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LIST OF ABRIVIATIONS:

List of Abbreviations:

AEP : Annual Energy Production

CERRA : Copernicus European Regional Reanalysis

CF : Capacity Factor

CMEMS : Copernicus Marine Environment Monitoring Service

DFS2 : Deep-water Format Series 2

ECMWF : European Centre for Medium-Range Weather Forecasts

EEZ: Exclusive Economic Zone

ERA5 : ECMWF Reanalysis v5

GEBCO: General Bathymetric Chart of the Oceans

GIS : Geographic Information System

Hs : Significant Wave Height

IRENA : International Renewable Energy Agency

LCOE : Levelised Cost of Energy

LCOH : Levelized Cost of Hydrogen

MIKE 21 SW : MIKE 21 Spectral Waves

OTEC: Ocean Thermal Energy Conversion

OWC : Oscillating Water Column

PTO : Power Take-Off

Te : Energy Period

Tp : Peak Period

TRL :Technology Readiness Level

UNCLOS :United Nations Convention on the Law of the Sea

WEC :Wave Energy Converter

WGS84 :World Geodetic System 1984

ABSTRACT:

Growing demand for low-carbon energy has increased interest in wave energy, given its high energy density and predictability. National-scale assessments of this resource within Algeria's Exclusive Economic Zone (EEZ) remain limited despite its ~2148 km coastline.

This study evaluates the wave energy resource along the Algerian littoral using multi-year wave data and the MIKE 21 SW model, combined with GIS-based spatial analysis to map resource distribution and delineate favourable zones. These zones were further assessed using the CorPower Ocean C4 converter to estimate Annual Energy Production (AEP) and identify priority sites.

The results provide suitability maps and a scientific basis for future site selection, supporting Algeria's renewable energy diversification objectives.

Keywords— Wave energy; MIKE 21 SW; CorPower Ocean C4; wave power; GIS; Algeria EEZ.

RÉSUMÉ:

La demande croissante en énergie bas-carbone a accru l'intérêt pour l'énergie houlomotrice, en raison de sa densité énergétique élevée et de sa prévisibilité. Les évaluations nationales de cette ressource au sein de la ZEE algérienne demeurent limitées, malgré un littoral d'environ 2148 km.

Cette étude évalue la ressource houlomotrice algérienne à partir de données de houle pluriannuelles et du modèle MIKE 21 SW, combiné à une analyse spatiale SIG pour cartographier la ressource et délimiter les zones favorables. Ces zones ont ensuite été évaluées via le convertisseur CorPower Ocean C4, par le calcul de la Production Énergétique Annuelle (AEP), afin d'identifier les sites prioritaires.

Les résultats fournissent des cartes d'aptitude et une base scientifique pour la sélection de sites, soutenant les objectifs algériens de diversification énergétique.

Mots-clés— Énergie des vagues ; MIKE 21 SW ; puissance des vagues ; SIG ; ZEE algérienne.

المخلص:

أدى تزايد الطلب على الطاقة منخفضة الكربون إلى تنامي الاهتمام بطاقة الأمواج، نظرًا لكثافتها الطاقوية العالية وقابليتها للتنبؤ. ورغم امتداد الساحل الجزائري على نحو 2148 كم، لا تزال التقييمات الوطنية لهذا المورد ضمن المنطقة الاقتصادية الخالصة (EEZ) للجزائر محدودة. تتناول هذه الدراسة تقييم مورد الطاقة الموجية على طول الساحل الجزائري باستخدام بيانات موجية متعددة السنوات ونموذج MIKE 21 SW، بالإضافة إلى تحليل مكاني قائم على نظم المعلومات الجغرافية (GIS) لرسم خرائط توزيع المورد وتحديد المناطق الملائمة. وقد خضعت هذه المناطق لتقييم إضافي باستخدام محول الطاقة CorPower Ocean C4، بهدف تقدير الإنتاج السنوي من الطاقة (AEP) وتحديد المواقع ذات الأولوية. توفر النتائج خرائط لملاءمة المواقع وأساسًا علميًا لاختيار المواقع مستقبلاً، بما يدعم أهداف الجزائر في تنويع مصادر الطاقة المتجددة.

الكلمات المفتاحية — طاقة الأمواج؛ نموذج MIKE 21 SW؛ محول CorPower Ocean C4؛ قدرة الأمواج؛ نظم المعلومات الجغرافية؛ المنطقة الاقتصادية الخالصة للجزائر

GENERAL INTRODUCTION:

GENERAL INTRODUCTION:

The global transition toward renewable energy sources has placed marine resources at the forefront of the search for sustainable alternatives to fossil fuels. Among the various forms of ocean energy, wave energy has attracted growing attention over the past two decades, owing to its high energy density, its relative predictability compared to wind and solar power, and the vast extent of coastal areas where it can potentially be harnessed (Falnes, 2007). As countries worldwide intensify efforts to diversify their energy mix and reduce greenhouse gas emissions, the systematic assessment of wave energy resources has become a necessary step toward identifying viable sites for future marine energy infrastructure.

This growing interest has translated into concrete deployments worldwide, from large-scale commercial demonstrators such as the grid-connected Perth Wave Energy Project in Australia (Heard, 2021). to a number of pilot installations in the Mediterranean Sea notably the REWEC3 breakwater integrated converter in Civitavecchia and the ISWEC gyroscopic device off Pantelleria, Italy that demonstrate the feasibility of wave energy conversion even in semi enclosed, moderate-energy basins (Dialyna & Tsoutsos, 2021) These international experiences provide useful technical and operational references for assessing wave energy potential in comparable, under exploited basins such as the Algerian sector of the Mediterranean.

Algeria, with a coastline extending over approximately 2,148 kilometers according to the National Institute of Cartography and Remote Sensing (INCT), possesses a wave energy potential that remains largely unexplored to this day. While research efforts have historically focused on wind and solar resources, in line with the high potential these two sectors present at the national level, wave energy remains a comparatively under-investigated avenue across the Algerian Exclusive Economic Zone (EEZ). This final year thesis aims to evaluate the wave energy potential within the Algerian EEZ, and to investigate the feasibility of its exploitation as a renewable energy source. Our approach combines wave data analysis derived from spectral numerical modelling with spatial mapping of the resource. More specifically, this work pursues three main objectives:

- **Calculate the wave energy potential** in the Algerian EEZ, based on significant wave height and wave period data;
- **Determine the spatial distribution of this potential** across the EEZ, highlighting seasonal and regional variations in the resource;

- **Identify suitable areas** for wave energy harvesting, based on wave resource intensity, bathymetric constraints, and spatial proximity to the coast, with a view to the potential deployment of wave farms.

This thesis is organized into four chapters:

Chapter 1, presents the global and national context of marine renewable energy, positions wave energy as a relevant resource for Algeria, and introduces the theoretical foundations of wave hydrodynamics and energy conversion.

Chapter 2, describes the study area, its geomorphological characteristics, and the wave and wind climate of the Algerian EEZ.

Chapter 3, presents the numerical modelling approach, including the MIKE 21 SW model setup, the data used, the methodology adopted, and the resulting site suitability assessment leading to the delineation of priority zones for wave energy exploitation.

Chapter 4, introduces the CorPower Ocean C4 converter and evaluates its energy production potential at the five selected deployment zones..

CHAPTER I: GENERALITIES

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1. Global Energy Context and Climate Change Challenges:

The global energy system is currently facing two major challenges: the heavy dependence on fossil fuels and the accelerating impacts of climate change. Since the Industrial Revolution, greenhouse gas emissions from fossil fuel combustion have led to a global temperature increase of approximately 1.1 °C above pre-industrial levels. According to the Intergovernmental Panel on Climate Change (IPCC), limiting global warming to 1.5 °C requires achieving net-zero CO₂ emissions by around 2050 (Masson-Delmotte et al., 2021). . Despite the rapid growth of renewable energy technologies, fossil fuels continue to dominate the global energy landscape. As shown in (Figure 1) oil, coal, and natural gas collectively accounted for approximately 513 EJ out of a total of 593 EJ of world primary energy consumption in 2023, representing nearly 87% of the global energy mix. Oil remained the single largest source at 199 EJ about 34%, followed by coal at 165 EJ (28%) and natural gas at 149 EJ also about 25%. Nevertheless, encouraging progress is evident: since 2010, renewables and nuclear energy have collectively avoided 1,371 EJ of fossil fuel use and approximately 109 gigatonnes of greenhouse gas emissions, while total renewable energy supply grew by 8% in 2024 (Statistical Review of World Energy 2025 | 74 Th Edition In Collaboration With, n.d.) This persistent reliance on carbon-intensive sources underscores the urgent need to accelerate the energy transition. Renewable technologies including solar, wind, and marine energy have emerged as increasingly competitive alternatives, offering not only substantial environmental benefits through reduced emissions, but also enhanced energy security through decreased dependence on imported fossil fuels. Among these alternatives, the ocean represents a significant and largely untapped source of renewable energy. Wave energy, in particular, offers high energy density and strong predictability compared to other renewable sources. In addition, The ocean contributes significantly in the climate system by absorbing a large portion of excess heat and atmospheric CO₂ (Meredith et al., 2019).

For Mediterranean countries, including Algeria, climate change impacts are expected to be more intense than the global average, with increased temperatures, reduced water resources, and rising sea levels (Azzopardi et al., 2020). In this context, the development of marine renewable energy, especially wave energy, represents a promising opportunity to enhance energy security while contributing to climate change mitigation.

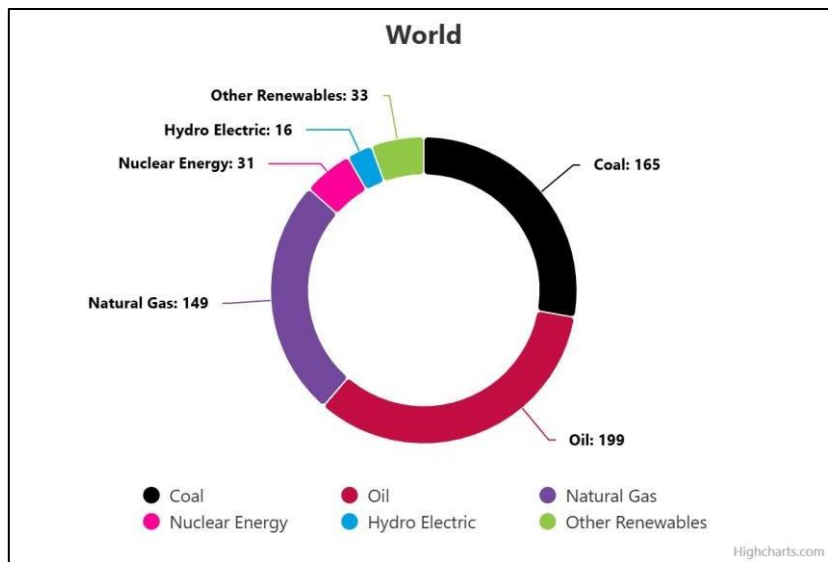


Figure 1: World primary energy consumption by source, 2023 (in exajoules). From <https://www.energyinst.org/statistical-review>

2. Classification of Renewable Energy Sources:

Renewable energy refers to energy that comes from natural sources that are quickly replenished, making them practically unlimited for human use. According to the International Renewable Energy Agency (IRENA), these sources are grouped into two categories: terrestrial energy (such as solar, wind, hydropower, biomass, and geothermal) and marine energy, which is obtained from the ocean in its different forms. This distinction highlights the wide range of renewable resources and the different technologies and regulations involved in developing energy projects on land and at sea.

2.1. Solar Energy:

It is the most abundant renewable resource on Earth. The amount of solar energy reaching the Earth's atmosphere is extremely large much higher than what humans currently consume. There are two main ways to use this energy: photovoltaic (PV) systems, which convert sunlight directly into electricity using special materials, and solar thermal systems, which use sunlight to produce heat that can generate electricity or be used in industrial processes (Luque & Hegedus, 2011). Thanks to the significant decrease in costs, solar PV has become the fastest growing source of electricity in the world, with a global installed capacity of more than 1,000 GW by 2022 (Agency, 2022).

2.2. Wind Energy:

It is produced by converting the kinetic energy of moving air into electricity using wind turbines. On land, modern wind turbines are typically between 80 and 150 meters high, with large rotor diameters ranging from 90 to 170 meters, and they usually have a capacity of 3 to 6 MW. Offshore wind turbines,

installed in marine environments, are generally larger and more powerful, with recent designs reaching capacities of 10 to 15 MW (Veers et al., 2019). By 2022, the global installed wind energy capacity had reached around 900 GW, making it one of the most important sources of renewable electricity after hydropower (IRENA, 2022).

2.3. Hydraulic Energy:

Hydraulic energy, also known as hydropower, is the oldest and most widely used form of renewable electricity. By 2022, its global installed capacity had exceeded 1,392 GW (IRENA, 2022). It works by using the energy of water stored at a higher level in reservoirs; when the water flows down through pipes, it turns turbines to produce electricity.

Another type, called run of river hydropower, does not need large reservoirs and is often preferred because it has a lower environmental impact. However, its electricity production depends on seasonal changes in river flow. In addition, small-scale hydropower is very important for providing electricity to remote and mountainous regions, especially in parts of Africa, Asia, and Latin America.

2.4. Biomass Energy:

This energy refers to the use of organic materials such as agricultural residues, forestry waste, household waste, energy crops, and even aquatic biomass to produce heat, electricity, or biofuels. Unlike many other renewable energy sources, biomass can be used whenever needed, making it a flexible and controllable source of energy. It can also help reduce carbon emissions, especially when combined with carbon capture and storage technologies (BECCS)(Fuss et al., 2018). However, the large-scale use of biomass raises some concerns, particularly because it may compete with food production and have negative impacts on land use and biodiversity.

2.5. Geothermal Energy:

Geothermal energy comes from the heat stored within the Earth's crust. This heat is naturally maintained by processes such as radioactive decay and the remaining heat from the Earth's formation. In regions with strong geothermal activity, such as volcanic areas or tectonic plate boundaries, high-temperature resources are used to generate electricity. Countries like Iceland, the United States, Kenya, and the Philippines are among the leading producers (Anatolitis et al., 2024)

In areas where the temperature is lower and found at shallow depths, geothermal energy is mainly used for heating. It is commonly applied in building heating, greenhouse agriculture, and industrial processes through ground-source heat pump systems.

3. Marine and Ocean Renewable Energies:

Marine and ocean renewable energies form a specific category of renewable resources that rely on the physical and chemical characteristics of the ocean. The ocean can be seen as the largest collector of solar energy on Earth, storing energy in different forms that can be used to generate electricity (Pelc & Fujita, 2002). The main types of ocean energy include wave energy, tidal range energy, tidal stream energy, ocean thermal energy conversion (OTEC), salinity gradient energy, and marine current energy. Compared to land-based renewable energy sources, marine energy has several advantages. It offers a higher energy density, meaning more energy can be produced in a smaller area, and it is generally more predictable. In addition, offshore installations reduce issues related to land use and visual impact (Mork et al., 2010). However, the marine environment is very challenging. Problems such as corrosion, biofouling, extreme weather conditions, and the high cost of installation and maintenance make the development of these technologies more complex.

Despite these difficulties, ocean energy is increasingly seen as an important part of the future energy mix, particularly for island countries and coastal regions that have limited access to land-based renewable resources.

The global technical potential of ocean energy is estimated about 748,000 TWh per year (MAGAGNA & others, 2020), which is much higher than the current global electricity consumption of about 28,000 TWh per year. Even though only a small part of this potential can be realistically exploited due to technical and economic limits, it still highlights the importance of ocean energy for future energy systems.

According to the International Energy Agency's Ocean Energy Systems programme, ocean energy could reach an installed capacity of 300 to 400 GW worldwide by 2050, if technological progress continues and costs decrease (MAGAGNA et al., 2019). Among the different technologies, wave energy and tidal stream energy are currently the most advanced and promising, and they receive most of the research and développement efforts.

Marine Renewable Energies are the suite of renewable energy resources located in or derived from the ocean, including wave, tidal, ocean current, thermal gradient and salinity-gradient sources that can be converted to electricity (Kim, 2013). They are sometimes treated together with offshore wind and floating solar when discussing offshore renewable systems and hybrid deployments (von Jouanne et al., 2025).

3.1. Tidal Energy :

Tidal energy is a form of renewable energy obtained from the regular rise and fall of sea levels, which is mainly caused by the gravitational forces of the Moon and the Sun. It is generally exploited in estuaries or funnel-shaped bays where the tidal range is significant, typically reaching at least 5 meters (Department of Energy, 1989; Gray and Gashus, 1972; Lissaman et al., 1979; Song, 1987; Yum, 1983; Shaw, 1974; Warnock, 1987). This type of energy relies on the potential energy created by the difference in water levels between high and low tides.

3.1.1 One-way, single-basin generation:

This represents the simplest method of utilizing tidal energy. Water is allowed to enter the basin through open sluice gates during high tide, which are then closed. When the external tide recedes, the stored water is released through turbines, generating electricity as shown on (Figure 2) This system generally provides around 5 hours of energy production, followed by a basin refilling period of approximately 6 to 7 hours ¹.

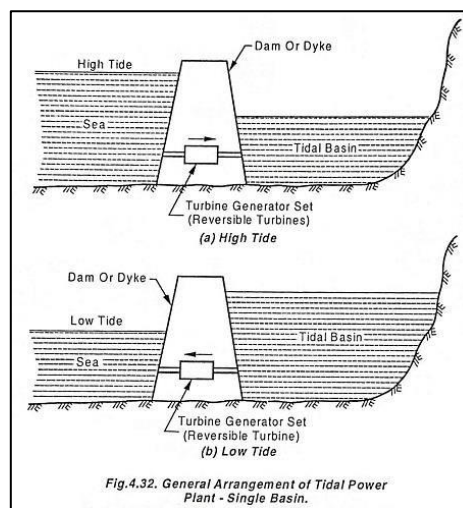


Figure 2 : General Arrangement of Tidal Power Plant, Single Basin. From <https://www.eeeguide.com/tidal-power-plant>

3.1.2 Two-way, single-basin generation:

In this system, electricity is generated during both the inflow and outflow of water between the sea and the basin. During operation, water is stored in the upper basin and released through the turbines into the lower basin, creating a continuous hydraulic head for electricity generation. The sluice gates

¹ <https://www.eeeguide.com/tidal-power-plant>

regulate the filling and emptying of both basins in accordance with the tidal cycle, enabling more regular power production compared with a single-basin system. Although this approach produces more energy compared to the one-way system at the same site, it operates with a lower average head. Consequently, larger and more expensive turbines are required ¹

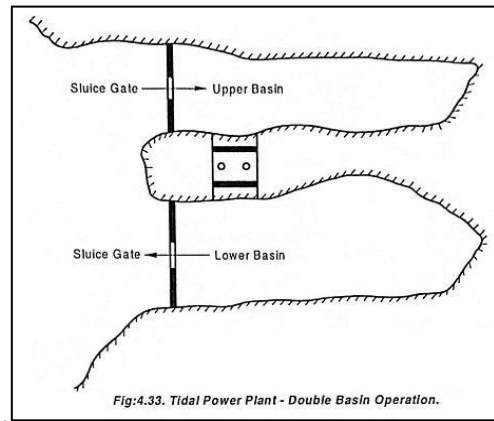


Figure 3 : Tidal Power Plant, Double Basin Operation. From <https://www.eeeguide.com/tidal-power-plant>

3.2. Ocean Currents energy :

This form of marine energy is based on the kinetic energy of water driven by ocean currents. Unlike wind, these currents are highly predictable since they are mainly influenced by gravitational interactions between the Earth, Moon, and Sun rather than atmospheric conditions. Due to the much higher density of water compared to air about 800 times, current turbines operate at relatively low rotational speeds around 7 to 20 rpm while still producing high energy output.

3.2.1 Converter Types:

3.2.1.1 Turbine Systems :

These systems operating on principles similar to those of wind turbines, convert the kinetic energy of moving water into mechanical rotation and subsequently into electricity. Depending on the orientation of the rotor axis relative to the current flow, turbine systems are generally classified into horizontal-axis and vertical-axis configurations. Horizontal Axis Current Turbines (HACTs) such as the MCT SeaGen (Figure 4), the turbine have a rotational axis aligned with the flow direction and are typically characterized by high hydrodynamic efficiency, although they may require yaw mechanisms when currents change direction. In contrast, Vertical Axis Current Turbines (VACTs) such as vertical-axis Darrieus turbine cluster (), possess a rotational axis perpendicular to the flow, allowing them to operate effectively regardless of current direction, which makes them particularly suitable for tidal environments where flow reversal occurs regularly.



Figure 4: The Seagen 1.2 MW device operating at Strangford Lough, Northern Ireland (U.K.)



Figure 5: vertical-axis Darrieus turbine cluster

3.2.1.2 Non-Turbine Systems:

Non-turbine technologies extract energy from ocean currents through mechanisms other than conventional rotating turbines. These systems generally rely on the oscillatory motion of hydrofoils, sails, kites, or other lifting surfaces that move under the action of water flow and convert the resulting mechanical motion into electrical power. Additional innovative concepts exploit vortex-induced vibrations (VIV), where alternating vortices generated around submerged cylindrical structures produce periodic oscillations that can be harnessed for energy generation. Although these technologies are generally less mature than turbine-based systems, they offer alternative solutions that may be advantageous under specific environmental and operational conditions.



Figure 6: Conceptual configuration of an oscillating-foil hydrokinetic turbine (HAO). From: <https://doi.org/10.1016/j.oceaneng.2015.05.011>

3.2.1.3 Installation, Foundations, and Spacing:

The installation of current energy devices depends on water depth and seabed conditions. Common foundation systems include monopiles (typically suitable up to 30 m depth), gravity bases made of steel or concrete, fixed piled jacket structures, and floating platforms for deeper waters. To reduce hydrodynamic interference between devices, spacing is important: lateral spacing is generally about 2.5 times the rotor diameter, while downstream spacing can reach up to 10 times the diameter.

3.3. Ocean Thermal Energy Conversion (OTEC) :

OTEC is a process that generates electricity by exploiting the temperature difference between warm surface seawater and cold deep-sea water. This technology operates based on the thermal gradient in the ocean, functioning as a heat engine. A minimum temperature difference of about 20°C is required for effective energy production, a condition commonly found in tropical regions where surface water temperatures are around 25°C and deep water (600–1000 m) is close to 5°C.

Ocean thermal energy conversion can operate through different thermodynamic cycles depending on how heat is transferred and converted into mechanical power. In the closed-cycle configuration, commonly based on the Rankine principle, warm surface seawater is used to vaporize a low-boiling working fluid such as ammonia; the resulting vapor expands through a turbine coupled to a generator before being condensed by cold deep ocean water and recirculated to sustain continuous operation. In contrast, the open cycle approach directly utilizes seawater by flashing warm surface water into vapor within a low-pressure vacuum chamber, where the generated steam drives a turbine and is subsequently condensed, allowing the production of both electricity and desalinated freshwater. A hybrid configuration combines elements of both systems to enhance overall efficiency by integrating their respective operational advantages. Overall, these conversion systems rely on repeated

vaporization and condensation processes, either through an intermediate working fluid or directly with seawater, to maintain a continuous energy conversion cycle.

3.4. Salinity Gradient Energy :

Salinity gradient energy refers to the energy obtained from the difference in salt concentration between seawater and freshwater. This form of energy is generated due to the natural mixing processes between saline and fresh waters. Although it is less developed and less commonly exploited compared to other marine renewable energy sources, studies indicate that the potential power dissipation from salinity and thermal gradients is significantly higher than that available from waves, tides, and ocean currents.

3.5. Wave Energy:

Wave energy is a form of marine renewable energy generated by the action of wind on the ocean surface, which creates waves carrying both kinetic and potential energy. The characteristics of these waves, such as their height and energy content, depend mainly on wind speed and duration. This continuous motion of the water surface represents a significant and exploitable energy resource, particularly in regions with a consistent wave climate. Through appropriate technologies, this energy can be captured and converted into electricity.

3.5.1 Extraction principles:

Nearly all of the energy contained in a wave approximately 95% is concentrated within the upper quarter of the wavelength, just below the water surface. This physical characteristic has directly shaped the diversity of conversion technologies developed to date, as different devices are designed to exploit different aspects of wave motion. Waves inherently carry three distinct motions: a horizontal front-to-back motion known as surge, a horizontal side-to-side motion referred to as sway, and a vertical up-and-down motion called heave. Each of these motions can be mechanically captured through specific rotational or translational mechanisms, and one of the most widely used classification frameworks for WECs is therefore based on which of these motions a device is primarily designed to exploit, or a combination thereof. In practice, point absorbers harness the heave motion to drive a piston vertically, terminators and oscillating wave surge converters target the surge, and attenuators respond to the pitch of the wave to drive a rotor. Among existing concepts, point absorbers constitute the largest share at 53%, followed by terminators at 33% and attenuators at 14% (Posterari et al., 2022).

3.5.2 Extraction technologies :

Wave Energy Converters (WECs) are technologies developed to capture the energy contained in ocean waves and transform it into electrical power. Although a large number of concepts and patented designs have been proposed, most devices can be classified according to their operating principles, energy conversion mechanisms, deployment location, and structural interaction with incoming waves. Based on deployment conditions, WECs are generally categorized as shoreline, nearshore, or offshore systems. From a hydrodynamic perspective, devices may also be distinguished according to the relationship between the wavelength and the dimensions of the absorber. Point absorbers are characterized by dimensions smaller than the incident wavelength, whereas terminators and attenuators are defined by their orientation relative to wave propagation, with the former positioned perpendicular and the latter parallel to the dominant wave direction. Despite the large number of concepts developed, most devices can be grouped into three main categories: oscillating water columns, oscillating body devices, and overtopping systems. This classification reflects differences in operating principles and deployment conditions. (Mitsuyasu et al., 1975a).

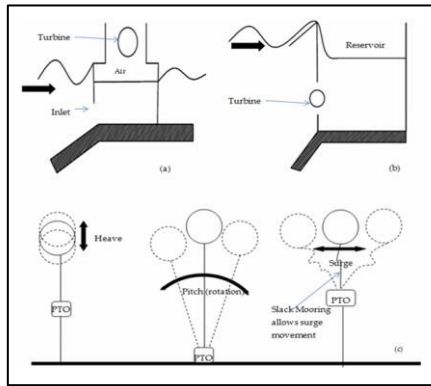


Figure 7: Classification of Wave Energy Converter (WEC) extraction technologies: (a) oscillating water column, (b) overtopping devices, and (c) oscillating bodies From: (Aderinto & Li, 2018)

4. Wave Energy as the Most Suitable Marine Renewable Resource for Exploitation

Ocean wave energy is estimated to have a global theoretical potential of about 29,500 TWh annually, exceeding current worldwide electricity consumption and placing it among the largest undeveloped renewable energy resources available today (Cornett, 2008). Its significance lies not only in the magnitude of the resource but also in its widespread and continuous availability. Coastlines on all inhabited continents are exposed to wave activity throughout the year, regardless of season, cloud conditions, or weather variability. This persistent availability represents a major advantage compared with land-based renewable energy sources, which are generally more dependent on atmospheric conditions.

The rationale for exploiting wave energy is largely based on its exceptionally high energy density. As shown in (Figure 8), wave power typically ranges between 2 and 3 kW per square metre of sea surface, whereas offshore wind energy densities are generally between 0.4 and 0.6 kW/m², and solar photovoltaic systems receive approximately 0.1 to 0.2 kW/m² under practical operating conditions (Falnes, 2007). This substantial difference implies that relatively limited offshore areas can generate power levels that are difficult to achieve using other renewable technologies. The underlying reason is the incompressible nature of water, which allows waves to transport both kinetic and potential energy across vast oceanic distances with relatively little loss. As a result, swells produced by storms in the open ocean often reach coastal regions while retaining a large proportion of their original energy.

Although variability remains a characteristic of all renewable resources, its impact is generally less pronounced for wave energy. Ocean swell systems follow well-established dispersive wave processes, enabling numerical forecasting models to provide reliable predictions over periods ranging from 24 to 72 hours, often with lower uncertainty than forecasts of wind speed or solar irradiance over comparable timescales (Reikard et al., 2011). In addition to this predictability, wave energy exhibits a seasonal behaviour that tends to complement solar power generation. Wave conditions are typically strongest during autumn and winter, when photovoltaic production is at its lowest. This inverse seasonal relationship enhances the value of wave energy within integrated renewable energy systems by helping to reduce overall fluctuations in power supply without necessarily increasing storage requirements proportionally.

From an environmental perspective, wave energy converters compare favourably with most terrestrial renewable energy technologies. Offshore facilities do not compete with agricultural or urban land uses and produce no shoreline-audible noise. Furthermore, life-cycle assessments consistently indicate low greenhouse gas emissions, generally in the range of 20 to 40 g CO₂-equivalent per kilowatt-hour, which is comparable to offshore wind energy systems (Paredes et al., 2019). Recent studies have also suggested that the restricted-access zones surrounding wave energy installations can provide additional ecological benefits. By limiting activities such as bottom trawling and creating hard-substrate habitats for sessile marine organisms, these areas may contribute to local marine conservation efforts, offering an environmental benefit rarely associated with land-based energy infrastructure.

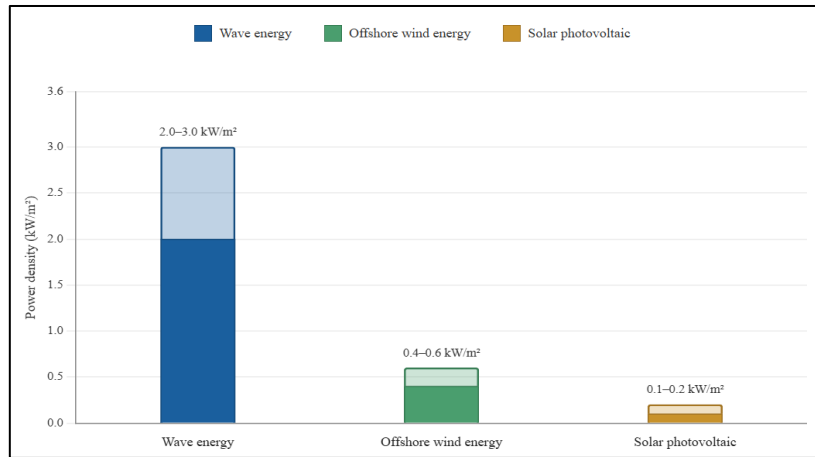


Figure 8: Comparison of mean energy power density (kW/m²) for wave energy, offshore wind, and solar photovoltaic technologies.source:(Falnes, 2007)

5. Algeria's energy context and transition strategy:

Algeria occupies a strategic position in the southern Mediterranean energy sector due to its significant hydrocarbon resources, including around 2,240 billion m³ of proven natural gas reserves and nearly 12 billion barrels of crude oil reserves (Petroleum, 2020). These resources make Algeria a major gas exporter and an important supplier to Southern Europe. However, the national economy remains highly dependent on hydrocarbons, which represent approximately 85–90% of export revenues and 60–65% of government income (Darbouche, 2011). This strong dependence makes Algeria particularly sensitive to global energy price swings. At the same time, domestic energy demand has grown steadily over the past two decades, averaging around 7% per year according to the World Bank (Hasni et al., 2021), while per capita consumption stands at 1.5 toe, one of the highest levels on the African continent according to Enerdata(Menakh, 2025).

Electricity generation remains largely dependent on natural gas, which represents more than 95% of installed capacity, reducing the amount of gas available for export. To address this challenge, Algeria introduced the Programme National des Energies Renouvelables (PNER), targeting 22,000 MW of renewable capacity by 2030, including solar, wind, biomass, geothermal, and hydropower resources (Hamiti, 2022). However, progress remains limited, with installed renewable capacity reaching only about 800 MW by 2023.

Algeria benefits from exceptional solar resources, particularly in the Sahara, where global horizontal irradiance ranges between 3,000 and 3,500 kWh/m²/year, (Stambouli et al., 2012). Wind resources are more moderate along coastal areas, with speeds between 3 and 5 m/s at 50 m height in the Tell Atlas, increasing in the Saharan interior and High Plateaus regions.

Despite this renewable potential, marine energy resources are not explicitly considered in current national energy planning. This is notable given Algeria's approximately 1,200 km Mediterranean coastline and its important offshore maritime area. The Algerian continental shelf is generally narrow along its Mediterranean coastline, particularly when compared to the wider shelves of the north-western Mediterranean basin, with notable spatial variation between the mountainous eastern coast and the wider embayment of the Gulf of Oran in the west. (Bouyahiaoui et al., 2015).

So The Integrating of wave energy into Algeria's energy transition could offer high benefits, such as complementing solar energy, using existing coastal infrastructure, and supporting industrial diversification and job creation in coastal regions.

6. Wave Generation Mechanisms:

Ocean waves are primarily generated by wind blowing across the surface of the ocean at multiple temporal and spatial scales, while other forces such as tides (very long-period waves) and earthquakes (causing tsunamis) can create ocean waves (Folley, 2016). The initial formation of waves on a calm sea surface is commonly explained by the resonance mechanism proposed by Owen M. Phillips. In this process, turbulent pressure fluctuations within the atmospheric boundary layer transfer energy to free-surface gravity waves when their phase speeds match. This results in a gradual, linear increase in wave amplitude starting from a quiescent state (Phillips, 1957). A complementary explanation was later developed by John W. Miles, who showed that wave growth can also arise from shear-flow instability. In this case, energy is extracted from the mean wind profile at a critical height where the wind speed equals the wave phase speed, producing an exponential growth of wave amplitude (Miles, 1957)

The development of wind-generated waves is mainly controlled by three factors: wind speed, fetch, and wind duration (Group, 1988). They start as small surface ripples and gradually grow as the wind keeps supplying energy. As the wind continues, the waves eventually reach a limit where they can no longer grow, because the energy gained from the wind is balanced by losses such as whitecapping. At this stage, the sea is said to be fully developed, and this state mainly depends on wind speed and fetch.

When the wind ceases, the waves do not disappear but continue to propagate over long distances with little energy loss. In this situation, they are referred to as swell waves, since they travel independently of the generating wind field. A simplified representation of these processes is shown in. (Folley, 2016).

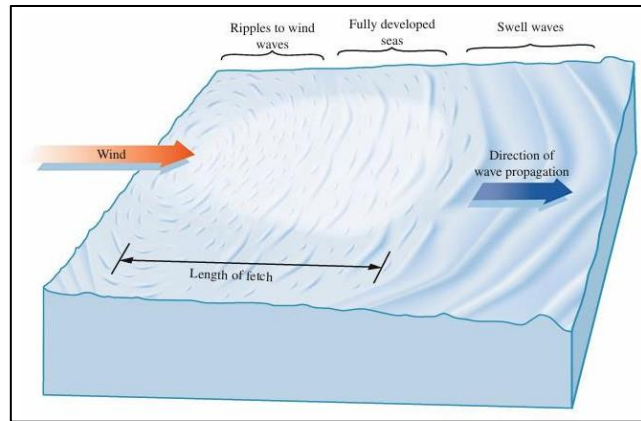


Figure 9: The generation of ocean waves: from ripples to swell waves as a function of fetch length. Adapted from (*Handbook of Ocean Wave Energy*, n.d.)

7. Physical Characteristics of Waves:

A basic wave is generally represented as a sinusoidal variation of the water surface elevation and is characterized by several main parameters:

Wave height (H): the vertical distance between the wave crest and the wave trough.

Wavelength (λ): the horizontal distance between two successive similar points of a wave, such as two crests.

Wave period (T): the time required for one complete wave cycle to pass a fixed point.

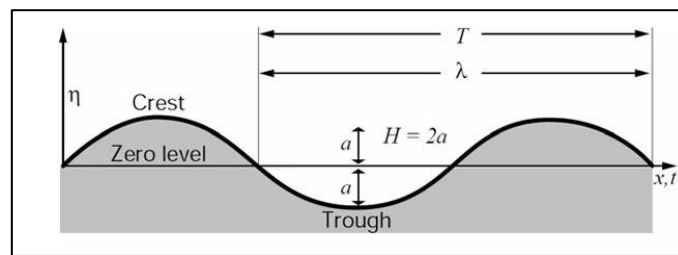


Figure 10: Definition of wave parameters over a sinusoidal wave (*Handbook of Ocean Wave Energy*, n.d.)

In addition, it is useful to define a number of other wave parameters:

Wave steepness: $s = H / \lambda$

Wave number: $k = 2\pi / \lambda$

Wave frequency (angular frequency): $\omega = 2\pi / T$

7.1. Statistical Description of Sea States:

7.1.1 Significant Wave Height (H_s):

It is defined as four times the square root of the zeroth spectral moment of the wave energy spectrum, and is statistically equivalent to the mean height of the highest one-third of waves under Gaussian assumptions.

$$H_s = 4\sqrt{m_0} \approx 4\sigma \quad \text{Equation 1}$$

7.1.2 Wave Period:

Peak Period (T_p): The inverse of the frequency (f_p) corresponding to the maximum of the variance density spectrum $S(f)$, characterizing the dominant wave component.

Mean Zero-Crossing Period (T_z): The average time between successive upward zero crossings of the sea surface elevation, calculated as:

$$T_z = \sqrt{\frac{m_0}{m_2}} \quad \text{Equation 2}$$

Where m_2 is the second spectral moment. (Tucker & Pitt, 2001)

Mean Energy Period (T_e): Also known as the spectral mean period $T_{m-1,0}$, it is the most physically meaningful period for wave energy calculations as wave power is proportional to T_e . It is defined as:

$$T_e = \frac{m_{-1}}{m_0} \quad \text{(Tucker & Pitt, 2001)}$$

7.1.3 Wave Direction and Spectral Description:

A complete statistical description of a random sea state requires a two-dimensional directional wave energy spectrum $S(f, \theta)$, which distributes total wave variance over frequency f and propagation direction θ . It is commonly expressed as the product of a one-dimensional frequency spectrum and a directional spreading function $D(f, \theta)$:

$$S(f, \theta) = S(f) \cdot D(f, \theta) \quad \text{Equation 3}$$

The directional spreading function is normalized and often parameterized using the cos^{2s} form:

$$D(\theta) = G(s) \cos^{2s} \left[\frac{\theta - \theta^-}{2} \right] \quad \text{Equation 4}$$

Where θ^- is the mean wave direction and s is the spreading parameter. Large values of s ($s > 50$) indicate narrow, well-defined swell propagation, while small values ($s < 10$) indicate broad, multi-directional wind seas (Mitsuyasu et al., 1975b).

8. Wave Propagation Processes:

8.1. Refraction:

Wave refraction occurs when waves propagate over varying bathymetry, causing changes in wave direction due to variations in phase speed. As waves enter shallower water, they slow down and tend to align with depth contours, resulting in the concentration or dispersion of wave energy depending on seabed geometry (Holthuijsen, 2010b).

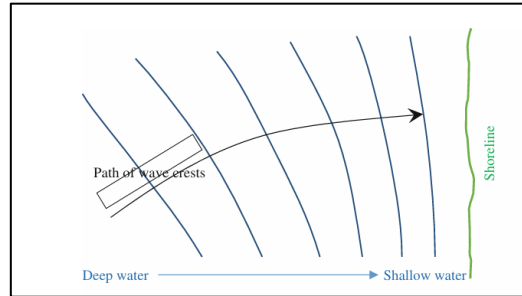


Figure 11: Wave refraction near the shore due to a change in water depth

8.2. Shoaling:

Shoaling describes the increase in wave height as waves move into shallower water due to conservation of energy flux. As group velocity decreases, wave height increases, leading to amplification of wave energy prior to breaking. This process is particularly significant over gently sloping continental shelves (Holthuijsen, 2010b).

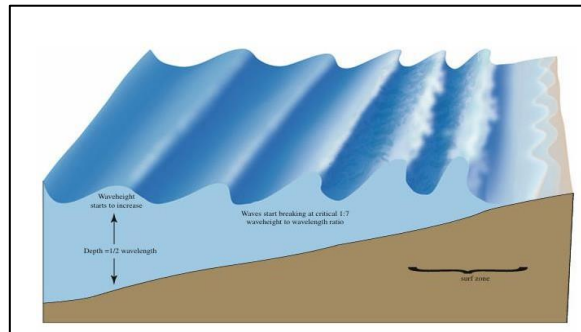


Figure 12: Change in wave shape due to water. Adapted from (*Handbook of Ocean Wave Energy*, n.d.)

8.3. Diffraction:

Wave diffraction occurs when waves interact with obstacles or propagate through openings, causing wave energy to spread laterally into sheltered areas. This process is important in coastal areas such as harbours and bays, where it governs the penetration of wave energy into protected areas. (Ochi, 1998).

8.4. Wave Breaking:

Wave breaking is the main process responsible for wave energy dissipation in shallow water. It occurs when waves become too steep and exceed a critical stability limit. The form of breaking, such as spilling, plunging, or surging, depends on both the seabed slope and the wave properties (Longuet-Higgins, 1953).

9. Wave Energy Theory:

9.1. Wave Energy Density:

The mechanical energy in a regular sinusoidal wave is split equally between potential energy from the displacement of the water surface and kinetic energy from the orbital motion of water particles.

The total wave energy density per unit sea surface area is given by:

$$E = \rho g H^2 / 8 = \rho g A^2 / 2 \quad \text{Equation 5}$$

Where:

$\rho \approx 1025 \text{ kg/m}^3$ is seawater density.

$g = 9.81 \text{ m/s}^2$.

H is the wave height, and A is the amplitude.

For irregular seas described by a variance spectrum $S(f)$, the energy density becomes:

$$E = \rho g \cdot m_0,$$

Where $m_0 = \int S(f) df$ is the zeroth spectral moment. Substituting $H_s = 4\sqrt{m_0}$, these yields:

$$E = \rho g H_s^2 / 16 \quad \text{Irregular seas}$$

This is half the value obtained for a regular wave of the same height an important distinction when working with real sea states (Barstow et al., 2008).

9.2. Wave Power Density:

Wave power density $P(\text{W/m})$ represents the rate of energy transport per unit crest width. It is the product of the wave energy density and the group velocity C_g :

$$P = E \cdot c_g = (\rho g^2 / 64\pi) \cdot H_s^2 \cdot T_e \quad (\text{W/m})$$

This simplifies to the practical formula recommended by the International Electrotechnical Commission technical specification IEC TS 62600-101:

$$P \approx 0.5 \cdot H_s^2 \cdot T_e \quad (\text{Kw/m})$$

Where:

H_s : is the significant wave height in metres.

T_e : is the energy period in seconds.

This is the standard formula used throughout this study for computing wave power density from ERA5 reanalysis data and MIKE 21 SW model outputs(Snodgrass et al., 1966).

10. Wave Energy Converters (WECs) and Energy Extraction Technologies:

As described in the first chapter, Wave Energy Converters (WECs) are devices designed to extract energy from ocean waves and convert it into electricity. They can be classified according to several criteria, including deployment location, operating principle, and interaction with wave motion. Despite the wide variety of concepts developed over the years, most WEC technologies are generally grouped into three main categories: oscillating water columns, oscillating body devices, and overtopping systems.

10.1. Oscillating Water Column (OWC):

The Oscillating Water Column (OWC) is one of the oldest and most widely studied wave energy converters. It consists of a partially submerged chamber where wave-induced water level oscillations compress and decompress the air above, driving a turbine to generate electricity. Early OWC systems were mainly installed onshore or integrated into coastal structures such as breakwaters, offering easier installation and maintenance but operating in lower-energy wave conditions.(Figure 13)

To access stronger offshore wave resources, several floating OWC designs have been developed, including the backward bent duct buoy, spar buoy, and sloped OWC. Their performance depends on local wave conditions, particularly wave height, period, direction, and water depth.

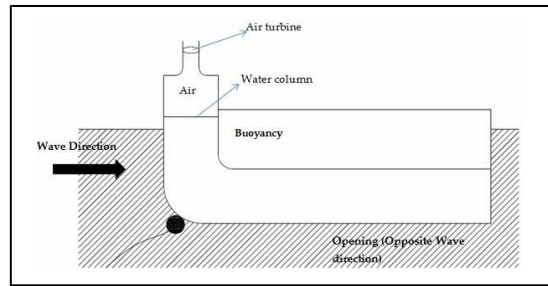


Figure 13: Schematic Representation of a Backward Bent Duct Buoy (Floating Oscillating Water Column)

Since the first OWC device was introduced by Masuda in the 1940s, significant improvements in design and numerical modelling have enhanced its efficiency. Prototype studies report energy conversion efficiencies typically ranging from 15% to 40%, depending on the device configuration and sea state...

10.2. Oscillating Body Devices:

Oscillating body systems extract energy from the sea by moving in response to the motion of ocean waves, utilizing either translational (typically heave) or rotational (typically pitch) degrees of freedom. These devices can be designed to operate while floating on the surface or while fully submerged in the water column. The fundamental working principle involves the wave motion oscillating the device's body, with a power take-off (PTO) system then converting this mechanical energy into electricity. They are divided into three subtypes based on their geometry and orientation.

10.3. Point absorbers:

They are compact buoys that capture wave energy primarily through vertical heave motion and can operate in waves from any direction. A well-known example is the Wave Energy Converter (WEC) developed at Uppsala University, Sweden, which consists of a surface buoy connected to a seabed-mounted linear generator. Its simple and robust design makes it suitable for deployment in wave energy farms.

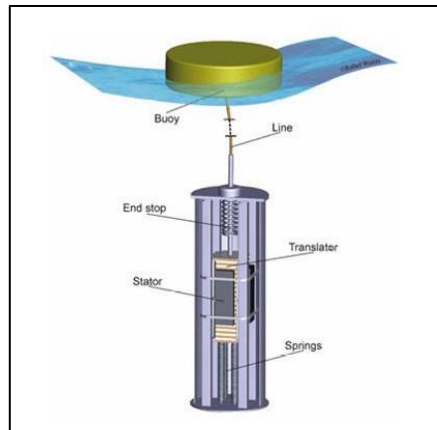


Figure 14: The WEC developed at Uppsala University

10.4. Attenuators:

They are elongated wave energy converters aligned parallel to the direction of wave propagation. They generate electricity from the relative motion between interconnected sections as waves travel along the device. The Pelamis system is the most well-known example of this technology (Figure 15).

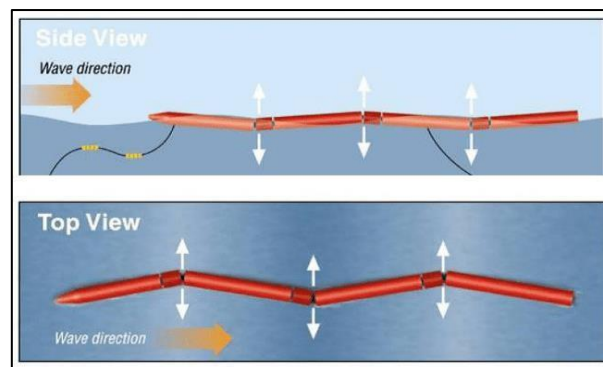


Figure 15: Pelamis WEC, side and top view, (Garbin, 2018).

10.5. Terminators :

are wave energy converters positioned perpendicular to the wave direction, capturing energy across the wave front. Electricity is generated from the oscillatory motion induced by incoming waves, typically through pitch motion. A notable example is Salter's Duck (Edinburgh Duck), one of the earliest and most influential terminator-type devices.

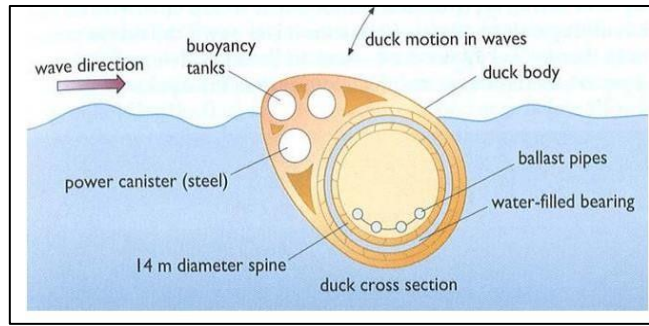


Figure 16: Salter's duck concept image with all the components, (Garbin, 2018).

10.6. Overtopping Devices:

Overtopping devices generate electricity by capturing wave water in a reservoir above sea level and releasing it through low-head turbines (Figure 17). They can be deployed offshore or integrated into coastal structures. The most well-known floating concept is the Wave Dragon, which uses reflectors to concentrate waves and increase overtopping (Figure 18). Other examples include the Seawave Slot Cone Generator (SSG) and the Tapchan, both designed to improve water capture efficiency through specific reservoir and channel configurations.

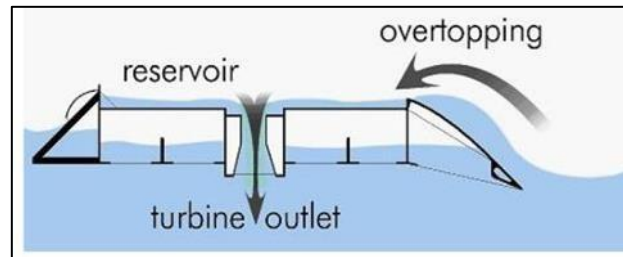


Figure 17: Schematic Representation of overtopping principle, (Garbin, 2018)

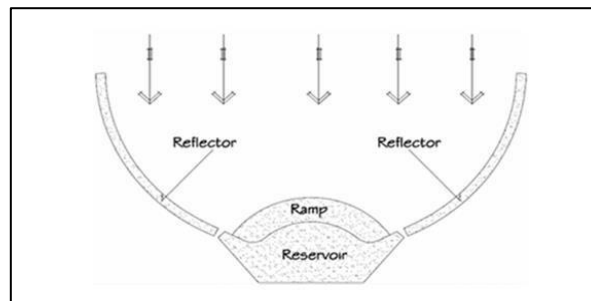


Figure 18: Schematic Representation of Wave Dragon, source (Tedd & Kofoed, 2009).

11. Power Take-Off Systems for WECs:

The power take-off (PTO) system converts the energy captured by the primary converter into electricity. As a key component of wave energy converters, it significantly influences device efficiency, size, weight, and overall performance. These characteristics directly affect the levelised

cost of energy (LCoE) (New & 2022, 2018). Since the PTO can account for 20–30% of the total capital cost of a wave energy converter, its optimisation is essential for improving both energy production and economic viability (Bedard et al., 2004).

11.1. Types of Power Take-Off System:

many different types of PTO systems exist, and the type of PTO chosen for a particular wave energy converter is often strongly correlated with the type of converter. The different main paths for wave energy to electricity conversion are schematised in (Figure 19).

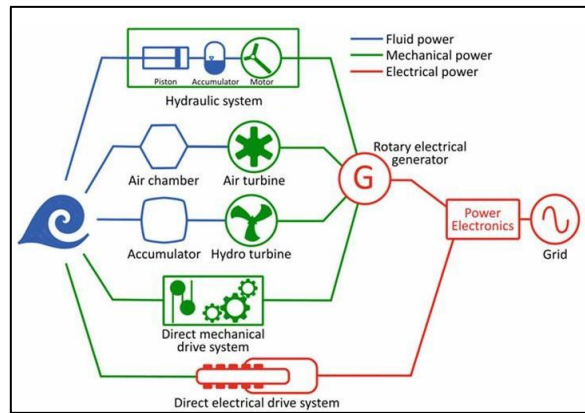


Figure 19: Different paths for wave energy to electricity conversion, source (Pecher & Kofoed, 2017)

The types of PTO systems can be categorized into five main categories and are described in the following sections.

11.2. Air Turbines:

Air turbines are primarily used in Oscillating Water Column (OWC) systems, where wave-induced airflow drives a self-rectifying turbine. The most common design is the Wells turbine, valued for its simple configuration but limited by relatively low efficiency and poor self-starting capability. Impulse turbines offer an alternative with improved starting performance and a wider operating range. Schematic of a wave energy converter where an air turbine is employed. (Figure 20).

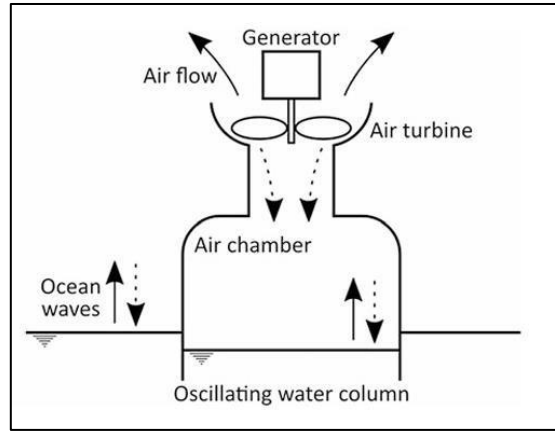


Figure 20 :Schematic of a wave energy converter where an air turbine is employed

11.3. Hydraulic Converters:

Hydraulic PTO systems are widely used in point absorbers and attenuators, where wave-induced motion drives hydraulic pistons connected to a generator. Their main advantage is the ability to smooth power fluctuations and handle large mechanical loads. However, challenges such as fluid leakage and component wear can affect long-term reliability.

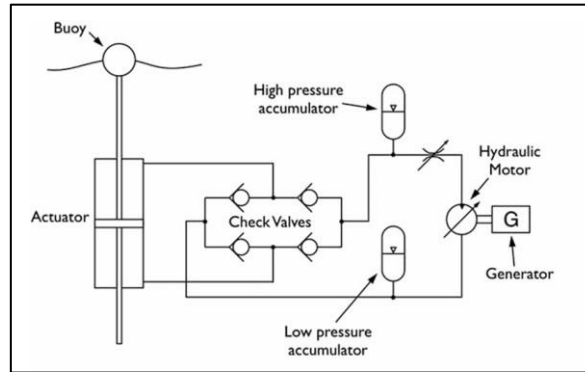


Figure 21: Example of a hydraulic PTO system for wave energy conversion , source (Pecher & Kofoed, 2017).

11.4. Hydro Turbines:

They are mainly used in overtopping wave energy converters, where water stored in an elevated reservoir is released through turbines to generate electricity. However, Kaplan turbines are commonly employed due to their high efficiency and ability to operate under variable flow conditions. However, their performance depends on maintaining sufficient water head and flow rates.(Figure 22).

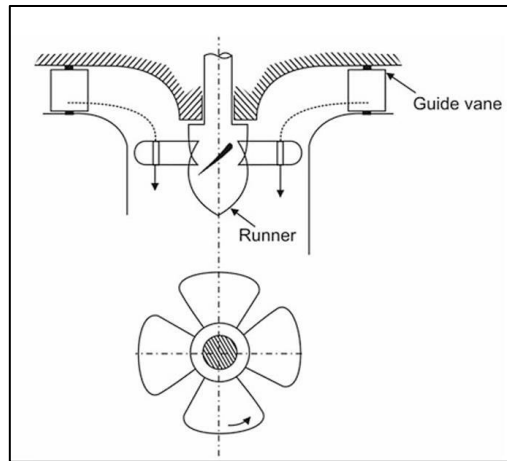


Figure 22: Schematic of a cross-section view of a Kaplan turbine (top) and bottom view of the runner (bottom),

Source, (Pecher & Kofoed, 2017)

11.5. Direct Mechanical Drive Systems:

Direct mechanical drive systems, convert wave-induced motion into electricity through mechanical transmission components connected to a conventional generator. By reducing intermediate conversion stages, they can achieve high efficiency. However, continuous cyclic loading can lead to wear and reliability issues in mechanical components.

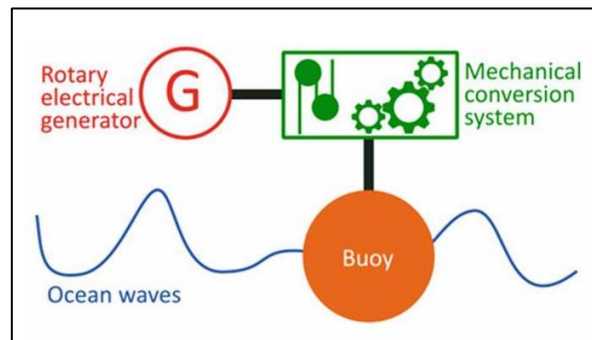


Figure 23: Illustration of a direct mechanical drive PTO system.

11.6. Direct Electrical Drive Systems:

Direct electrical drive systems, use linear generators to convert wave-induced motion directly into electricity, eliminating the need for intermediate hydraulic or pneumatic systems. This approach reduces mechanical complexity and can improve conversion efficiency. However, the design of linear generators remains challenging due to the precise alignment required between moving and stationary components.()

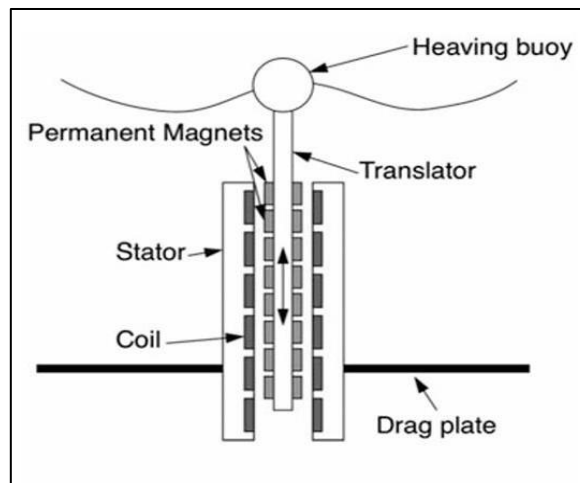


Figure 24: A schematic of a direct linear drive system for wave energy conversion.(Pecher & Kofoed, 2017)

12. Challenges and Impacts of Wave Energy Converter Deployment:

The deployment of wave energy converters (WECs) may modify local wave climate conditions, leading to alterations in sediment transport processes and coastal morphology. Reductions in significant wave height have been observed downstream of device arrays, although these effects generally attenuate with increasing distance from the installation.(Dean & Dalrymple, 1991).

Environmental impacts may include localized seabed scour around device foundations, the generation of electromagnetic fields from submarine power cables, and potential disturbances to marine ecosystems through underwater noise, collision risk, and habitat modification. Although existing studies generally report limited impacts for individual devices, the cumulative and long-term effects associated with large-scale arrays remain uncertain.(Sorensen, 2006)

Technological and economic constraints include structural survivability under extreme wave loading conditions and relatively high levelized cost of energy compared with other renewable energy technologies. Despite these limitations, ongoing technological advances and continued policy support may enhance the future competitiveness of wave energy systems.(Penney et al., 1952).

Finally, spatial allocation of wave energy projects may face challenges related to social acceptance, particularly in coastal regions with high tourism value or strong aesthetic and recreational importance.

13. Partial Conclusion:

This first part of the thesis established the global, national, and theoretical context for assessing wave energy potential in the Algerian Exclusive Economic Zone. It highlighted the central challenge of the energy transition: reducing greenhouse gas emissions while keeping renewable energy economically competitive, a challenge that has driven growing interest in marine energy sources. Among these, wave energy stands out for its high energy density and its complementarity with solar and wind power, even though the technology remains at an early stage of development. In the Mediterranean, and particularly along the Algerian coast, it appears to be the most suitable marine resource to exploit.

At the national level, Algeria's energy system remains largely dependent on hydrocarbons despite rising demand, and current renewable energy strategies focus mainly on solar and wind. Evaluating wave energy potential is therefore essential for diversifying the energy mix and supporting future energy planning.

Building on this context, the fundamental concepts underlying wave energy were presented, covering wave generation, physical characteristics, propagation processes, and energy estimation methods, along with the main types of Wave Energy Converters (WECs), their operating principles, and the technological, environmental, and economic challenges affecting their deployment. This theoretical foundation is essential for evaluating wave energy potential and selecting suitable conversion technologies for coastal applications.

The following chapters focus on the study area, followed by the numerical modeling approach used for the assessment of wave energy resources.

CHAPTER II:
STUDY AREA

CHAPTER 02:

Study Area and Offshore Environmental Conditions:

1. Overview of the Algerian Exclusive Economic Zone (EEZ):

The Algerian Exclusive Economic Zone (EEZ) is defined in accordance with Part V of the United Nations Convention on the Law of the Sea (UNCLOS), which grants coastal states sovereign rights for the exploration, exploitation, conservation, and management of natural resources within a maritime zone extending up to 200 nautical miles (370 km) from the territorial sea baseline (Nordquist, 2011). Algeria ratified UNCLOS in 1996.

In this study, the selected EEZ area (Figure 25Error! Reference source not found.) in the Mediterranean Sea extends between 35.0707° N and 38.8009° N in latitude, and from -2.2123° to 8.6421° E in longitude. This area is bounded to the west by maritime limits with Morocco and Spain, and to the east by Tunisia and Libya, covering a significant portion of the Algerian maritime zone.(*Littoral Algérien : Une Nouvelle Étude Porte La Longueur à 2148 Km - El Watan*, n.d.)

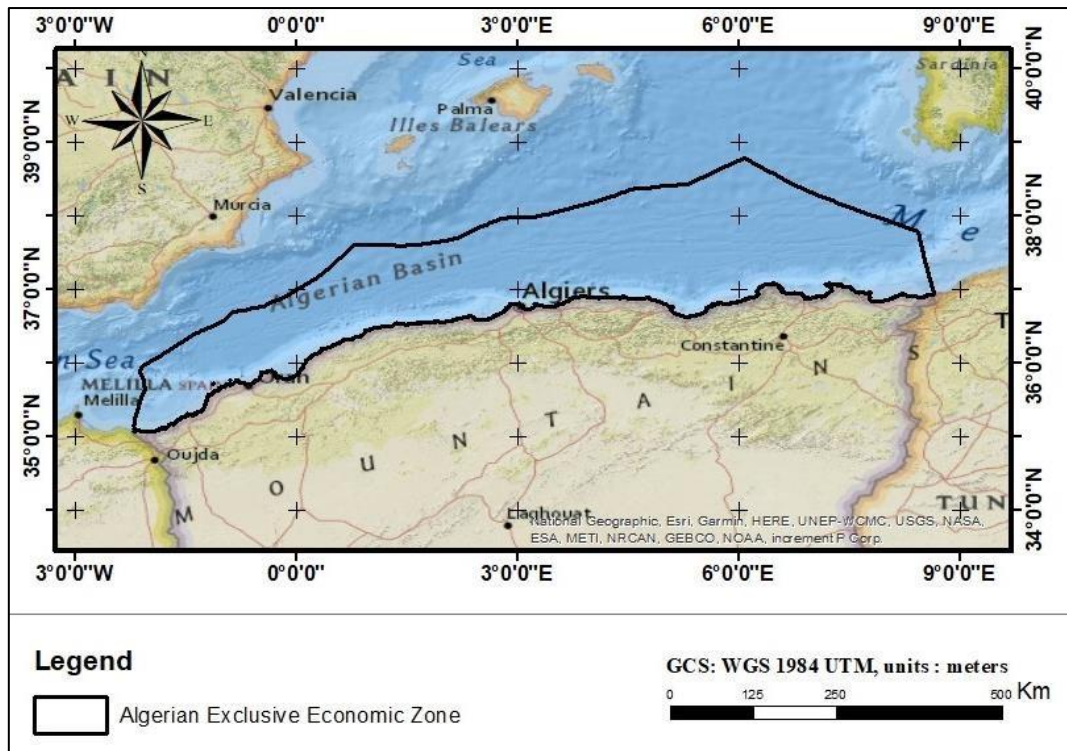


Figure 25:Map of the Algerian Exclusive Economic Zone "EEZ"

The Algerian coastline extends approximately 2,148 km along the southern shore of the western Mediterranean Sea, from Ras Honaine at the Moroccan border in the west (1.74°W) to El Kala near the Tunisian border in the east (8.60°E) (Amarouche et al., 2020a). This updated estimate, based on more advanced measurement techniques, provides a more accurate representation of the coastal configuration. The coastline forms the entire northern boundary of the Algerian EEZ and represents one of the longest Mediterranean coastlines in North Africa.

The EEZ includes a wide range of bathymetric features, from the continental shelf and slope to the deep abyssal plains of the Algerian basin. In the western Mediterranean basin, water depths increase rapidly offshore, reaching more than 2,500–2,800 m in the central Algerian sub-basin (Amarouche et al., 2021). This sub-basin is bounded by the Balearic Islands and the southern Iberian Peninsula to the north, the Sardinian Channel to the east, and the Strait of Gibraltar to the west, where Atlantic waters and swell enter the Mediterranean.

Once inside this basin, the water is shaped by three powerful forces:

Layering (Stratification): warm Atlantic water on top, saltier "intermediate" water in the middle, and cold, heavy water at the bottom.

Swirling Currents (Circulation): The water moves in a fast coastal current that often breaks off into massive swirling eddies that can be up to 200 km wide and reach over 1,000 meters deep.

Wind and Weather (Atmospheric Forcing): Winds constantly push against the surface, stirring the water and causing deep, nutrient-rich water to rise to the top (upwelling).

These oceanographic conditions, including circulation patterns, stratification, and atmospheric forcing that affect wave generation and propagation.

The Algerian EEZ has significant potential for marine renewable energy development. It is exposed to dominant wave-generating winds from the north and northwest, which contribute to a consistent wave energy resource. In addition, the relatively short distance between the coastline and deeper waters reduces the cost of offshore installations. Furthermore, the proximity of major coastal cities and industrial areas supports the integration of wave energy into the existing energy infrastructure (Yahia Meddah et al., 2023).

2. Geographical Characteristics of the Coastline:

The Algerian coastline can be subdivided into three main geographical sectors, each characterized by distinct morphological features, bathymetric conditions, and wave exposure patterns. (Figure 26)

The western sector, extending from Ras Honaine to Cherchell (approximately 1.74°W to 2.20°E), is characterized by alternating wide embayments, such as the Gulf of Oran and the Bay of Arzew and rocky headlands with steep cliffs.

The central sector, from Cherchell to Cap Djinet (approximately 2.20°E to 3.70°E), is influenced by the proximity of the Tell Atlas Mountain ranges, resulting in a predominantly rocky and cliffed coastline associated with a relatively narrow continental shelf.

The eastern sector, extending from Cap Djinet to El Kala (approximately 3.70°E to 8.60°E), is characterised by gentler topography, including sandy beaches, coastal plains, lagoons, and ecologically significant wetlands such as those found in El Kala National Park .

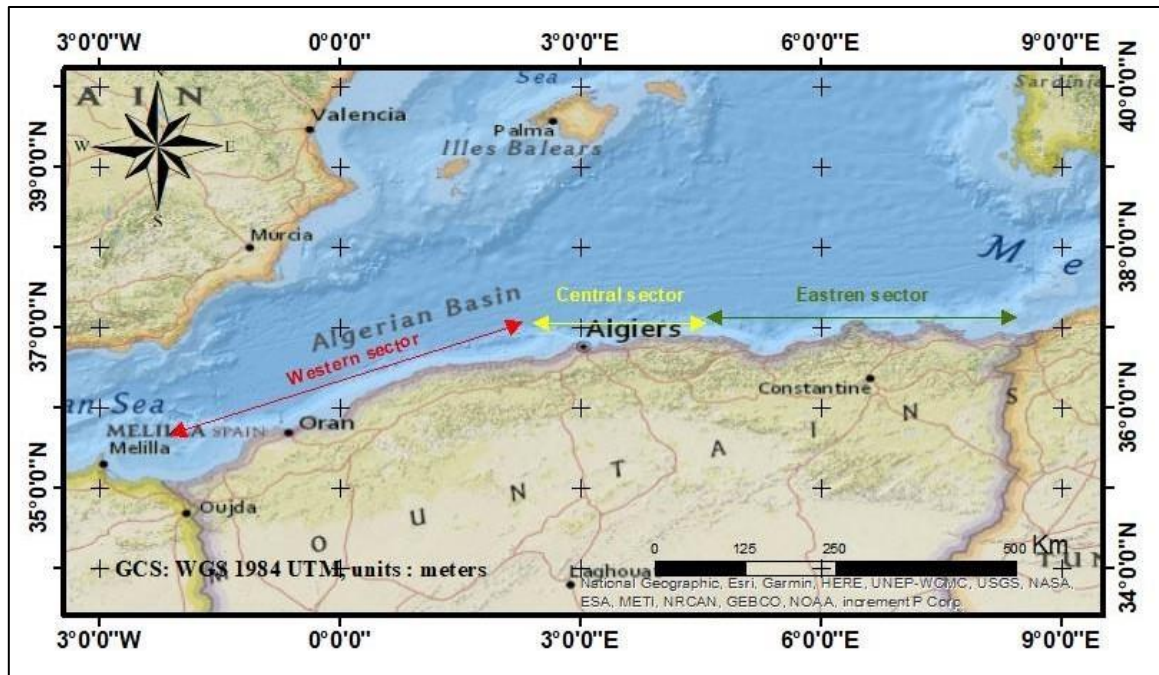


Figure 26 : Geographical Sectors of the Algerian Coastline

The Algerian coastline is generally oriented WSW–ENE (around N70°E), which means it is mainly exposed to waves coming from the north and north-west. This orientation generates a longshore transport of wave energy from west to east, which is consistent with the observed sediment transport along the coast (Salem Cherif et al., 2019). In addition, waves generated in the western Mediterranean,

particularly by Mistral and Tramontane winds, reach the Algerian coast at an oblique angle, causing wave refraction over the continental shelf before they arrive in nearshore areas.

The continental shelf along the Algerian coast is relatively narrow compared to other Mediterranean regions. Its width is typically around 10–20 km in the central and eastern parts, while it can reach up to 40–50 km in the western sector, especially in the Gulf of Oran. The shelf break, corresponding to the 200 m depth, is generally located within 15–25 km from the shoreline (Amarouche et al., 2020b). This narrow shelf allows offshore wave energy to reach the coast with limited energy loss due to bottom friction, which is an important factor for wave energy assessment.

Several coastal features along the Algerian coastline are particularly relevant for wave energy studies. The Gulf of Oran (35.5°N, 0.6°W) is the largest bay in the western part and is partially protected from north-westerly waves by Cap Falcon. The Bay of Algiers (36.7°N, 3.1°E) forms a well-defined semicircular shape, while the Gulf of Annaba (37.0°N, 7.7°E) is sheltered by Cap de Garde, resulting in lower wave exposure compared to open coastal areas. These areas could be suitable for the installation of wave energy devices due to their proximity to infrastructure and relatively moderate wave conditions.

3. Coastal Geomorphology:

3.1. Main Coastal Land Forms :

The coastal geomorphology of Algeria reflects a complex tectono-sedimentary evolution linked to the convergence of the African and Eurasian plates during the Cenozoic era (Boukhari et al., 2023), shaping a diversified coastline composed of rocky headlands, cliffs, sandy beaches, coastal dunes, estuaries, deltas, lagoons, and wetlands (Millot, 1999). Rocky coasts account for about 40–45% of the total coastline and are mainly found in the central sector between Algiers and Bejaia. Sandy beaches are generally located in sheltered areas between rocky headlands and are more developed in the eastern sector, particularly near the Gulf of Annaba. Several rivers such as the Cheliff, Soummam, and Seybouse contribute to the formation of estuarine and deltaic environments (Arnone et al., 1990). The most important deltas include the Cheliff and Seybouse. Coastal lagoons and wetlands are mainly concentrated in the eastern region, especially in the El Kala area (Lionello et al., 2014).

3.2. Coastal Morphology Influencing Wave Processes:

The morphology of the Algerian continental shelf significantly influences wave energy transformation from offshore to nearshore areas. The narrow shelf in the central sector is about 15 km limits bottom

friction effects, preserving most wave energy at the coast. Conversely, the wider shelf in the Gulf of Oran about 40 and 50 km promotes greater energy dissipation and more complex wave conditions (Holthuijsen, 2010a).

Submarine canyons, such as the Chercell Canyon (central sector) and Bejaia Canyon (eastern sector), extending from depths of 400–600 m, also affect wave propagation through local energy focusing or dispersion caused by refraction (Masselink et al., 2014). The steep shelf-slope transition further contributes to wave transformation, particularly for long-period waves (Cullen-Unsworth et al., 2014).

Coastal features such as headlands and capes also play a role in wave energy distribution. Rocky headlands can reduce wave energy in sheltered areas through diffraction effects, while energy tends to concentrate near headland tips due to wave convergence (Ouillon, 2018). This has been observed at Cap Ivi, Cap Carbon, and Cap de Garde, highlighting the importance of such features when selecting sites for wave energy installations.

4. Climatological Data :

The climate of northern Algeria is Mediterranean (Csa), with hot, dry summers and mild, wet winters (Wethey & Woodin, 2022). Coastal temperatures range from about 16–18°C annually, with warmer summers (24–26°C) and cooler winters (11–13°C). Rainfall increases from west to east, varying from around 400 mm in Oran to over 800 mm in Annaba (Khedimallah et al., 2020). This seasonal climate influences wave energy, with the most energetic conditions occurring during winter storms.

Winter winds are mainly from the north and north-west and generate the highest wave energy (Trigo et al., 1999), while summer winds are generally weaker, including the Etesian winds and the Sirocco from the Sahara (Ottaviani et al., 2020). At a regional scale, strong winds such as the Mistral and Tramontane contribute to wave formation in the western Mediterranean (Da Silva et al., 2020).

Sea surface temperature varies from about 13–14°C in winter to 25–27°C in summer (Millot, 1987). It is influenced by the Algerian Current, which flows eastward along the coast and may slightly affect wave propagation through the formation of eddies (Millot & Taupier-Letage, 2005).

4.1. Wave Climate Conditions :

The wave climate of the Algerian Exclusive Economic Zone exhibits pronounced seasonal variability driven by Atlantic storm systems and regional wind patterns. Analysis of twenty years of wave data (2005–2025) from Puertos del Estado reveals distinct characteristics across three representative locations along the coast. The following sections describe the wave climate for each study area.

4.1.1 Eastern Sector :

The eastern sector of the Algerian coast experiences a moderate wave climate characterized by moderate energy input from Atlantic storm systems. The region is more sheltered by the Mediterranean basin geometry compared to western areas, resulting in lower overall wave energy. The annual wave climate is dominated by the northwest (NW) direction, reflecting the influence of Atlantic weather systems and regional wind patterns.

4.1.1.1 Annual Wave Climate (Global Wave Rose):

The global wave rose (Figure 27) shows that the northwest direction dominates at 25 to 30% frequency, representing the primary wave generation mechanism throughout the year. A secondary northeast–east (NE–E) directional mode is visible in the annual average, contributing approximately 15 and 20% of wave occurrences. This bimodal directional distribution reflects the transition between dominant Atlantic storm systems (NW) and local wind patterns (NE–E). The annual average significant wave height is approximately 1.0 meter, indicating moderate wave energy potential for this sector.

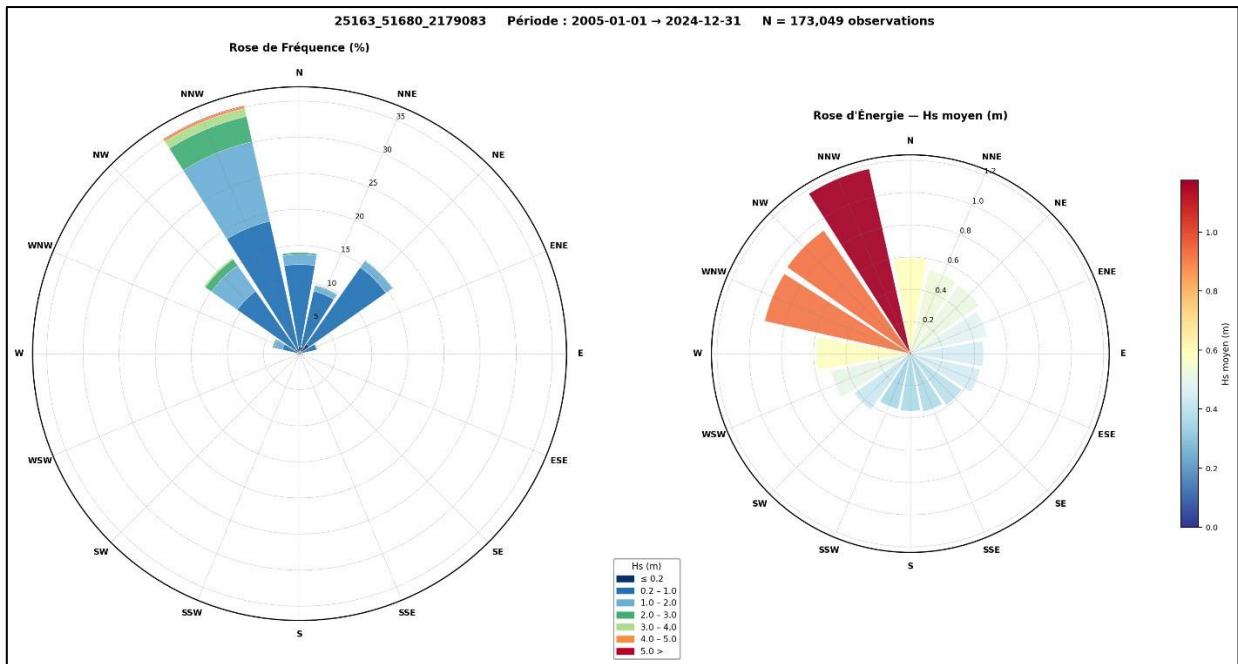


Figure 27 : Annual Wave Rose for the Eastern Sector

4.1.1.2 Seasonal Variability (Seasonal Wave Roses):

The seasonal wave roses (Figure 28) reveal pronounced seasonal variability in the eastern sector. Winter conditions (December–February) show strong NW dominance at 25 to 30% frequency with significant wave heights ranging from 0.8 to 1.4 meters. Spring (March–May) displays a gradual

transition with NW frequency of 20 to 25% and intermediate wave heights of 0.6–1.0 meter. Summer (June–August) shows the weakest wave energy, with significant wave heights between 0.4 and 0.8 meter and a more balanced bimodal distribution between NW and NE–E directions. Autumn (September–November) shows a gradual return to winter conditions with NW frequency increasing to 20 and 25%.

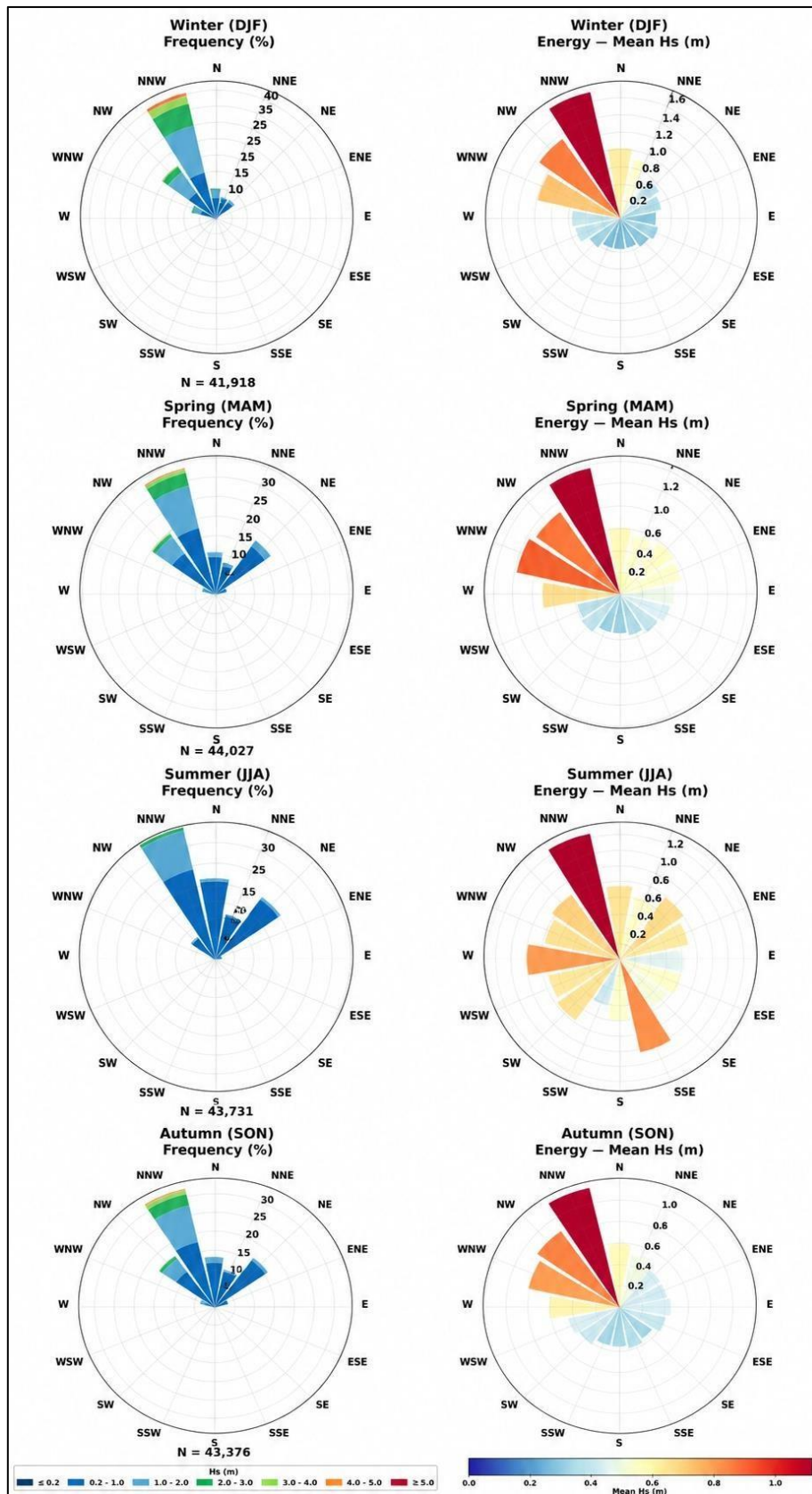


Figure 28: Seasonal Wave Rose for the Eastern Sector

4.1.1.3 Spectral Analysis and Temporal Variability:

The spectral time series (Figure 29) for the eastern shows that Winter months represent the highest energy concentrations, with peaks typically reaching 4 and 5 meters and occasional extreme events exceeding 6 meters during intense Atlantic storms. Summer months display dramatically reduced energy levels, with mean wave heights typically below 1 meter. Spring and autumn transition periods show intermediate energy levels with gradual shifts between the energetic winter and calm summer regimes. The directional vectors in the spectral time series exhibit a predominantly northwest orientation throughout the year, with intermittent deviations toward the northeast–east sector during the summer months. Extreme events ($H_s >$) occur 2 or 3 times per winter season, typically concentrated in December–February. The seasonal cycle is highly regular and repeatable across the 20-year observation period, with no significant long-term trend.

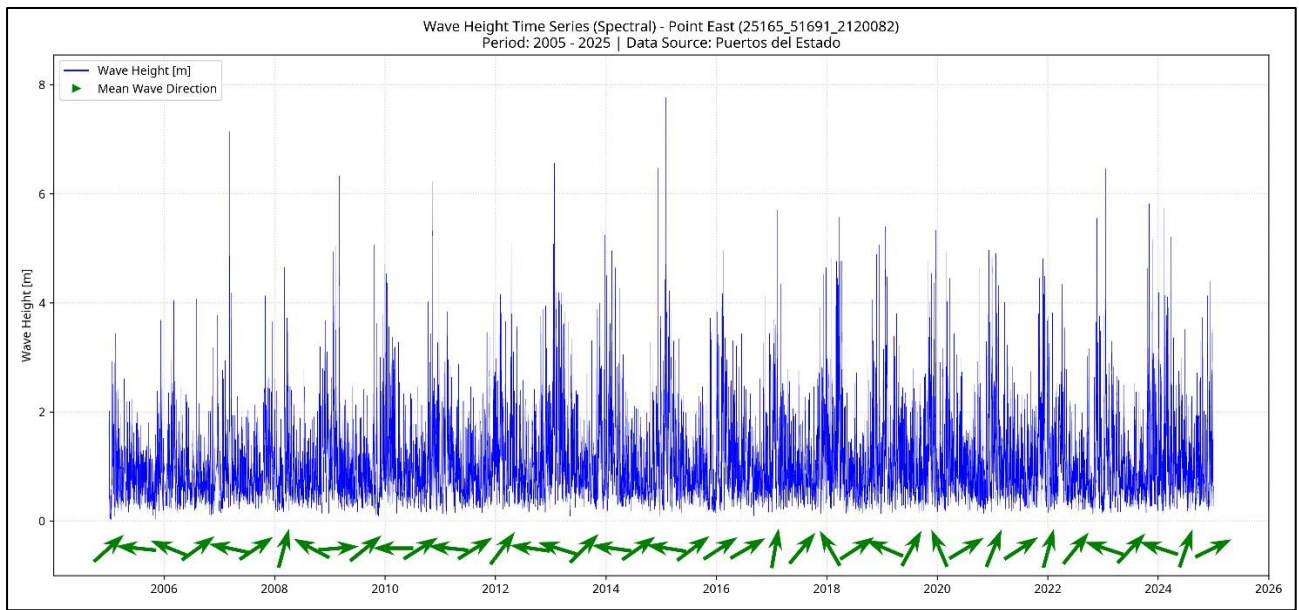


Figure 29: Wave Energy Time Series (Eastern Algeria, 2005–2025)

4.1.2 Central Sector :

4.1.2.1 Annual Wave Climate (Global Wave Rose):

The global wave rose (Figure 30) demonstrates that the northwest direction maintains strong dominance at 30–35% frequency in the annual average, with a clearly visible secondary northeast–east (NE–E) mode contributing 15, 20% of occurrences. This bimodal characteristic is more pronounced in the central sector than in the eastern region, reflecting the transitional nature of this location.

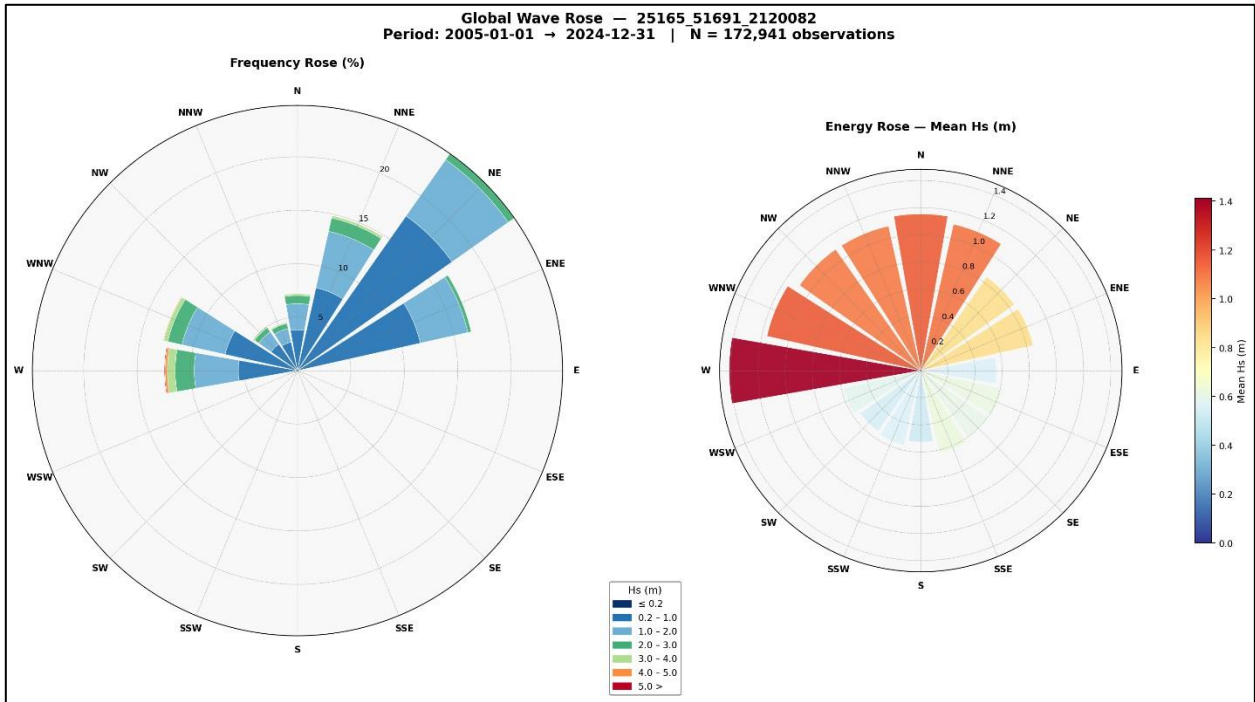


Figure 30: Annual Wave Rose for the Central Sector

4.1.2.2 Seasonal Variability (Seasonal Wave Roses):

The seasonal wave roses (Figure 31) display marked seasonal variability characteristic of the central sector. Winter (December–February) shows strong NW dominance at 30 and 35% frequency with significant wave heights ranging from 1.0 to 1.6 meters. Spring (March–May, Figure 2b) displays a gradual transition with NW frequency of 25, 30% and intermediate wave heights of 0.7 and 1.2 meters. Summer (June–August) shows significantly lower wave energy with significant wave heights of 0.5 to 0.9 meter and a more balanced bimodal distribution between NW and NE–E directions. Autumn (September–November) shows a gradual return to winter conditions with NW frequency increasing to 25 and 30%.

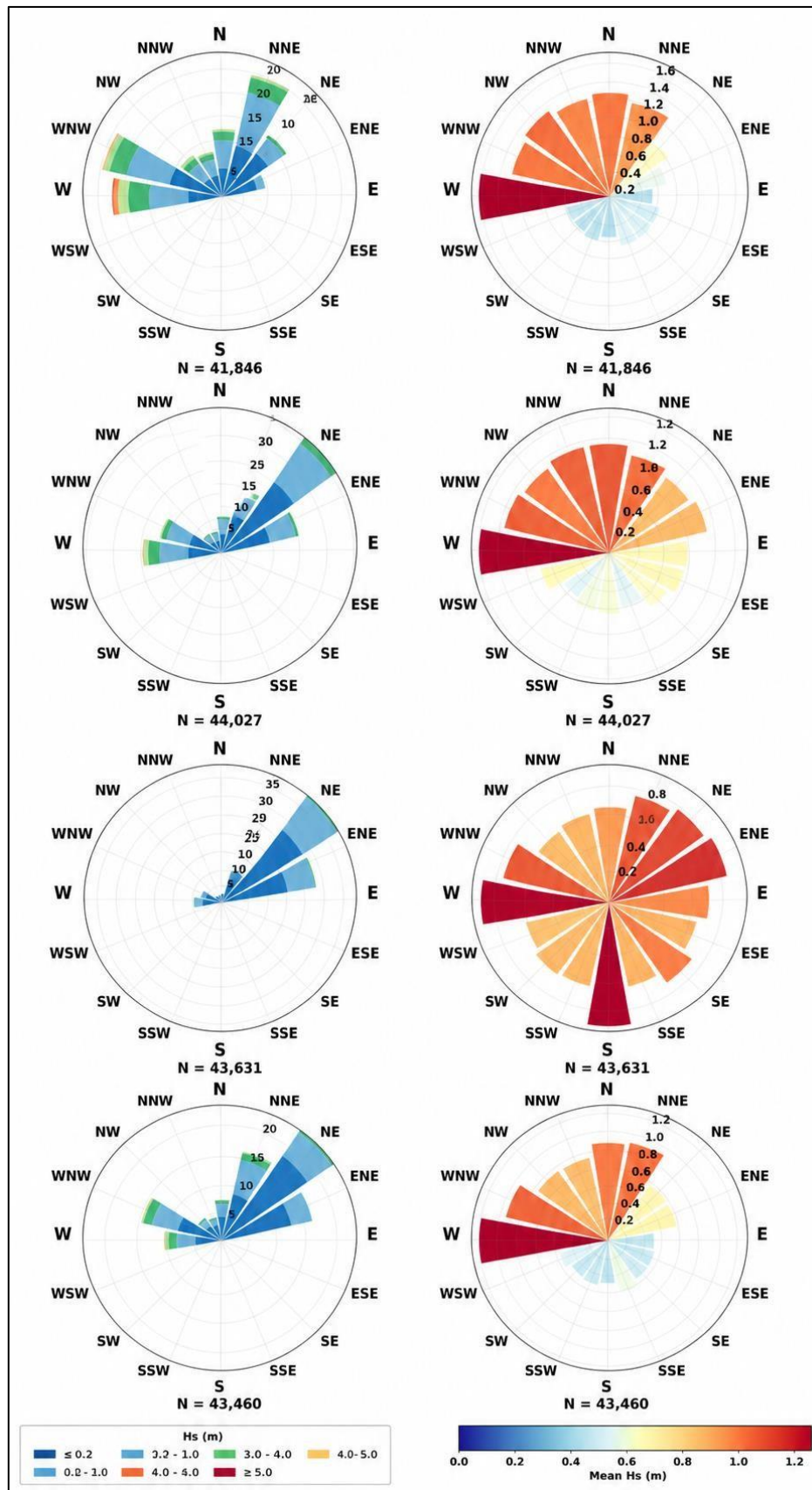


Figure 31: Seasonal Wave Rose for the central Sector

4.1.2.3 Spectral Analysis and Temporal Variability:

The spectral time series (Figure 32) for the central sector reveals a strong seasonal energy modulation pattern. Winter months consistently show the highest energy concentrations, with peaks frequently reaching 5–6 meters and occasional events exceeding 6 meters during severe Atlantic storms. Summer months display dramatically reduced energy levels, with mean wave heights typically below 1 meter. Spring and autumn transition periods show intermediate energy levels with gradual shifts between winter and summer regimes. The directional characteristics remain predominantly northwest throughout the year, as shown by the consistent orientation of directional arrows in the spectral time series. Extreme events ($H_s > 5$ m) occur 3–4 times per winter season, more frequently than in the eastern sector. The seasonal pattern is consistent and reproducible, providing reliable data for long-term resource assessment.

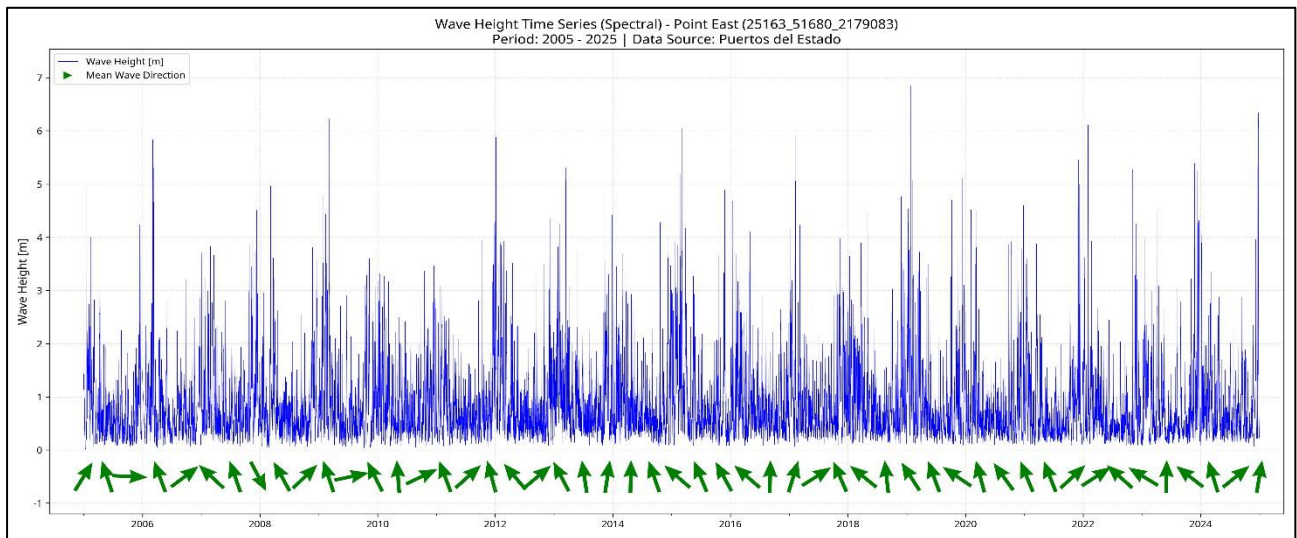


Figure 32: Wave Energy Time Series (Central Algeria, 2005–2025)

4.1.3 Western Sector:

The western sector exhibits the highest wave energy of the three study regions. This sector benefits from direct exposure to Atlantic storm systems and maximum fetch from Atlantic weather patterns, resulting in the most energetic wave conditions along the studied Algerian coast. The wave climate is characterized by strong seasonal variability and pronounced northwest dominance throughout the year.

4.1.3.1 Annual Wave Climate (Global Wave Rose):

The global wave rose (Figure 33) demonstrates the strong concentration of wave energy in the northwest sector at 35 and 40% frequency, with minimal contribution from other directions. The

bimodal wave regime is present but less pronounced compared to the eastern and central sectors, with the secondary northeast–east (NE–E) mode contributing only 10 to 15% of occurrences. The annual average significant wave height is approximately 1.2 and 1.5 meters.

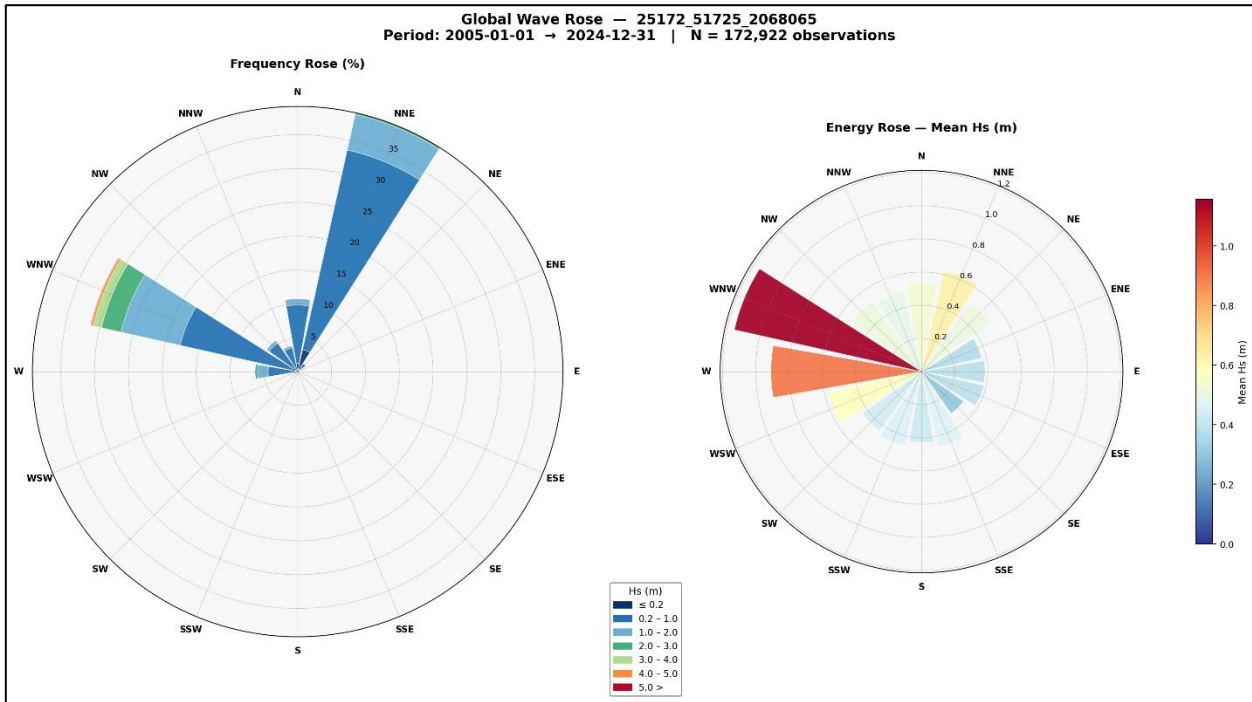


Figure 33: Annual Wave Rose for the western Sector

4.1.3.2 Seasonal Variability (Seasonal Wave Roses):

The seasonal wave roses (Figure 34) shows that Winter (December–February) shows very strong NW dominance at 35 and 40% frequency with significant wave heights ranging from 1.2 to 1.8 meters. Spring (March–May) displays a gradual transition with NW frequency of 30 to 35% and intermediate wave heights of 0.8 to 1.4 meters. Summer (June–August) shows lower wave energy with significant wave heights of 0.6 to 1.0 meter, still higher than other sectors, with NW dominance maintained at 30 to 35% frequency. Autumn (September–November) shows a gradual return to winter conditions with NW frequency increasing to 30 and 35%.

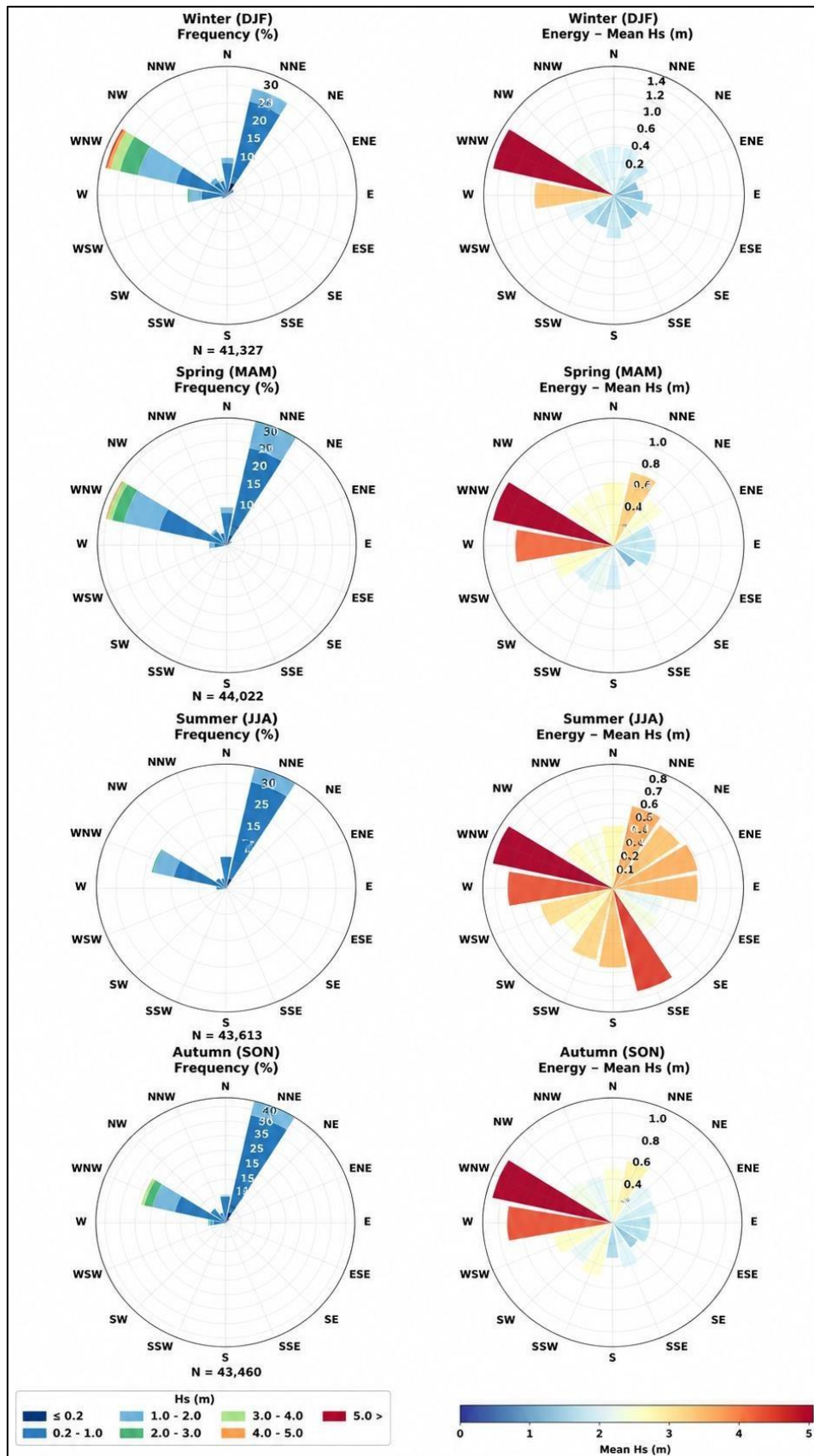


Figure 34: Seasonal Wave Rose for the western Sector

4.1.3.3 Spectral Analysis and Temporal Variability:

The spectral time series (Figure 35) For the western sector, the analysis demonstrates the most intense seasonal energy modulation pattern. Winter months consistently show the highest energy concentrations, with peaks frequently reaching 5 to 7 meters and occasional extreme events exceeding 7 meters during the most severe Atlantic storms. Summer months display substantially reduced energy levels, with mean wave heights typically below 1 meter. Spring and autumn transition periods show intermediate energy levels, with gradual shifts between winter and summer regimes.

The directional characteristics reveal a persistent northwest orientation across all seasons, with mean wave directions consistently pointing toward the northwest sector. Extreme events with significant wave heights greater than 5 meters occur 3 to 4 times per winter season, with the highest magnitude peaks observed at this western location. The strong seasonal cycle and stable directional patterns provide favourable conditions for wave energy resource assessment and development planning.

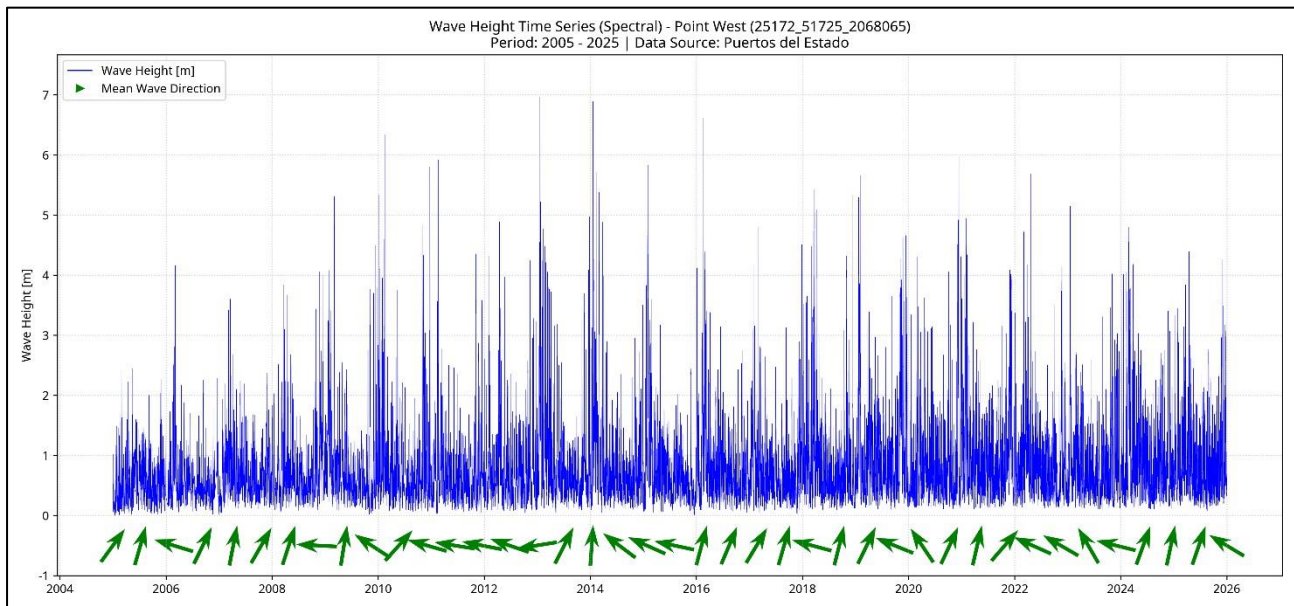


Figure 35 : Wave Energy Time Series (western Algeria, 2005–2025)

4.2 Wind Climate Conditions :

The wind climate in the Algerian Exclusive Economic Zone exhibits pronounced seasonal variability driven by atmospheric systems and regional wind patterns. Analysis of wind data from 2005–2025 from three representative locations along the coast reveals distinct characteristics. The following sections describe the wind climate for each sector, progressing from general characteristics to specific examples.

4.2.1 Eastern Sector :

The eastern sector of the Algerian coast experiences a moderate wind climate characterized by moderate energy input from atmospheric systems. The region is more sheltered by the Mediterranean basin geometry compared to western areas, resulting in lower overall wind energy. The annual wind climate is dominated by the Southwest (SW) direction, reflecting the influence of regional wind patterns.

4.2.1.1 Annual Wind Climate (Global Wind Rose):

The global wind rose for eastern sector (Figure 36) demonstrates that the Southwest direction maintains strong dominance in the annual average, contributing to wind occurrences. This unimodal distribution reflects a consistent wind pattern throughout the year. The annual average significant wind speed is approximately 11.1 m/s.

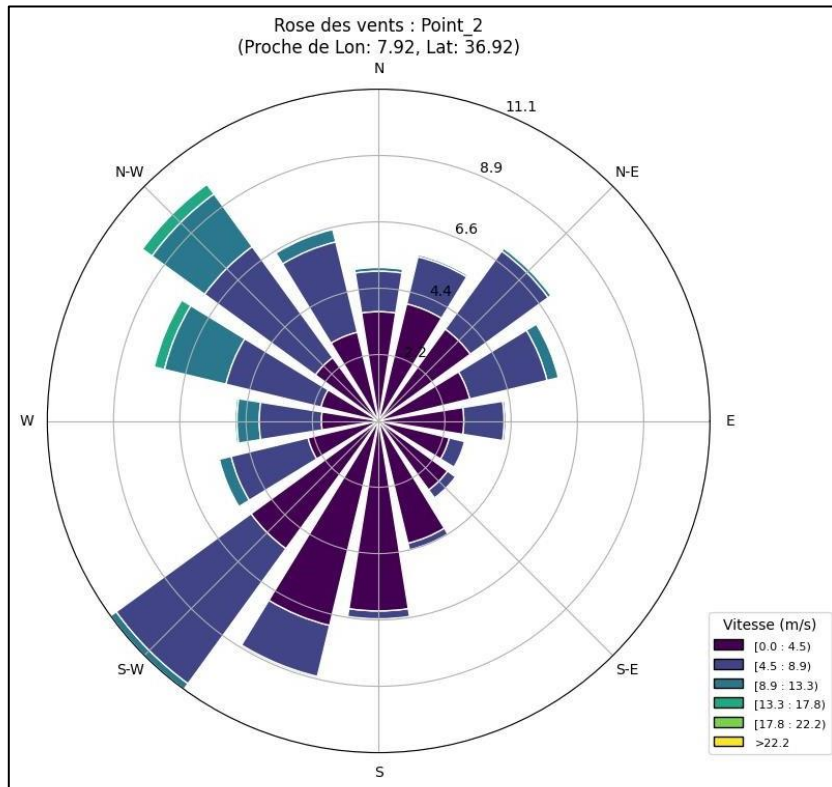


Figure 36: Annual wind Rose for the Eastern Sector

4.2.1.2 Seasonal Variability (Seasonal Wind Roses):

The seasonal wind roses of the eastern sector (Figure 37) reveal pronounced seasonal variability. Winter (December–February) shows strong SW dominance, with significant wind speeds up to 18.0 m/s. Spring (March–May) displays a gradual transition with varied directions, primarily Northwest

(NW) and Southwest (SW), with speeds up to 10.9 m/s. Summer (June–August) shows more varied directions, including NW, Northeast (NE), and Southeast (SE), with peak speeds around 12.5 m/s. Autumn (September–November) shows a return to SW dominance, with speeds up to 13.1 m/s.

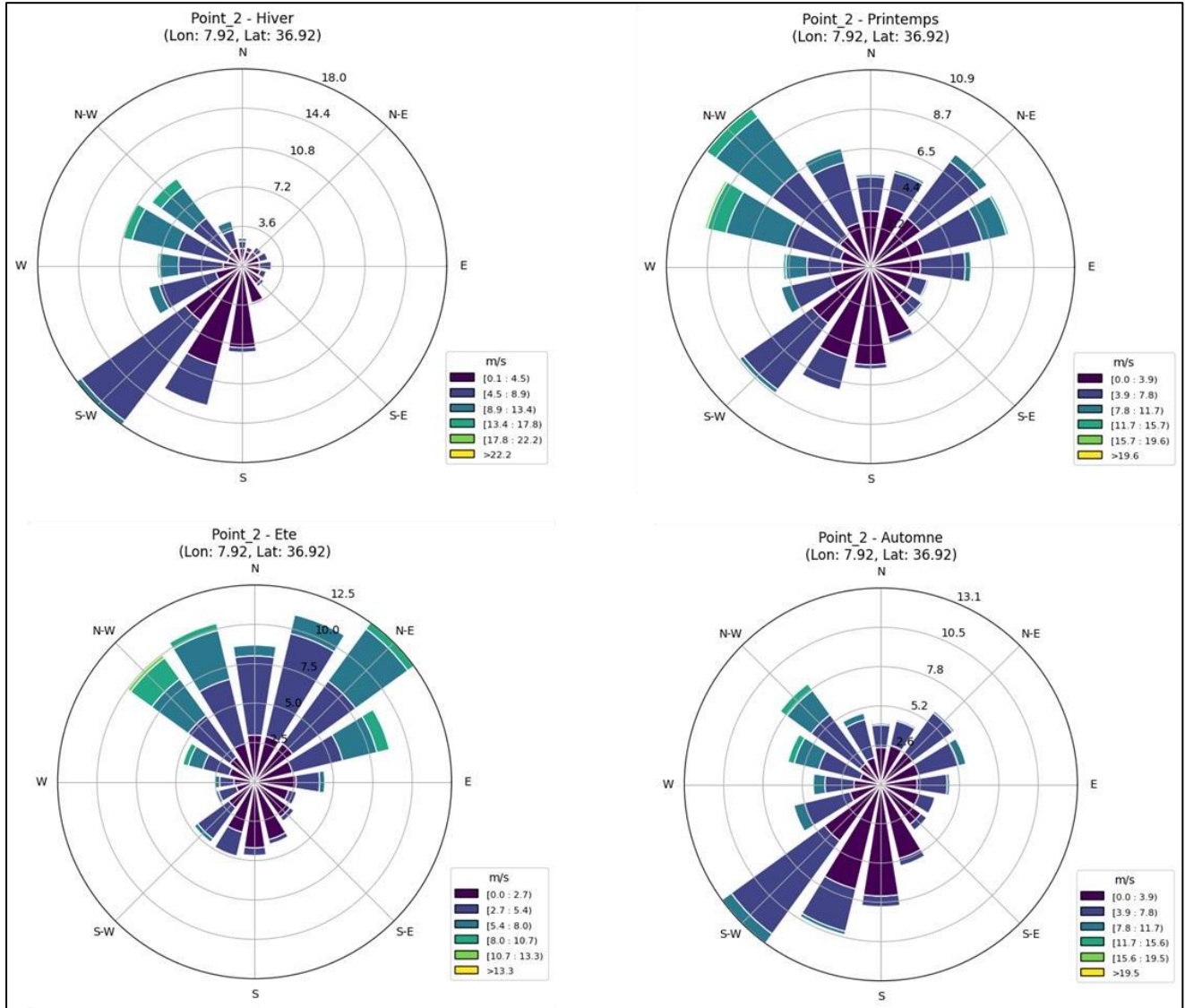


Figure 37: Seasonal wind Rose for Eastren sector

4.2.1.3 Spectral Analysis and Temporal Variability:

Winter months consistently show the highest wind energy concentrations, with peaks typically reaching 18.0 m/s. Summer months display dramatically reduced energy levels, with mean wind speeds typically below 12.5 m/s. Spring and autumn transition periods show intermediate energy levels with gradual shifts between the energetic winter and calmer summer regimes. The directional characteristics remain predominantly Southwest throughout the year, as shown by the orientation of

directional arrows in the spectral time series. Extreme events (wind speeds > 18 m/s) occur 2 to 3 times per winter season, typically concentrated in December–February.

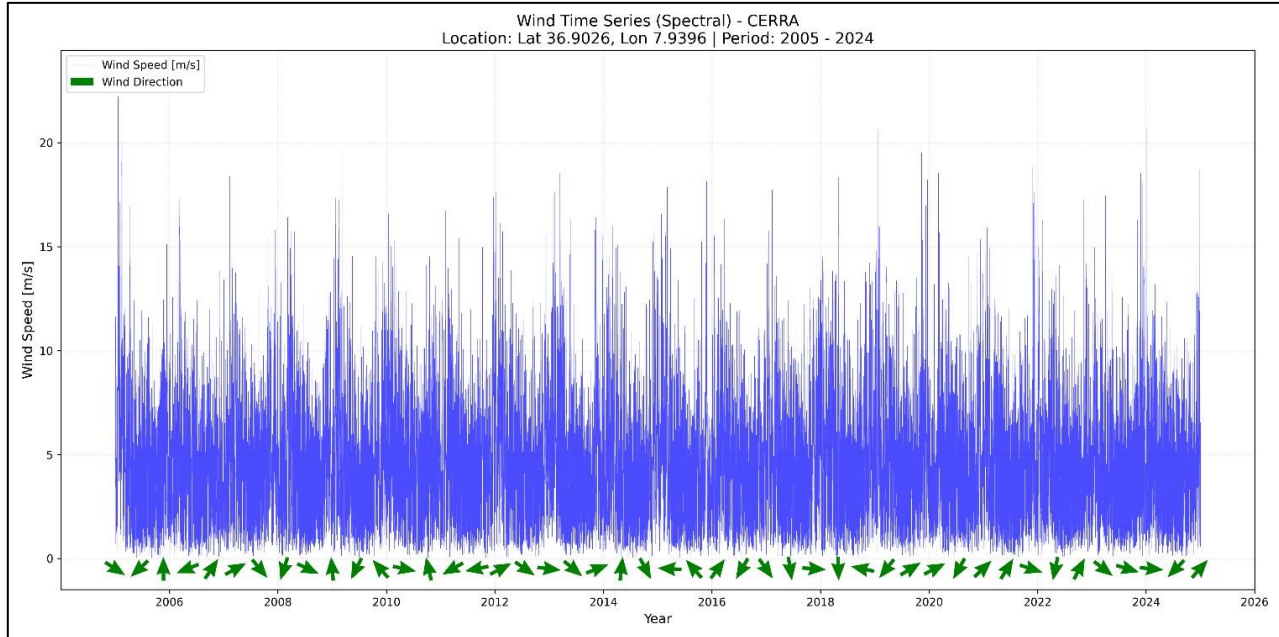


Figure 38 : Wind Energy Time Series (Eastern Algeria, 2005–2025)

4.2.2 Central Sector :

This sector experiences intermediate wind energy characteristics driven by moderate exposure to atmospheric systems and improved fetch compared to the east. The wind climate is characterized by clear seasonal variability and a pronounced East-Northeast (E-NE) directional distribution.

4.2.2.1 Annual Wind Climate (Global Wind Rose):

The global wind rose for central sector (Figure 39) demonstrates that the East-Northeast direction maintains strong dominance in the annual average, with a clearly visible secondary Northwest (NW) mode contributing to wind occurrences.

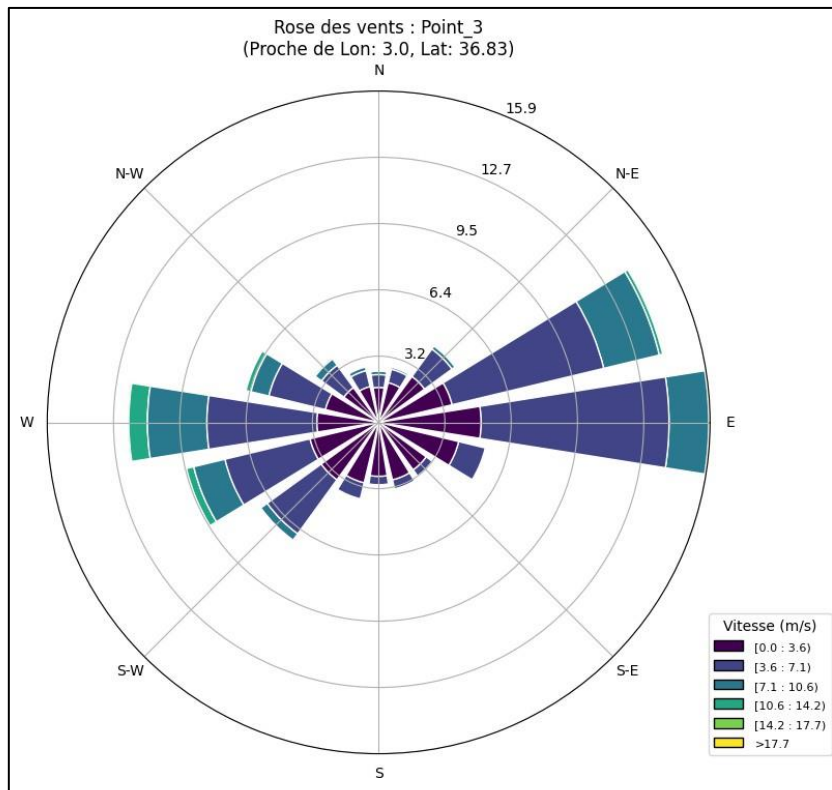


Figure 39: Annual wind Rose for the central Sector

4.2.2.2 Seasonal Variability (Seasonal Wind Roses):

The seasonal wind roses for central sector (Figure 40) display marked seasonal variability. Autumn shows strong E-NE dominance, with significant wind speeds up to 14.3 m/s. Summer records the highest wind speeds, reaching up to 25.9 m/s, predominantly from the E-NE. Winter sees a shift to a dominant West-Southwest (W-SW) direction, with speeds up to 15.5 m/s. Spring exhibits a return to E-NE dominance, with maximum speeds of approximately 15.8 m/s.

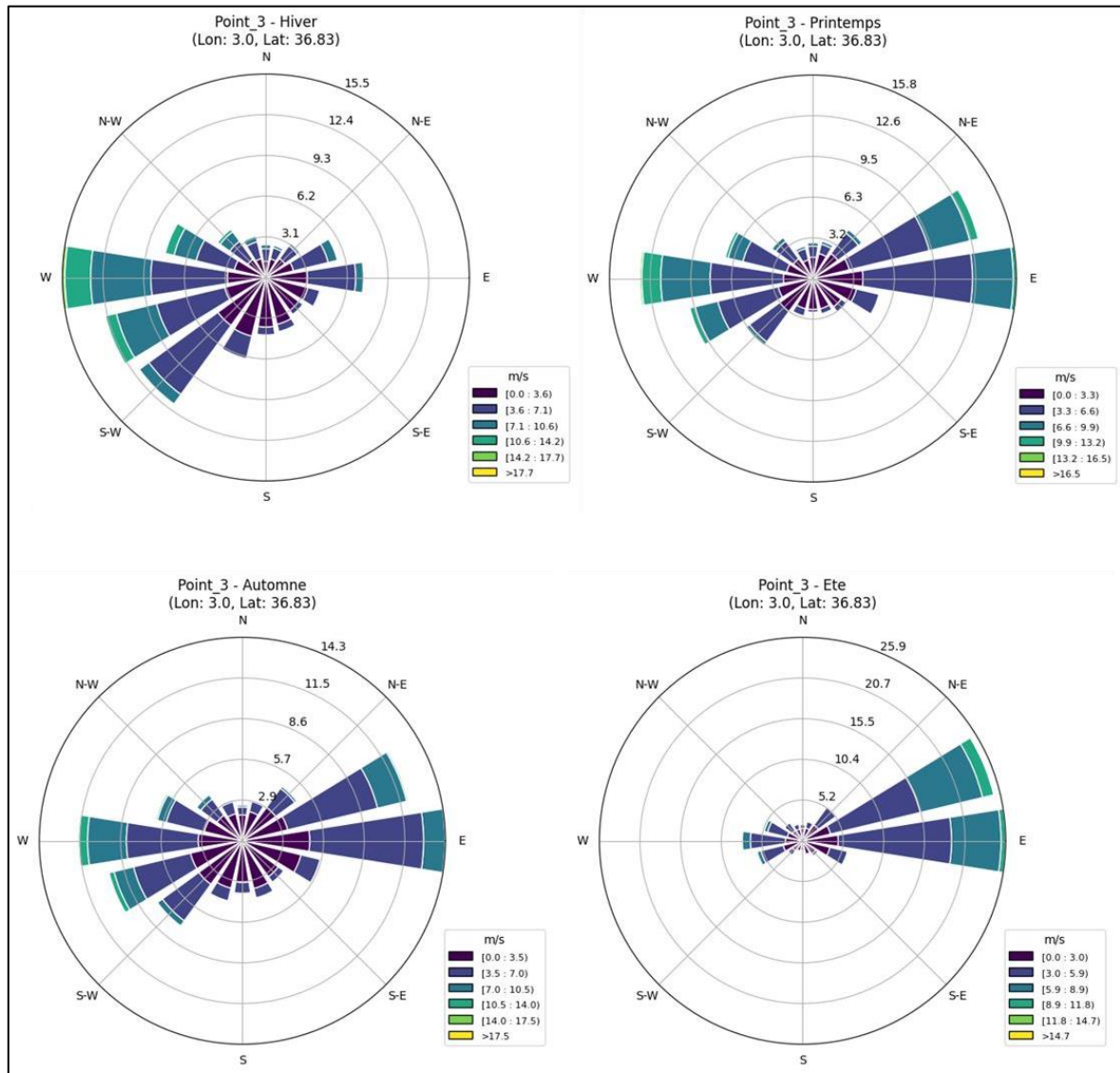


Figure 40: Seasonal wind Rose of central sector

4.2.2.3 Spectral Analysis and Temporal Variability:

The spectral time series for the central sector (Figure 41) reveals a strong seasonal wind speed. Winter months show high wind energy concentrations, with peaks frequently reaching 15.5 m/s. Summer months display exceptionally high energy levels, with mean wind speeds typically above 20 m/s and peaks reaching 25.9 m/s. Spring and autumn transition periods show intermediate energy levels with gradual shifts between winter and summer regimes. The directional characteristics remain predominantly East-Northeast, as shown by the consistent orientation of directional arrows in the spectral time series. Extreme events (wind speeds > 20 m/s) occur 3 to 4 times per summer season, more frequently than in the eastern sector.

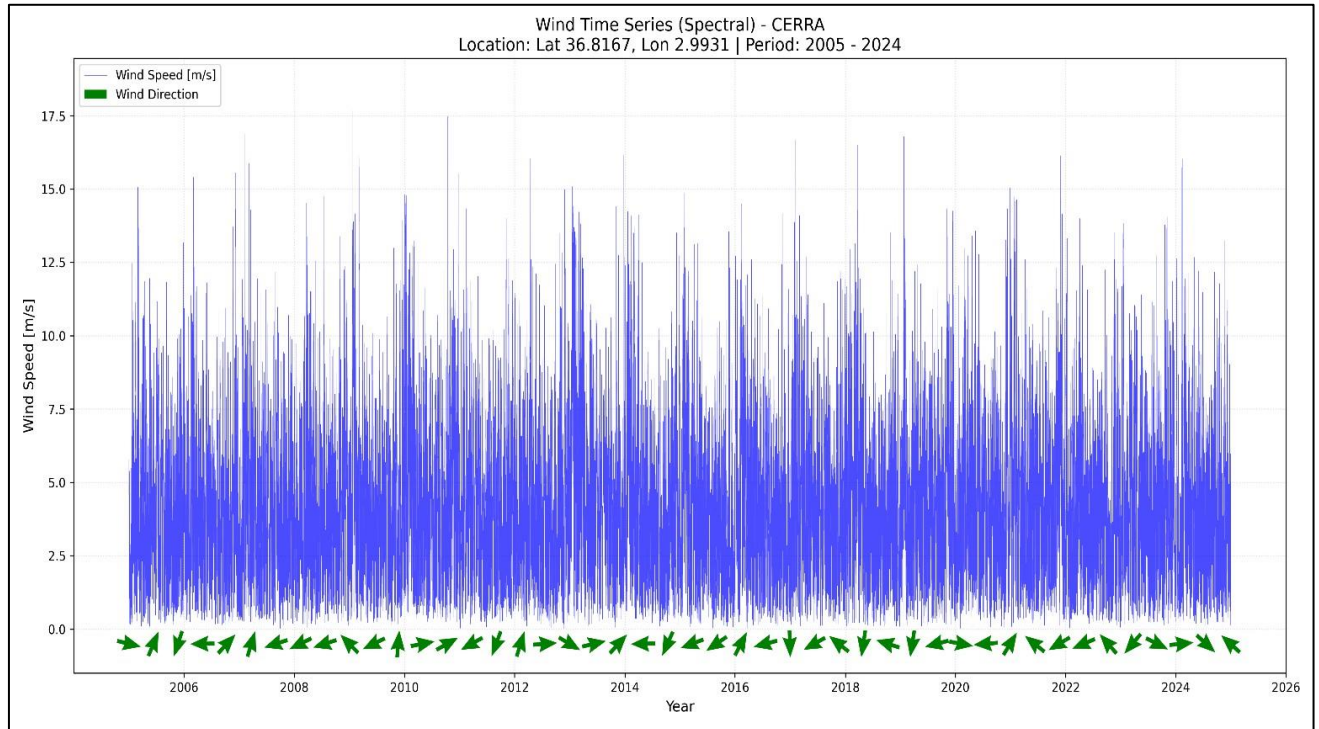


Figure 41: Wind Energy Time Series (central Algeria, 2005–2025)

4.2.3 Western Sector :

4.2.3.1 Annual Wind Climate (Global Wind Rose):

The global wind rose for western sector (Figure 42) demonstrates the strong concentration of wind energy in the western sector at 35 and 40% frequency, with minimal contribution from other directions. The unimodal wind regime is present but less pronounced compared to the eastern and central sectors, with the secondary Northeast (NE) mode contributing only 10 to 15% of occurrences.

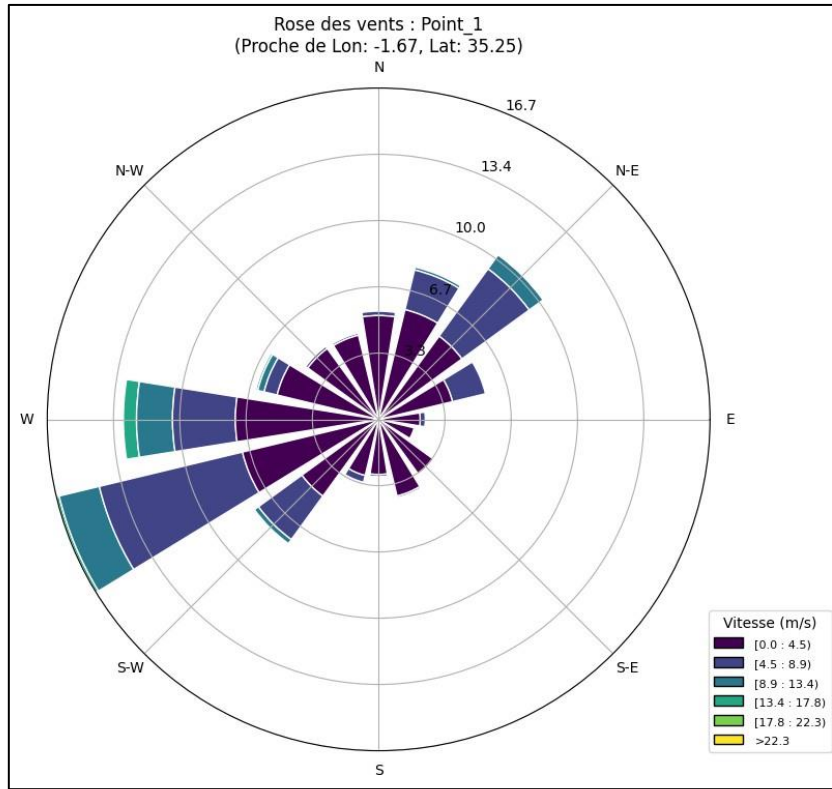


Figure 42: Annual wind Rose for the western Sector

Seasonal Variability (Seasonal Wind Roses):

Winter (December–February) shows strong W-SW dominance, with significant wind speeds ranging up to 18.0 m/s. Spring (March–May) displays a gradual transition with W-SW dominance maintained at 30 and 35% frequency and intermediate wind speeds of 17.2 m/s. Summer (June–August) shows lower wind energy with significant wind speeds of 16.0 m/s, still higher than other sectors, with W-SW dominance maintained at 30 and 35% frequency. Autumn (September–November) shows a gradual return to winter conditions with W-SW dominance and speeds up to 15.7 m/s.

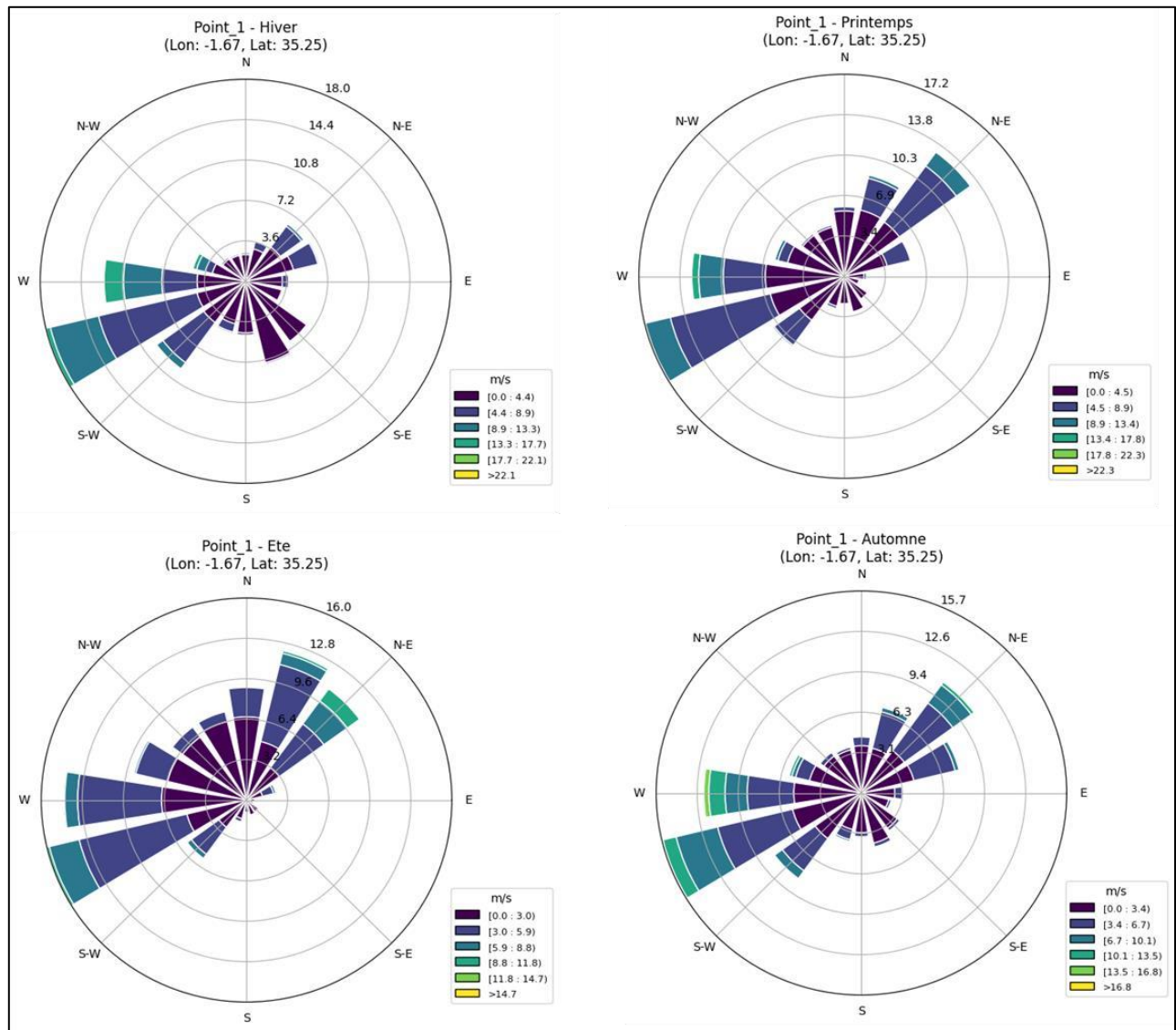


Figure 43: seasonal wave roses for the western sector

4.2.3.2 Spectral Analysis and Temporal Variability :

The spectral time series for the western sector (Figure 44) demonstrates shows that: Winter months have the highest energy concentrations, with peaks frequently reaching 18.0 m/s and occasional extreme events exceeding 18 m/s during the most severe atmospheric systems. Summer months display low energy levels, with mean wind speeds typically below 16.0 m/s. Spring and autumn transition periods show intermediate energy levels with gradual shifts between winter and summer regimes. The dominant direction is the Northwest across all seasons, with mean wind directions pointing to the W-SW. Extreme events (wind speeds > 18 m/s) occur 3 to 4 times per winter season, with the highest peaks observed in this western location.

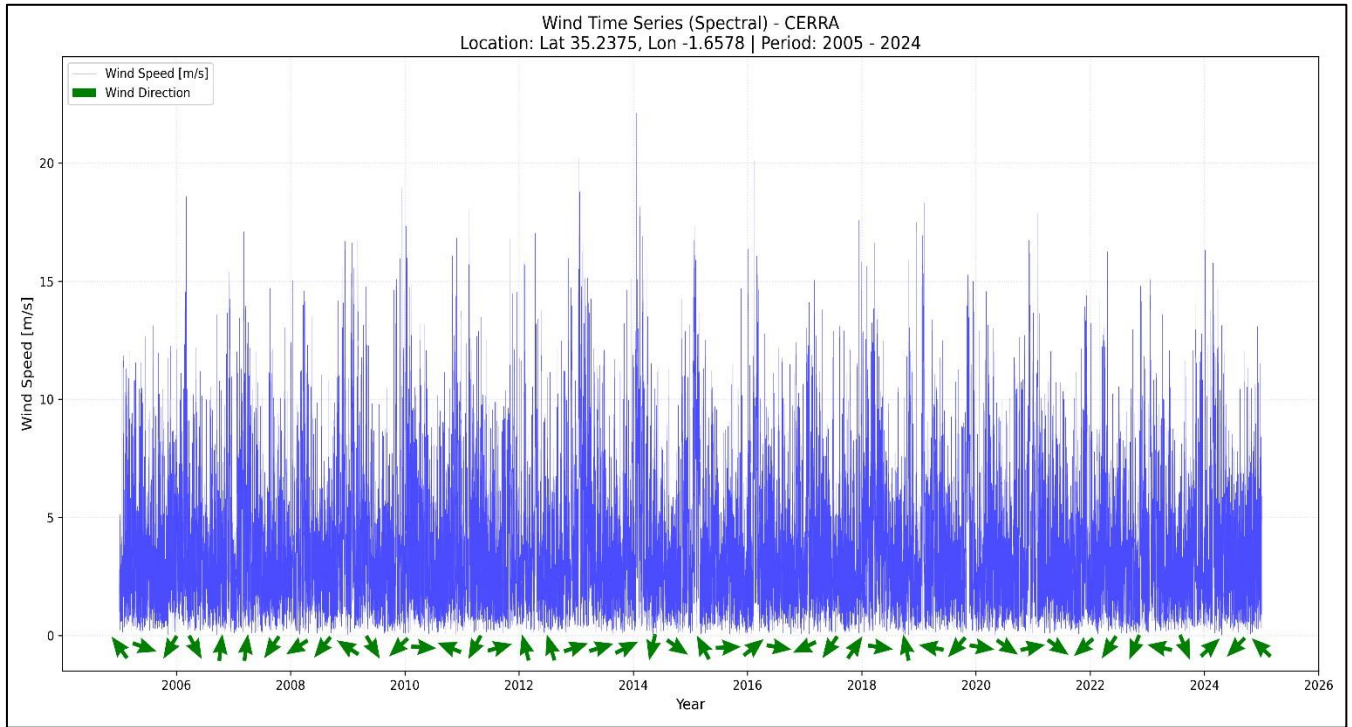


Figure 44 : Wind Energy Time Series (western Algeria, 2005–2025)

5 Partial Conclusion :

This chapter has presented the main geographical, geomorphological, oceanographic, and climatological characteristics of the Algerian Exclusive Economic Zone (EEZ). The analysis highlighted the influence of coastal morphology, bathymetry, wind regimes, and wave climate on the spatial distribution of marine energy resources. The results indicate a clear west-to-east gradient in wave energy conditions, with the Eastern sector exhibiting the most energetic environment. These findings provide the environmental context and baseline conditions required for the wave energy resource assessment developed in the following chapter.

CHAPTER III:
NUMERICAL MODELING

CHAPTER 03 :

1. Model présentation:

1.1. MIKE Software and Numerical Modelling Tools:

MIKE 21 is professional modelling tools developed by Danish Hydraulic Institute (DHI), a globally recognized institution specialized in water and marine environments. These software suites are widely used in coastal and marine engineering to simulate waves, currents, water levels, and hydrodynamic processes.

MIKE 21 is designed for two-dimensional (2D) modelling and is particularly suitable for coastal areas, estuaries, and rivers. The tool also provides efficient data management and visualization features that help users analyse and interpret simulation results.

In this study, the computational mesh required for the simulations was generated using the mesh generator available in the MIKE Zero platform.

1.2. Mesh Generator:

MIKE Zero provides a working environment for generating both flexible mesh (FM) and fixed meshes used in MIKE models. Flexible meshes are particularly useful because they allow the nesting of several mesh resolutions within the same domain, improving the representation of complex coastal areas. An appropriate mesh is essential to ensure accurate and reliable simulation results.

The mesh generator also includes interpolation tools for triangular elements, with two main interpolation methods available: Nearest Neighbour and Linear Interpolation (DHI, 2014).

For the present study, the mesh was generated using the “MeshGenerator” module based on:

The geographic coordinate system WGS 1984;

The coastline of the study area;

Bathymetric data stored in.xyz format.

1.3. MIKE21 models:

1.4. Spectral Waves (Mike SW):

The specific module used here is MIKE 21 Spectral Waves (SW). It solves the spectral Wave Action Equation (WAE), which governs the evolution of the directional wave energy spectrum in space and time. Written in its propagation form, the equation reads :

$$\partial N / \partial t + \nabla \cdot (c^{\rightarrow} N) = S / \sigma$$

Where :

$N = E(\sigma, \theta) / \sigma$: is the wave action density spectrum

σ : is the intrinsic angular frequency

$c^{\rightarrow}$: is the group velocity vector in the four-dimensional phase space (x, y, σ, θ)

S is the net source term representing the sum of all energy input and dissipation mechanisms.

S : is the net source term representing the sum of all energy input and dissipation mechanisms.

The physical processes represented in MIKE 21 SW include wind-wave generation through atmospheric energy input, nonlinear wave-wave interactions responsible for energy transfer across frequencies, and whitecapping dissipation caused by wave breaking in deep waters. The model also accounts for bottom friction dissipation in intermediate and shallow areas, depth-induced wave breaking in nearshore zones, as well as wave refraction and shoaling generated by variations in bathymetry and ambient currents.

1.5. Supporting tools:

1.6. ArcGIS:

ArcGIS is a Geographic Information System (GIS) platform developed by ESRI, a leading company specialized in spatial analysis and mapping technologies. ArcGIS provides an integrated environment for creating, editing, managing, analysing, and visualizing geographic data for a wide range of scientific and engineering applications.

The platform supports different types of spatial data, including vector layers, raster datasets, geodatabases, and point cloud data. It also offers numerous tools for spatial analysis, terrain modelling, interpolation, coordinate system transformation, and remote sensing applications.

In this study, ArcGIS was used for many specific tasks like the manual digitization of bathymetric points from Navionics nautical charts in the nearshore zone. The spatial merging and interpolation of bathymetric data from two distinct sources into a single coherent surface, and the export of all spatial layers in XYZ point format for subsequent use in the MIKE Zero Mesh Generator.....

1.7. Python:

Python is a high-level, interpreted, open-source programming language originally created by Guido van Rossum and first released in 1991. Over time, it has become one of the most widely used languages in scientific computing, data science, and geospatial analysis, mainly due to its simple syntax, extensive ecosystem of libraries, and strong compatibility with other software tools.

In earth and ocean sciences, Python is commonly used to process large multidimensional datasets, automate geospatial workflows, perform statistical analysis, and interact with numerical modelling systems. The data processing, visualization, and format conversion tasks carried out in this study were entirely implemented through a set of dedicated Python scripts, each targeting a specific stage of the workflow.

The first script handles the conversion of atmospheric wind forcing data from NetCDF format, provided by the CERRA reanalysis dataset, into the DFS2 format required by MIKE 21 SW as wind input. It reads multidimensional NetCDF data encompassing time, spatial coordinates, and the 10-metre wind components U10 and V10, applies the necessary unit conversions and temporal filtering, and writes the output directly into a MIKE-compatible DFS2 file.

The second script generates wind roses at three target locations along the Algerian coast from the same CERRA reanalysis NetCDF dataset, extracting time series of the 10-metre wind speed (si10) and wind direction (wdir10) at the nearest grid node to each point, filtering invalid values, and producing stacked bar-type directional roses normalized to percentage frequency with wind speed classes encoded in a color scale. The third script follows the same visualization approach but operates on post-processed simulation results stored in Excel format, generating wave roses representing the joint distribution of significant wave height and wave direction at selected points without requiring access to the original model files.

The fourth script converts the MIKE 21 SW simulation output from the native DHI unstructured mesh format (DFsu) into standard NetCDF format (.nc). It opens the DFsu file, reads all physical variables along with their time series and unstructured mesh geometry, extracts element coordinates and the

projection string, and writes a CF-1.8 compliant NetCDF4 file with time encoded as hours since the Unix epoch, zlib-compressed variables, and full metadata including units and long names.

The remaining two scripts produce spatial wave statistics maps from the converted NetCDF simulation output covering the Algerian coast for the period 2015–2025. Both follow the same core pipeline: the H_s time series is loaded in memory efficient chunks, and three statistical indicators are computed, the mean significant wave height (mean H_s), the $H_{1/10}$ as the average of the top 10% of wave heights, and the H_{50} as the average of the top 50%, before being interpolated onto a regular geographic grid using linear interpolation. The first map script produces three full-domain maps at 0.01° resolution with overlaid land, EEZ, country, and wilaya boundaries. The second generates nine sector-specific maps at a finer 0.005° resolution, dividing the coastline into Western, Central, and Eastern sectors, and additionally overlays the -200 m isobath derived from the bathymetric variable. The libraries used for these scripts are as follows:

Xarray and netCDF4 for reading and handling multidimensional NetCDF data (time, spatial coordinates, and wind components U10 and V10);

NumPy for numerical operations such as unit conversions, temporal filtering, and array manipulation;

Mikeio, a Python library developed for working with Danish Hydraulic Institute (DHI) file formats (DFS0, DFS2, mesh files), enabling direct creation of MIKE-compatible inputs.

Input data collection and preparation:

Three main categories of input data are required to set up and force the wave model: bathymetric data describing the seafloor morphology, atmospheric wind data which provide the energy input for wave generation, and a coastline dataset defining the land–sea boundaries of the computational domain. Each dataset was collected from appropriate sources and processed through specific preprocessing steps to ensure consistency and compatibility before being integrated into the modeling workflow.

2. Wind Forcing Data (CERRA Reanalysis):

In this study, wind forcing was derived from the Copernicus European Regional ReAnalysis (CERRA), a high-resolution regional reanalysis product produced under the Copernicus Climate Change Service (C3S) of the European Centre for Medium-Range Weather Forecasts (ECMWF), in collaboration with several European national meteorological services.

CERRA provides atmospheric fields over the European domain at a horizontal grid spacing of approximately 5.5 km and at 3 hourly temporal resolutions. Comparing to the ERA5 global reanalysis, which operates at roughly 31 km resolution, CERRA offers considerably finer spatial detail of wind patterns, especially in the Mediterranean Sea.

The dataset used contains time series of the 10 m wind components U10 and V10 over the period 01/01/2015 to 31/12/2024 in NetCDF format, and the MIKE 21 SW requires wind forcing in DHI's proprietary DFS2 format. The Python script described in Section 3.4.2 was used to read the NetCDF variables, perform any necessary spatial reprojection, and write the wind field as a temporally and spatially varying DFS2 file using the mikeio library. This file was then loaded directly as the wind forcing input in the MIKE 21 SW model configuration, corresponding to a total of 29,224 time steps at 3-hourly resolution over the 2015–2024 period.

3. Coastline Data:

The coastline dataset defines the closed land boundary of the computational domain and is essential for the Mesh Generator to correctly distinguish between land and ocean cells. In this study, the coastline was obtained from the Natural Earth dataset (physical vector data, scale 1:10m, version 4.1.0), using its most recent available version. The data were imported into ArcGIS, where the Algerian coastline was first clipped to the study area extent. The resulting geometry was then visually inspected and corrected where necessary to ensure consistency. Finally, the coastline was converted from vector format into XYZ point format to make it compatible with the MIKE Zero Mesh Generator for use as a boundary input.

4. Bathymetric Data:

Composite bathymetric dataset was therefore constructed by merging two complementary data sources:

4.1. Navionics, Nearshore Zone (0 to 50 m depth):

For the coastal area extending from the shoreline down to the 50 m isobath, bathymetric data were taken from Navionics nautical charts. Navionics is a well-known marine mapping provider that compiles depth information from official hydrographic surveys, vessel sonar measurements, and additional user-contributed data.

In this study, the bathymetry was manually digitized in ArcGIS by extracting depth points directly from the chart layers and assigning the corresponding depth values to each point. The longitude and

latitude of every point were then computed to build a georeferenced XYZ point cloud. All data were kept in the WGS 1984 coordinate system to ensure consistency with the rest of the modelling inputs.

4.2. GEBCO, Offshore Zone (beyond 50 m depth):

Beyond the 50 m isobath, bathymetric data were obtained from the General Bathymetric Chart of the Oceans (GEBCO), a joint initiative of the International Hydrographic Organization (IHO) and the Intergovernmental Oceanographic Commission (IOC) of UNESCO. GEBCO provides one of the most complete global datasets of ocean depths available to the scientific community (<https://www.gebco.net>). In this study, the GEBCO 2026 Grid was used, offering global bathymetric coverage at a spatial resolution of 15 arc-seconds (approximately 450 m in the study area).

The dataset was downloaded in NetCDF format from the official GEBCO portal and clipped to the study domain before processing. Finally, it was merged with the nearshore bathymetric data and interpolated onto a single consistent grid, which was then exported in XYZ format to support the generation of the computational mesh.

5. Mesh and bathymetry results:

The triangular mesh generated from the MIKE 21 mesh generator was analysed. Since we investigated a regional-scale model of the Mediterranean basin, a variable grid spacing ranging from 0.004° in nearshore areas to 0.1° offshore was adopted. The mesh consists of 11,928 triangular elements and 7088 nodes. (Figure 45).

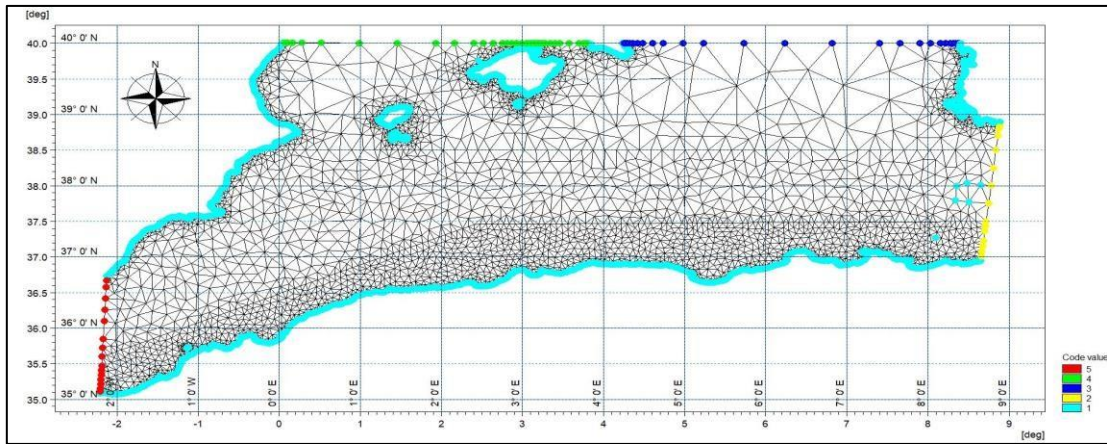


Figure 45: The mesh of the Computational area (study area) at a regional scale.

After interpolating the mesh, we obtained the bathymetric data for the computational zone (Figure 46):

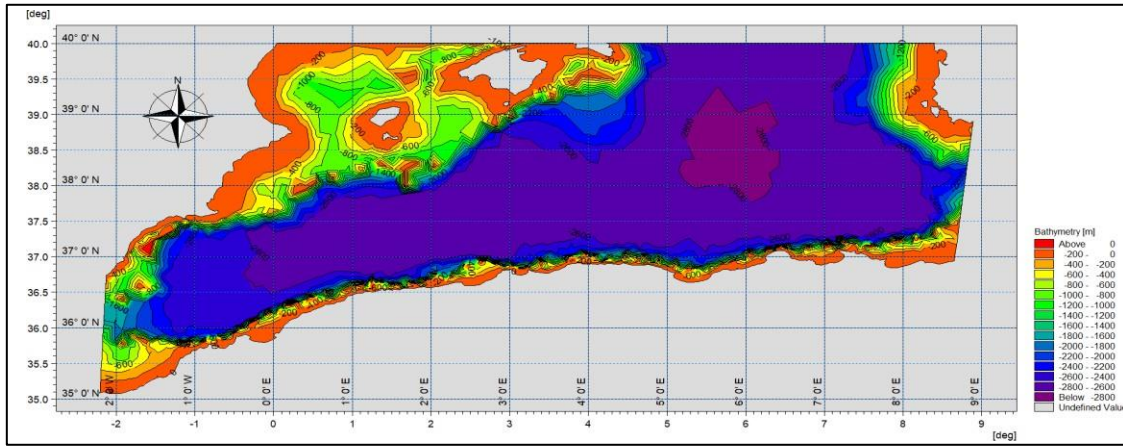


Figure 46: Bathymetry of the Computational area (study area) at a regional scale.

5.1. The interpretation of the bathymetry:

The northern margins of the domain are dominated by relatively wide continental shelves associated with the French, Spanish, and Ligurian coasts. In particular, the Gulf of Lion (around 3°E–5°E) exhibits the broadest and most gently sloping shelf, strongly influenced by sediment inputs from the Rhône River system. This shelf extends for several tens of kilometres before reaching the shelf break at approximately 120 and 150 m depth. In contrast, the Algerian margin to the south is characterized by a very narrow continental shelf, generally only a few kilometres wide. To the northeast, the Ligurian Sea forms a narrow and elongated sub-basin reaching depths of about 2200 to 2600 m, confined between the Maritime Alps, the Ligurian coastline, and Corsica. Along the Spanish margin, the Gulf of Valencia represents an intermediate-depth embayment that progressively deepens southward.

The Balearic Islands (Mallorca, Menorca, and Ibiza) appear as isolated shallow platforms rising above surrounding depths of 1000–1400 m. These islands correspond to remnants of continental blocks that remained exposed during the Miocene opening of the basin. Although they share a similar geological origin with the Algerian margin, they were not subjected to the same compressional tectonic processes, which explains their broader morphology and relatively lower seismic activity.

The central and eastern part of the domain is occupied by the Algero-Provençal abyssal plain, where water depths generally exceed 2800 m. This area corresponds to a relatively young oceanic crust in the Mediterranean and is characterized by a flat, extensive morphology shaped by alternating pelagic and turbiditic sediment deposition from surrounding margins.

At the eastern boundary, the seafloor gradually shoals toward the Sardinian margin. The Sardinia Channel acts as a morphological sill controlling the exchange of intermediate and deep waters between the western Mediterranean Basin and the Tyrrhenian Sea. Depths in this corridor vary roughly between 400 and 2000 m, with locally complex bathymetric features.

5.2. Algerian bathymetry:

The Algerian continental margin is characterized by a very narrow continental shelf (0 to –200 m), appearing as a thin strip of shallow waters along the coast. In most areas, the shelf is less than 5–10 km wide before it rapidly drops into deeper waters, making it one of the narrowest shelves in the Mediterranean. This morphology is mainly controlled by the active convergence between the African and Eurasian plates about 4 to 6 mm/year, which contributes to the uplift of the Tell Atlas and limits the development of wide shallow platforms.

The continental slope (–200 to –1400 m) is steep and irregular, with local gradients often exceeding 5° to 15°, reflecting strong tectonic control from offshore thrust and reverse faults linked to the Tell–Atlas system. It is also incised by several submarine canyons, such as the Algiers Canyon, which transport sediments from rivers like the Isser, Soummam, and Seybouse toward the deep basin through turbidity currents. Beyond the slope, the Algerian Exclusive Economic Zone gradually transitions into the Algero-Provençal Basin, where the seabed becomes flatter and is dominated by sediment accumulation from continental sources.

In the eastern sector, the bathymetry is highly contrasted, with rocky headlands generating abrupt submarine slopes and tightly packed isobaths over short distances. Offshore of Jijel, this area exhibits strong flexural deformation of the oceanic lithosphere due to African–Eurasian plate convergence, forming deep asymmetric basins at the base of the margin where thick sedimentary sequences accumulate. Further east, toward Annaba, this structural control remains visible, although over shorter spatial scales, and is locally influenced by Miocene volcanic features that add complexity to the seabed morphology. (Figure 47)

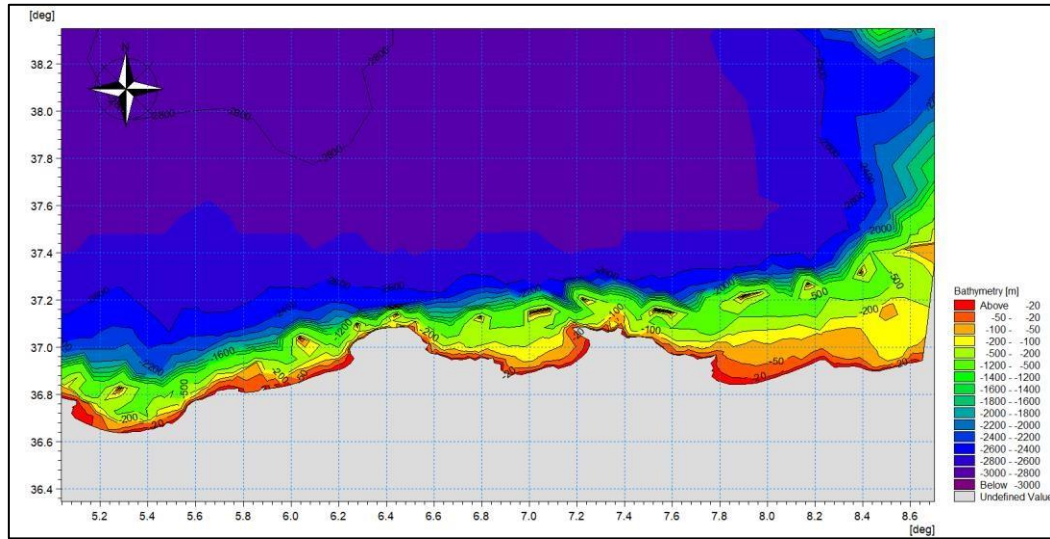


Figure 47: Eastern Sector Bathymetry of the Algerian Margin

The central sector, particularly offshore of the Bay of Algiers, is marked by an extremely narrow continental shelf, reduced to approximately 4 km before a sharp shelf break into the deep Algerian Basin. This abrupt transition is reinforced by the presence of deep submarine canyons, especially the Algiers Canyon, which deeply incise the slope and channel sediments toward the abyssal plain through gravity-driven flows. The region is also tectonically active, with evidence of crustal thrusting and intense compressional deformation related to African–Eurasian convergence, which contributes to seismic activity, including the 2003 Boumerdès earthquake. (Figure 48)

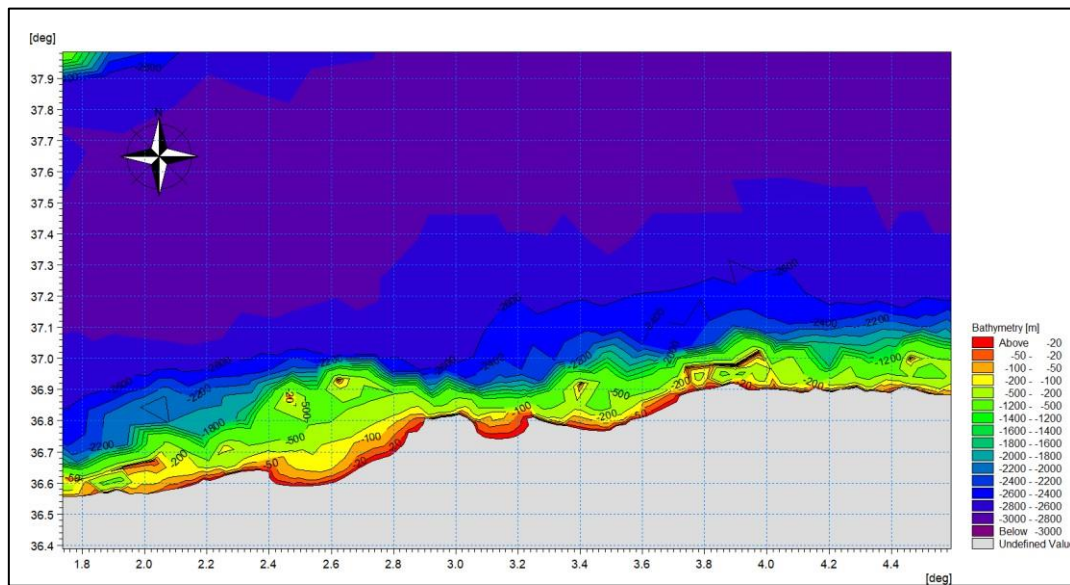


Figure 48 : Central Sector Bathymetry of the Algerian Margin.

In the western sector, the margin is generally smoother and less tectonically complex. Offshore of Ghazaouet, the continental shelf is relatively wider and forms a gently sloping submarine platform before reaching the shelf break. Moving eastward toward Mostaganem, however, the shelf gradually narrows and becomes more linear, reflecting a transition toward a more typical narrow-margin morphology. (Figure 49).

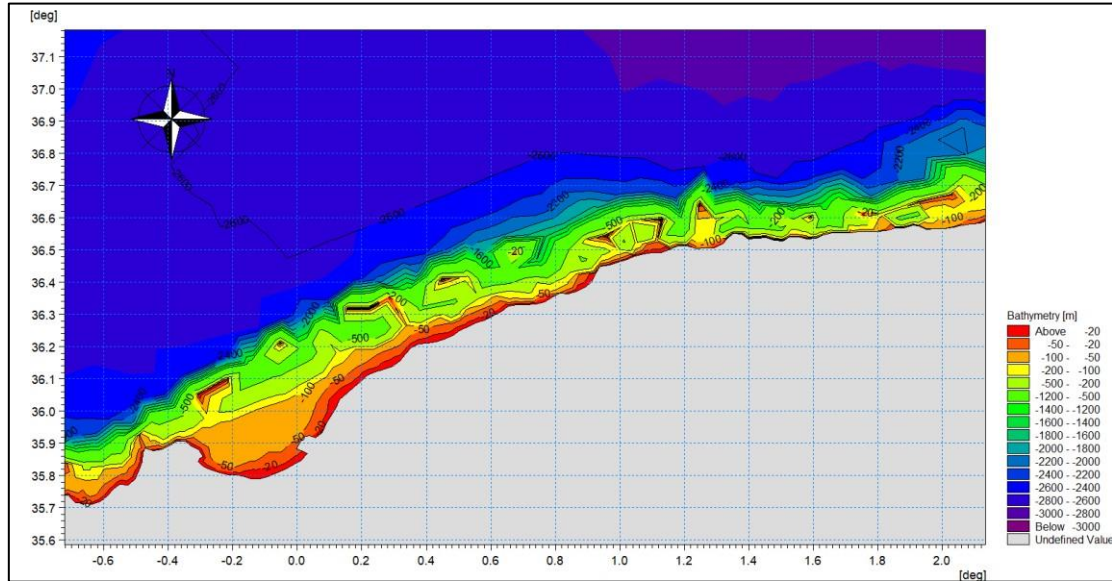


Figure 49 : Western Sector Bathymetry of the Algerian Margin.

6. Wave Model Setup and Configuration:

6.1. Spectral Discretization:

In the MIKE 21 model, the wave energy spectrum was discretized into 25 logarithmically spaced frequency bins, ranging from 0.055 Hz with a frequency factor of 1.1. The directional space was divided into 16 uniformly distributed bins, covering the full 360° wave spectrum. No distinction between wind sea and swell components was applied.

6.2. Boundary Conditions:

Open Sea boundaries were defined as lateral boundaries for the model domain.

6.3. Wind Forcing:

Wind forcing was applied as a spatially and temporally varying field with a 3-hour update interval over the entire simulation period. It was based on DFS2 wind data generated from the CERRA reanalysis, as described. No tidal current forcing was included, as tidal effects in the Mediterranean are generally weak and considered negligible for wave propagation in this study.

6.4. Physical Parameters:

WhiteCapping was parameterized using the Komen et al. (1984) formulation; taking constant value of Dissipation coefficient ($C_{dis}=1.9$, and $\Delta=0.5$), and bottom friction was accounted for using a Nikuradse roughness height taking 0.04 as constant value.

6.5. Model Calibration:

To ensure the reliability of the wave model outputs, a calibration process was carried out prior to the full simulation run. The whitecapping dissipation coefficient (C_{dis}) was tested over a range of values, from 4.5 down to 1.9, in order to identify the setting that best reproduces observed sea-state conditions. Model outputs were compared against in-situ measurements from coastal buoys operated by Puertos del Estado, located along the Spanish Mediterranean coast, which provided a reliable reference dataset for the western basin.

7. Results and Interpretation:

7.1. Wave Climate Analysis of Algerian Coast (2015–2025):

The 10-year simulation period (2015–2025) provides a statistically robust basis for characterizing the spatial distribution of wave energy across the western Mediterranean and the Algerian Exclusive Economic Zone (EEZ). The analysis integrates three complementary statistical indicators, the mean significant wave height (mean H_s), the energetic wave height parameter $H_{1/10}$ (mean of the top 10% of H_s values), and the median significant wave height H_{50} at three spatial scales; the western Mediterranean basin, the full Algerian EEZ, and the three coastal sectors (Western, Central, and Eastern). Together, these indicators characterize not only average energy conditions but also storm-driven energetic episodes and long-term central tendency, offering a multi-dimensional perspective on the exploitable wave resource.

7.2. Global Scale, Western Mediterranean Basin:

The western Mediterranean basin is a dynamically active marine environment, dominated by the Mistral and Tramontane wind systems. These predominantly northwesterly winds, as indicated by the 20-year wind climatology (2005-2025) (Figure 50) with high speeds in the north (9 to 10 m/s), generate a prevailing wave field. The Mean Significant Wave Height (H_s) map for 2015-2025 (Figure 51) reveals that the highest wave energy concentrates in the northeastern quadrant (4°E–9°E, 37°N–40°N), with a mean H_s exceeding 1.8 m. This area benefits from unrestricted fetch and deep open water. Conversely, the waters south of Spain and the Alboran Sea exhibit low energy (mean H_s below

0.6–0.8 m), shielded by the Iberian Peninsula. The Balearic Islands also introduce an additional localized diffraction shadow around 1°E–2°E, reducing wave energy.

median significant wave height remains generally below 1.2 m (Figure 53), representing the calmest wave climate within the Algerian EEZ.

The eastern portion, extending from Béjaïa to El Tarf, presents a markedly different picture. This area is directly exposed to the Algero-Provençal Basin, with no upstream geographic barriers to attenuate incoming swells. Mean H_s rises between 1.4 to 1.8 m (Figure 51), $H_{1/10}$ approaches 3.5 to 4.0m near the EEZ boundary (Figure 52), and the median significant wave height increases to approximately 1.3 to 1.6 m (Figure 53). The persistence of higher values across all three indicators highlights the more energetic wave climate of the northeastern EEZ and confirms the presence of a well-defined offshore zone characterized by enhanced wave energy potential.

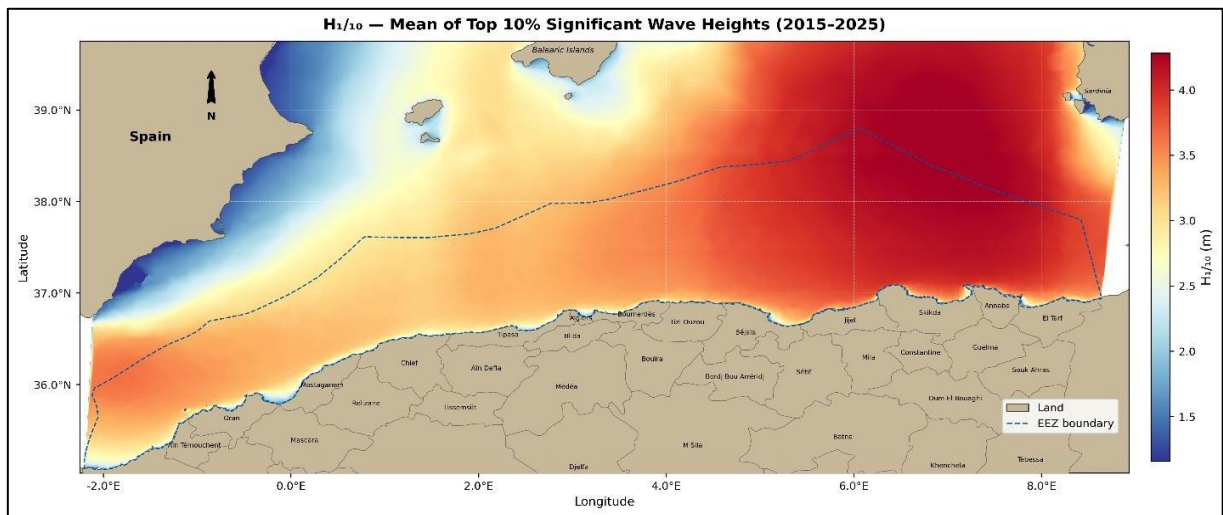


Figure 52: Mean of Top 10% Significant Wave Heights ($H_{1/10}$) (2015–2025)

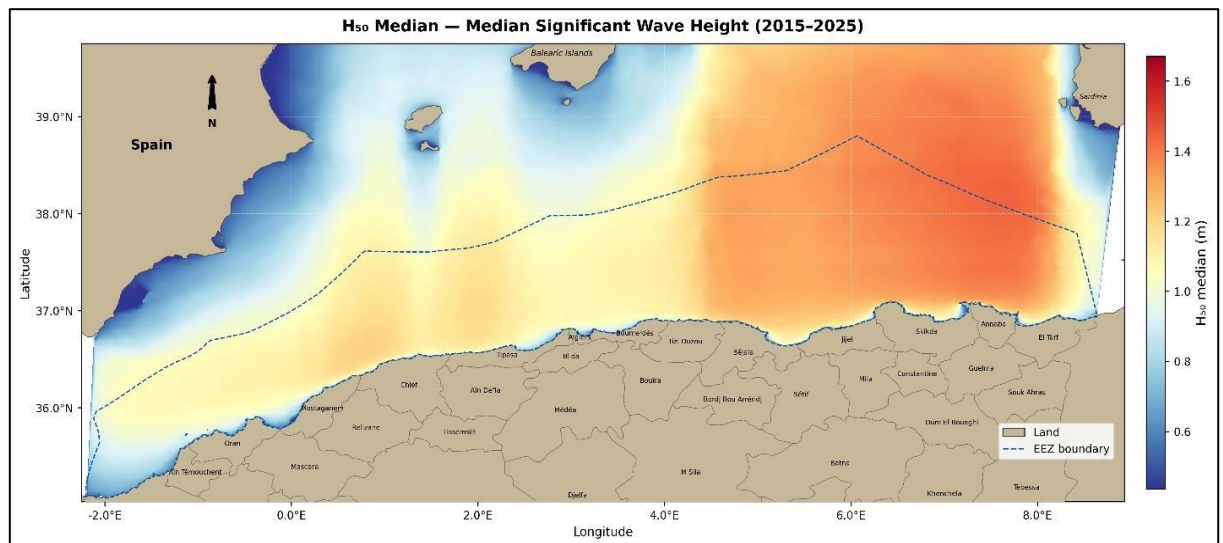


Figure 53: Median of Significant Wave Heights (H_{50}) (2015–2025).

7.4. Local Scale, Sector Analysis :

7.5. Central Sector (1.8°E – 5.4°E) :

The Central Sector spans the most urbanized portion of the Algerian coast, from Tipasa through Algiers and Boumerdès to the approaches of Béjaïa. Across all three maps, a consistent north to south decrease in wave conditions is observed. Offshore areas north of 37°N record $H_{1/10}$ values near 4.0m (Figure 54), median significant wave heights (H_s median) ranging between approximately 1.3 and 1.5 m (Figure 55), and mean H_s values between 1.6 and 1.8 m (Figure 56). Moving southward toward the coast, all indicators progressively decrease, with $H_{1/10}$ dropping to 1.8 to 2.5m, median H_s falling below 1.0 m, and mean H_s reaching 0.8 and 1.2 m in the shallowest nearshore waters. This gradual but persistent decrease is primarily controlled by the very narrow continental shelf, where the –200m isobath lies only about 10 to 15km from shore, limiting the spatial window available for bottom-induced wave dissipation.

Two localized sheltered zones are visible across all three maps. The Gulf of Algiers (approximately 3.0°E, 36.8°N) appears as a distinct lower energy area, partially protected by Cap Matifou (approximately 3.25°E, 36.82°N) to the east, where wave refraction redistributes energy along the shoreline. A comparable but weaker attenuation is observed near Béjaïa (approximately 5.0°E, 36.75°N), where Cap Carbon (approximately 5.15°E, 36.78°N) and the irregular shelf morphology induce partial wave shadowing. By contrast, the open coast between Boumerdès and the Isser plain (3.6°E–4.8°E; 36.8°N–36.9°N) sustains the highest nearshore wave conditions of the sector, with $H_{1/10}$ up to 2.5m (Figure 54), median H_s values around 1.0 m (Figure 55), and mean H_s of approximately 1.0 to 1.2m (), owing to its broadly northerly exposure and absence of significant offshore obstacles.

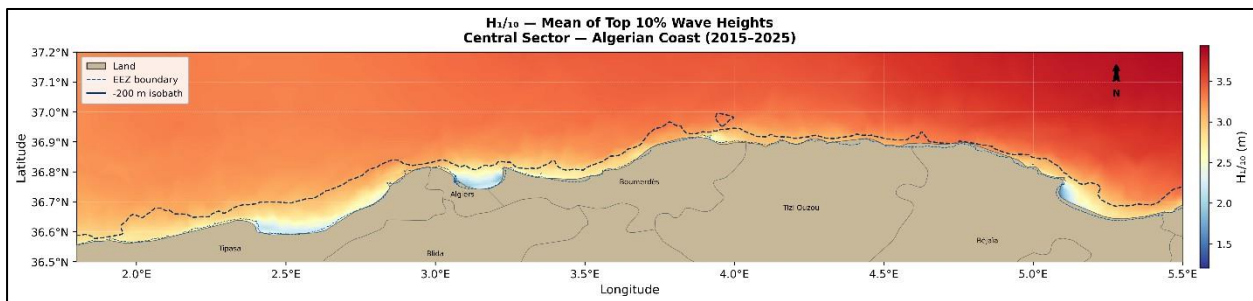


Figure 54: Mean of Top 10% Wave Heights *Central Sector* ($H_{1/10}$) *Algerian Coast (2015–2025)*.

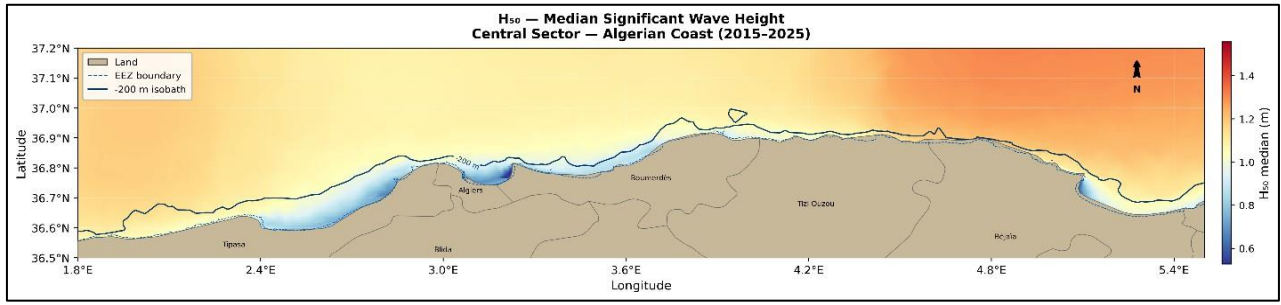


Figure 55 : H_{50} Median significant Wave Heights *Central Sector, Algerian Coast (2015–2025)*.

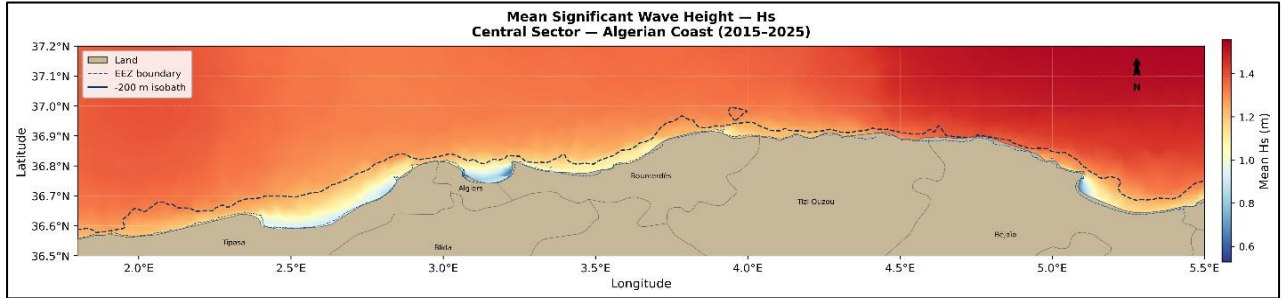


Figure 56: Mean Significant Wave Height (H_s) of Central Sector for Algerian Coast (2015–2025).

7.6. Eastern Sector (5.8°E – 9.0°E):

The Eastern Sector, extending from Jijel through Skikda and to El Tarf (approximately 8.30°E, 36.77°N) near the Tunisian maritime boundary, is the most energetically intense portion of the Algerian coastline. All three maps are dominated by high values throughout both the offshore domain and the nearshore coastal band. $H_{1/10}$ values approach or reach 3.5, 4.0 m across most of the sector (Figure 57), the median significant wave height remains consistently between approximately 1.2 and 1.5 m (Figure 58), and mean H_s ranges between 1.4 and 1.8 m over large portions of the domain (Figure 59). This sustained high-energy pattern results from two reinforcing factors: direct and unobstructed exposure to northerly and northwesterly swells propagating across the full Mediterranean fetch, combined with an exceptionally narrow and steep continental shelf that allows deep-water wave conditions to reach the coast with minimal prior attenuation.

The only notable exception to this otherwise uniform pattern is the Gulf of Annaba (approximately 7.2°E, 36.95°N), visible as a distinct lower-wave-height area across all three maps. Here, Cap de Garde (approximately 7.79°E, 36.97°N) partially blocks incoming northerly swells, and wave energy is further reduced by refraction and bottom friction over the shallow irregular bathymetry, bringing median H_s locally below 1.0 m (Figure 58) and mean H_s down to approximately 1.0 and 1.2 m (Figure 59).

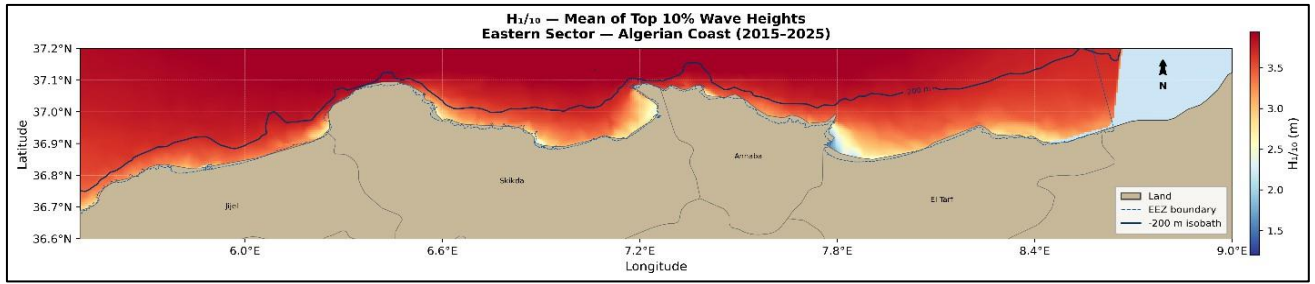


Figure 57: Mean of Top 10% Wave Heights($H_{1/10}$) of *Eastern Sector in Algerian Coast (2015–2025)*

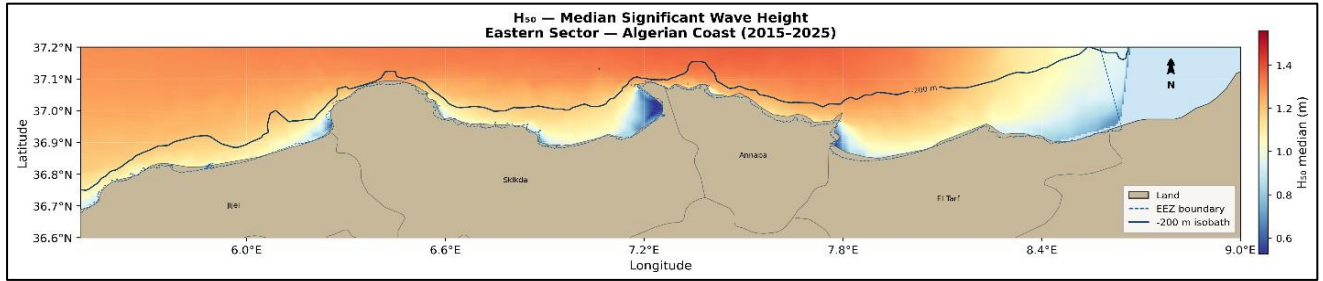


Figure 58: H_{50} Median Significant Wave Heights of *Eastern Sector in Algerian Coast (2015–2025)*

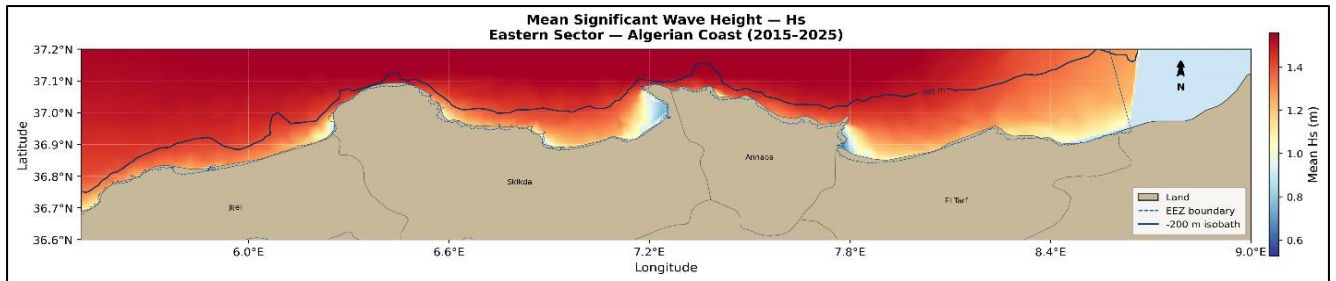


Figure 59: Mean Significant Wave Height (H_s) Eastern Sector of Algerian Coast (2015–2025).

7.7. Western Sector ($-2.1^\circ\text{E} - 1.4^\circ\text{E}$):

The Western Sector is the most spatially complex of the three, characterized by sharply contrasting energy regimes within the same domain. The most visually striking feature across all three maps is the extensive low-energy zone occupying the northwestern quadrant, roughly north of 37°N and west about 1.4°E . In this area, $H_{1/10}$ falls below 1.5 and 2.0 m (Figure 60), H_{50} median drops to approximately 0.6–0.8 m (Figure 61), and mean H_s remains below 0.6 and 0.8 m (Figure 62), in stark contrast to the warm orange-red tones characterizing the Central and Eastern sectors. This low-energy shadow is primarily controlled by the Iberian Peninsula, which blocks and deflects northwesterly swell systems before they can penetrate into the northwestern Algerian maritime zone.

Moving eastward, wave energy recovers rapidly and coherently. By the Prime Meridian (0.0°E), $H_{1/10}$ values in the offshore zone already reach 3.5 to 4.0 m (Figure 60), indicating a sharp exposure gradient

with significant implications for coastal infrastructure in the transitional zone around 1.0°E to 0.5°E . A secondary localized attenuation is visible at the Gulf of Oran (about 35.8°N , 0.7°W), where the semi-enclosed geometry and the sheltering effect of the Canastel headland reduce mean H_s to 0.8 and 1.0m (Figure 62). Further east, approaching Mostaganem (approximately 35.9°N , 0.1°E) and the Chlef coastal plain (about 36.2°N , 1.3°E), conditions transition toward the moderate energy levels of the Central Sector, with $H_{1/10}$ in the 2.5 to 3.0 m range (Figure 60). The noticeably wider continental shelf in this part of the Western Sector allows more gradual wave energy dissipation, producing smoother spatial gradients across all three indicators compared to the abrupt transitions typical of the Central and Eastern sectors.

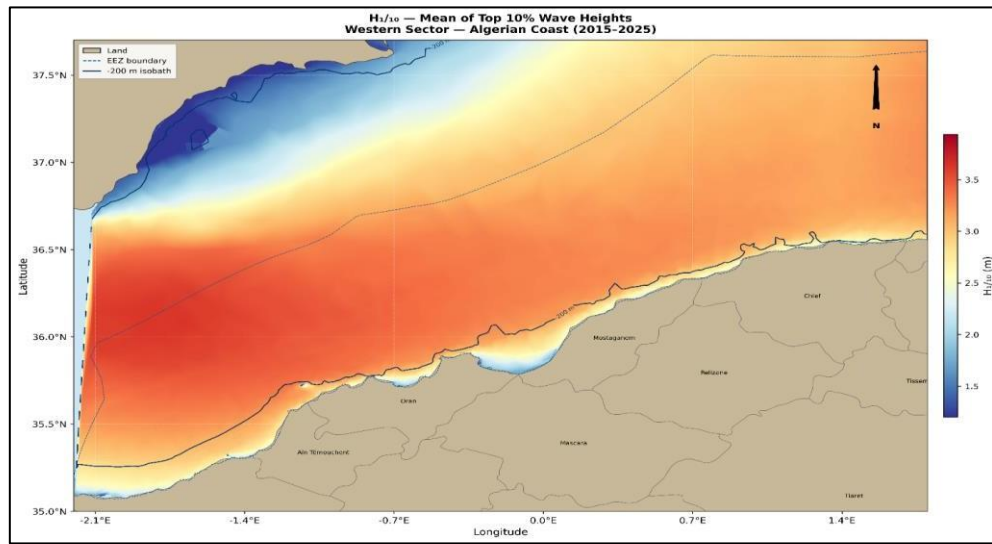


Figure 60: Mean of Top 10% Wave Heights($H_{1/10}$) of *Western Sector in Algerian Coast (2015–2025)*.

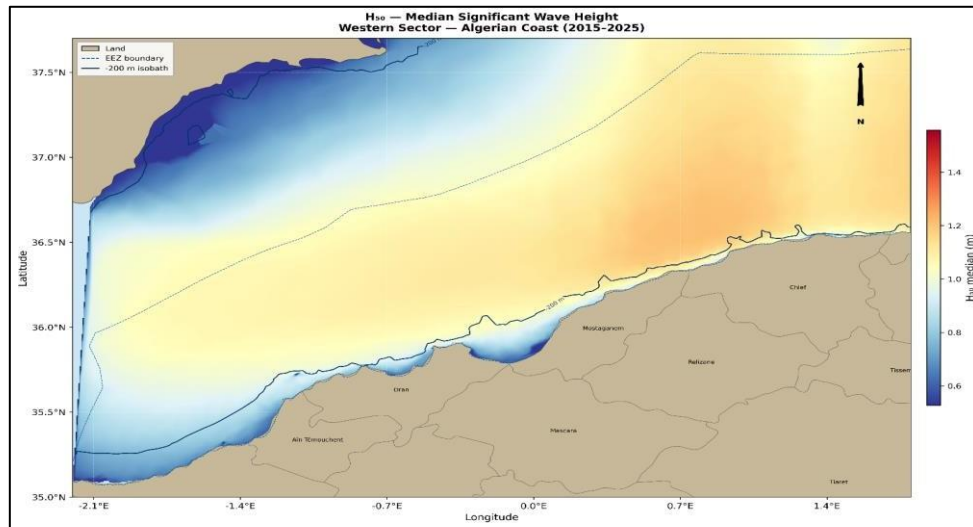


Figure 61: H_{s0} Median Significant Wave Heights Western Sector of Algerian Coast (2015–2025).

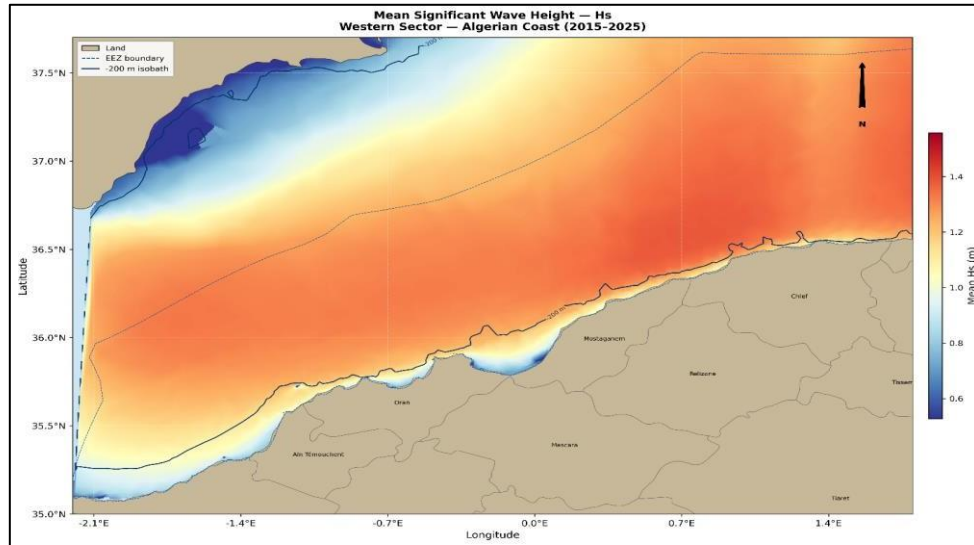


Figure 62: Mean Significant Wave Height (H_s) of Western Sector in Algerian Coast (2015–2025).

8. Site Suitability Assessment and Delineation of Priority Zones for Wave Energy Exploitation Along the Algerian –200 m Isobath:

Following the detailed interpretation of wave climate characteristics across the Algerian coastline, this section synthesizes the findings to delineate and assess the most favorable zones for wave energy exploitation. The objective is to identify regions along the –200 m isobath that exhibit optimal conditions for the deployment of wave energy conversion technologies, thereby guiding future strategic development. This assessment moves beyond raw data presentation to focus on the inherent exploitability of these identified areas, considering their consistent wave energy potential.

9. Delineation of Favorable Zones for Exploitation:

Based on the analysis of mean significant wave height (H_s) distribution, distinct areas emerge as particularly conducive to wave energy extraction across the Algerian coast. These zones are characterized by a sustained and robust wave climate taking account the values of H_s between (1.3m to 1.6m), rendering them highly exploitable for energy conversion. The identification of these priority areas is essential for directing subsequent technical and economic feasibility studies toward the most suitable zones.

9.1. Eastern Sector: High Potential for Large-Scale Development:

The Eastern Sector stands out as possessing the most extensive and consistently favorable zones for wave energy exploitation. As shown in (Figure 63), significant offshore expanses within the –200 m isobath, particularly along the coastlines of Jijel, Annaba, and El Taref, exhibit wave conditions demonstrably suitable for energy capture. These regions indicate a widespread and energetic wave

regime, suggesting a high potential for large-scale wave energy projects. The consistent presence of these optimal locations implies that the wave resource is not only substantial but also reliably available, making this sector a prime candidate for strategic investment and development in wave energy technologies.

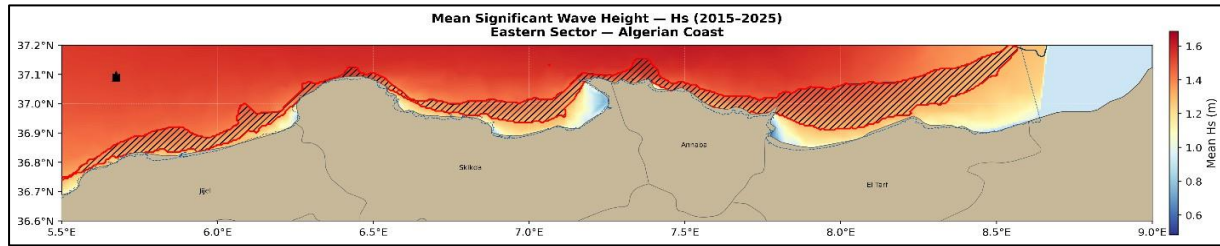


Figure 63: Mean Significant Wave Height of Eastern Sector along Algerian Coast (2015–2025)

9.2. Central Sector: Targeted Offshore Opportunities:

In the Central Sector, the assessment reveals specific offshore areas within the -200 m isobath that present favorable conditions for wave energy exploitation as shown on (Figure 64). While these zones may be more localized compared to the Eastern Sector, they nonetheless exhibit a wave climate that is consistently within an exploitable range. These strategically significant regions, typically situated further from immediate coastal influences, offer viable opportunities for targeted wave energy installations. Their identification underscores the potential for focused development efforts, where detailed site-specific analyses can optimize the deployment of wave energy converters.

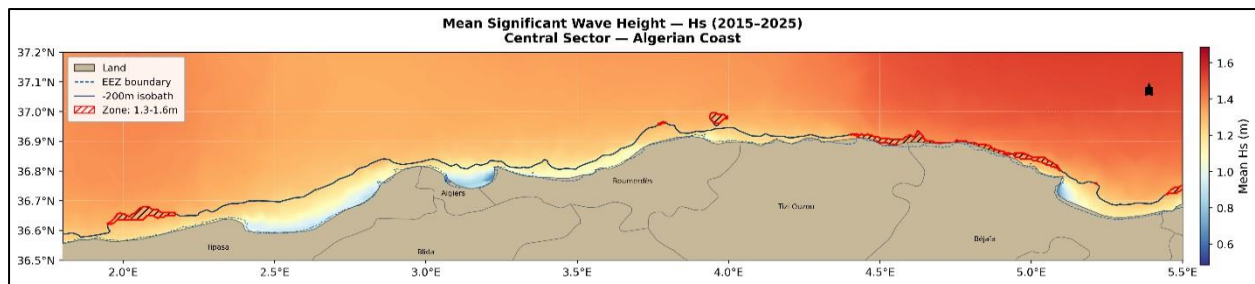


Figure 64: Mean Significant Wave Height of Central Sector along Algerian Coast (2015–2025).

9.3. Western Sector: Limited Potential and Localized Viability:

The Western Sector generally presents a more constrained distribution of favorable zones for wave energy exploitation, indicating a predominantly lower energy potential compared to other regions. As illustrated in (Figure 65), significant portions of its offshore areas within the -200 m isobath, particularly near the coastlines of Oran, Mostaganem, Ain Temouchent, and Tlemcen, exhibit wave conditions that are less energetic and thus less suitable for large-scale energy harvesting. While some

localized regions do show conditions sufficiently energetic for effective conversion, these areas are notably sparse and limited in extent. The presence of these small, distinct zones confirms that opportunities for developing wave energy projects exist, but they would necessitate a highly targeted approach, focusing on these specific viable locations to maximize efficiency and operational returns within a generally moderate to low wave climate.

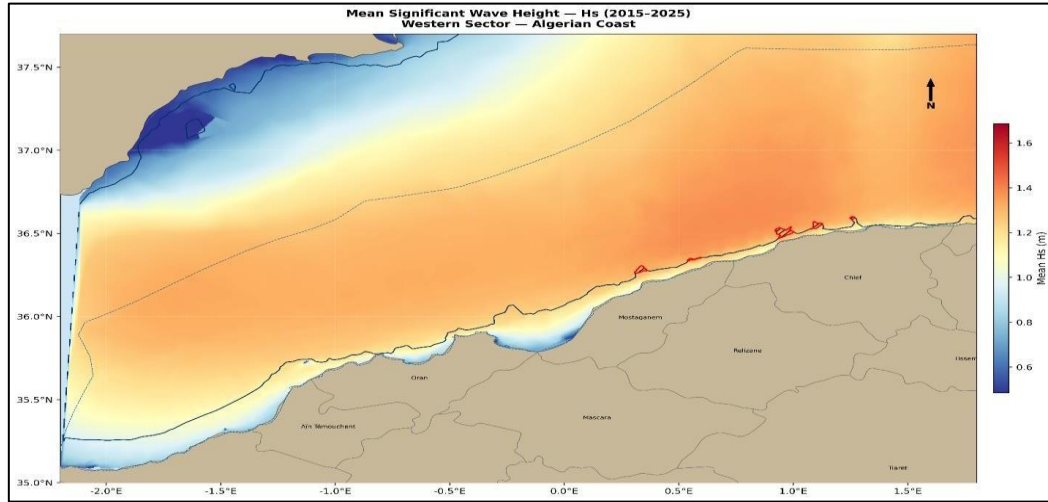


Figure 65: Mean Significant Wave Height of Western Sector along Algerian Coast (2015–2025).

10. Comparative Assessment of Wave Energy Potential Across Sectors:

Among the three sectors, the Eastern Sector exhibits the highest wave energy potential, with mean significant wave heights consistently between 1.4 and 1.6 m over extensive offshore areas, followed by the Central Sector with moderate values of 1.3 to 1.5 m confined to more localized zones. The Western Sector records the lowest energy levels, with H_s frequently below 1.3 m, limiting viable sites to isolated locations. This west-to-east increasing gradient confirms the Eastern Sector as the most suitable region for large-scale development, while the Central and Western sectors require a more targeted approach.

11. Partial conclusion:

This chapter presented the methodological framework adopted for wave climate assessment along the Algerian coast. The MIKE 21 Spectral Wave model was configured over the western Mediterranean domain using a flexible triangular mesh of 11,928 elements, forced by CERRA reanalysis wind data over the period 2015–2025. Bathymetric data were constructed from Navionics for the nearshore zone and GEBCO for offshore depths, integrated within ArcGIS before being incorporated into the computational mesh.

The simulation results reveal a west-to-east gradient of increasing wave energy across the Algerian EEZ. The Eastern Sector records the highest mean significant wave heights, ranging from 1.4 to 1.8 m, with the most spatially extensive exploitable zones along the –200 m isobath. The Central Sector presents intermediate conditions with localized offshore opportunities, while the Western Sector exhibits the most constrained energy regime, largely due to the sheltering effect of the Iberian Peninsula. These findings provide a spatially structured foundation for the site suitability assessment presented in the following chapter.

CHAPTER IV:
WAVE POWER ASSESSMENT

CHAPTER 04 :

1. Introduction and Justification of WEC Selection:

The selection of a suitable Wave Energy Converter (WEC) technology for a specific marine site is a critical engineering challenge. It requires a careful match between the device's operational characteristics, including rated power, design wave height, mooring configuration, and power take-off system, and the statistical properties of the local wave climate. In this study, the area of interest is located along the -200 m isobath of the Algerian Exclusive Economic Zone (EEZ), which corresponds to the outer limit of the continental shelf and the beginning of the continental slope. At these water depths, the installation of seabed-fixed structures becomes technically challenging and economically costly due to the complexity of foundation construction. Consequently, floating Wave Energy Converters represent the most practical and feasible option. These devices operate at the sea surface and are maintained in position using mooring lines and anchoring systems (energy & 2016, 2017).

The -200 m isobath was selected as the reference deployment zone for several technical and strategic reasons. First, it is located beyond the zone affected by depth-induced wave breaking and significant shoaling, allowing the full offshore wave energy resource, as characterized by the wave maps developed in this study, to be preserved at the deployment site. Second, a water depth of 200 m falls within the operational range of modern deep-water mooring systems, including tension-leg configurations such as the UMACK anchor system employed by CorPower Ocean, which has been successfully validated under comparable Atlantic conditions. Finally, the relatively short distance between the -200 m isobath and the Algerian coastline, typically 15–25 km along the central sector and 35–50 km in the western sector, helps keep submarine cable lengths within economically viable limits, reducing grid connection costs and improving the overall feasibility of wave energy developments.

Among the wave energy converter (WEC) technologies currently nearing commercial maturity, the CorPower Ocean C4 point absorber was selected as the reference device for this assessment for several reasons. It is one of the few WEC technologies for which full scale offshore deployment results have been published in peer-reviewed literature, demonstrating both successful electricity generation and survivability under severe Atlantic Ocean conditions. The device has also achieved a reported mass-to-energy ratio of approximately 300 tons per megawatt, representing a significant improvement over many earlier wave energy technologies. In addition, its tension-leg mooring system is well suited to

the deep-water conditions found along the Algerian shelf break. Another important advantage is the availability of detailed technical information, including product specifications, deployment experience, and future development plans, which have been made publicly accessible through both the company's documentation and peer-reviewed publications. These characteristics make the CorePower Ocean C4 a suitable and well-documented reference technology for evaluating the wave energy potential of the Algerian EEZ.²

2. CorePower Ocean C4 Technical Description:

2.1. Design Philosophy:

CorPower Ocean's wave energy converter is inspired by the operating principle of the human heart, which stores and releases energy to reduce the effort required during each pumping cycle. Similarly, the buoy uses a pneumatic pre-tension system that defines its equilibrium position and assists the downward motion after each upward stroke. This enables efficient bidirectional energy conversion while requiring active force generation mainly during the upward movement. The design also helps protect the power take-off system during severe sea states by naturally detuning the device from incoming waves.

During normal operation, the buoy is tuned to oscillate close to the resonance frequency of incoming waves through a combination of mechanical systems and control algorithms, maximizing energy capture. A key component is the WaveSpring technology, a pneumatic spring with a non-linear force displacement response that improves phase control and extends the operational bandwidth beyond that of conventional point absorbers.

The concept was initially validated through 1:16 scale tank tests at the Central School of Nantes and later demonstrated at full scale during Stage 3 dry tests at the European Marine Energy Centre (EMEC), where efficiencies approaching 99% were reported. This highly efficient resonance-control system is one of the main reasons for the high annual energy production of the CorPower Ocean C4 relative to its relatively low structural mass (Figure 66).

² [CorPower Ocean — 5X More Efficient Wave Energy Technology](#)

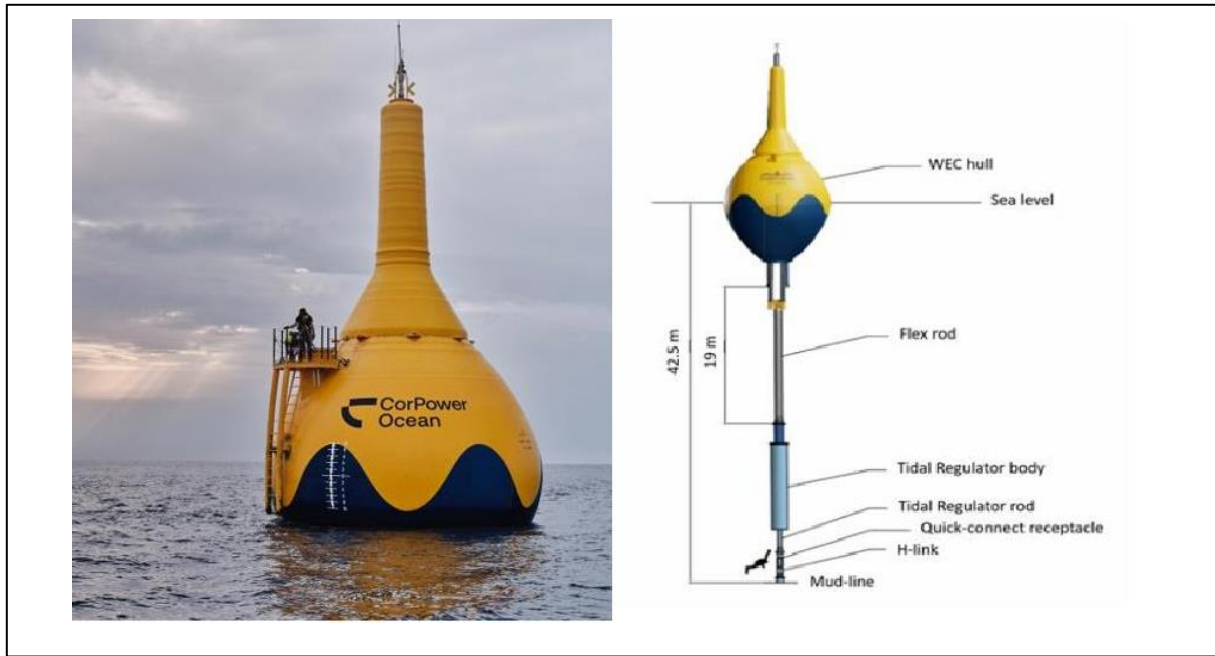


Figure 66 : CorPower Ocean C4 Wave Energy Converter: Full-Scale Device and Schematic Configuration of the Mooring and Power Conversion System.

2.2. Technical Data Sheet:

(Table 1). presents the complete technical data sheet of the CorPower Ocean C4 wave energy converter, as documented in the EWTEC 2025 proceedings (Dickson et al., 2025) ,and the CorPower Ocean product communications.

1.1 Category	Parameter / Specification	Value / Full Details
GENERAL IDENTIFICATION	Manufacturer	CorPower Ocean AB, Hågersten, Sweden
	Device designation	C4 WEC (4th generation)
	Technology class	oscillating body device ; Point absorber
	Operating principle	Heave-dominated oscillating buoy with WaveSpring phase control
	Development stage (2025)	Stage 4 complete: Stage 5 (pilot array) in progress
	Technology Readiness Level	TRL 7 (full-scale ocean-tested, 2023)

1.1 Category	Parameter / Specification	Value / Full Details
BUOY SPECIFICATIONS	Operational range (Hs)	0.25 to 8m
	Installation depth	40m
	Device rating	350kW
	Buoy diameter	9m
	Height	18m
	Weight	100tonnes
	Hull material	Light composite (fibreglass/carbon fibre)
	Total device mass (buoy + PTO + mooring)	≈ 300 te/MW (mass-to-energy ratio)
	Drive train location	Fully internal to the buoy hull
POWER TAKE-OFF (PTO) SYSTEM	PTO type	Cascaded gearbox: increases rotational speed from the slow wave-driven motion + direct-drive permanent-magnet generator
	Rated PTO capacity	300 kW (C4 dry test rated)
	Peak power demonstrated	600 kW (measured at Aguçadoura, Q4 2023)
	Controller type	Model-Predictive Control (MPC)
	WaveSpring efficiency	99% (measured in Stage 3 testing)
	Simulation model accuracy	96–99% goodness of fit (wave-to wire model vs. measured) Fig. 11.
SURVIVABILITY PERFORMANCE	Design extreme wave height	Cyclic loads up to 4 MN (400 te); dry-test verified

1.1 Category	Parameter / Specification	Value / Full Details
	Measured storm survivability	H _{max} = 18.5 m (Storm Domingos, Nov 4 2023 from IHPT record)
	Survival mechanism	Inherent detuning buoy sheds energy passively in storm waves
	Storms survived (first deployment)	4 majors storms, Q4 2023
ELECTRICAL SYSTEM	Grid connection standard	33/66 kV compatible with offshore wind grid standards
	Cluster configuration (CorPack)	10–30 MW per cluster hub
	Grid connection interface	Single fiber + radio-link control per hub
	Device control	Autonomous PLC per individual WEC device
DEPLOYMENT RECORD	First ocean deployment	Q3–Q4 2023, Aguçadoura test site, Portugal
	Grid export achieved	Yes, in Portuguese national grid, remote operation from Stockholm
	O&M access method	Internal ladder + hatch, verified offshore
	Next milestone	Stage 5: 4-device certified array, DNV-GL certification by 2027
COMMERCIAL ROADMAP	LCOE projection (2032)	≈ €70/MWh
	LCOE projection (2040)	≈ €40/MWh
	LCOE projection (2050)	≈ €30/MWh
	Commercial product availability	Certified and warrantied WEC product by 2027
	First commercial wave farm	Saoirse Project: 4.9 MW off County Clare, Ireland (by 2030)

Table 1 : Technical Fact Sheet: CorPower C4 (4th Generation).

2.3. Mooring and Anchoring system :

The system employs a tension-leg mooring configuration combined with a tidal regulation mechanism to ensure stability and maintain the buoy in its optimal position under varying sea conditions. The anchoring solution is based on the UMACK (Universal Marine Anchor Concrete Kelp) system, which is installed through a pull-down deployment method that eliminates the need for heavy-lift vessels, thereby reducing installation complexity and costs. The design is suitable for a broad range of water depths, from approximately 30 m to over 200 m, making it applicable to both intermediate and deep-water environments. The mooring system consists of two tension legs connected to the UMACK anchors through hinged joints, allowing controlled movement while preserving the overall stability and performance of the device.



Figure 67 : CorPower Ocean C4 Mooring and Anchoring System.source,(Dickson et al., 2025)

2.4. Structured Verification Programme:

The development of CorPower Ocean's wave energy technology follows the five-stage verification framework established by the IEA-OES. This structured progression ensures that technical milestones are met and risks are mitigated prior to commercial deployment. Stage 1 (2012–2013) involved initial concept validation through small-scale laboratory experiments at Universidade do Porto and KTH, confirming the theoretical basis for active phase-control. Stage 2 (2014–2015) focused on critical

system components, utilizing a 5 kW PTO prototype for dry and tank testing to establish the feasibility of the WaveSpring concept and the cascaded gearbox design.

The program transitioned to larger scales during Stage 3 (2015–2018) with the deployment of a 1:2 scale device at the European Marine Energy Centre (EMEC). This phase provided empirical data on survivability and confirmed the WaveSpring system's operational efficiency at 99%. Stage 4 (2018–2023) consisted of full-scale demonstration using the C4 prototype at the Aguçadoura site. Results included successful grid integration, peak power generation of 600 kW, and verified structural integrity during 18.5 m wave events (Storm Domingos), establishing a Technology Readiness Level of TRL 7. The final phase, Stage 5 (2024–2027), involves the deployment of a four-device pilot array at Aguçadoura. This stage is designed to validate array-scale performance and operational maintenance procedures, aiming for DNV-GL certification and commercial readiness by 2027.



Figure 68: CorPower Ocean's Five-Stage Technology Verification Roadmap (2012–2027).

2.5. Summary of Experimental Results: Aguçadoura Full-Scale Deployment (2023):

The full-scale deployment of the C4 prototype at the Aguçadoura test site provided critical empirical validation of the system's operational performance under real ocean conditions. The following key results, as documented in the EWTEC 2025 proceedings (Dickson et al., 2025), represent significant milestones for CorPower Ocean's technology:

- a. **Structural Resilience and Extreme Weather Survivability:** The device demonstrated exceptional robustness by successfully weathering four major Atlantic storms without any loss

of structural integrity or mooring failure. Most notably, during Storm Domingos (November 2023), the C4 survived a record-breaking maximum wave height of 18.5 m (H_{max}). The system's transition into a "passive detuned" survival mode effectively mitigated mechanical loads and machinery motions, validating the proposed survivability strategy.

- b. **Power Generation and Grid Integration:** A peak instantaneous power output of 600 kW was successfully exported to the Portuguese national grid. Operations were managed remotely from the Stockholm control center, demonstrating the reliability of the control and communication architecture across a wide range of sea states during the three-month deployment period.
- c. **High-Fidelity Numerical Model Validation:** A strong correlation was established between experimental data and the "wave-to-wire" digital twin simulation model. The goodness of fit for power conversion signals ranged between 96% and 99%, confirming the model's high accuracy in predicting machinery dynamics and energy yield across all tested conditions.
- d. **Breakthrough in Structural Efficiency:** The C4 WEC achieved a benchmark mass-to-energy ratio of 300 te/MW. This represents a significant technological leap, as this ratio is 5 to 10 times lower than that of previous wave energy converters (typically ranging from 1,500 to 3,000 te/MW), thereby proving the economic potential of the concept through reduced material intensity.
- e. **Validation of O&M Procedures:** Operational and maintenance (O&M) protocols were verified in situ, including safe internal access (via ladder and hatch) and the full disconnection and tow-back procedures for onshore servicing. These results confirm the logistical feasibility of large-scale commercial farm operations. (Dickson et al., 2025)

3. Wave Energy Resource Assessment at the –200 m Isobath:

3.1. Wave Climate Modelling Approach and Data Sources:

The wave climate characterization at the -200 m isobath presented in this chapter is based on high-resolution numerical simulation results generated using the MIKE 21 Spectral Waves (SW) module by DHI, as detailed in Chapter Numerical Modeling. The model was forced using the CERRA (Copernicus European Regional Reanalysis System) database and produced time series of significant wave height (H_s), energy period (T_e), and mean wave direction (θ) for the 2015–2025 reference period. The results were stored in NetCDF format at a spatial resolution strictly consistent with the bathymetric grid adopted for the Algerian continental shelf.

3.2. Definition of the Five Deployment Zones:

The Eastern Sector of the Algerian EEZ is subdivided into five offshore deployment zones delineated along the –200 m isobath, based on geographical position and proximity to coastal infrastructure. Their boundaries were defined using the GEBCO 2026 bathymetric contour, intersected with the Algerian coastline and the EEZ outer limit. As summarised in (Table 2) and illustrated in (Figure 69), the zones span from Jijel in the west (Zone 5) to El Tarf at the Tunisian border (Zone 1), covering a total area of approximately 2,902 km², with exposure levels ranging from very high fetch conditions in Zone 5 to moderately sheltered conditions in Zones 1 and 2. These contrasting characteristics directly influence the wave energy regime at each site, as discussed in the following sections.

Zone ID	Coastal Reference	Longitude Range	Area at -200m (Km ²)	Exposure Class
Zone 1	El Tarf (E border)	8.0E - 9.0E	~333 km ²	Moderate (Tunisian border sheltering)
Zone 2	Annaba	7.0E - 8.0E	~691 km ²	Moderate (Cap de Garde partial Shelter)
Zone 3	Skikda (Bay centre)	6.5E - 7.0E	~790 km ²	High (widest zone - most exposed)
Zone 4	Baie de Skikda (W)	6.0E - 6.5E	~395 km ²	High (NW open fetch)
Zone 5	Jijel (W extreme)	5.5E - 6.0E	~693 km ²	Very high (most exposed NW sector)
TOTAL	Eastern Sector	5.5E - 9.0E	~2,902 km ²	/

Table 2 : Summary of the Five Deployment Zones.

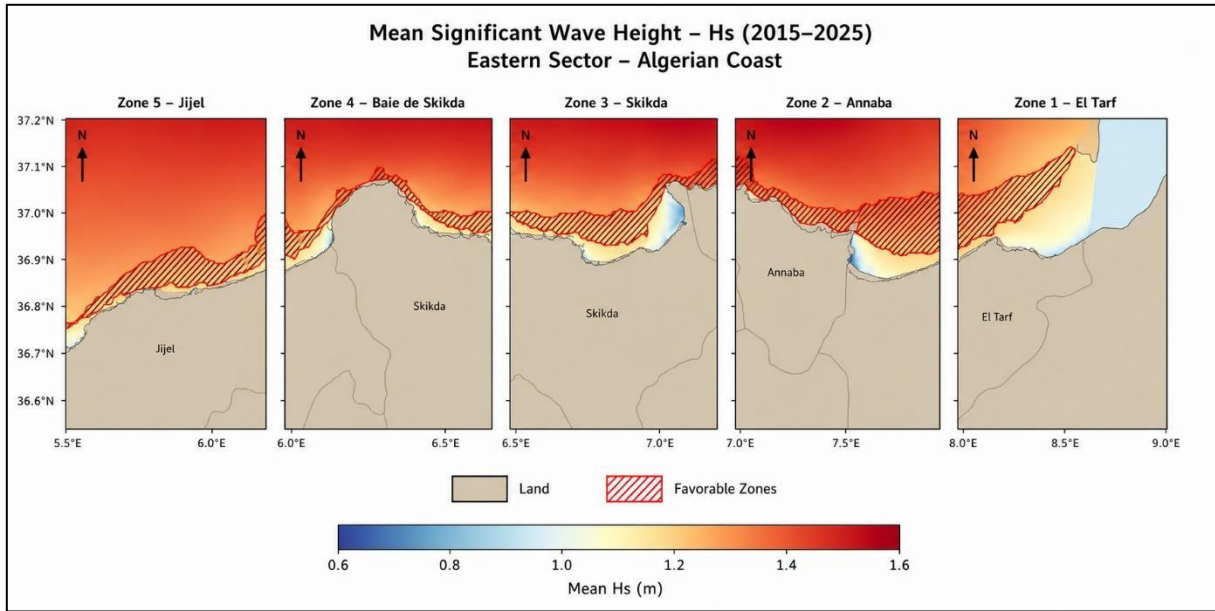


Figure 69: Mean Significant Wave Height along the Eastern Sector of the Algerian Coast, with the five offshore deployment zones delineated at the –200 m isobath (2015–2025)

4. Wave Power Calculation Methodology :

4.1. Standard Wave Power Density Formula:

The wave energy flux (power per unit crest width) at each deployment zone is computed from the spectral wave parameters extracted directly from the MIKE 21 SW simulation outputs. Following the standard deep-water approximation applicable at the –200 m isobath. As defined by the International Electrotechnical Commission technical specification IEC TS 62600-101, and derived from the conservation of energy flux in linear wave theory ($P = E \cdot c_g$), the standard formula for irregular seas in deep water is:

$$P = (\rho \times g^2 / 64\pi) \times H_s^2 \times T_e$$

Where: P = Wave power density (kW/m).

H_s = Significant wave height (m).

T_e = Energy period.

ρ = 1025 kg/m³ (seawater density).

4.2. CorPower C4 Power Matrix

The reference wave energy converter adopted for this assessment is the CorPower C4, a point-absorber device with a rated capacity of 400 kW and a nominal operational envelope spanning $H_s \in (0.25, 8.0)$ m and $T_p \in [2, 22]$ s. The device-specific power matrix P_{ij} [kW], giving the actual electrical output for each sea state $(H_{s,i}, T_{p,j})$, was digitised from the supplementary materials of (Figure S1) and is presented in [FigureFigure 70— CorPower C4 power matrix].

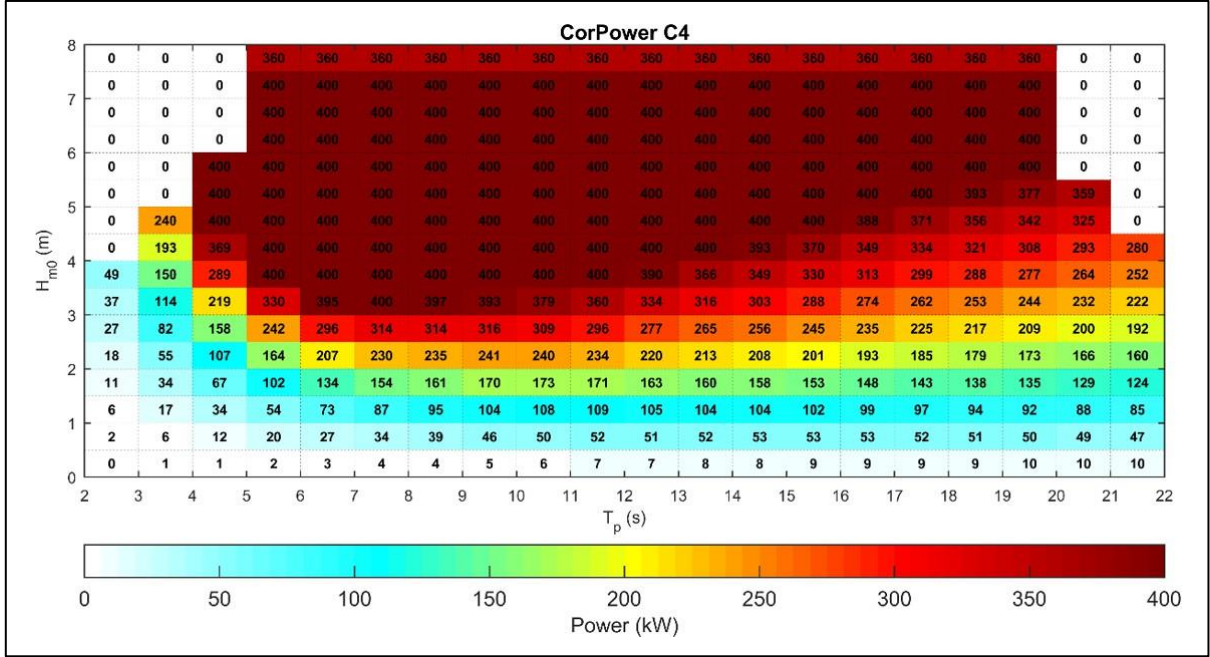


Figure 70: Power matrices of CorPower's C4. The matrix show case the power output per unit and per sea-state bin (x-axis: peak wave period, y-axis: significant wave height in spectral format), never exceeding the rated capacities of 400 kW.

4.1. Array Layout and Device Spacing within 1 km²:

The spatial arrangement of WEC devices within an array is governed by hydrodynamic, structural, and navigational constraints. The primary hydrodynamic constraint is the wake interaction between adjacent devices: if devices are spaced too closely, the wave shadow created by upstream devices significantly reduces the resource available to downstream devices, degrading overall array performance. Published array layout studies for point absorbers shows that the recommend minimum distance =100m . so In 1 km2 we will have 100 devices.

4.2. Interpretation for all five zones:

Across all five zones (El Tarf, Annaba, Bay of Skikda, Skikda, and Jijel), the wave energy matrices indicate that the most frequent sea states are consistently concentrated at low to moderate conditions,

typically with significant wave heights between 0.5 and 2.5 m and peak periods of 4 to 10 s. While these frequent conditions represent the baseline, the highest energy levels are associated with larger wave heights (2 to 5 m) and longer periods (8 to 13 s). Although these energetic sea states occur less frequently, they contribute most significantly to the annual wave energy potential in each region. The resource intensity generally increases from east to west, with Zone 5 (Jijel) exhibiting the highest energy potential, characterized by a prominent core of power levels exceeding 3.0 MWh·m⁻¹MWh·m⁻¹, while the other zones show a more moderate but reliable wave energy resource.

4.1. Sea-State Scatter Matrix and Occurrence Frequencies:

To characterise the joint distribution of sea states at each deployment zone over the 2015 to 2025 reference period, the 3-hourly time series of (Hs, Te) are discretised into a two-dimensional scatter matrix. The Hs axis is divided into bins of 0.5 m width spanning 0–8 m (16 bins), and the Te axis into bins of 1 s width spanning 2–22 s (20 bins), consistent with the bin structure of the CorPower C4 power matrix. For each bin (i, j), the mean annual occurrence frequency r_{ij} [h/yr] is computed as

$$r_{ij} = \frac{N_{ij} \cdot \Delta t}{N_{\text{years}}}$$

where N_{ij} is the number of 3-hourly time steps falling within bin (i, j), $\Delta t = 3$ h is the model output timestep, and $N_{\text{years}} = 10$ years is the simulation duration. Sea states with $H_s \leq 0.25$ m or $H_s > 8.0$ m are excluded from the scatter matrix prior to binning, as they fall outside the CorPower C4 operational envelope and therefore contribute zero power to the energy calculation.

Since the MIKE 21 SW model outputs the energy period T_e directly from the spectral moment ratio $T_{m-1,0}$, while the C4 power matrix is indexed by peak period T_p , a conversion is applied prior to bin assignment. The standard JONSWAP spectral relationship, appropriate for the swell-dominated and mixed sea conditions of the Mediterranean (Majidi et al., 2021), is used:

$$T_p = \frac{T_e}{0.90}$$

This relationship assumes a JONSWAP spectral shape with peak enhancement factor $\gamma = 3.3$, which is representative of fetch-limited and moderately developed seas such as those encountered along the Algerian EEZ. The resulting wave energy resource scatter matrices for the five deployment zones, showing the joint distribution of incoming wave energy flux $E_{ij} = J_{ij} \cdot r_{ij} / 10^3$ [MWh/m/yr] with occurrence frequencies [h/yr] annotated per cell, are presented in [Figure 71].

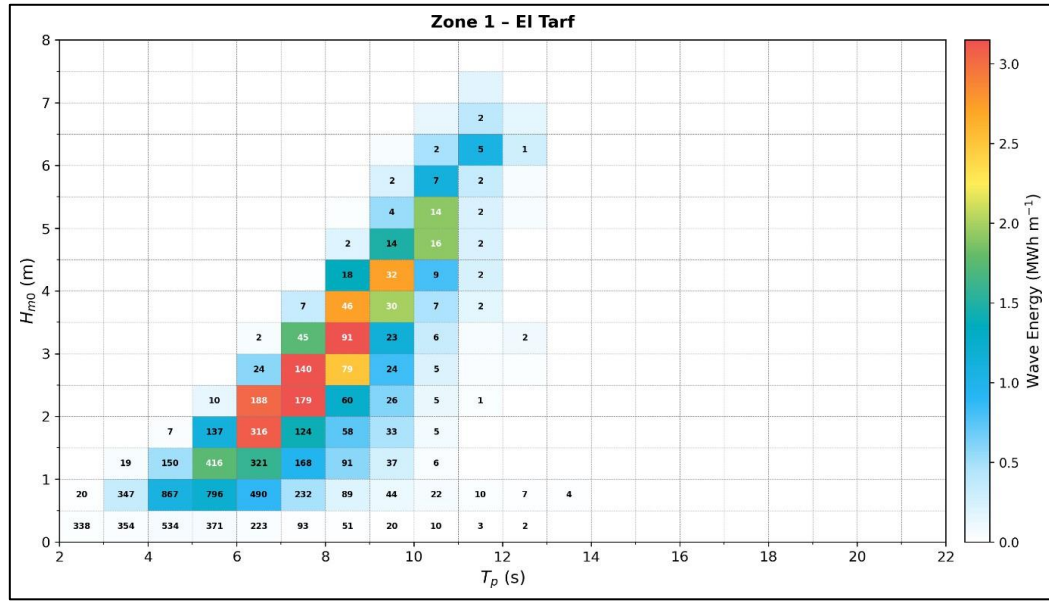


Figure 71: Joint Distribution of Wave Energy as a Function of Peak Wave Period and Significant Wave Height in Zone 1 (El Taref).

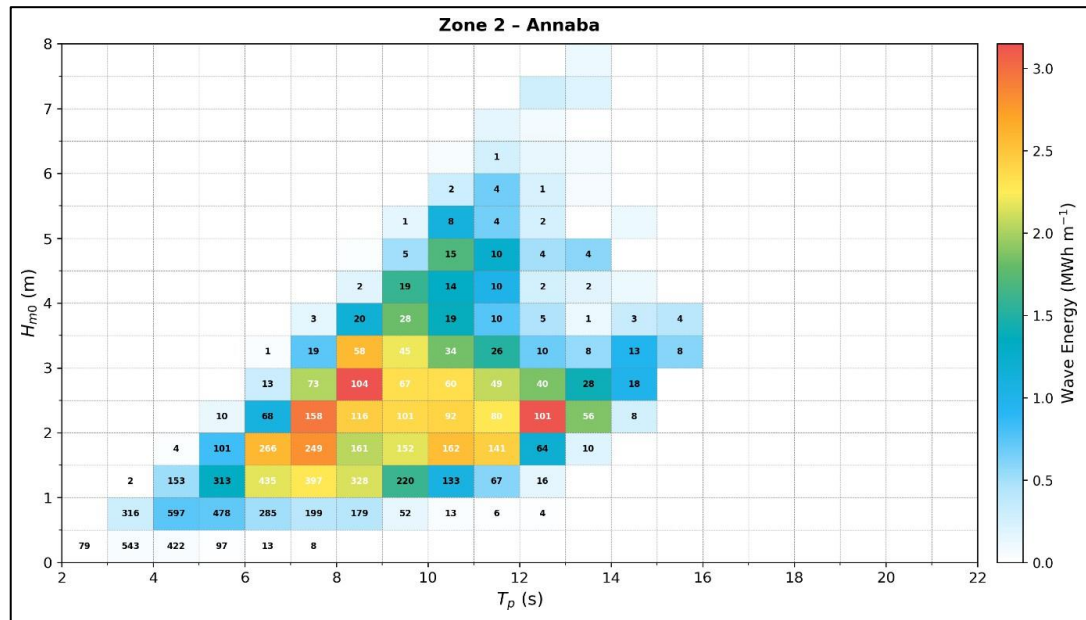


Figure 72: Joint Distribution of Wave Energy as a Function of Peak Wave Period and Significant Wave Height in Zone 2 (Annaba).

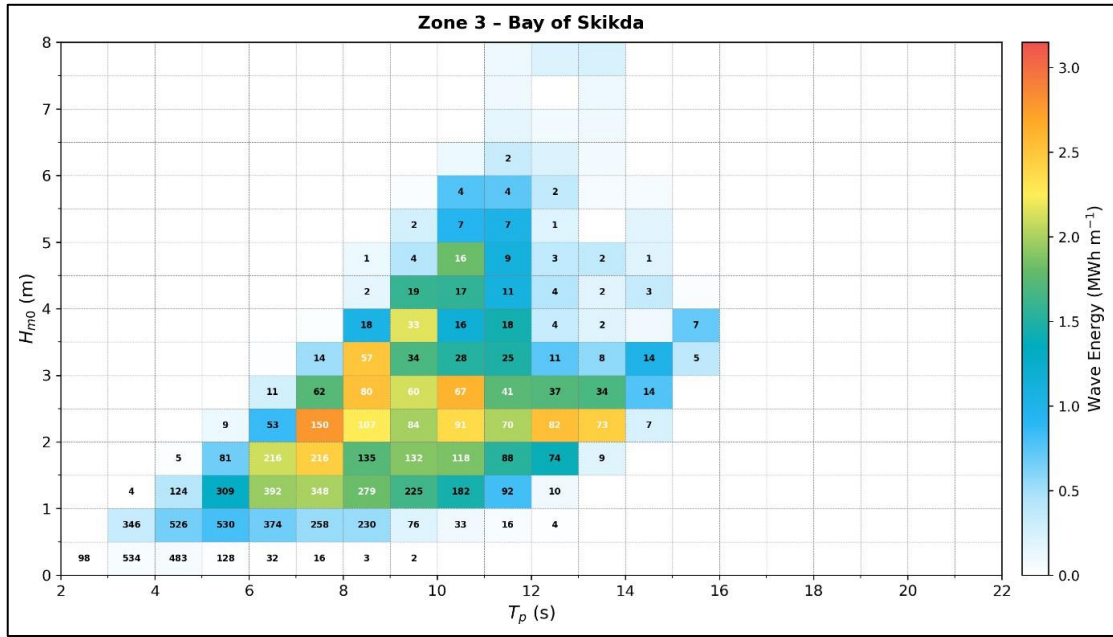


Figure 73: Joint Distribution of Wave Energy as a Function of Peak Wave Period and Significant Wave Height in Zone 3 (Bay of Skikda).

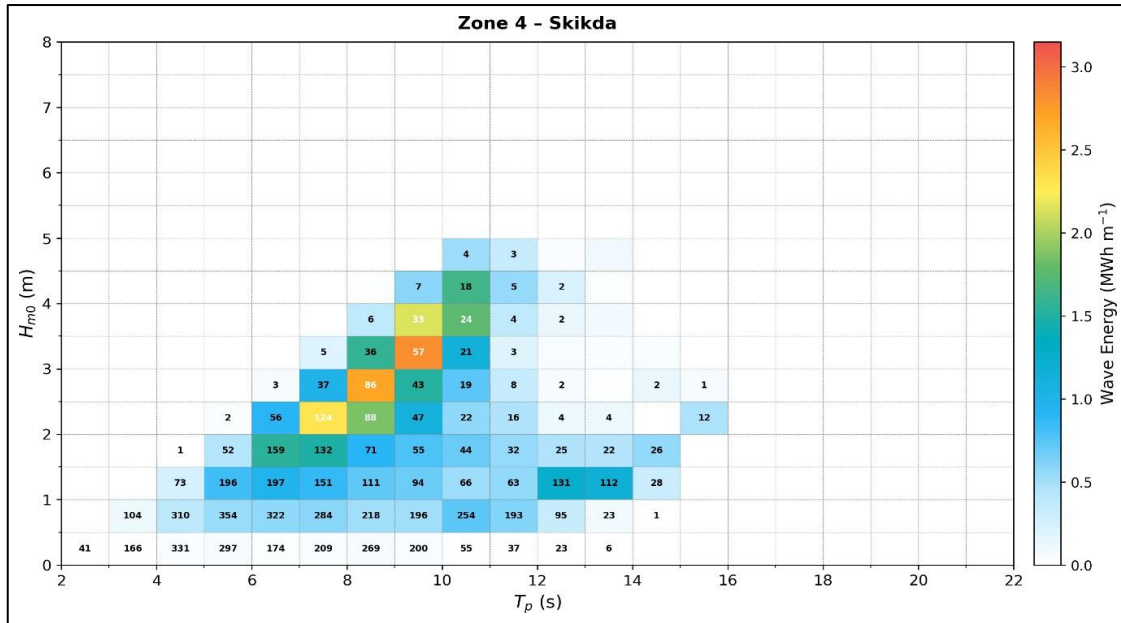


Figure 74: Joint Distribution of Wave Energy as a Function of Peak Wave Period and Significant Wave Height in Zone 4 (Skikda).

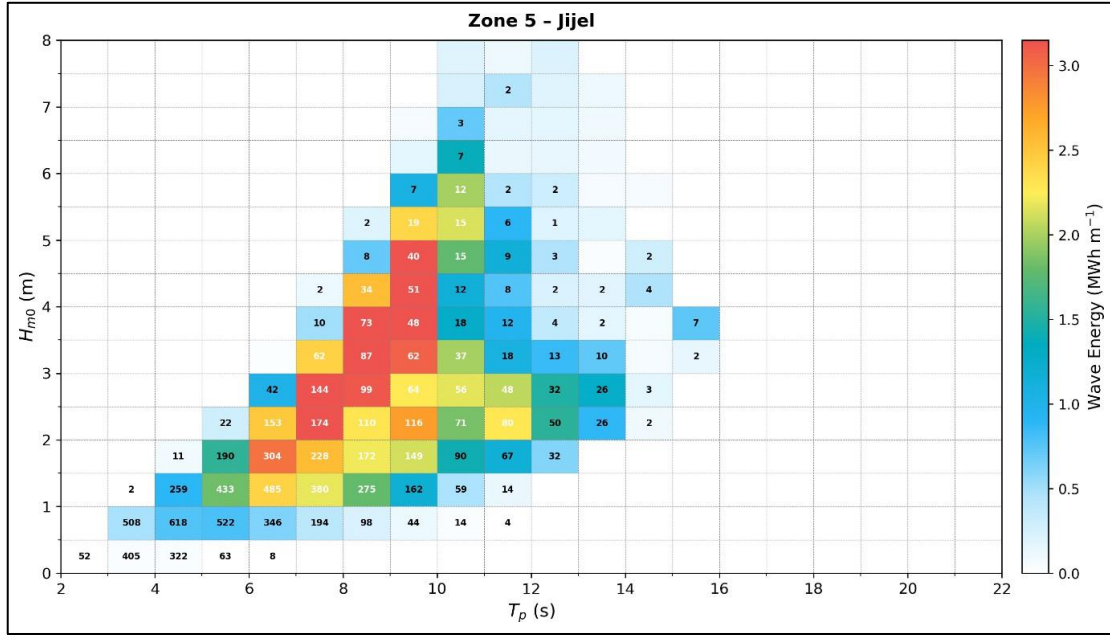


Figure 75 : Joint Distribution of Wave Energy as a Function of Peak Wave Period and Significant Wave Height in Zone 5 (Jijel).

4.2. Annual Energy Production

The Annual Energy Production (AEP) at each deployment zone is calculated by convolving the sea-state occurrence matrix r_{ij} with the C4 device power matrix P_{ij} , scaled by the total number of deployed devices N_d , following the methodology of Clemente et al. (2026, Eq. 5):

$$AEP = N_d \cdot \sum_{i,j} r_{ij} \cdot P_{ij}(H_s, i, T_p, j)$$

where N_d is the number of CorPower C4 devices deployed within the zone, determined at a layout density of 100 devices/km². This formulation accounts for the full variability of the wave climate across all sea states within the operational envelope

4.3. Capacity Factor:

The capacity factor (CF) quantifies the ratio of the mean realised power output to the rated device capacity, and serves as a dimensionless indicator of site-device compatibility. It is defined as (Majidi et al., 2021):

$$CF = \frac{\overline{P_{rated}}}{\overline{P}} \times 100[\%]$$

where the mean power $\overline{P}$ [kW] is derived from the AEP as:

$$\overline{P} = \frac{AEP_{single}}{8760} \quad \text{and} \quad P_{rated} = 350 \text{ kW is the nominal rated power of the CorPower C4 used.}$$

4.4. Results interpretation :

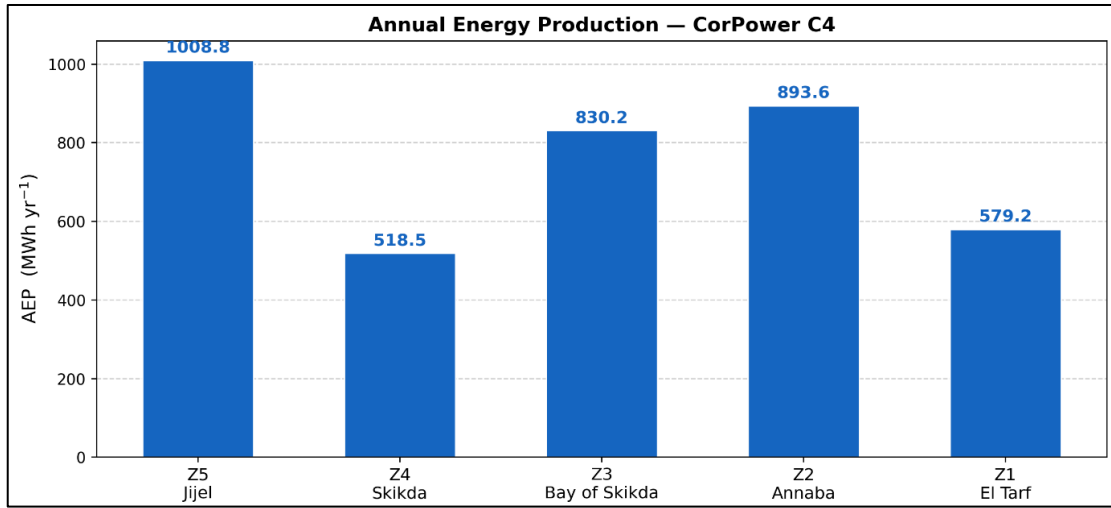


Figure 76: Annual Energy Production (CorPower C4).

The interpretation shows that the comparison of Annual Energy Production (AEP) for the CorPower C4 device across the five zones reveals significant variability in energy potential, with values ranging from approximately 518 to 1009 MWh yr⁻¹. Zone 5 (Jijel) stands out as the most productive site, achieving the highest AEP of 1008.8 MWh yr⁻¹, followed closely by Zone 2 (Annaba) at 893.6 MWh yr⁻¹ and Zone 3 (Bay of Skikda) at 830.2 MWh yr⁻¹. In contrast, Zone 4 (Skikda) and Zone 1 (El Tarf) show lower production levels, with 518.5 and 579.2 MWh yr⁻¹ respectively. These results highlight that while all zones possess wave energy potential, the westernmost zone (Jijel) and the eastern central areas (Annaba and Bay of Skikda) offer the most favorable conditions for maximizing the energy output of the CorPower C4 technology.

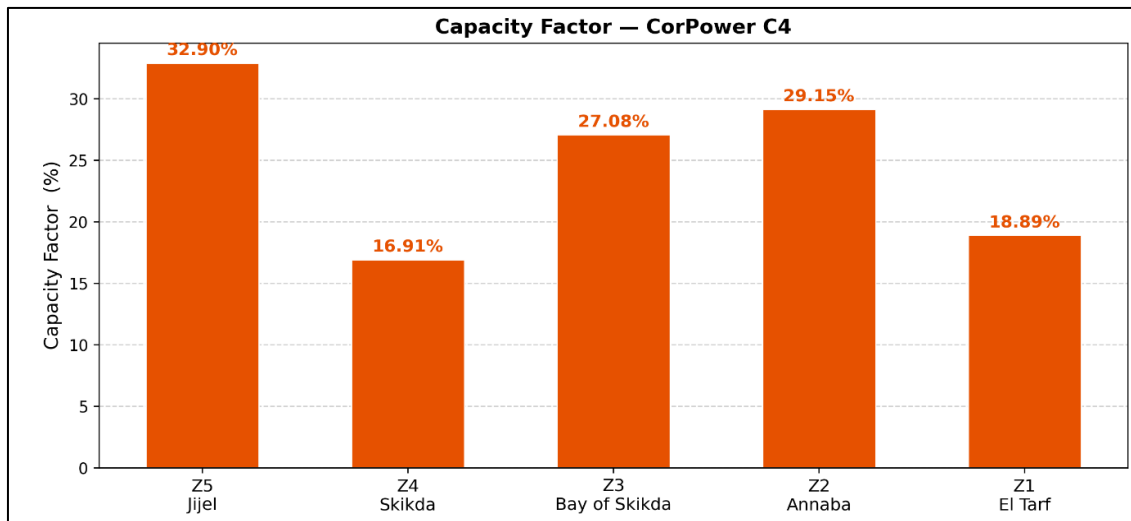


Figure 77: Capacity Factor (CorPower C4).

The capacity factor results for the CorPower C4 device confirm the spatial pattern observed in AEP, with values ranging from 16.91% to 32.90% across the five zones. Zone 5 (Jijel) records the highest capacity factor at 32.90%, indicating the most efficient utilization of the device's rated capacity, followed by Zone 2 (Annaba) at 29.15% and Zone 3 (Bay of Skikda) at 27.08%. Zone 1 (El Tarf) and Zone 4 (Skikda) show considerably lower capacity factors of 18.89% and 16.91% respectively, reflecting weaker and less consistent wave energy resources at these sites. Overall, these results reinforce that Jijel offers the most favorable conditions for the CorPower C4, operating at nearly twice the efficiency of the least productive zone, while the eastern central zones (Annaba and Bay of Skikda) remain attractive secondary options for deployment.

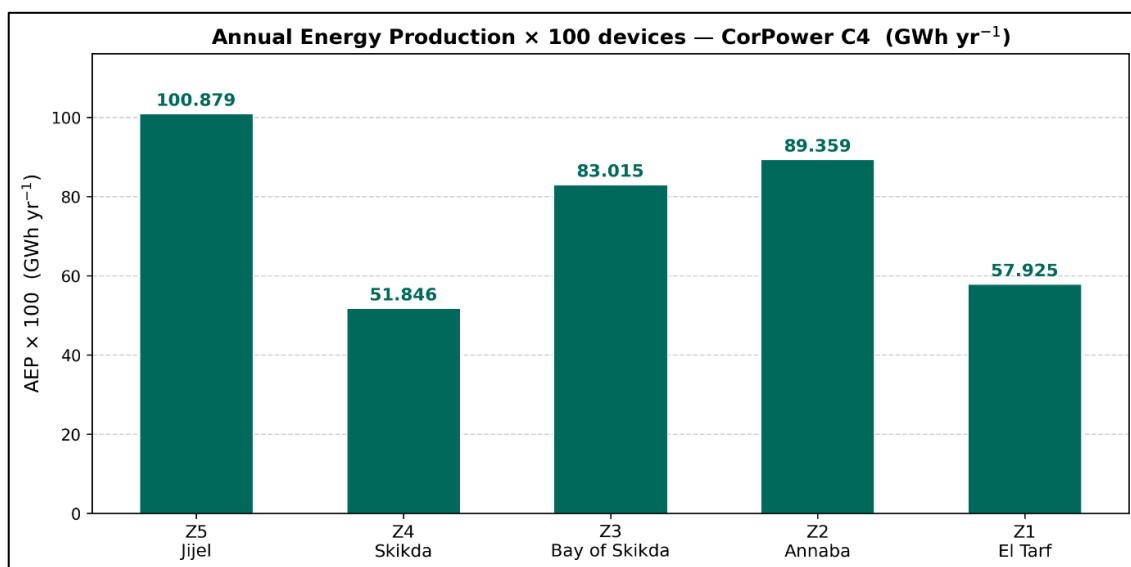


Figure 78: Annual Energy Production * 100 Devices (CorPower C4).

Scaling the AEP to a farm of 100 CorPower C4 devices illustrates the potential utility-scale energy yield across the five zones, with values ranging from 51.85 to 100.88 GWh yr⁻¹. Zone 5 (Jijel) again leads with a projected output of 100.88 GWh yr⁻¹, nearly double that of Zone 4 (Skikda), the lowest-performing site at 51.85 GWh yr⁻¹. Zone 2 (Annaba) and Zone 3 (Bay of Skikda) follow with 89.36 and 83.02 GWh yr⁻¹ respectively, confirming their status as strong secondary candidates, while Zone 1 (El Tarf) produces 57.93 GWh yr⁻¹. This scaled comparison underscores that deployment site selection has a major impact on farm-level energy output, with Jijel offering nearly twice the production capacity of Skikda for an equivalent number of installed devices.

5. Partial Conclusion :

This chapter presented the technical basis for assessing wave energy exploitation at the -200 m isobath, using the CorPower Ocean C4 point absorber as the reference converter. The choice of this device was justified by its validated full-scale performance, its favourable mass-to-energy ratio, and the suitability of its tension-leg mooring system for the deep-water conditions encountered along the Algerian shelf break. The wave power assessment methodology was then described, combining the sea-state occurrence matrices derived from the MIKE 21 SW simulations with the C4 power matrix to estimate the Annual Energy Production and capacity factor at each of the five deployment zones defined along the Eastern Sector.

The results confirm the west-to-east gradient identified in the previous chapter. Zone 5 (Jijel) achieves the highest AEP (1008.8 MWh/yr) and capacity factor (32.90%), reflecting its more energetic and consistent wave climate. Zones 2 and 3 (Annaba and Bay of Skikda) show intermediate but still favourable performance, with capacity factors above 27%, while Zones 1 and 4 (El Tarf and Skikda) record the lowest values, below 19%. When scaled to a farm of 100 devices, projected annual production exceeds 100 GWh/yr in Zone 5, nearly double that of Zone 4.

Overall, these results indicate that Zone 5, followed by Zones 2 and 3, offers the most favourable conditions for CorPower C4 deployment along the Algerian coast, providing a quantitative ranking that can support future site selection and development planning.

GENERAL CONCLUSION:

GENERAL CONCLUSION :

This study set out to assess the wave energy potential within the Algerian Exclusive Economic Zone, combining numerical wave modelling, statistical climate analysis, and techno-economic evaluation of wave energy conversion systems, with the ultimate aim of identifying viable deployment zones along the Algerian Mediterranean coast.

The MIKE 21 Spectral Wave model, forced by ten years (2015–2025) of CERRA reanalysis wind fields over an unstructured mesh of 11,928 nodes, provided a spatially detailed and physically consistent characterisation of the wave climate across the Algerian EEZ. The simulated wave parameters including mean significant wave height (H_s), energetic height ($H_{1/10}$), median fifty-year height (H_{50}), energy period (T_e), and wave power density revealed a clear west-to-east gradient in resource intensity, with the eastern coastal sector consistently exhibiting higher energy levels, driven by the predominance of north-to-north-easterly swells and the influence of the Algerian Current system.

Five candidate deployment zones were identified and assessed at the –200 m isobath along the eastern coastline, spanning from El Tarf (Zone 1) to Jijel (Zone 5). The annual energy production (AEP) was computed for each zone using the CorPower C4 point-absorber, employing a joint occurrence matrix of H_s and T_p over the full simulation period, combined with the manufacturer's power matrix. Zone 5 (Jijel) emerged as the most energetically favourable site, with an AEP of approximately **1,008.8 MWh/yr per device** and a capacity factor of **32.90%**, followed by Zone 2 (Annaba). Assuming uniform CorPack array deployment at 100 devices/km² with a 100-metre centre-to-centre spacing and an availability factor of 0.94, the aggregate production potential at Jijel reaches a level competitive with other Mediterranean wave energy sites documented in the literature

This work constitutes the first systematic, model-based assessment of wave energy potential specifically within the Algerian EEZ, and provides a quantitative foundation for integrating marine renewable energy into Algeria's national energy transition strategy under Law 04-09 and its subsequent amendments.

Research Perspectives:

- 1. Extension of the study to the central and western EEZ sectors:** the present analysis focused on five eastern zones. Future work should extend the deployment suitability framework to the central (Béjaïa–Alger) and western (Oran–Tlemcen) sectors to produce a nationally comprehensive atlas of exploitable wave energy sites.
- 2. Validation of the MIKE 21 SW model with in-situ measurements:** the numerical results should be validated against buoy records or satellite altimetry data (e.g., Copernicus CMEMS) to quantify model uncertainty, particularly for extreme sea states relevant to structural design.
- 3. High-resolution nearshore modelling for selected sites:** nested high-resolution model focusing on the Jijel and Annaba nearshore should be developed to account for bathymetric refraction, diffraction, and coastal interactions that the regional model does not resolve at device scale.
- 4. Techno-economic feasibility study and LCOE assessment:** the AEP figures obtained should serve as input for a full levelised cost of energy (LCOE) analysis, incorporating CAPEX, OPEX, installation costs, and grid connection infrastructure, to evaluate economic competitiveness against conventional and other renewable sources in the Algerian context.
- 5. Environmental impact assessment:** dedicated study of the ecological interactions between WEC arrays and the local marine environment including effects on benthic habitats, sediment transport, and migratory species is essential before any permitting process.
- 6. Grid integration and storage studies :** Given the intermittent nature of wave energy, a power systems study assessing the integration of wave energy output with the national grid, potentially combined with other marine renewables (offshore wind) or storage, is recommended to evaluate the realistic contribution of this resource to Algeria's energy mix.
- 7. Exploration of complementary WEC technologies:** this study was limited to the CorPower C4 point-absorber. Comparative assessment of other mature technologies particularly oscillating water column (OWC) devices adapted to Mediterranean swell characteristics , could reveal site-specific advantages at certain locations along the Algerian coast.

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ANNEXES:

Annexe:

Business model Canvas

***Création d'un bureau d'études en ingénierie
maritime et énergies renouvelables offshore :
HoulEole Ingénierie***

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2025-2026

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Introduction

L'Algérie, traditionnellement positionnée comme un acteur majeur des énergies fossiles en Méditerranée, se trouve aujourd'hui à un tournant stratégique de son histoire énergétique. Face à l'impératif mondial de décarbonation et à la nécessité de diversifier son économie, le pays dispose d'un atout considérable : un littoral de plus de 2148 km doté d'un potentiel en énergies marines renouvelables (EMR) encore largement inexploité. Si l'accent a jusqu'à présent été mis sur le solaire terrestre, les technologies offshore notamment l'éolien en mer et l'énergie houlomotrice (énergie des vagues) offrent des perspectives industrielles et énergétiques exceptionnelles.

Ces ressources marines représentent une opportunité unique pour propulser la transition vers l'hydrogène vert, un vecteur énergétique d'avenir pour lequel l'Algérie ambitionne de devenir un hub régional à destination de l'Europe. Cependant, le développement d'installations offshore de grande envergure nécessite une maîtrise parfaite des conditions météo-océaniques, des contraintes géotechniques et des impacts environnementaux. C'est dans ce contexte que s'inscrit la création de notre bureau d'études spécialisé. En combinant l'évaluation de pointe des potentiels éolien et houlomoteur avec des prestations d'ingénierie et d'études maritimes standards, notre structure vise à devenir le partenaire technique de référence pour les développeurs, les industriels et les institutions publiques engagés dans l'économie bleue en Algérie.

I. Présentation du Projet

I.1. Idée du projet (solution proposée)

HoulEole ingénierie est un bureau d'études et de conseil basé à Alger, structuré sous la forme juridique d'une SARL et agréé par le Centre National du Registre du Commerce (CNRC) sous le **code d'activité 607007 – Bureau d'ingénierie et d'études techniques**. Dans le domaine de l'ingénierie et du conseil en énergies marines et environnement. Né du constat des limites des méthodes conventionnelles en Algérie souvent coûteuses, gourmandes en énergie et freinées par un manque crucial de données actualisées et d'expertise locale intégrée, ce projet pionnier apporte une alternative hautement écologique, économique et durable. En combinant des campagnes de mesures *in situ* de haute précision avec des outils de modélisation numérique avancés (tels que MIKE 21, SWAN) et des solutions géospatiales de pointe (ArcGIS Pro, Python), l'entreprise traduit les données brutes de vent, de vagues et de courants en cartographies opérationnelles et

analyses de productible fiables. Le cœur de métier de **HoulEole ingénierie** réside dans la validation de la faisabilité technique et de la viabilité économique de projets complexes et innovants le long du littoral algérien notamment le couplage de parcs hybrides offshore (éolien et houlomoteur) avec des unités de dessalement d'eau de mer ou des électrolyseurs pour la production d'hydrogène vert tout en garantissant la maîtrise des études maritimes standards indispensables à tout aménagement côtier, telles que l'hydrodynamique, la sédimentologie et l'évaluation des impacts environnementaux.

I.2 Les valeurs suggérées

Notre bureau d'études fonde sa proposition de valeur sur quatre piliers fondamentaux :

- **Précision et Rigueur Scientifique** : Utilisation de modèles numériques de pointe et de données historiques fiables (réanalyses multi-décennales) pour minimiser les risques d'investissement des développeurs (réduction des incertitudes sur le LCOE/LCOH).
- **Souveraineté Énergétique et Expertise Locale** : Offrir une alternative locale aux cabinets de conseil étrangers, réduisant ainsi les coûts pour nos clients tout en développant un savoir-faire algérien hautement qualifié.
- **Innovation Durable** : Promouvoir des solutions hybrides innovantes et respectueuses des écosystèmes marins et littoraux (préservation de la biodiversité, gestion de la dynamique sédimentaire).
- **Approche Clé en Main** : Accompagner le client de la phase de préfaisabilité et d'identification des sites pilotes jusqu'à l'assistance technique lors de la phase de conception.

I.3 L'équipe (Les Étudiants)

Ce projet de fin d'études est mené par un groupe d'étudiants de la spécialité Génie Côtier et Aménagement du Littoral de l'ENSSMAL. Chaque membre apporte une expertise complémentaire et des compétences consolidées tout au long d'un cursus rigoureux, renforcé par des applications pratiques et une vision stratégique du domaine marin et de l'énergie offshore :

- **BELMAMOUN ALAA** : Dotée d'une expertise pointue en géomatique, elle est spécialisée dans la cartographie numérique et la mise en œuvre des Systèmes d'Information

Géographique (SIG). Son travail de fin d'études lui a permis de consolider des compétences pratiques de haut niveau dans le traitement de données spatiales et le développement d'outils de visualisation. Elle maîtrise l'élaboration de modèles d'aide à la décision, essentiels pour cartographier les zones d'exclusion et identifier avec exactitude les sites d'implantation potentiels du projet.

- **BRIKI SAHAR** : Spécialisée dans les aspects de l'aménagement du littoral et de la gestion intégrée des zones côtières, elle a développé une expertise approfondie dans l'analyse réglementaire et l'évaluation de la vulnérabilité des côtes. Son parcours lui permet d'anticiper et de mesurer avec rigueur les impacts environnementaux des installations marines. Grâce à sa maîtrise des cadres légaux et des critères de durabilité, elle veille à la parfaite intégration écologique et administrative des solutions proposées.
- **CHERFII NABIL** : Passionné par les technologies marines renouvelables, il s'est spécialisé dans le volet énergétique offshore et la transition bas-carbone. Ses compétences techniques englobent le traitement avancé des bases de données météo-océaniques et la configuration technique des systèmes hybrides (éolien et houlomoteur). Son esprit d'analyse et sa maîtrise des calculs de productibilité énergétique lui permettent de concevoir des architectures d'approvisionnement optimales et adaptées aux conditions marines réelles.
- **MEKKI AHLEM** : Au cours de son cursus en ingénierie côtière, il a acquis des compétences pointues en dynamique sédimentaire et océanique. Chargé principalement de l'analyse des processus hydrodynamiques, de la modélisation de la propagation de la houle et des interactions fluide-structure en zone côtière, ses travaux s'appuient sur une solide maîtrise des outils de simulation. Ses expériences académiques et pratiques lui permettent d'évaluer avec précision le comportement des structures marines face aux forces météo-océaniques, un élément clé pour garantir la viabilité technique du projet.

L'équipe a su conjuguer ces compétences techniques spécialisées avec une approche transverse de la gestion de projet et une sensibilité aux enjeux d'innovation, garantissant ainsi une exécution efficace, scientifique et structurée de ce projet d'aménagement et d'énergie offshore.

I.4 Les activités clés

Dans le cadre de ce mémoire, nos activités se structurent autour de cinq axes principaux :

- **Caractérisation du Climat Maritime** : Analyse des chroniques de houles et de vents (données de bouées, réanalyses) pour déterminer le potentiel énergétique brut.
- **Modélisation Numérique Côtière** : Simulation de la transformation des vagues du large vers la côte (réfraction, déferlement) pour évaluer les sollicitations sur les structures.
- **Cartographie Thématique SIG** : Superposition des contraintes environnementales et techniques (bathymétrie, nature des fonds, zones protégées) pour le choix des sites.
- **Couplage Énergie et Aménagement** : Étude d'impact hydro-sédimentaire du sillage des parcs offshore sur la dynamique sédimentaire des plages adjacentes.
- **Évaluation d'Ingénierie de Procédés** : Analyse conceptuelle de la connexion des systèmes marins aux infrastructures terrestres (dessalement de l'eau, électrolyseurs).

I.5 Planning de réalisation du projet (PFE)

Tableaux I.1 – Planning de réalisation du projet

Phases	Tâches	Durée (Mois)				
		1	2	3	4	5
Phase 1	Élaboration du plan détaillé du projet, analyse des besoins du secteur énergétique algérien, recherche bibliographique sur les EMR (éolien offshore et houlomoteur).	X				
Phase 2	Centralisation et traitement des données météo-océaniques brutes (chroniques de houles/vents) et acquisition des données bathymétriques.	X				
Phase 3	Structuration des bases de données géospatiales sous SIG et exécution des scripts de traitement pour cartographier les contraintes littorales.		X			
Phase 4	Configuration, calibration et exécution des modèles de propagation numérique de la houle du large vers la côte (SWAN, MIKE 21).	X				
Phase 5	Analyse d'impact hydro-sédimentaire, évaluation des Interactions fluide-structure et dimensionnement préliminaire des scénarios d'aménagement.		X			
Phase 6	Évaluation de l'ingénierie de procédés (couplage des parcs aux électrolyseurs pour l'hydrogène vert et aux unités dessalements) et synthèse.	X				

II. Nature des innovations

- **Innovation du marché** : Introduction d'une solution intégrée d'ingénierie numérique et cartographique pour l'évaluation fine du gisement éolien offshore et houlomoteur le long du littoral algérien, répondant à un besoin critique et non satisfait des opérateurs énergétiques nationaux et des investisseurs internationaux pour le développement de la filière hydrogène vert.
- **Innovation incrémentale** : Amélioration continue des algorithmes de calcul (Lois de Weibull) et mise à niveau de nos logiciels de simulation hydrodynamique côtière pour optimiser la précision des livrables et réduire les temps de traitement informatique au fil des projets.
- **Innovation radicale** : Développement de méthodologies d'évaluation basées sur l'hybridation des ressources (couplage éolien flottant et énergie des vagues) combinées à la modélisation du Nexus Énergie-Eau (dessalement direct pour alimentation d'électrolyseurs), offrant une alternative radicale et stable aux études de faisabilité énergétique conventionnelles terrestres.
- **Innovation technologique** : Utilisation d'outils numériques avancés de modélisation côtière spectrale (MIKE 21) et de planification spatiale multicouches sous SIG (ArcGIS Pro) pour concevoir des configurations d'installations offshore hautement performantes, sécurisées face aux tempêtes et respectueuses des zones d'exclusion écologiques ou industrielles.

III. Analyse stratégique du marché

III.1 Le segment du marché

Notre bureau cible quatre segments de clientèle prioritaires :

Segment 1 : Institutions publiques, ministères et agences étatiques : Ministère de l'Énergie, Ministère de l'Hydraulique, Ministère de l'Environnement, SONATRACH, SONEGAS, APRUE, LEM et ANRH. Ces acteurs majeurs expriment un besoin critique en études de préfaisabilité et en cartographies thématiques pour orienter la feuille de route de la Stratégie Nationale Hydrogène Vert (2040) et planifier l'espace maritime algérien.

Segment 2 : Industriels et développeurs de projets énergétiques : Consortiums nationaux et internationaux souhaitant concevoir et implanter des parcs hybrides offshore (éolien flottant et houlomoteur) couplés à des électrolyseurs ou à des systèmes de dessalement d'eau de mer (SWRO).

Segment 3 : Acteurs des Travaux Publics et aménageurs du littoral : Entreprises de dragage, autorités portuaires et collectivités locales nécessitant des prestations d'ingénierie maritime standard (études de propagation de la houle, conception de digues, modélisation de la sédimentation, études d'impact environnemental).

Segment 4 : Opérateurs de l'eau et du dessalement : L'AEC (*Algerian Energy Company*) et les exploitants de stations de dessalement par osmose inverse. Ils constituent un marché naturel pour nos études de couplage énergétique offshore (visant à décarboner leur procédé très énergivore) et nos diagnostics techniques sur les infrastructures côtières (conduites de prise d'eau de mer et de rejet de saumure face au transport sédimentaire).

III.2 Mesure de l'intensité de la concurrence

Entreprise	Description	Forces	Faiblesses
LEM (Laboratoire d'Études Maritimes)	Entreprise publique algérienne de référence sous tutelle du Ministère des Travaux Publics, spécialisée dans l'ingénierie maritime, portuaire et côtière.	Leader historique incontestable ; accès exclusif aux données bathymétriques et hydrodynamiques d'État ; forte expérience en infrastructures portuaires.	Structure rigide ; focus quasi exclusif sur les travaux publics conventionnels (digues, ports) ; expertise limitée sur les EMR (éolien en mer, houlomoteur).
CNERIB / Centres de Recherche Nationaux	Centres d'études et de recherche étatiques travaillant sur le génie civil, l'aménagement du territoire et le littoral.	Forte base de données techniques ; adossement réglementaire solide ; maîtrise de la géotechnique côtière.	Processus bureaucratiques lents ; missions principalement orientées vers la recherche publique plutôt que l'ingénierie commerciale agile pour le secteur privé.
ANRH (Agence Nationale des Ressources Hydrauliques)	Établissement public cartographiant et analysant les ressources en eau, incluant la frange littorale et le suivi sédimentaire.	Banque de données historiques immense sur l'hydrologie et la dynamique côtière algérienne ; expertise terrain reconnue.	Focalisation historique majeure sur les ressources terrestres (barrages, nappes) ; manque d'outils dédiés aux technologies énergétiques offshore.
Grands Cabinets Privés Algériens (ex: SIDEM ou équivalents ingénierie)	Bureaux d'études nationaux de grande envergure intervenant dans le secteur des infrastructures industrielles et hydrauliques.	Grande flexibilité commerciale ; maîtrise parfaite des études d'impact environnemental (EIE) et des procédures d'agrément en Algérie.	Dépendance technologique vis-à-vis des logiciels étrangers ; compétences centrées sur le terrestre et le dessalement standard sans maîtrise du Nexus EMR-Hydrogène.

III.3 La Stratégie Marketing

Pour atteindre efficacement nos clients et établir une présence solide sur le marché algérien, nous suivrons les étapes suivantes :

- **Participation à des Salons et Foires Industrielles :** Participer à des événements industriels et énergétiques majeurs pour présenter nos solutions d'ingénierie offshore à un public ciblé et établir des contacts stratégiques. Notamment :
 - Salon ERA (Salon International des Énergies Renouvelables, de l'Environnement et du Développement Durable).
 - NAPEC (North African Petroleum Exhibition & Conference — essentiel pour Sonatrach et l'hydrogène vert).
 - SIEE Pollutec (pour le Nexus Eau-Énergie et le contact avec l'AEC et les acteurs du dessalement).
- **Collaborations avec des Institutions Académiques et de Recherche :** Travailler en étroite synergie avec des universités et centres de recherche nationaux d'excellence (ENSSMAL, CDER, USTHB) pour co-développer des méthodologies de calcul, valider la précision de nos modèles numériques côtiers et promouvoir l'expertise locale qualifiée.
- **Partenariats Stratégiques :** Collaborer avec des entités clés et des acteurs du secteur pour intégrer nos expertises maritimes standards et nos études de gisement dans leurs grands projets d'aménagement (ex: partenariats techniques avec des développeurs d'infrastructures ou des bureaux d'études environnementales pour porter ensemble des dossiers d'envergure).
- **Publicité en Ligne :** Utiliser des campagnes ciblées sur LinkedIn Ads et Google Ads en configurant des mots-clés hautement techniques (*LCOE offshore, modélisation MIKE 21 Algérie, production hydrogène vert, étude d'impact littoral*) afin de toucher directement les directeurs techniques, chefs de projets et décideurs des ministères et grands groupes (Sonatrach, Sonelgaz, AEC).
- **Réseaux Sociaux et Présence Digitale :** Créer et maintenir des profils actifs sur LinkedIn (le réseau B2B par excellence) pour partager des livres blancs techniques, des cartographies

thématiques issues de nos simulations, et des notes d'analyse sur la transition énergétique en Méditerranée. Concevoir et mettre en ligne un Site Web Institutionnel vitrine, intégrant un portfolio de nos compétences en hydrodynamique et sédimentologie.

- **Canaux de Distribution** : Vente Directe (B2B) en démarchant et en s'approchant directement des industries cibles, des exploitants de stations de dessalement (SWRO) et des institutions étatiques. Réponse rigoureuse aux appels d'offres nationaux et internationaux pour les études maritimes standards et de planification spatiale.

Programme de fidélisation (HoulEole Elite Partners)

L'objectif de ce programme est d'assurer une satisfaction maximale, d'asseoir notre rôle de partenaire technique de confiance et de garantir la fidélité à long terme de nos clients industriels et institutionnels. Le programme comporte :

- **Système de Points d'Ingénierie** : Les clients accumulent des points pour chaque volume d'études commandé (études maritimes standards ou évaluations de potentiel), où chaque tranche budgétaire contractée annuellement équivaut à un certain nombre de points :
 - **100 points** : 5% de réduction sur une future étude maritime standard (ex: étude sédimentaire ou de propagation de houle).
 - **250 points** : 10% de réduction sur un futur livrable cartographique ou une mise à niveau de modèle numérique.
 - **500 points** : Une journée de consultation et d'audit technique gratuit sur site pour l'optimisation ou le diagnostic d'installations côtières existantes (intake/outfall de dessalement, etc.).
- **Avantages Additionnels** :
 - Les membres du programme bénéficient d'un support technique et d'un traitement prioritaire pour l'exécution rapide de leurs simulations numériques en cas d'urgence (ex : tempête ou alerte érosion).

- Les membres ont un accès exclusif avant-première à nos notes de conjoncture météo-océaniques et à nos bases de données de réanalyses actualisées du littoral algérien.

Plan d’Action Opérationnel

Premier Trimestre (T1)

- Développer et lancer officiellement le site web de HoulEole Ingénierie et configurer les profils professionnels sur les réseaux sociaux (LinkedIn).
- Activer les premières campagnes de communication digitale ciblée sur les décideurs de la transition énergétique en Algérie.
- Assurer notre présence et notre visibilité dans les premiers séminaires nationaux liés à l'économie bleue et à l'hydrogène vert.

Deuxième Trimestre (T2)

- Concrétiser et signer les accords de partenariat avec les centres de recherche nationaux (CDER, ENSSMAL) pour consolider notre caution scientifique.
- Organiser des webinaires techniques à destination des ingénieurs du secteur public et privé sur l'apport de la modélisation spectrale (SWAN/MIKE 21) pour la sécurisation des infrastructures en mer.
- Publier une première étude de cas concrète (ex: cartographie du potentiel houlomoteur sur un site pilote de la côte algérienne) sur notre site web et LinkedIn pour démontrer notre savoir-faire.

Troisième Trimestre (T3)

- Développer des relations publiques actives en transmettant des communiqués de presse et des articles de fond dans des revues spécialisées dans l'énergie et le secteur maritime algérien.
- Poursuivre les campagnes de prospection directe (B2B) auprès de Sonatrach, Sonelgaz et l'AEC pour proposer nos services d'évaluation du couplage offshore / hydrogène vert.

- Ajuster les campagnes de publicité en ligne en fonction des performances et des segments de clientèle les plus réactifs.

Quatrième Trimestre (T4)

- Évaluer l'ensemble des performances marketing, analyser le taux de conversion des démarches B2B et mesurer la notoriété acquise par le bureau d'études.
- Recueillir les retours techniques et fonctionnels des premiers clients (notamment sur la clarté de nos atlas SIG et rapports maritimes standards) afin d'ajuster notre offre commerciale.
- Planifier la stratégie de l'année suivante en s'alignant sur les nouvelles opportunités réglementaires et les appels d'offres de la feuille de route nationale de l'hydrogène vert.

Produit

HoulÉole Ingénierie commercialise des prestations intellectuelles spécialisées structurées en trois gammes complémentaires, couvrant l'ensemble de la chaîne de valeur de l'évaluation ENR maritime jusqu'à la mise en œuvre.

Gamme 1 — Évaluation du Potentiel ENR Maritime

- Études de potentiel éolien offshore : modélisation Weibull, AEP, facteur de charge
- Études de potentiel houlomoteur : flux de puissance (Hs, Te), cartographie littorale
- Modélisation numérique côtière : MIKE 21, SWAN, WAVEWATCH III
- Cartographie SIG géospatiale du littoral algérien (atlas interactifs)
- Mesures in-situ : campagnes bathymétriques, bouées météo-océaniques, lidars

Gamme 2 — Faisabilité Technico-Économique

- Études LCOE (Levelized Cost of Energy) pour parcs éoliens offshore
- Études LCOH (Levelized Cost of Hydrogen) pour la production d'hydrogène vert
- Dimensionnement de parcs hybrides (éolien + houlomoteur + PEM électrolyseur)
- Analyses de corrélation éolien/vague et optimisation du couplage
- Modélisation financière : CRF, VAN, TRI, analyse de sensibilité

Gamme 3 — Conseil, Conformité & Accompagnement

- Évaluations d'Impact Environnemental (EIE) pour installations maritimes
- Conseil réglementaire : Loi 04-09, Loi 02-01, Décret 13-218, ZEE, CBAM/MACF
- Assistance à Maîtrise d'Ouvrage (AMO) — suivi de projet de A à Z
- Rapports exécutifs synthétiques à destination des décideurs et investisseurs

Prix

La politique tarifaire de HoulÉole repose sur une tarification à la valeur (value-based pricing), adaptée à la complexité et à l'impact stratégique de chaque mission. Les prix reflètent l'expertise rare et la valeur générée pour le client (réduction du risque d'investissement, conformité réglementaire, optimisation des sites).

Grille Tarifaire Indicative

Type de prestation	Fourchette indicative (DA)
Étude de potentiel ENR (site unique)	1 500 000 – 3 000 000 DA
Étude de faisabilité complète (LCOE/LCOH)	3 000 000 – 6 000 000 DA
EIE pour installation maritime	2 000 000 – 4 000 000 DA
AMO / Conseil stratégique (forfait annuel)	4 000 000 – 8 000 000 DA
Accès base de données littorale (abonnement)	500 000 – 1 200 000 DA/an
Étude de corrélation éolien/houle multi-sites	2 500 000 – 4 500 000 DA

Politique de Remises et Conditions

- Remise partenariat pluriannuel : 10 à 15% pour contrats de 2 ans et plus
- Remise organismes publics : 10% dans le cadre d'appels d'offres institutionnels
- Programme HoulÉole Elite Partners : fidélisation par système de points d'ingénierie
 - 100 points → 5% de réduction sur une future étude standard
 - 250 points → 10% de réduction sur un livrable cartographique
 - 500 points → Journée d'audit technique gratuit sur site
- Acompte de 30% à la signature, solde à la livraison du rapport final

IV. Plan de production et d'organisation

IV.1 Le processus de production (Ingénierie et Livrables)

Le processus de production des études d'ingénierie numérique, des atlas cartographiques et des analyses de gisements offshore se déroule en plusieurs étapes successives. Ces étapes sont cruciales pour assurer la rigueur scientifique et la haute précision du produit final (rapports et modèles) utilisé par nos clients pour la validation de projets d'hydrogène vert ou d'aménagements côtiers standards.

IV.1.1 Acquisition et centralisation des données de référence

L'acquisition des données météo-océaniques et géospatiales est la première étape cruciale de notre processus. Elle garantit que toutes les informations nécessaires à nos simulations sont disponibles et conformes aux critères de fiabilité requis pour minimiser les incertitudes de projet.

- **Fournisseurs de données et ressources** : Copernicus Marine Service (CMEMS), ECMWF (données de réanalyse globale ERA5), bases bathymétriques GEBCO, NOAA, ainsi que les fiches techniques certifiées des constructeurs d'équipements offshore (Vestas, CorPower Ocean).
- **Contrôle Qualité** : Réception, filtrage et inspection des séries temporelles brutes pour éliminer les valeurs aberrantes (données manquantes, artéfacts de mesure) et vérifier leur cohérence physique par rapport au littoral algérien.
- **Stockage et Sécurisation** : Structuration et stockage des bases de données historiques (vent, houle, courants, bathymétrie) sur des serveurs locaux sécurisés et des bases de données géospatiales (Geodatabases sous ArcGIS Pro).

IV.1.2 Traitement numérique et analyse statistique (Le Cœur du Procédé)

Le traitement de la donnée est la phase de transformation où les données brutes sont converties en indicateurs énergétiques et hydrodynamiques opérationnels.

- **Scripts de traitement statistique (Python)** : Exécution de codes Python personnalisés pour ajuster les distributions de vitesse du vent via les lois de Weibull, calculer la variabilité saisonnière et évaluer le productible brut.

- **Génération des indicateurs physiques** : Calcul précis de la puissance houlomotrice, de la direction moyenne des flux et traitement des hauteurs significatives de houle (\$H_s\$) et des périodes de pic.
- **Génération graphique** : Édition automatisée des roses des vents et des roses de houle propres à chaque zone d'étude le long du littoral.
- **Contrôle Qualité** : Vérification mathématique des résultats statistiques par comparaison croisée avec des données locales de bouées in situ si disponibles, afin de valider les modèles de gisement.

IV.1.3 Modélisation hydrodynamique et études maritimes standards

Cette étape intègre la modélisation physique des processus côtiers indispensables à tout aménagement en mer ou couplage industriel.

- **Configuration des modèles spectraux** : Injection de la bathymétrie et des forçages de houle du large dans les logiciels de simulation côtière spectrale (MIKE 21 SW / SWAN).
- **Simulations de propagation** : Exécution des calculs numériques pour simuler la transformation des vagues (réfraction, déferlement, diffraction) à l'approche de la frange côtière.
- **Modélisation de la dynamique sédimentaire** : Évaluation des transits sédimentaires littoraux et de l'impact hydrodynamique du sillage des parcs offshore sur le recul ou l'avancée du trait de côte des plages adjacentes.
- **Contrôle de stabilité du modèle** : Calibration des coefficients de frottement sur le fond et vérification des critères de convergence pour garantir des simulations hydrodynamiques (MIKE 21 HD) hautement réalistes.

IV.1.4 Ingénierie de procédés et couplage du Nexus Énergie-Eau-Hydrogène

- **Conception du couplage technique** : Dimensionnement préliminaire de la configuration des parcs hybrides (éolien flottant et houlomoteur) et modélisation de l'intermittence de la production électrique.

- **Ingénierie du Nexus** : Calcul de la puissance requise pour alimenter les unités de dessalement par osmose inverse (SWRO) et dimensionnement des électrolyseurs industriels pour la production stable d'hydrogène vert.
- **Analyse financière de faisabilité** : Calcul mathématique rigoureux des indicateurs de viabilité : CAPEX, OPEX, LCOE (coût de l'énergie) et LCOH (coût de l'hydrogène), mis en perspective avec les benchmarks internationaux.

IV.1.5 Conditionnement, emballage et livraison des livrables

- **Préparation des Unités de Vente (Rapports Finaux)** : Édition du rapport d'ingénierie final comprenant la synthèse exécutive, les fiches techniques d'implantation par site et les recommandations d'aménagement.
- **Atlas Cartographique** : Compilation et mise en page sous ArcGIS Pro de l'atlas cartographique multicouche, superposant le potentiel énergétique et les zones d'exclusion (zones protégées, câbles sous-marins, couloirs de navigation).
- **Documentation et Archivage numérique** : Emballage numérique comprenant la livraison des rapports au format PDF protégé, les cartes interactives (SIG), les fichiers sources des modèles de houle (DHI) et les scripts Python exécutés. Remise officielle des dossiers en main propre sous format papier relié haute définition et supports de stockage physiques chiffrés lors d'une réunion de restitution.

IV.2 L'approvisionnement

IV.2.1 Politique d'achat

- **La matière première (Données de référence)** : Séries temporelles et données de réanalyse météo-océaniques multi-décennales (vent, houle, courants), données satellitaires haute résolution, données bathymétriques côtières et globales.
- **Matériaux et fournitures (Logiciels et Licences d'ingénierie)** : Licences d'exploitation pour logiciels de modélisation spectrale et hydrodynamique marine, licences de Systèmes d'Information Géographique (SIG), environnements de programmation et bibliothèques géospatiales.

- **Équipement** : Stations de travail (Workstations) haute performance dotée de processeurs multicœurs puissants et de cartes graphiques (GPU) dédiées au calcul intensif, serveurs de stockage de données sécurisés (NAS), traceurs grand format (Plotters) pour l'impression des atlas cartographiques, équipements bureautiques complets et infrastructure réseau.

IV.2.2 Les fournisseurs

- **Fournisseurs de Matières Premières (Bases de données)** : Copernicus Marine Service (CMEMS), ECMWF (European Centre for Medium-Range Weather Forecasts), GEBCO (General Bathymetric Chart of the Oceans), NOAA.
- **Fournisseurs de logiciels et licences** : DHI Group (éditeur de MIKE 21 HD-SW), ESRI France/Algérie (éditeur d'ArcGIS Pro), Python Software Fondation (solutions open-source).
- **Fournisseurs d'équipements informatiques et serveurs** : Enseignes spécialisées de distribution informatique IT en Algérie (ex: Matrix Informatique, EURL High Tech Systems, ou équivalents matériels serveurs Dell/HP Algérie).

IV.2.3 Politique de paiement et délai de réception

- **Politique de Paiement** : Pour optimiser les coûts technologiques et assurer une gestion saine des flux de trésorerie, nous négocierons des contrats de souscription logicielle annuels modulables avec des options de paiement échelonné pour l'acquisition des serveurs informatiques lourds. Nous privilégierons les formules d'abonnements académiques ou "Start-up" auprès des éditeurs (comme ESRI ou DHI) pour réduire le coût des licences initiales, et établirons des accords à long terme pour stabiliser le coût des renouvellements.
- **Délais de Réception** : S'agissant de ressources immatérielles (données et licences logicielles), les délais de réception après paiement sont quasi immédiats (téléchargement et activation des clés d'accès). Pour le matériel informatique lourd (Workstations), nous planifierons les achats un mois avant le démarrage des phases de calcul intensif en collaborant avec des distributeurs locaux garantissant un service après-vente (SAV) rapide pour éviter tout arrêt des serveurs de simulation.

IV.3 Main d'œuvre

Au début du projet, le bureau d'études démarrera avec l'équipe fondatrice issue de l'**ENSSMAL (spécialité Génie Côtier et Aménagement du Littoral)**, composée de quatre ingénieurs spécialisés :

- Un ingénieur expert en Géomatique, SIG et développement Python.
- Un ingénieur expert en Hydrodynamique marine et Modélisation numérique côtière.
- Un ingénieur spécialisé en Systèmes Énergétiques Offshore et Génie des procédés.
- Un ingénieur spécialisé en Aménagement du littoral, Environnement et Cadre réglementaire.

Au cours des six prochaines années, face à la montée en charge des projets nationaux d'hydrogène vert et des demandes d'études maritimes standards, nous recruterons progressivement des ingénieurs juniors en calcul de structures en mer, des techniciens en levés hydrographiques ainsi qu'un responsable du marketing et du développement commercial.

IV.4 Les principaux partenaires

- **Fournisseurs de données et outils** : Copernicus Marine, DHI Group (MIKE 21), ESRI (ArcGIS Pro).
- **Fournisseurs d'équipement de calcul** : Distributeurs officiels de stations de travail haute performance et de serveurs en Algérie.
- **Institutions académiques et de recherche** : **ENSSMAL** (École Nationale Supérieure des Sciences de la Mer et de l'Aménagement du Littoral), **CDER** (Centre de Développement des Énergies Renouvelables), USTHB, USTO.
- **Organismes de Régulation et de Certification (Validation des critères)** : Ministère de l'Énergie et des Énergies Renouvelables, Ministère de l'Hydraulique (tutelle de l'ANRH et de l'AEC), Ministère de l'Environnement, CNRC (Centre National du Registre du Commerce).
- **Agences de Communication et Marketing** : Cabinets de conseil en communication digitale B2B basés à Alger (pour le déploiement du site web et de la stratégie LinkedIn).

- **Organismes de soutien à l'entrepreneuriat** : NESDA / ANADE (Agence Nationale d'Appui et de Développement de l'Entrepreneuriat).
- **Organismes de Financement** : ASF (Algerian Startup Fund).
- **Structures d'accompagnement** : Blue Incubator (Incubateur de l'ENSSMAL).

V. Plan financier

TABLEAU V.1 – Les charges des équipements

Matériel	Prix (DA)
Stations de travail haute performance (Workstations GPU)	1,400,000.00
Serveur de stockage sécurisé (NAS) et infrastructure réseau	850,000.00
Licence logicielle de simulation hydrodynamique spectrale (MIKE 21)	3,200,000.00
Licence Système d'Information Géographique (ArcGIS Pro)	950,000.00
Ordinateurs portables professionnels et moniteurs 4K	650,000.00
Traceur grand format (Plotter A0) pour atlas maritimes	450,000.00
Équipements réseau, onduleurs et infrastructure IT	400,000.00
Mobilier de bureau et aménagement de l'espace	350,000.00
Matériel d'arpentage et instrumentation technique de base	500,000.00
Consommables de démarrage (supports, cartouches, papier)	250,000.00
Total	9,000,000.00

TABLEAU V.2 – Les Charges fixes et variables du projet

Nature des Coûts	Catégorie de charge	Prix (DA)
Coûts fixes	Equipements (Maintenance, cloud, licences)	1,200,000.00
Coûts fixes	Local (Loyer annuel du bureau à Alger)	960,000.00
Coûts fixes	Marketing & Abonnements (Salons, prospection B2B)	400,000.00
Coûts fixes	Salaires & Charges (Équipe d'ingénieurs)	7,200,000.00
Coûts variables	Consommables (Supports de stockage, impressions)	300,000.00
Coûts variables	Energie (Électricité serveurs et calcul intensif)	180,000.00

TABLEAU V.3 – Le cout du projet et le prix de vente unitaire

Indicateur	Valeur (DA)
Coût global du projet (Investissement + BFR)	12,500,000.00
Coût unitaire (Coût de revient d'un Homme-Mois)	420,000.00
Prix de vente unitaire moyen (Tarif Homme-Mois)	650,000.00

TABLEAU V.4 – Le volume des ventes prévisionnelles

Mois	Quantite (Unité)	Mois	Quantite (Unité)	Mois
Janvier	2	Janvier	2	Janvier
Février	2	Février	2	Février
Mars	3	Mars	3	Mars
Avril	3	Avril	3	Avril
Mai	4	Mai	4	Mai
Juin	4	Juin	4	Juin
Juillet	5	Juillet	5	Juillet
Août	2	Août	2	Août
Septembre	4	Septembre	4	Septembre
Octobre	5	Octobre	5	Octobre
Novembre	6	Novembre	6	Novembre
Décembre	6	Décembre	6	Décembre
TOTAL	46	TOTAL	46	TOTAL

TABLEAU V.5 – Chiffre d'affaires annuel et dépenses annuelle (DA)

Mois	Quantité (Unité)	CA (Quantité x Prix de vente)	Coût	Résultat
Janvier	2	1,300,000.00	853,000.00	447,000.00
Février	2	1,300,000.00	853,000.00	447,000.00
Mars	3	1,950,000.00	873,500.00	1,076,500.00
Avril	3	1,950,000.00	873,500.00	1,076,500.00
Mai	4	2,600,000.00	894,000.00	1,706,000.00
Juin	4	2,600,000.00	894,000.00	1,706,000.00
Juillet	5	3,250,000.00	914,500.00	2,335,000.00
Août	2	1,300,000.00	853,000.00	447,000.00
Septembre	4	2,600,000.00	894,000.00	1,706,000.00
Octobre	5	3,250,000.00	914,500.00	2,335,000.00
Novembre	6	3,900,000.00	935,000.00	2,965,000.00
Décembre	6	3,900,000.00	935,000.00	2,965,000.00
TOTAL	46	30,000,000.00	10,690,000.00	19,310,000.00

TABLEAU V.6 – La rentabilité

Indicateur de rentabilité	Valeur
Seuil de rentabilité (en DA) /année	9 873 000,00 DA
Seuil de rentabilité (en Unité) /année	15,2 Unités
Seuil de rentabilité (en jour)	120 jours

VI. Faisabilité Technique et Modèle Pilote (Avant-Projet)

Dans le cadre d'un projet de création d'entreprise (bureau d'études *HoulEole Ingénierie*), la phase "prototype" ne correspond pas à un produit physique ou à un système industriel déjà implanté, mais à **la validation de notre méthodologie de calcul et de notre chaîne de traitement de données** sur un site pilote virtuel le long de la côte algérienne.

VI.1 Objectif du Modèle Pilote

L'objectif est de démontrer la capacité future de notre bureau d'études à traiter de bout en bout une étude d'évaluation de potentiel offshore (éolien/houlomoteur) couplée à des études maritimes standards, en utilisant notre propre chaîne algorithmique (Python/SIG).

VI.2 Préparation et Structure de la Méthodologie

- **Acquisition des données** : La méthodologie repose sur la collecte de données météo-océaniques globales en open-source (Copernicus Marine, ERA5).
- **Traitement statistique** : Développement et validation des scripts de calcul sous Python (lois de Weibull, calcul des flux de puissance) pour automatiser l'analyse des gisements énergétiques.
- **Cartographie SIG** : Structuration de notre base de données géospatiale sous ArcGIS Pro pour cartographier les zones d'exclusion et définir les coordonnées des sites d'implantation potentiels.

VI.3 Limites du Projet et Perspectives du Futur Bureau d'Études

Note de conclusion du projet : En raison du statut de projet de création (bureau d'études non encore établi juridiquement), de **contraintes de temps strictes** liées au calendrier universitaire, et de **l'absence d'accès à des données de terrain *in situ*** (mesures réelles de bouées ou levés bathymétriques fins du littoral algérien), ce travail constitue un **modèle d'avant-projet de préfaisabilité**.

L'accès à des **logiciels d'ingénierie lourds de haute gamme** (tels que la suite commerciale complète MIKE 21 de DHI) ainsi que l'acquisition de données locales de précision feront partie des premiers investissements matériels et partenariats stratégiques (notamment avec le LEM, l'ANRH ou le CDER) dès le lancement officiel et l'ouverture commerciale de notre structure

HoulEole Ingénierie. Pour l'instant, les outils open-source (Python) et les données satellitaires validés dans ce mémoire prouvent la viabilité technique et scientifique de notre démarche.



Figure 1. Logo du Bureau.

VII. Canva Bmc

1. Partenaires Clés • Fournisseurs de données & outils : Copernicus Marine, DHI Group (MIKE 21), ESRI (ArcGIS Pro). • Fournisseurs d'équipements : Distributeurs officiels de serveurs et Workstations en Algérie. • Institutions académiques & recherche : ENSSMAL, CDER, USTHB, USTO. • Organismes de régulation : Ministère de l'Énergie, Ministère de l'Hydraulique (ANRH, AEC), Ministère de l'Environnement, CNRC. • Financement & Accompagnement : ASF (Algerian Startup Fund),	2. Activités Clés • Caractérisation du climat maritime (données de bouées et réanalyses). • Modélisation numérique côtière (simulations hydrodynamiques MIKE 21). • Cartographie thématique SIG & Planification spatiale. • Ingénierie du Nexus (couplage parcs offshore / dessalement / hydrogène vert). • Études maritimes standards (impact hydro-sédimentaire).	3. Proposition de Valeur • Validation de la faisabilité technique & économique des projets complexes et innovants (éolien offshore, houlomoteur) sur le littoral algérien. • Souveraineté & Expertise locale : Alternative nationale de haute précision face aux cabinets étrangers. • Réduction du risque financier (minimisation des incertitudes sur le LCOE / LCOH). • Approche clé en main : de la préfaisabilité à l'assistance technique.	4. Relations Clients Programme de fidélisation (HoulEole Elite Partners) via un système de points : • 100 pts : 5% de réduction sur une future étude standard. • 250 pts : 10% de réduction sur un livrable cartographique. • 500 pts : 1 journée d'audit technique gratuit sur site (Intake/Outfall dessalement). • Avantages additionnels : Support prioritaire en cas d'urgence littorale et accès anticipé aux bases de données.	5. Segments Clients • Segment 1 : Institutions & Agences étatiques (Ministère de l'Énergie/Hydraulique, SONATRACH, SONELGAZ, AEC, ANRH, LEM). • Segment 2 : Industriels & Développeurs énergétiques (Consortiums pour parcs hybrides offshore couplés à des électrolyseurs). • Segment 3 : Aménageurs du littoral & Travaux Publics (Autorités portuaires, dragage, digues).
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NESDA / ANADE, Blue Incubator (ENSSMAL).

6. Ressources Clés

- Humaines : Équipe de 4 ingénieurs spécialisés ENSSMAL (Géomatique, Hydrodynamique, Énergie offshore, Réglementation).
- Technologiques : Logiciels MIKE 21 et ArcGIS Pro ; scripts Python de traitement.
- Matérielles : Stations de calcul GPU, serveurs NAS sécurisés, Traceur A0.
- Matière première : Séries temporelles météo-océaniques multi-décennales et bathymétrie.

7. Canaux

- Vente Directe (B2B) : Démarchage de grands comptes et réponse aux appels d'offres publics/privés.
- Salons & Foires : Présence stratégique aux salons ERA, NAPEC et SIEE Pollutec.
- Présence Digitale : Campagnes LinkedIn Ads ciblées et site web vitrine avec portfolio d'études.

- Segment 4 : Opérateurs de l'eau (AEC, exploitants de stations de dessalement par osmose inverse).

8. Structure des Coûts

Investissements Équipements initiaux : 9 000 000,00 DA

- Stations de travail GPU (Calcul intensif) : 1 400 000,00 DA
- Serveur NAS & Réseau sécurisé : 850 000,00 DA
- Licence annuelle MIKE 21 : 3 200 000,00 DA
- Licence annuelle ArcGIS Pro Advanced : 950 000,00 DA
- Ordinateurs portables & Écrans 4K : 650 000,00 DA
- Traceur grand format (Plotter A0) : 450 000,00 DA
- Équipements réseau, onduleurs, mobilier : 750 000,00 DA
- Matériel d'arpentage et instrumentation de base : 500 000,00 DA
- Consommables de démarrage : 250 000,00 DA

Charges d'Exploitation Annuelles :

- Coûts fixes (Salaires équipe 3 ingénieurs, loyer Alger, maintenance, marketing) : 9 760 000,00 DA
- Coûts variables (Énergie calcul intensif, stockage, déplacements littoraux) : 800 000,00 DA

TOTAL COÛT GLOBAL DU PROJET (Investissement + BFR) : 12 500 000,00 DA

9. Flux de Revenus

- Vente de contrats d'études d'ingénierie et de modélisation côtière facturés sur la base d'unités d'ingénierie (Homme-Mois).
- Prix de vente unitaire moyen : 650 000,00 DA / Homme-Mois.
- Volume annuel prévisionnel : 46 unités vendues (réparties sur les différents contrats de l'année).
- Revenus complémentaires : Prestations d'audits techniques rapides sur site, levés sédimentaires ou édition d'atlas cartographiques thématiques spécifiques.

CHIFFRE D'AFFAIRES ANNUEL PRÉVISIONNEL : 30 000 000,00 DA