid and open at the bottom [18].

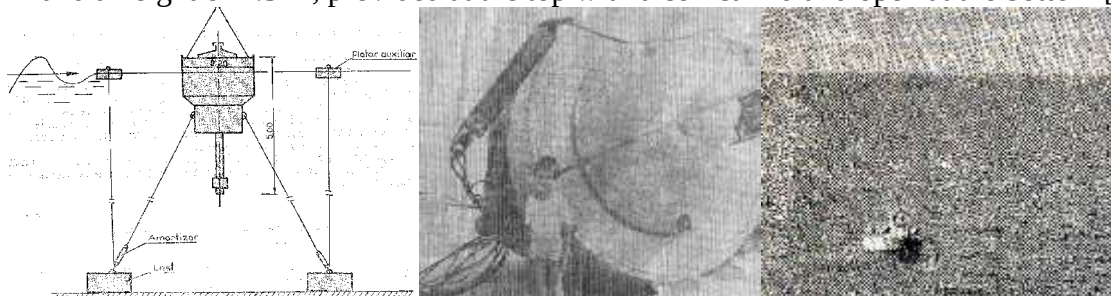


Figure 4.3 Experimental model G-2 [19]

4.1.1.3 MV-1 wave micropower plant

The MV-1 system is based on the principle of the oscillating column, unlike other similar installations, it has a geometry that allows for the production of a residual oscillating column with an amplitude greater than that of the generating waves. [19].

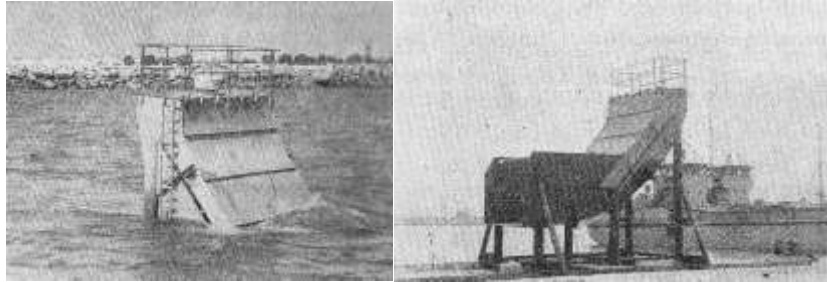


Figure 4.3 Model experimental MV-1 [19]

4.2 Classification

Over time, numerous technologies have been developed to harness wave energy, which can be classified according to different criteria, such as their operating principle, size, orientation or destination [32].

Despite the large number of technologies for converting wave energy, they can be classified according to their distance from the shore. They are:

- Onshore systems – installed directly on the coast;
- Nearshore systems;
- Offshore systems – designed to operate at depths greater than 100 m.

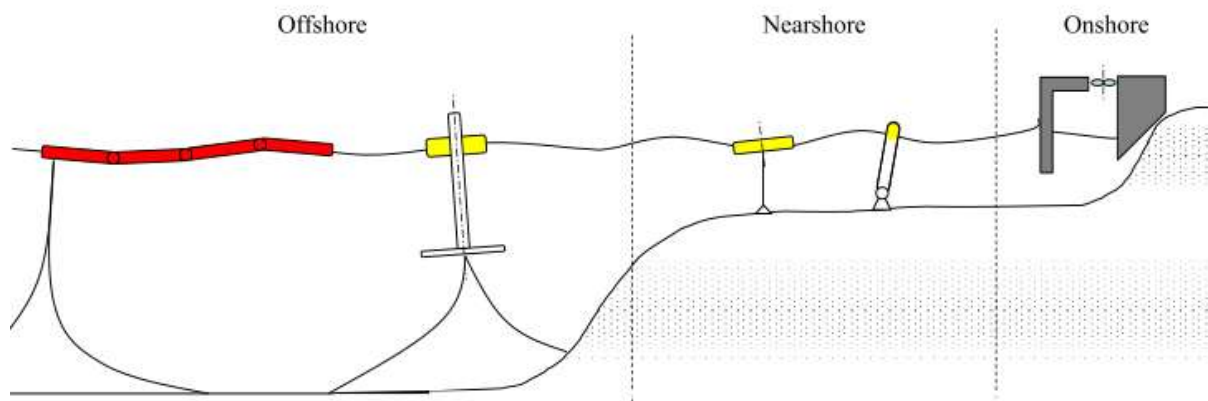


Figure 4.4 Classification according to distance from shore [33]

Approximately 80% of current technologies fall into the following types of wave energy systems [34], [35]:

- Point Absorbers;
- Attenuators/WPD – Wave Profile device;
- OWC - Oscillating Water Columns systems;
- OWP - Overtopping Wave Power devices;
- OWSC - Oscillating Wave Surge Converters.

4.3 PTO - Power Take-Off systems

Capture and conversion systems, also called Power Take-Off (PTO), convert the oscillatory movement of the capture device (float, water column or flap) into electrical energy, while managing the frequency and amplitude irregularities specific to waves. Depending on the operating principle, PTO systems are divided into [26]:

- Hydraulic.
- Hydropneumatic.
- Oscillating Water Column.
- Linear Electric Generators.

4.4 Practical methods to store wave energy

Due to the intermittent nature of energy, it is necessary to identify storage solutions in different forms. Technical means allow the storage of energy generated by waves in [18], [36]: electric accumulators, hydrogen (through water hydrolysis), hydraulic accumulators, compressed air.

4.5 Modern systems

Since the 1970s, technologies for harnessing renewable energy sources have undergone remarkable progress, improving considerably in terms of both performance and cost. In recent years, advances in modern electronics and other scientific fields have significantly influenced research in the field of wave energy harnessing. New generations of systems capable of efficiently harnessing the energy of small waves have been developed.

4.5.1 CorPower Ocean

The technology developed by CorPower Ocean is based on buoy-type floating devices, anchored to the seabed, which move vertically under the action of waves. The movement is transmitted to an internal mechanical and hydraulic system, where the kinetic energy of the waves is transformed into electrical energy. A distinctive element of the company's technology is the WaveSpring system, inspired by the biomechanical principles of the functioning of the human heart, which allows the dynamic adjustment of the device to maximize energy capture under normal operating conditions and to ensure the protection of the structure during storms or extreme waves [37].

4.5.2 AquaBuoy

AquaBuoy is a point absorber WEC designed to convert the mechanical energy of ocean waves into electrical energy. The AquaBuoy system consists of a floating cylindrical buoy, with a diameter of 6 m, connected to a long vertical tube, located below the water surface. The entire system is 30 m long and is designed to operate in waters with depths exceeding 50 m [38]. The operating principle is based on the vertical movement of the buoy under the action of waves.

4.5.3 AWS (Archimedes WaveSwing)

The Archimedes Wave Swing (AWS) is a wave energy conversion technology based on the submerged Point Absorber type, which works by capturing the hydrostatic pressure variations induced by the passage of waves. The system is composed of two telescopic cylindrical structures: a lower part fixed to the seabed (the base) and a movable upper part, called the float or “bell”. The interior of the system is filled with pressurized air, acting as a “pneumatic spring”. When the crest of a wave passes over the device, the hydrostatic pressure increases, compressing the air inside and forcing the float to descend

4.5.4 OEBuoy

The OEBuoy system is a float-type WEC based on Oscillating Water Column (OWC) technology. The device is distinguished by its asymmetric hydrodynamic geometry, being designed to extract energy from both the vertical motion of the wave and the pressure exerted by the wave front. The device uses a partially submerged structure, open at the base below sea level, which traps a mass of water inside a pneumatic chamber. As waves pass the device, the water level inside the column oscillates. The movement acts like a piston, compressing and decompressing the volume of air trapped above the water column. The compressed air is forced through a bidirectional turbine, which maintains the same sense of rotation regardless of the direction of the air flow.

4.5.5 Pontoon

The Pontoon system (also known as Floating Pontoon Wave Energy Converter) is part of the point absorber device category, being one of the simplest and most robust solutions for capturing marine energy. The Pontoon is composed of two distinct elements [39]: the floating body, a highly buoyant structure, usually made of steel or special concrete, which oscillates vertically under the action of the hydrostatic force of the waves, and the anchoring system that keeps the pontoon in a fixed position.

4.5.6 Langlee

The Langlee system is a system designed to operate in semi-submerged areas (nearshore or offshore). It is based on the oscillation of mechanical wings activated by the circular motion of water particles below sea level. Unlike point absorbers that use vertical oscillation, the Langlee extracts energy by using the horizontal and vertical components of the wave. The device is equipped with two articulated wings that move back and forth under the action of the dynamic pressure of the waves. The wing arms actuate hydraulic pistons that pump fluid under high pressure to a hydraulic motor coupled to a conventional electric generator.

4.5.7 CETO

The CETO solution consists of connecting a submerged buoy, via flexible links, to a fixed structure located on the seabed, where a hydraulic motor is installed. The buoy's movement drives hydraulic cylinders (in earlier versions, such as CETO 5) or direct electric generators (in new versions, CETO 6) [40].

4.5.8 Oyster 2

Oyster 2 is a WEC designed to be installed in nearshore areas, at depths of between 10 and 15 meters. The technology is based on capturing the kinetic and potential energy of translational waves propagating towards the shore. The system uses a large oscillating structure, similar to a gate, hinged at its base on the seabed. As waves pass over the device, the oscillating body (the flap) is pushed back and forth by the orbital and translational motion of the water. The oscillation of the flap drives two double-acting hydraulic pistons, which pump fresh water under high pressure through a submarine pipeline to a turbine located on shore. A modular metal structure, partially filled with air to provide the buoyancy necessary to maintain a vertical position at rest.

4.5.9 Oyster

Oyster is a device designed to capture coastal wave energy, typically installed at relatively shallow depths (10-15 meters). The system uses a large capture surface positioned perpendicular to the direction of wave travel. The oscillation axis of this panel is firmly anchored to the seabed. The horizontal force of the waves pushes the panel back and forth. The mechanical movement is taken over by a pivoting arm that drives a pumping system [41].

4.5.10 SeaBased AB

The SeaBased system is a submerged point absorber type WEC, characterized by the use of a permanent magnet linear generator located on the seabed. The surface unit, or float, is a cylindrical or spherical buoy that floats on the water surface and is designed to follow the vertical movement of waves. This is connected via a transmission system, consisting of a high-strength steel cable, directly to the conversion unit, or linear generator. The linear generator is located in a watertight concrete or steel housing fixed to the seabed and comprises a stator and a transducer equipped with permanent magnets, transforming the mechanical movement of the float into electrical energy.

4.5.11 SSG

SSG is a wave energy conversion technology based on the principle of intentional obstruction. Unlike point absorbers, SSG does not use the oscillation motion, but captures the potential energy of the water collected above sea level.

The device is built as a massive structure with a ramp or cone-shaped front face, equipped with several superimposed tanks. The ascent ramp directs the incident waves to rise and exceed the edges of the tanks, while the storage tanks, located at different heights, allow the capture of water from both small and large waves, maximizing hydraulic efficiency. The accumulated energy is converted into electricity through the PTO system, which consists of a low-head Kaplan-type hydraulic turbine or a patented multi-stage turbine, coupled to an electric generator.

4.5.12 BFHB (Bottom Fixed Heave Buoy)

BFHB (Bottom Fixed Heave Buoy) is a WEC designed to capture marine energy through the vertical movement of waves. The device is rigidly anchored to the seabed, which gives it stability and allows the efficient exploitation of the vertical oscillation movement of

the float. By fixing it to the seabed and operating on the principle of relative movement between the float and the base structure, the BFHB ensures constant and efficient capture of wave energy, reducing the influence of lateral currents and uncontrolled movements, being suitable for the exploitation of marine energy resources in areas with moderate to deep depths.

4.5.13 Oceantec

Oceantec is a wave energy conversion system developed by the Spanish company Oceantec Energías Marinas, supported by Tecnalia Corporación Tecnológica and Iberdrola to harness renewable marine resources. A large float generates variations in a column of water that compresses and decompresses air in an upper chamber, this airflow being used to drive turbines connected to electrical generators. The device captures wave energy through the movement of the internal water column, which compresses the air above and sets in motion turbines placed at the top, generating electricity.

4.5.14 WaveStar

WaveStar is a point absorber wave energy converter, originally developed by the Danish company Wave Star Energy, for capturing the energy of ocean waves and generating electricity through a floating system with multiple buoys. The device consists of a platform supported by pillars fixed to the seabed, on which are mounted 20 semi-submersible floats arranged in series, which follow the vertical movement of the waves. The upward and downward movements of these floats are converted hydraulically into a constant rotational torque on an electric generator through an optimized PTO system.

4.5.15 PWEC

PWEC (Pendulum Wave Energy Converter) is a WEC designed to capture and convert the kinetic energy of wave motion into electrical energy through an oscillating mechanism. The system uses a pendulum or articulated arm, anchored to the seabed or to a fixed structure, which oscillates under the action of incident waves. The movement of the pendulum is transmitted to a PTO system, which can be hydraulic, mechanical or electrical, to generate electrical energy.

4.5.16 Pelamis

The Pelamis system is based on a segmented and articulated structure. The assembly consists of several rigid cylindrical tubes, interconnected by flexible mechanical joints. The passage of waves causes angular inclinations at the joints. The bending movement drives hydraulic pumps that send pressurized liquid to turbines, driving electric generators [42].

4.5.17 WaveBob

WaveBob is a two-body point absorber WEC originally developed by the Irish company Wavebob Ltd. for the capture of ocean wave energy and its conversion into electrical energy. The device is designed as a buoy composed of two oscillating structures that move relatively under wave action, an operation used to extract wave energy through a hydraulic PTO system or linear generator. Wavebob is designed to be deployed in deep water, in modular offshore assemblies, where the relative movement between the two bodies is optimized for wave energy absorption and continuous electrical generation.

4.5.18 Wave Dragon

This is a wave energy harnessing system that combines the principle of the intentional obstacle with that of the inclined plane. The obstacle consists of two guide wings, which concentrate the water mass in a basin located at a higher level than the sea level. The accumulated water then falls on a bank of turbines, connected to electric generators, generating electricity. The development of the system was financially supported by the European Union and the Danish authorities, representing a scalable solution for the exploitation of wave energy. The high performance of the system is due to the high efficiency of hydraulic capture and conversion, as well as simple and low-cost maintenance [43].

4.5.19 Wave-driven hydropneumatic power plant MV-5

The solution was developed by the Naval Academy “Mircea cel Bătrân”, in collaboration with the Scientific Research Center for the Naval Forces and the Faculty of Electrical Engineering of the Technical University “Gh. Asachi”. The main components of the hydropneumatic power plant are the hydropneumatic collector and the multi-blade turbine. The collector is based on the principle of the intentional obstacle, and the oscillations of the water column in the enclosure are strongly influenced by the aerodynamic resistance of the air column [44].

4.6 Large-scale exploitation

Initiatives to implement large-scale systems have frequently encountered technical problems. The strong vibrations induced in the floats by wave dynamics generate mechanical stresses, which can lead to the degradation of the structural elements, misalignment of the kinematic assembly and, in severe cases, to the total destruction of the system.

The large-scale implementation of WEC systems requires extensive investigations, the dynamics of innovations outlines an optimistic trajectory towards achieving competitive prices on the energy market. For a closed basin like the Black Sea, reaching the profitability threshold will require a paradigm shift: the transition from individual converters to multi-source hybrid systems and the exploitation of breakwater-integrated WEC structures as capture platforms, a strategy that promises the efficient integration of wave energy into the national energy portfolio.

5 Harnessing wave energy in the Romanian Black Sea littoral area

The relatively low variability of the wave regime in the Black Sea basin is an advantage for the implementation of systems for harnessing wave energy. Their lower energy level requires the adaptation of existing technologies, typically designed for higher energy regimes.

The current research provides a preliminary assessment of the feasibility of implementing wave energy systems in the Romanian Black Sea littoral area. It analyzes the energy efficiency and explores the hypothesis that scaled-up versions of these systems would lead to increased efficiency in the context of local conditions. To test the hypothesis, 18 representative WEC technologies were evaluated and scaled, and their efficiency was assessed at three study points. The results provide valuable information on the efficiency and compatibility of different wave energy technologies for this region.

5.1 Research methodology

The efficiency of 18 wave energy conversion systems was evaluated based on oceanographic data obtained through mathematical modeling of the sea state provided by CMEMS through the ERA5 reanalysis dataset [45], bathymetric data were extracted from GEBCO [46] covering the period 1990–2024 for the 3 study points (P1, P2, P3). The data provided by CMEMS through the ERA5 reanalysis dataset is available with a spatial resolution of 1° and a temporal resolution of 1 hour.

The annual energy production (AEP), measured in MWh, is estimated by bilinear interpolation of the WEC power matrix with the characteristic sea state matrix corresponding to the analyzed region. It can be calculated using the following formula [25]:

$$AEP = \sum_{i=1}^{nT} \sum_{j=1}^{nH} p_{ij} \cdot P_{ij} \quad (5.1)$$

where: nT represents the number of cells on the horizontal axis, corresponding to the discretization of the wave period; nH represents the number of cells on the vertical axis, corresponding to the discretization of the wave height; p_{ij} – describes the sea state at a certain point, defined by row i (corresponding to the wave period T_e) and column j (corresponding to the wave height H_s) according to the cell in the sea state matrix, and P_{ij} represents the electrical power produced by the WEC corresponding to the cell defined by the specific combination of the wave period (defined by row i) and the wave height (defined by column j).

The capacity factor C_f is defined as the ratio between the maximum power production of the WEC and the theoretical power available from the wave energy resource over a given period, expressed in %. C_f highlights the annual energy provided by the device in relation to the maximum theoretical energy it could deliver if it were to operate continuously at its nominal power. This is an essential parameter for evaluating the performance of WECs in terms of energy generation capacity. It can be calculated using the following equation [31]:

$$C_f = 100 \times \frac{P_e}{P_n} \quad (5.2)$$

where: P_e represents the maximum power produced, also known as the nominal power, and P_n is the power produced by the WEC in a specific context (wave height and wave period) for a defined period.

The capture width, c_w , evaluates the actual extraction capacity of the equipment and directly depends on two critical factors: the geometry and dynamic response of the floating structure, and the efficiency of the PTO system. The capture width can be determined using the relationship [47]:

$$c_w = \frac{P_e}{P_w} [m] \quad (5.3)$$

where P_w , the front capture power, represents the resultant between the component elements of the wave front transport energy in both directions P_x and P_y .

The Capture Width Ratio (c_{wr}) evaluates the hydrodynamic efficiency of the system strictly in terms of its physical dimensions. The c_{wr} parameter is determined according to the mathematical relationship:

$$c_{wr} = \frac{P_n}{d_{wec}} [\%] \quad (5.4)$$

where: P_n - nominal power of the wave energy harnessing system in the context of a certain height and period [kW]; d_{wec} - WEC diameter or active front width.

Froude's scaling law states that wave height scales linearly with λ , wave periods scale with the square root of λ , and power scales with $\lambda^{3.5}$ of the geometric scale [39]. Each selected WEC was subjected to a scaling analysis using a scale factor (λ) ranging from 0.69 to 1.31, in steps of 0.01, where $\lambda = 1$ represents the original scale. Values of $\lambda < 1$ correspond to a downscaled version, while values of $\lambda > 1$ indicate an upscaled version of the WEC. The process of upscaling ($\lambda > 1$) or downscaling ($\lambda < 1$) follows the Froude similarity principle, which preserves the dynamic similarity between the model and the prototype by maintaining the equality of the Froude number [48]:

$$Fr = \frac{U}{\sqrt{gL}} \quad (5.5)$$

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

For the study, λ varied between 0.69 and 1.31. According to Froude scaling, the main parameters of the device and the wave field are related as follows [31]:

$$L_{scaled} = L_0 \times \lambda \quad (5.6)$$

$$T_{scaled} = T_0 \times \sqrt{\lambda} \quad (5.7)$$

$$P_{scaled} = P_0 \times \lambda^{3.5} \quad (5.8)$$

The prototype power matrix $P_0(H_s, T_p)$ provides the average power generated as a function of the significant wave height (H_s) and the peak period (T_p). For the analysis of scaled devices, the measured sea states are converted to prototype equivalent conditions [31]:

$$H_{s_{proto}} = \frac{H_{s_{real}}}{\lambda} \quad (5.9)$$

$$T_{proto} = \frac{T_{real}}{\sqrt{\lambda}} \quad (5.10)$$

The instantaneous power generated by the rescaled device is:

$$P_{scaled} = P_0(H_{s_{proto}}, T_{proto}) \times \lambda^{3.5} \quad (5.11)$$

For each sea state record in the measured time series, the corresponding power of the scaled device is calculated using Froude scaling laws. The total annual energy is determined as the time-average of all instantaneous power values over the simulated period. Therefore, the AEP is expressed as [49]:

$$AEP = \frac{1}{N_{years}} \sum_{t=1}^{N_{steps}} P_{scaled}(t) \Delta t \quad (5.12)$$

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

The analysis was performed for a total of 342399960 iterations, across the three study points, considering 18 WEC technologies, 65 scaling factors and 306810 wave state samples (hourly data over a 35-year period). All *AEP* estimates were normalized to the scaled nominal power to obtain C_f annual average .

5.2 Location

The study points were selected based on several criteria imposed by the marine spatial planning framework [14]. The main factors considered in the selection process were: wave height, wave period, proximity to the shore (to minimize: the distance to connect to the National Energy System, maintenance and operation costs) and the absence of obstacles, in accordance with the maritime spatial planning plan.

From the available areas, study points P1 and P2 were selected, and point P3 was chosen near the port of Constanta, to allow the evaluation of systems in areas closer to the shore, with shallower depths and reduced energy potential. The identified study points have the following characteristics:

Table 5.1 Characteristics of the study points P1 P2 P3

Study point	Coordinates	Distance from shore (km)	Depth (m)	H_s (m)		T_e (s)		Available power (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

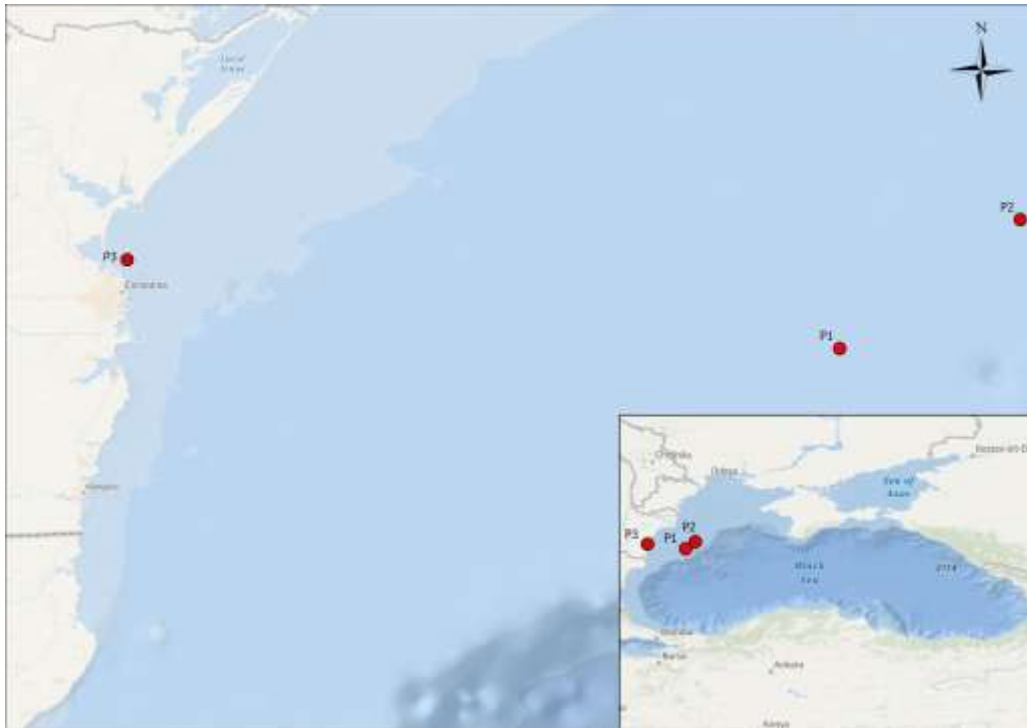


Figure 5.1 Location of the study points P1, P2 and P3

5.3 WECs analyzed in the study

Most WECs can achieve good results in the Romanian Black Sea littoral area, provided that they are scaled according to the local hydrographic characteristics [31]. Studies have shown that the optimal scaling ratio does not depend on the gross power of the system [39]. For technological reasons, these systems can be scaled up to 40% compared to the original model [48]. The following systems were selected for evaluation:

Table 5.2 Characteristics of the analyzed WECs

WEC	Power Take-off (PTO)	Rated power/unit P_e [kW]	EMEC classification
CorPower Ocean	Hydraulic pump	400	Point Absorber
Aqua Buoy	Water turbine	250	Point Absorber
OEBuoy	Turbine	2880	OWC
AWS	Linear generator	2470	Point Absorber
Pontoon	Hydraulic motor	3619	Point Absorber
Langlee	Hydraulic motor	1665	OWSC
CETO	Hydraulic motor	260	Point Absorber
Oyster	Hydraulic pump	290	OWSC
Oyster 2	Hydraulic pump	3332	Point Absorber
Seabased AB	Linear generator	15	Point Absorber
SSG	Turbine	20000	OWP
Heave buoy (BFHB)	Linear generator	2192	Point Absorber
Oceantec	Linear generator	500	Point Absorber
Wave Star	Linear generator	2709	Point Absorber
PWEC	Pendulum	479	Point Absorber
Pelamis	Hydraulic motor	750	WPD
Wave Bob	Hydraulic motor	1000	Point Absorber
Wave Dragon	Hydraulic motor	7000	OWP

5.4 Simulation

The simulation of the performance of WECs involved the use of the MATLAB software application. By running the code, it was possible to evaluate the systems both at the original scale and at the resized scale, under the conditions established in the study.

5.5 In-depth study of the CorPower Ocean solution

The solution proposed by CorPower Ocean (CPO) involves the use of a buoy anchored to the seabed, the innovation of the solution consists in the use of a pre-tensioned system that pushes the buoy towards the bottom while the waves lift it, a system called "WaveSpring". The movement on the vertical axis is captured by means of hydraulic pistons which in turn drive a hydraulic motor connected to an electric generator.

The simulation of the system evolution over a 35-year period (1990–2024) was based on data provided by the Copernicus Marine Environment Monitoring Service (CMEMS), through the ERA5 reanalysis dataset, with a spatial resolution of 1°, as well as bathymetric data from the General Bathymetric Chart of the Oceans (GEBCO). This information was used to characterize the wave regime at the three points of interest (P1, P2 and P3).

Table 5.3 CorPower Ocean results (multiannual average 1990-2024)

Capacity factor [%]			Capture Width Ratio [%]			capture width [m]			Annual energy production [MWh/year]		
P1	P2	P3	P1	P2	P3	P1	P2	P3	P1	P2	P3
11.61	12.16	7.64	1.39	1.39	1.39	12.48	12.53	12.52	407	426	267

The simulation results of the wave energy conversion system highlight that the best results can be obtained at study point P2, similar results were recorded at P1. Point P3 presented the lowest values of energy production.

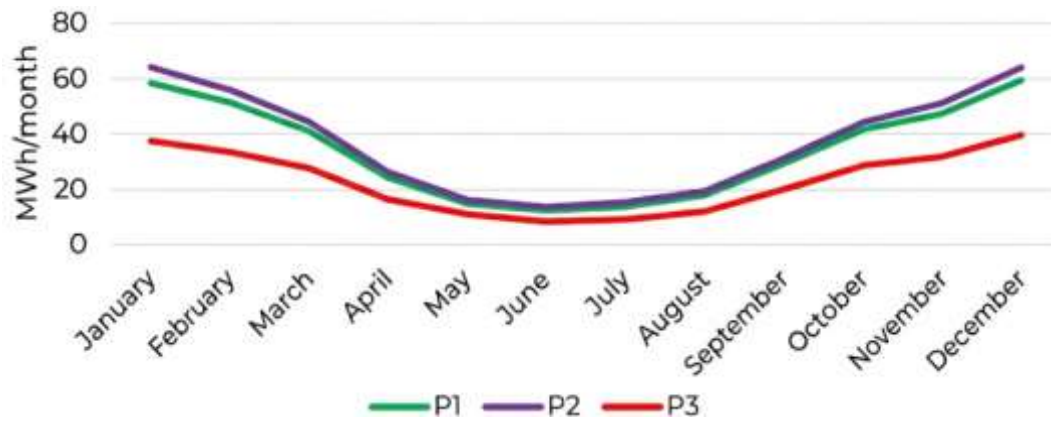


Figure 5.2 Graph of average monthly power supplied by CorPower Ocean (1990-2024)

In terms of the monthly distribution of energy production, December stands out as the most productive month, while July records the lowest values of energy produced in all three points of interest.

At a seasonal level, autumn represents the most favorable period for harnessing wave energy in the case of locating the system at points P1 and P2, while for point P3, winter proves to be the season with the highest energy potential.

5.6 Results

The results presented were determined for ideal conditions without taking into account a number of factors due to the lack of data. A control strategy for the wave harnessing systems was not used, the use of a strategy could increase the efficiency of the systems.

5.6.1 Annual energy production and capacity factor

The evaluation of the 18 WEC technologies: CorPower Ocean[50], Aqua Buoy [51], AWS (Archimedes Wave Swing) [39], OEBuoy [39], Pontoon [39], Langlee (Floating 3 body Oscillating Flap) [52], CETO [53], Oyster [54], Oyster 2 (Bottom Fixed Oscillating Flap Buoy) [55], SeaBased AB [56], SSG (Sea Slot-cone Generator) [57], BFHB (Bottom Fixed Heave Buoy) [52], OceanTec [58], Wave Star [59], PWECC [60], Pelamis [61], Wave Bob [39], Wave Dragon [57] with production powers ranging from 250kW to 20000kW, facilitates the identification of the most appropriate WEC technology for the three study points located along the Romanian Black Sea coast. Differences can be observed between WEC technologies in terms of AEP and C_f in table 5.4.

Figure 5.3 comparatively illustrates the estimated average annual energy production for the selected WEC systems, evaluated at the three study points: P1, P2 and P3.

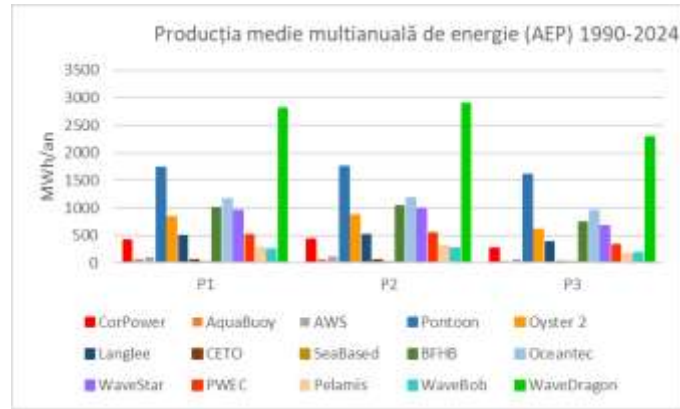


Figure 5.3 Multiannual average energy production 1990-2024

Table 5.4 Characteristics of the analyzed WECs (scale factor $\lambda = 1$)

WEC	Rated power/unit P_e (kW)	Annual energy production AEP (MWh/year)			Capacity factor 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

The seasonal variability of the Black Sea offers a perfect complementarity with solar energy: the photovoltaic deficit during the season can be compensated by the energy produced by harnessing wave energy.

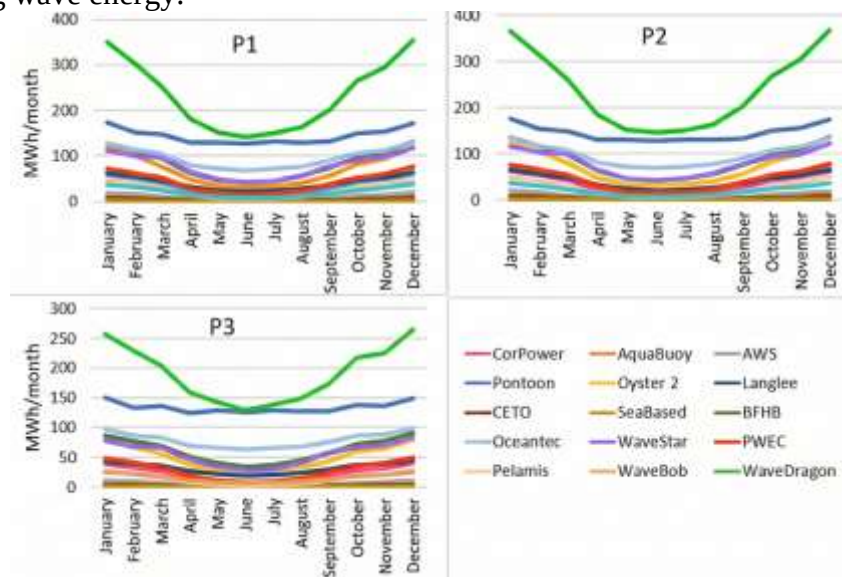


Figure 5.4 Average monthly production in the study points P1 P2 P3

The variability of energy production reflects seasonal fluctuations in meteorological and oceanographic conditions on the Romanian Black Sea coast. The production peaks are directly correlated with the intensification of the wind regime in the December-January period, which generates high sea agitation. The May-July period is marked by low wind speeds, a factor that inevitably leads to a minimal energy potential of wave resources in the studied areas.

5.6.2 Scaling

As part of the performance evaluation methodology, AEP and C_f were calculated for each selected WEC in all study locations (P1, P2 and P3). To assess the adaptability of the equipment to local conditions, the calculations integrated the application of a geometric scaling factor (λ), whose values were varied in the range 0.69 - 1.31, using a discretization step of 0.01.

The scaling process had a significant impact on the variation of C_f . Reducing the device size (downscaling $\lambda < 1$) led to an increase in C_f , indicating a higher efficiency in energy capture. In contrast, increasing the device size ($\lambda > 1$) led to a decrease in C_f , suggesting a lower efficiency under the given wave conditions.

The simulated data confirm the hypothesis that downscaling WEC systems leads to an increase in C_f under Black Sea conditions.

Upscaling of the devices resulted in a decrease in C_f , affecting energy production under dominant wave regime conditions. The results indicate that upscaling WECs reduces efficiency.

For each location, the optimal size for each WEC technology was identified by calibrating the scaling factor, aiming to achieve a maximum for the AEP and C_f indicators. To clearly highlight the impact of the resizing on the overall performance, the optimal results are presented in contrast to the reference values obtained at the limits of the analysis interval ($\lambda = 0.69$, respectively $\lambda = 1.31$).

Table 5.5 Capacity factor C_f at scaling factor $\lambda = 0.69$, $\lambda = 1$, $\lambda = 1.31$

WEC	C_f (%) $\lambda = 0.69$			C_f (%) $\lambda = 1$			C_f (%) $\lambda = 1.31$		
	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

At all study points in the Black Sea, the energy efficiency for the evaluated WECs remains below 26%, a result that is consistent with expectations for seas with low energy potential, such as the Black Sea [25].

Table 5.6 Annual energy production AEP at scaling factor $\lambda=0.69$, $\lambda=1$ și $\lambda=1.31$

WEC	AEP (MWh/year), $\lambda=0.69$			AEP (MWh/year), $\lambda=1$			AEP (MWh/year), $\lambda=1.31$		
	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

Regarding annual energy production (AEP), the spatial hierarchy of productivity ($P2 > P1 > P3$) previously identified at a general level no longer remains uniform.

Table 5.7 Optimum scale factor for WECs

WEC	P1				P2				P3			
	λ	AEP (MWh/year)	λ	C_f (%)	λ	AEP (MWh/year)	λ	C_f (%)	λ	AEP (MWh/year)	λ	C_f (%)
CorPower Ocea	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

Reducing the size has a beneficial effect on C_f , as all evaluated technologies achieved the best results at the minimum considered resizing factor, $\lambda = 0.69$. Increasing the size for all evaluated WECs leads to a decrease in the C_f value. Regarding the resizing in relation to AEP, the optimal resizing factor varies depending on the technology, the maximum energy production can be obtained either by increasing or by reducing the size, depending on the specific characteristics of each WEC.

The results for the three study points confirm that oversizing leads to an increase in AEP, this is often done at the expense of lower energy efficiency C_f .

6 Conclusions

Wave energy represents a renewable source that is still untapped in Romania, which could contribute to achieving the new national energy objectives. Due to the relatively calm sea regime, the gross energy potential of waves on the Romanian coast is modest. To date, studies have not been able to conclude the profitability of implementing wave energy valorization systems for the Black Sea coast.

The results presented were determined for ideal conditions, without considering the variability of the wave regime, due to the lack of available data. A control strategy was not applied for the wave energy systems, but the use of a strategy could lead to an increase in their efficiency. The study used power matrices for several wave energy systems, which present an uncertainty level between 10% and 40%, according to Babarit et al. The results should be interpreted taking into account this degree of uncertainty [55].

The research aimed to evaluate the performance of 18 WEC technologies, both at original size and for scaled versions, in three points of interest, considering the annual energy production AEP and the energy efficiency C_f . Energy performance does not always correspond to economic performance. All evaluated WECs show a similar behavior in terms of energy production at all study points.

The results indicate that the use of scaled WECs could improve wave energy utilization on the Romanian Black Sea littoral. By optimizing the system size for specific wave conditions, it is possible to increase the total energy capture. The strategy could lead to more efficient and reliable energy generation, better utilizing an important marine resource. The results emphasize that the optimal design of a WEC is not absolute, but depends on the specific economic factors of the project, such as whether the objective is to maximize total revenues (favoring AEP) or to ensure a high and constant utilization of the nominal capacity (favoring C_f). Each WEC technology has a specific ability to adapt to different environmental conditions and operational sizes.

The current study can represent a valuable resource for decision-makers, investors and project developers in identifying the most suitable WEC technology for implementation on the Romanian Black Sea coast, depending on the objective pursued: maximizing total energy production or optimizing conversion efficiency.

6.1 Obtained results

This research evaluated the feasibility of implementing 18 wave energy technologies on the Romanian Black Sea coast, highlighting the following particularities:

- The comparative analysis indicated study point P2 as the most favorable location for wave energy extraction, outperforming points P1 and P3 through superior resources and greater stability of long-term energy yield.
- The study demonstrates that the direct use, without scaling, of systems designed for oceanic regimes is not effective in the Black Sea basin.

In conclusion, the implementation of wave energy systems in the Black Sea is technically feasible, provided that the systems are adapted to the local energy spectrum.

6.2 Original contributions

This paper brings a series of novel elements in the field of evaluating renewable energy resources in the Black Sea basin, the most relevant contributions being:

- An original contribution consists in selecting the three study points.
- Developing a unified methodological framework for evaluating the performance of WEC systems.
- Analysis of the behavior of the CorPower C4 system in the wave regime in the Romanian Black Sea coastal area
- Multi-criteria evaluation of 18 WEC technologies.
- Development of an analysis framework based on the fine variation (step of 0.01) of the scaling factor (λ), allowing the precise identification of the optimal scaling factor [63].

6.3 List of original publications

The results of theoretical research and numerical simulations regarding the optimization of wave energy conversion systems and the assessment of energy efficiency in the Romanian sector of the Black Sea, obtained during the doctoral studies, were utilized as follows:

Articles published in BDI indexed specialized journals:

- T.-A. Teodorof, A. G. Majidi, M. O. Popescu, „SCALING WAVE ENERGY CONVERTERS FOR MAXIMUM EFFICIENCY ALONG THE ROMANIAN BLACK SEA COAST”, *AnnalsARSciEng*, vol. 17, nr. 2, pp. 32-50, dec. 2025, doi: 10.56082/annalsarscieng.2025.2.32.

Articles published in WoS indexed journals:

- T.-A. Teodorof, A. G. Majidi, M. O. Popescu, „WAVE ENERGY POTENTIAL AND WEC PERFORMANCE ALONG THE ROMANIAN BLACK SEA COAST”, *SCIENTIFIC BULLETIN Series C: Electrical Engineering & Computer Science*, vol. 88, nr. 1, pp. 465-478, 2026.

6.4 Perspectives for further developments

The analysis of the theoretical foundations and the current technological context highlights the fact that wave energy represents a renewable resource with major strategic potential, characterized by the highest power density among all sources derived from solar radiation. Its integration into the national and European energy portfolio directly responds to current decarbonization directives (such as REPowerEU) and promises to diversify and increase the resilience of the Electric Power System.

The advancement of research and the successful implementation of wave energy technologies in the Black Sea area are conditional on solving major technical, economic and regulatory challenges.

The potential for technological improvement in the field of marine energy exploitation is substantial. A particularly promising research direction is the optimization of automatic control algorithms (predictive and reactive piloting) of WEC systems.

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