The Potential for harvesting wave energy offshore NEOM region, Northern Red Sea

EFFAT UNIVERSITY
COLLEGE OF ENGINEERING
DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

The Potential for Harvesting Wave Energy Offshore NEOM Region, Northern Red Sea

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APPROVAL PAGE

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This thesis, written by **Misaa Abduljbbar Ibrahim Alkhayyat** under the direction of her thesis supervisor and approved by her thesis committee, has been presented to and accepted by the Dean of Graduate Studies and Research on April 22nd, 2020, in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Energy Engineering.

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I hereby declare that this thesis titled **"The Potential for Harvesting Wave Energy Offshore NEOM Region, Northern Red Sea"** is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that the proposed dissertation has not been previously or concurrently submitted for the award of any degree, at Effat University, any other University or Institution.

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ABSTRACT

The Red Sea region represents a challenge for wave modeling and analysis due to its distinct wave structures induced by the spatially and temporally varying forcing wind fields. By incorporating wind and wave data series from 1985 to 2015 in the Advanced Research Weather and Forecasting model and WAVEWATCH III, the present study attempts to find the best site for installing wave energy converters (WEC) in the North Red Sea along the eastern Gulf of Aqaba and the NEOM bay in the northern Red Sea. Besides, the analysis determines the most suitable wave energy converter system using available wind and wave model data provided by KAUST. A total of 8 points were selected and analyzed to test the potential of wave energy at NEOM coastlines along the Gulf of Aqaba and NEOM Bay. The highest peak period found in the selected area was 4 seconds based on the wave hindcast generated on a 1-km resolution grid, and the highest wave found was 0.79 m. Based on the present results, the Gulf of Aqaba, with a mean wave power of 1.98 kW/m at P2 is a good candidate for a WEC system. Possible installation of wave energy converters in the selected areas is discussed in this thesis, including farms of point absorbers with the integration of wave and solar sources (DEIM). Based on preliminary information regarding the NEOM region, potential environmental and social challenges were also identified in this study for the viability of wave energy exploitation.

Keywords: Wave energy converter, Wave power, Renewable Energy, NEOM, Red Sea.

ملخص الرسالة

الهدف من هذه الدراسة هو التحقق من إمكانية استخدام الطاقة الموجية البحرية وتحويلها إلى طاقة كهربائية على سواحل منطقة نيوم الواقعة في المملكة العربية السعودية في شمال البحر الأحمر، والتي تشمل خليج العقبة وخليج نيوم. الدراسة اعتمدت على تقييم مدى فعالية وكفاءة توليد الطاقة الموجية من خلال تحليل ومقارنة بيانات الرياح والأمواج منذ عام 1985 وحتى عام 2015 والمتاحة لدى جامعة الملك عبدالله للعلوم والتقنية. تشمل الدراسة استعراض تقنيات الحصاد الموجي والعثور على أفضل المواقع لتركيب وإنشاء محولات الطاقة الموجية من خلال دراسة ثمانية مواقع في منطقة نيوم. بناءً على التحليل والنتائج وجد أن خليج العقبة يعد أفضل المواقع لإنشاء محولات الطاقة الموجية إذ تبلغ متوسط القوة الموجية نحو 1.98 كيلوواط / م وأعلى ارتفاع موجي يصل إلى 0.79 متر عند الموقع (ب2) ، وتبلغ أعلى فترة ذروة موجية في المنطقة المحددة 4 ثوان بناء على التحليل الموجي بدقة 1 كم. كما ناقشت الدراسة أنواع مختلفة من مولدات الطاقة الموجية المناسبة لمنطقة نيوم ، وذلك عن طريق تحليل ومقارنة نظام مولد الطاقة الموجية DEIM ، والذي يعتمد على تقنية الامتصاص النقطي والدمج بين الطاقة الموجية والشمسية من خلال عدة مزارع لتوفير الطاقة اللازمة ومقارنتها بالشبكة العمومية. استنادًا إلى المعلومات الأولية المتعلقة بمنطقة نيوم ، استنتجت الدراسة وجود بعض التحديات الاجتماعية والبيئية والتي قد تواجه تقنية الطاقة الموجية في هذه المنطقة.

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List of Abbreviations

DEIM	Department of Energy, Engineering Information, and Mathematical Models
OBREC	Overtopping Breakwater for Energy Conversion
OWC	Oscillating Water Column
PTO	Power Take-Off
REPDO	Renewable Energy Project Development Office
SDGs	Sustainable Development Goals
SDG#7	Ensure access to affordable, reliable, sustainable and modern energy for all
SDG#14	Conserve and sustainably use the oceans, seas and marine resources for sustainable development
SV	Seasonal Variability index
SWAN	State-of-the-art Shallow Water Wave model
WEC	Wave Energy Converter
WW3	WAVEWATCH III
WRF	Weather Research Forecasting

List of Symbols

C	Wave celerity
C_g	Group velocity
COV	Coefficient of Variation
g	Gravitational acceleration
h	Local water depth
H_s	Significant wave height
L	Wavelength
MV	Monthly Variability index
P	Energy flux per meter wavefront
P_{12}	Mean wave power for the lowest-energy month
P_{M1}	Mean wave power for the highest-energy month
P_{S1}	Mean wave power for the highest-energy season
P_{S4}	Mean wave power for the lowest-energy season
P_{year}	Mean wave power over the year
T	Wave period
T_e	Energy period
T_p	Peak period
α	Coefficient of wave spectrum shape
μ	Average power
ρ	Density of seawater

Chapter 1: Introduction

1.1 Overview

In 2016, a report by the World Energy Council [1], reported that there is a potential of 32,000 TWh of wave power per year, including 1300 TWh/year in the Mediterranean Sea and Atlantic Archipelagos [2]. More recently, the International Energy Agency [3] announced in 2019 that electricity production from marine development increased in 2018 by an estimated 16 per cent. In the sustainability scenario, 2000-2030, ocean power generation is expected to hit 15 TWh [2]. Wave energy has the most important renewable energy sources with many advantages compared to other types of renewable energies. However, wave power needs the existence or creation of particular ecological conditions. To utilize this power, it is imperative to draft a structure that can catch and collect the energy transmitted by the waves to use it productively. Despite the recent interest in marine energy, wave energy technology is just at the beginning stage of improvement, being focused primarily on wave power. Wave energy is distributed between (i) the potential energy part, where the water is constrained against gravity from the wave trough and peak, and (ii) the active vitality segment, that is, the water's fluctuating speed. Another important factor is that the structure must have the capability to endure the marine atmosphere, specifically stormy weather, wherein the wave power fundamentally increments [4 – 6]. The present study attempts to locate the best spot for wave energy converters (WEC) in the Red Sea, focusing on the NEOM region, while also identifying the most suitable converter system to harvest wave energy. The study is based on wave height, wave peak period, mean wave power, distance to shoreline, and wind speed. Besides, the study considers the social and environmental factors as well as site constraints.

1.2 Problem Statement

The Kingdom of Saudi Arabia set ambitious goals in its national transformation program and Vision 2030, to step away from oil reliance and shift resources expended on oil and gas exploration activities to other higher-value uses. This goal is accomplished by setting an energy roadmap to supply 10% of the country's energy consumption from renewable sources, with an initial target of 3.45 GW of renewable energy production by 2020 and 9.5 GW by 2023 [7]. Naturally, KSA has renewable energy sources, particularly solar and wind, as it lies in the middle of the sunbelt with average sunshine of 8.9 hours per day across most provinces, and a high annual average wind speed along the central, northeast, and western regions [8]. The shares of renewable energy in Saudi Arabia are less than 1%, but now the goal is to increase those shares to more than 10% heavily. In this context, Saudi Arabia launched several programs, projects, and initiatives in the area of renewable energy [9]. Many alternative energy sources, such as hydroelectricity, marine energy, geothermal thermal energy, have also been harnessed by many countries around the world. The potential of generating electricity from marine renewable energy is immense, and it is identified as an asset that still needs to be utilized for sustainable generating electricity. Due to its proximity to the Red Sea coast, desalination plants located near the coastlines can benefit grandly from the generation of electricity using wave energy converter systems. To the best of the authors' knowledge, no research has been conducted to investigate the potential of wave energy in the NEOM region, and no current programs are considering this viable choice, as Saudi Arabia did not plan yet to use this form of energy. In this study, multiple attempts were made to identify the best location for WECs based on NEOM's monthly distribution of mean wave height and the mean wind. The projected outcomes of this study were the possibility of identifying the best converter system to harvest wave energy in the Red Sea, site-specific screening for installing a WEC device, and understanding the impact of wave energy production on the sustainability of social and environmental factors.

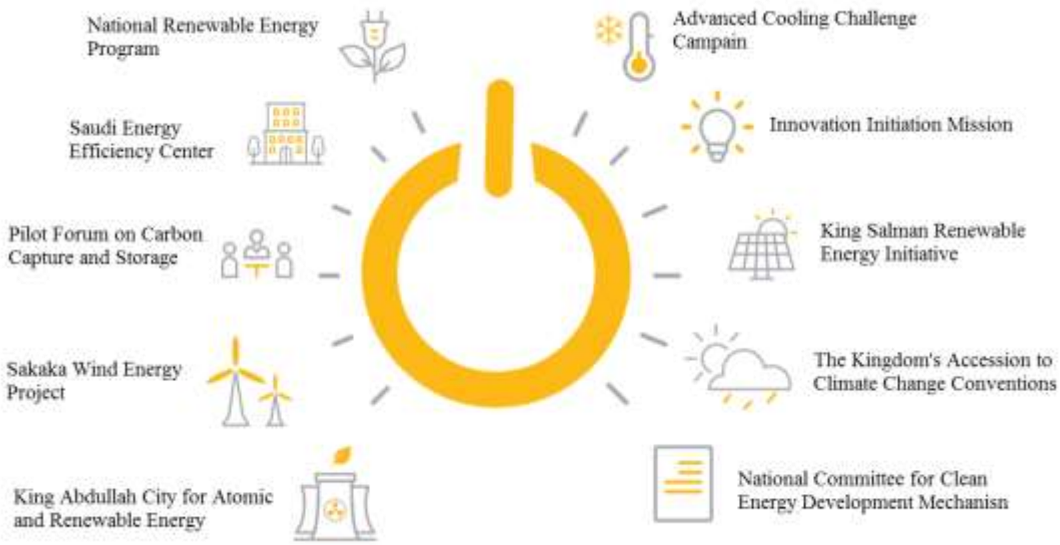


Figure 1.1 Programs, projects, and initiatives in the area of renewable energy [9].

1.3 Objective

The objective of this thesis is to explore and investigate the potential of harvesting wave energy along the eastern Gulf of Aqaba and the NEOM bay in the northern Red Sea, identify the potential environmental and social challenges of implementing wave energy converters in NEOM Region and finally, identify the suitable system for extracting wave energy at this region.

1.4 Importance and Motivation

The Renewable Energy Project Development Office (REPDO) of the Ministry of Energy, Industry and Mineral Resources of Saudi Arabia (MEIM) recently reported a significant increase in the share of renewable energy, generating 40 GW of solar and 16 GW of wind energy over the next decade [9]. Solar energy produces an irregular variation of the temperatures and pressures in different regions of the globe, leading to winds blowing from high to low pressures and consequently creating waves across the ocean surface. Thus, wave power can be regarded in that sense as another type of solar energy, where wave energy converters (WECs) convert the wave energy to electricity. Like other types of renewable energy, wave energy has similar issues due to its variability and unpredictability. In recent years, many countries have turned towards the development and use of WECs as a means of wave energy extraction. In the last decades, there has been a significant development in wave energy technology as a new source of renewable energy because of the requirement of decreasing the emission of greenhouse gases. It may be expected that wave energy will play a larger role in years to come in the supply systems of energy, even though at present, there are no wave energy converters that can be commercialized. For Saudi Arabia, wave energy can be another renewable energy source, in particular for the desalination plants located near the coastlines of the Red Sea coast.

1.5 Contribution

This research investigated the best location of WECs to generate energy from waves. The study was divided into four parts; the first part is examining the Red Sea climatology, including wind and wave distribution. In contrast, the second part investigated the best area for WECs, the third studied the different types of WECs, and the fourth part selected the suitable WECs in NEOM coastlines based on the wave conditions. The projected outcomes of this study were the possibility of identifying the best converter system to harvest wave energy in the Red Sea, site-specific screening for installing a WEC device, understanding the impact of wave energy production on the sustainability of social and environmental factors and achieving the goal of 2030 vision to step away from depending on oil and focusing on Renewable sources.

1.6 Outline of the Thesis

The thesis has been divided into seven chapters. In chapter 2, we review the main characteristics of ocean waves, the representation of waves, and an extensive study of the literature review in wave energy development, investigation, and assessment, Chapter 3 investigates the wind and wave characteristics of the Red Sea region including a Meteo-Oceanographic analysis in the NEOM Region, wind analysis, and wave analysis. Chapter 4 was dedicated to Wave Energy Converters (WECs) and their classification, testing, and commercialization. Chapter 5 describes the methodology adopted in this study in selecting the study area, wave energy modeling, and wave energy converters' selection. Results and discussion are presented in chapter 6, including WEC output performance, analyze the environmental and social impact of installing WECs and the constraints and limitations of implementing wave converters at the Red Sea. Finally, chapter 7 draws the main conclusion of this thesis and future work suggestions.

Chapter 2: Background and Literature Review

2.1 Overview of Ocean Wave Energy

Wave energy is an abundant energy source all over the world [1, 4]. It is an unconventional renewable energy source that is of interest due to its wide prevalence and density across the globe. Waves are mainly produced by the interaction between the wind and the sea surface, where the wind is continuously acting as a tangential force contributing to the formation of waves. Waves are also the result of the gravitational pull of the sun and the moon in the earth, creating what is known as tide waves. The flux of wave energy is contained in waves as both kinetic energy and potential energy. The amount of energy transmitted, and thus the size of the resulting waves depends largely on the wind speed, the length of time it blows for, and the distance through which it blows over the water [9, 10].

Oceans cover up to 70% of the Earth's surface and can produce thermal energy as a result of solar radiation, mechanical energy generated by the waves and tides, as well as other renewable energy such as salinity gradients. These types of energy are used in many applications, such as generating electricity, pumping water, and water desalination. Due to the complex characteristics of ocean waves and their energy extraction hydrodynamics, the development of such technology is still in the early stage of development, especially in wave power, but it is expected to become more competitive and commercially viable soon [11, 12].

The concept of wave energy can be summarized as follows: the oceans' water is continuously moving, with the sun and moon's gravitational pull oscillating the oceans' surface twice a day, while the wind disturbs it into waves, as shown in Figure 2.1. Winds are produced by the earth's differential warming, transmitting some of their energy to a type of waves as they travel over open bodies of water [13]. The flux of wave energy is contained in waves as both kinetic energy (in the movement of the particles of seawater) and potential energy (in the amount of seawater displaced from the mean sea level). The amount of energy transmitted, and thus the size of the resulting waves depends mainly on the wind speed, the length of time it blows for, and the distance through which it blows over the water [14].

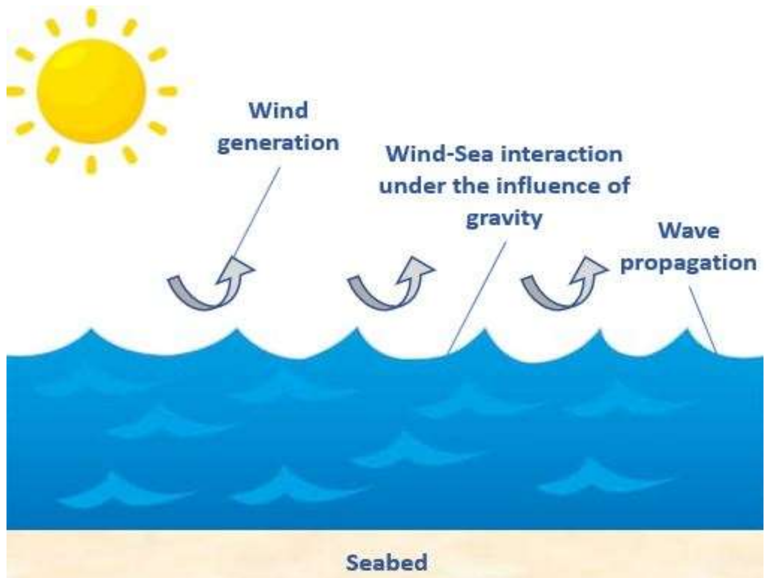


Figure 2.1 Concept of wave energy.

2.2 Characteristics of Waves

The key parameters used to characterize waves are their length and height, as well as the water depth to which they spread. The extent of propagation (shallow, intermediate, and deep water) depends primarily on the depth level. All other parameters can be calculated theoretically from these quantities, such as water velocities and acceleration and kinematics (motion) under waves. Deepwater waves, inshore water waves, disruptive, constructive, and refracted waves are the main types of sea waves. Therefore, there are two major wave groupings based on regular and irregular waves [15]. In comparison to nonlinear waves, the linear waves, known as sinusoidal waves, are characterized by continuous movement. The problem is that real ocean waves usually are not regular. As a result, the wave height and wave period change in a stochastic manner, depending on the value of each parameter.

2.3 Representation of Waves

Sea waves can be defined as regular waves (sinusoidal) or irregular waves. While ocean waves are never sinusoidal, low amplitude swells may come close to sinusoidal as shown in Figure 2.2.

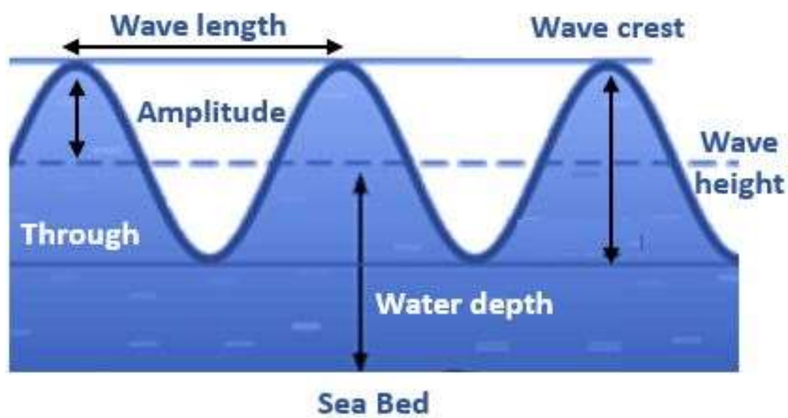


Figure 2.2 Representation of a regular wave.

Waves that travel away from their source are classified as swell waves. The stronger the winds in the source field, the bigger the swell will be, the more it will fly. It is possible to extract wave energy in various ways, including from deep-water areas and also along the shore. The waves can be classified as deep-water waves if the water depth is higher than half a wavelength of the waves (L/2). The ocean transmits wave energy via circular orbital motion by moving in circular orbits and returns to the same location.

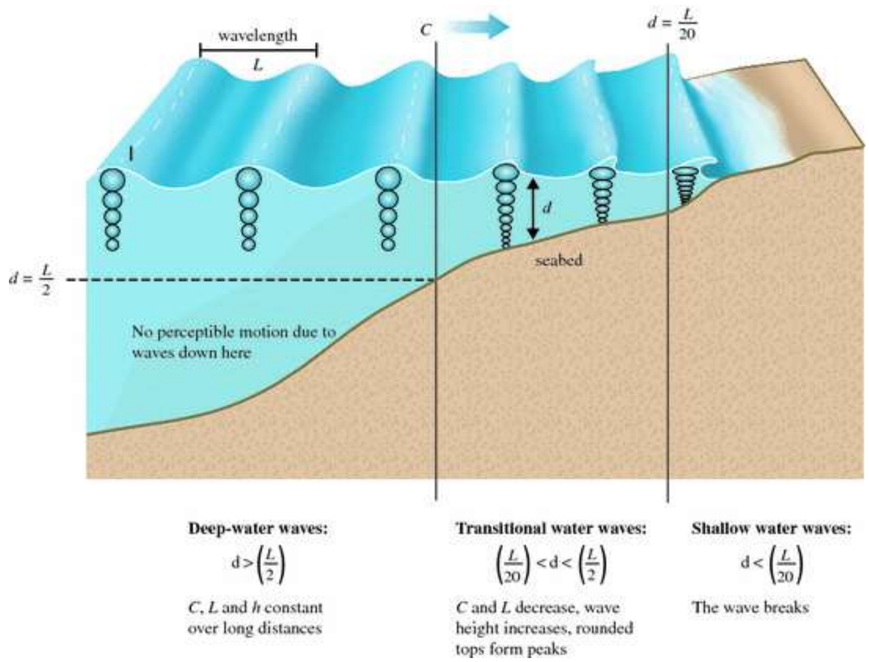


Figure 2.3 Wave depth propagation [16].

Figure 2.3 indicates that the highest orbits are on the surface of the water, having both the highest potential and kinetic energy, so that specific systems (e.g., wave attenuators) in deep water will have a more substantial generation potential than they would in shallow waters.

2.4 Previous Studies

The interest in wave energy has increased markedly over recent decades because of the requirement to decrease the emission of greenhouse gas. Most of the technology developments in wave energy are particularly in Northern European countries where different wave energy conversion technologies are applied, such as in the United Kingdom and Norwegian Sea [17]. An assessment of wave energy potential and its harvesting approach along the Indian coast has been conducted by Sannasiraj et al. [18]. Seventy-three locations have been selected on the Indian coast [1], where the maximum power found reached 20 to 25 kW/m. Shadman et al. [19] investigated wave energy generation along the Brazilian coastline using numerical models and conclude that there is a great potential of wave energy resources reaching 91.8 GW. Wang et al. [20]

performed a long-term wind and wave energy resource assessment in the South China sea based on 30-year hindcast data. Results showed that the maximum power generated may reach 65 kW/m. Alaoui et al. [21] highlighted the existence of a significant ocean wave energy located in the region between Essaouira and Agadir in Morocco. In assessing the potential of wave energy in some location in Portugal, Rusu et al. [22] found the selected location present a great potential of wave energy resources. Nezhad et al. [23] showed that wave energy near Qeshm, Chabahar, and Anzali of the Iranian coastlines present the best potential of wave energy generation. In the Red Sea region, only a few studies have investigated the assessment of wave energy. Metwally et al. [24] generated a wave atlas, Ralston et al. [25] presented a two-year simulation summary of wave conditions in the Red Sea. Aboobacker et al. [26] used a long term assessment for wave energy in the Red Sea using numerical simulation. Langodan et al. [27, 28] conducted an extensive assessment of harvesting wave and wind energy with a detailed analysis of northern, central, and southern parts of the Red Sea using the Advanced Weather Research Forecasting model. Langodan et al. [29, 30] were able to develop an extensively wind and wave behavior that leads to the estimation of the wind and wave potential in the red Sea region. Four main wind and wave systems are the most dominant in the climate of the Red Sea, as discussed in [29]. With this great amount of research on wave energy, it can be anticipated that wave energy will play a larger role in the coming years in the supply systems of energy, as reported by World Energy Council [1] and the International Energy Agency [4]. Based on different government and non-government research studies, interest in wave power has been progressively increasing. In regions such as Australia, South America, Canada, and the South Coast of Africa have been recognized as high wave energy generation areas [12].

Figure 2.4, adapted from [31], illustrates the total wave power distribution for various coastal environments based on the National Oceanic and Atmospheric Administration's WAVEWATCH III data. By analyzing the graph in Figure 2.4, Australia, USA, and Chile have more significant wave power resources compared to countries in Europe.

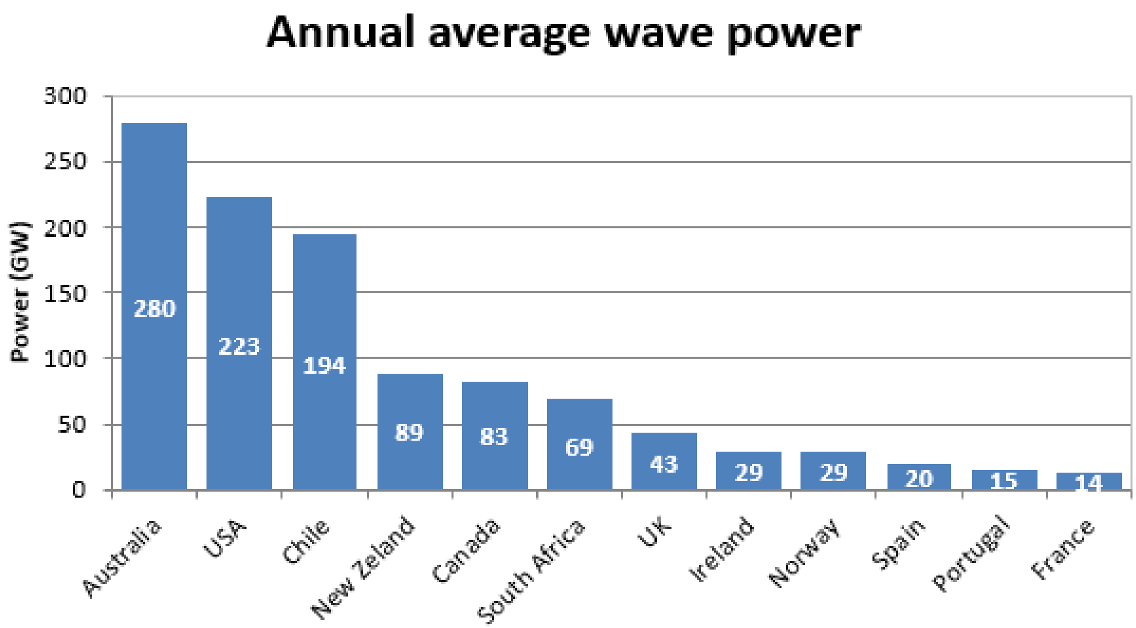


Figure 2.4 Estimation of the total annual average wave power by countries [31].

On the wave energy converters (WECs) research activities, the first WEC patent issued in 1799 was developed in France [32]. Wave energy converter research and development began in Great Britain in 1975 through several programs [33]. Sweden constructed one of the world's largest commercial wave energy at Sotenäs, including 42 devices and producing a power of 1.05 MW [1]. In 1985, on the coast near Bergen, Norway, significant efforts were made to build two real-size converters with a rated power of 350 kW and 500 kW [34]. Activities in this field remained largely at the academic level in Europe until the early 1990s [35]. A small-scale, oscillating water column (OWC) built-in Islay, Scotland, in 1991, is the most notable achievement of this era [36]. Two OWCs were installed in Asia around the same time, including a 60-kW converter combined with a breakwater in the port of Sakata, Japan, and a 125-kW bottom-standing power plant in Trivandrum, India [37]. One of the failed devices of the time is the 2-MW converter in Scotland, destroyed by the waves. A 400-kW OWC was installed in Portugal in 1999, followed in Scotland in 2000 by a 300-kW Limpet [37, 38]. The floating-point absorber SEAREV was first published in France in 2003 [39]. Two years later, in Port Kembla, Australia, a new version of this absorber was developed, and a semi-industrial 1:5 scale prototype, named Wave Dragon, was dropped into Denmark's water [2]. Mattiazzo [40] analyzed the possibilities of using wave energy in the Mediterranean Sea by focusing on the Inertial Sea Wave Energy Converter (ISWEC) technology. Several other converters were launched later in 2008, including a Pelamis in northern Portugal, 16 OWC systems in Mutriku, Spain, and an Oregon State University floating system [32, 41]. A feasibility study conducted by Cascajo et al. [2] evaluated the possibility of building a new infrastructure that combines a breakwater and a WEC (OBREC) to provide energy to the commercial port of Valencia, Italy. Franzitta et al. [42], performed an assessment to analyze the energy production in the Maltese islands, by using an innovative type of Wave Energy Converter based on the prototype of a linear generator realized by University of Palermo consist of wave energy source and off-shore photovoltaic (PV) technology (DEIM). A floating system of 25 kW and an Osprey in the UK were also designed in Denmark. A 75kW attenuator ARRECIFE was tested in Spain, 2019, to work with the most common waves from 1 to 5m high waves [43].

Chapter 3: Wind and Wave Characteristics of the Red Sea Region

3.1 Wind and Wave Characteristics and Patterns

The Red Sea is a seawater inlet linking the Suez Canal, Aqaba Gulf, and the Sinai Peninsula to its North with the Indian Ocean via the Bab el Mandeb Strait and the Aden Gulf. The total surface of the Red Sea is roughly 438,000 km^2, with 2,000 km along the coast and a maximum width of 355 km [16]. Figure 3.1 shows that the Red Sea has three distinct depth zones: a shallow shelf with a depth of fewer than 50 meters, a deep zone between 500 and 1,000 meters, and a central axis between 1,000 and 2,900 meters. The Red Sea is a challenge in wave modeling and analysis due to narrow topography and the existence of multi-faceted winds over the region. The two distinct and opposing wave configurations at the center of the Red Sea, driven by reverse winds and converging in the center, also creates challenges for wind and wave modeling. By using the Weather Research Forecasting (WRF) version 3.6.1 model [27], a high-resolution local model at 5-10 km resolution and 1-h interval assimilating conventional observations from surface stations, upper-air soundings, and satellite observations [44], with a wave model WAVEWATCH III (WW3), a third-generation spectral wave model developed at NOAA/NCEP (National Oceanic and Atmospheric Administration/National Centers for Environmental Prediction, USA) [27]. Both are customized for the Red Sea. KAUST researchers were able to create simulations for wind and wave dynamics by using the Advanced Weather Research Forecasting model to generate a high-resolution (10-km) atmospheric reanalysis over the Red Sea region during the period (1985 to 2015) [29, 30]. They reported four major wind systems for generating waves those are blowing from (1) the North throughout the year, (2) the south in winter, (3) the west through Tokar gap on the Sudanese coast in summer, and (4) the east through the mountain valleys along Saudi coast in winter. These results represent the first study of wind and wave trends in the Red Sea region [29, 30].

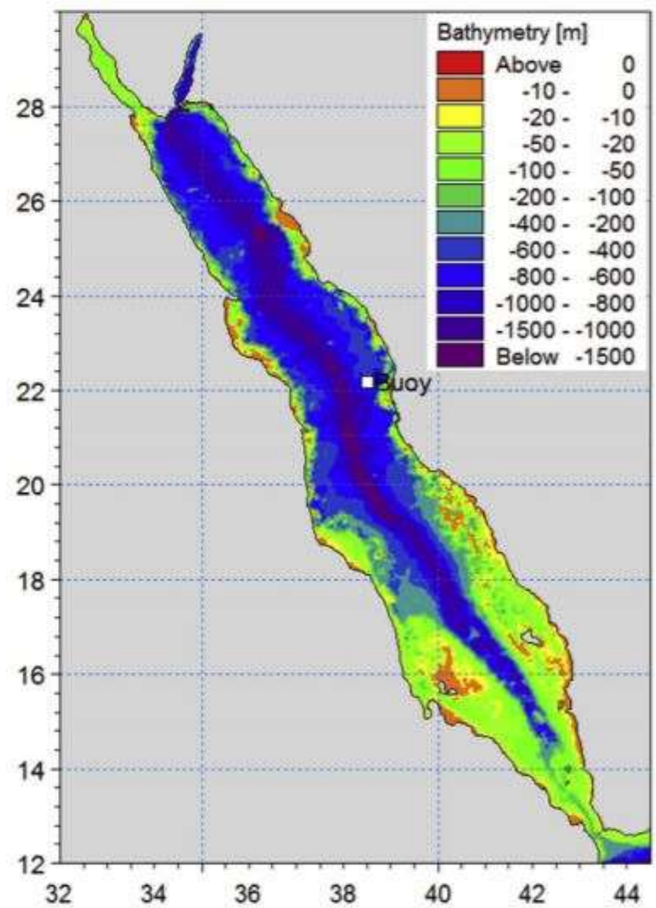


Figure 3.1 Domain and bathymetry covering the Red Sea [26].

3.1.1 Wind Characteristics

The Red Sea is situated between Arabia and Africa, and the topography of the Red Sea determines the wind and its characteristics. Different wind regimes dominate in the Red Sea due to its location between two distinct regions, as each region has different climatic conditions. Mountains surround the Red Sea on both sides, and the wind is forced to blow along the basin axis due to the presence of mountains [29]. Strong winds blow across the Red Sea and the Suez Gulf throughout the year from the northwest direction, and this blowing wind travels further down the southern strait. The wind blowing over the Red Sea is often strengthened by the Mediterranean storms.

During the months from May to October, the most potent and fast northwest winds prevail over the Red Sea and its basin. The Northeast monsoon dominates the Arabian Sea in the winter months from November to February [29]. Southeast winds prevailed over the southern Red Sea are the product of the monsoon winds blowing over the Gulf of Aden, and it redirected towards the Bab el Mandeb Strait due to the presence of high mountains on the African and Arab sides. The co-occurrence of winds from the northwest and the southeast converge at the center of the Red Sea, creating a convergence zone about 180.

Four wind patterns prevail in the Red Sea [27]: (1) The winds influenced by the Mediterranean sea that reach the southern part of the basin of the Red Sea; (2) Monsoon-influenced winds entering the southern Red Sea after being diverted from the Gulf of Aden; (3) On the African side, a strong wind blows daily through the Tokar Gap during June and September. The wind blowing through the Tokar Gap gets intensified due to the Katabatic effect - resulting from the difference in temperature when two different physical characteristics occur, as happens in the Red Sea and its surroundings. These winds mainly blow eastward, but then they turn to the south; (4) The winds blowing through the valleys of the Arabian Peninsula and frequently results in strong winds. Figure 3.2 illustrates the four systems.

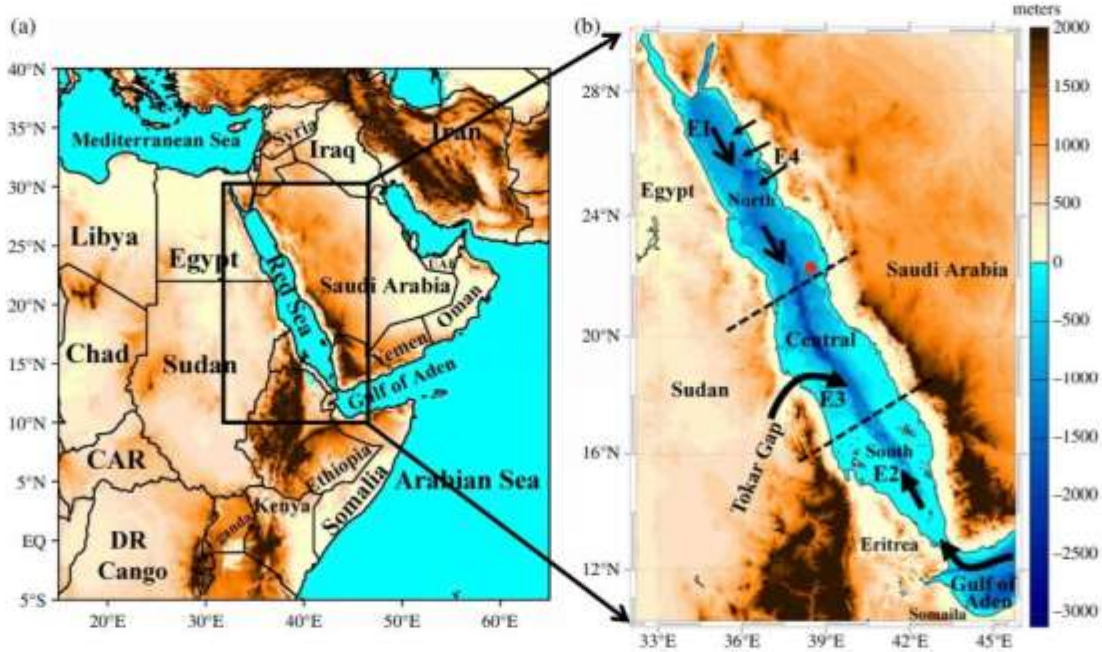


Figure 3.2 (a) Larger study area is showing the Red Sea and adjacent regions. (b) The Red Sea [29].

Figure 3.3 demonstrates the spatial distribution of winds in the Red Sea as the mean wind speed (panels a, c) and maximum wind speed (panels b, d) during summer and winter, respectively. The colored bars show wind speed in meters/sec occurring during the various summer and winter months. This is derived from 30-year data at a 10-km resolution grid, generated using atmospheric models and mean represent the average wind speed of multiple seasons. The maximum refers to the maximum wind speed that occurred in the 30 years for the season [29]. The difference between the winter and summer seasons that wind never stops; it is a constant geographical phenomenon. Throughout summer, we can see the highest mean values, with high wind intensity being seen in the North, and these winds are affected by the Mediterranean storms. The highest mean values are attributed to the monsoon winds that region in the winter season in the southern Red Sea.

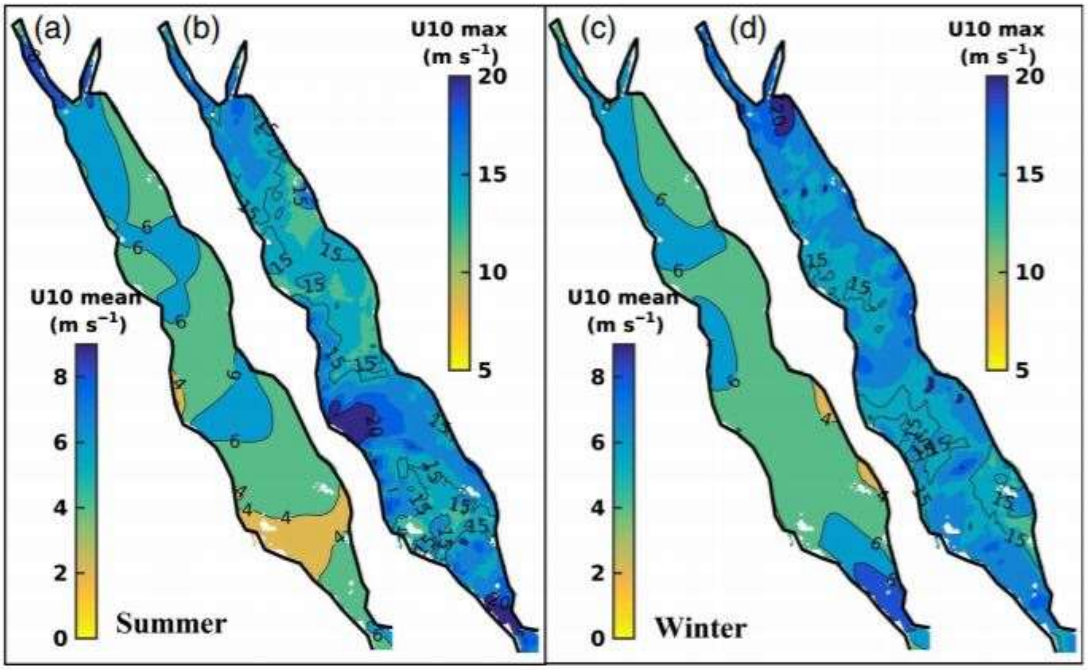


Figure 3.3 Mean and maximum wind speed distribution of the Red Sea (1985-2015) [29].

3.1.2 Wave Characteristics

For climatology of the Red Sea wave, we illustrate the spatial and temporal differences between three parts of the Red Sea, respectively northern, central and southern (N, C, S). Figure 3.2 split the basin accordingly [30].

Figure 3.4 provides the general distribution of the mean and maximum significant wave height, in the summer (panels a and b) and the winter months (panels c and d), respectively. The color bars represent different parameter ranges in these figures and for each point the maximum refers to the highest value in the entire 30-year time series. Throughout summer, the general distribution of mean H_s values in most parts of the basin manifests the dominant position of the Mediterranean Sea meteorological inputs. The exception is the southern part of the basin, suggesting that these impulses are not strong enough to reach this area (more than 2000 km from the northern end). Consider that the Tokar Gap winds produce the highest waves in the basin in summer. The different locations of the two larger wave areas in panels 2a and 2b are an important oceanographic feature [30].

The reason for this is the different behavior of wind-generated fetch-limited waves under a compact jet that expands with decreasing wind speeds when funneling out to sea. The expansion is more constrained under 'normal' conditions and depends on both wind speed and fetch; a maximum wave height is reached at some distance from the coast. In comparison, the waves rise correspondingly faster particularly in strong wind cases and the peak is reached sooner. For a shorter fetch, the rapid wind speed decreases with distance due to the wider jet expansion, another aspect may be the rare interaction between a storm in the north and winds in the Tokar Gap.

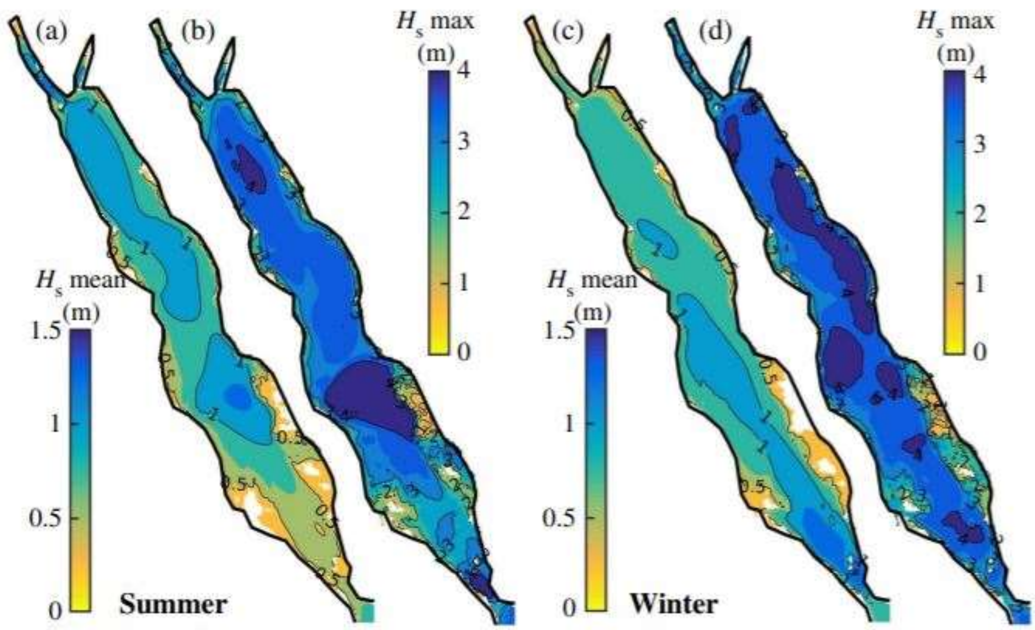


Figure 3.4 Mean and maximum significant wave heights distribution in the Red Sea (1985-2015) [30].

The main difference between summer and winter is the presence of high waves in the Red Sea's southern part. These are produced by the southern winds connected to the northeast monsoon, which prevail throughout the season but without achieving extreme values. This leads to relatively high waves in Figure 3.4 (c) compared to the maxima in Figure 3.4 (d). In the southeastern Red Sea, the waves are significantly attenuated by the islands, in particular coral reefs. This also results in a well-defined preferential flux of energy along the Red Sea's main axis, with swell characteristics much of the time as a result of regular wave propagation from the north (E1) [30].

Figure 3.5 shows the statistical distribution of Hs in the three areas of the basin as shown in Figure 3.2. In area N, the waves height range between 1 and 2 m, with the highest waves generated by the frequent northerly storms. While areas C and S are more concentrated on the low wave heights, less than 1 m. Nevertheless, more occurrences in area C are observed for the highest range (> 2,25 m), due to the occasional very strong Tokar Gap winds, particularly when superimposed to a northerly event.

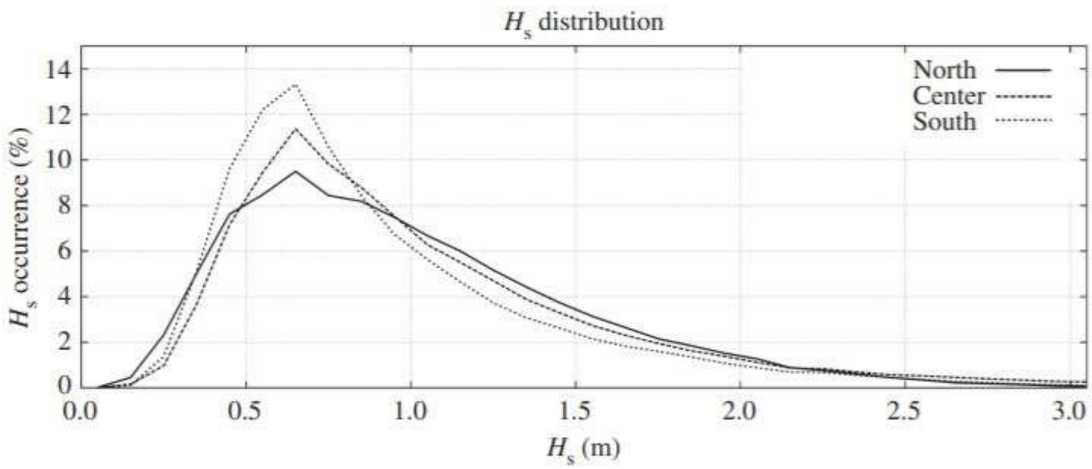


Figure 3.5 Statistical distribution of the significant wave heights in the three areas [30].

There are four wind systems (E1, E2, E3, and E4) indicated by arrows in Figure 3.2. System E1 is driven by Mediterranean Sea pulses-either by the typical non-summer months' storms or by the Etesian winds over the Aegean Sea during the hot season. The pulses move across the Nile delta and the Suez Gulf, then propagate to the south as a relatively cold, energetic front. Based on annual averages, these are the most powerful waves in the basin that migrate to the southern end of the Red Sea, sometimes as swells and sometimes as wind sea while the weather is propagating to the south [44].

System E2 is from October to April, and it is considered as the most regular wind regime in the southern Red Sea. The waves generated by E2 propagate northwards, strongly attenuating as they approach the northern end of the Red Sea. When both the E1 and the E2 systems are present, almost a unique situation may appear in the Red Sea. Those two opposing wind systems converge around the middle of the Red Sea when a pulse from the Mediterranean reaches the basin, and an extended E2 system is present. The warmer E2 air ascends over the moving southward, colder air from the north, leading to a peculiar locally cloudy and drizzling situation in the middle of a vast sunny area [44]. It is complicated for waves, especially in their active generation areas, where we have the unusual case of two opposing wind-wave systems.

The third system, E3, is associated with the Tokar Gap wind that blows in the summer, from July to September [44]. The variability of E3 is controlled by the summer wind regimes, as it occurs at a crossroads of influences from the seasonal Indian Ocean monsoon cycle to the south and the Sahara Desert and the eastern Mediterranean Sea to the north. The E3 system is influenced by the local land – sea breeze cycle of the Red Sea, particularly the thermally induced wind that originates from the night cooling on the high African planes that propagates down the Tokar Gap with a katabatic effect to and across the Red Sea. This wind generates the highest waves in the Red Sea (up to and above 5 m), particularly if they interact with the E1 system.

The least globally important but still locally relevant system is the E4 system, which describes the jets that blow down in the northern part of the Arabian Peninsula through narrow valleys leading to high waves locally [44]. Certain patterns of wind and wave occur occasionally, but are not regular or stable enough to be considered significant in local climatology.

To summarize, the waves in the north of the Red Sea basin, caused by the winds influenced by the Mediterranean Sea, reach the Bab el Mandeb and those waves are referred to E1. It occurs throughout the year and may differ in summer and winter seasons due to the strong cold wind from the Mediterranean storms [30]. The strong winds from the Mediterranean storms create high waves in the Northern part of the Red Sea, and as these moves south, their height tends to decrease. The wave related to monsoon winds is referred to as E2, and these waves are produced for a shorter period since the monsoon winds only exist for a short time from October to April. The waves are quite high during this time, and the height of the waves is decreasing as they begin to move north. The wave referred to as E3 is produced because of the Tokar Gap jet's, generating large waves. Such waves are the most powerful waves in the Red Sea. The winds blew through the valleys of the Arabian Peninsula also creates short-lived and less-energetic waves in the northern Red Sea (marked as E4). E1 waves have no specific season and time, while the E2, E3, and E4 waves are defined in season and time. The waves existing in the Red Sea are more dominant in the North, but the waves are less dominant in the central and southern part of the Red Sea. Also, the waves show a decreasing trend in the Red Sea. While E1 waves show a very high decreasing trend in their height, E2 and E3 waves show a milder decreasing trend. The E4 waves are submerged in the E1 if there is any relevance between the two waves [30].

Table 1. Dominant wind and wave systems in the Red Sea [44].

System	Characteristics
E1	This system blows year-round, mostly from northwest to southeast extending to the southern part of the basin.
E2	This is aligned with the northeast monsoon and blows from the northwest To the south end of the basin, which usually stretches deep into the Red Sea during winter season.
E3	The Tokar Gap wind blows through the valley halfway down the African coast; it's highly associated with the summer monsoon and differential heating, is present during the summer months, and generates the highest waves in the basin.
E4	Jets exiting the narrow valleys in the northern part of the Arabian Peninsula are causing waves that are not very large but can be superimposed on those of the E1 system.

3.2 Meteo-Oceanographic Analysis in NEOM Region

3.2.1 Wind Analysis

Weather Research Forecasting (WRF) was implemented at 5km horizontal resolution. The simulation covers the period 2001–2015 at 1-hr intervals. The mean wind speeds over the NEOM are shown in Figure 3.6. The winds are mostly northwesterly across the sea, more intense over the Gulf of Aqaba in most months. Most of the months, land to sea breeze appears. During winters, milder winds are apparent from land to sea, while in summer, it has a stronger wind regime across the area and weaker winds observed from sea to land.

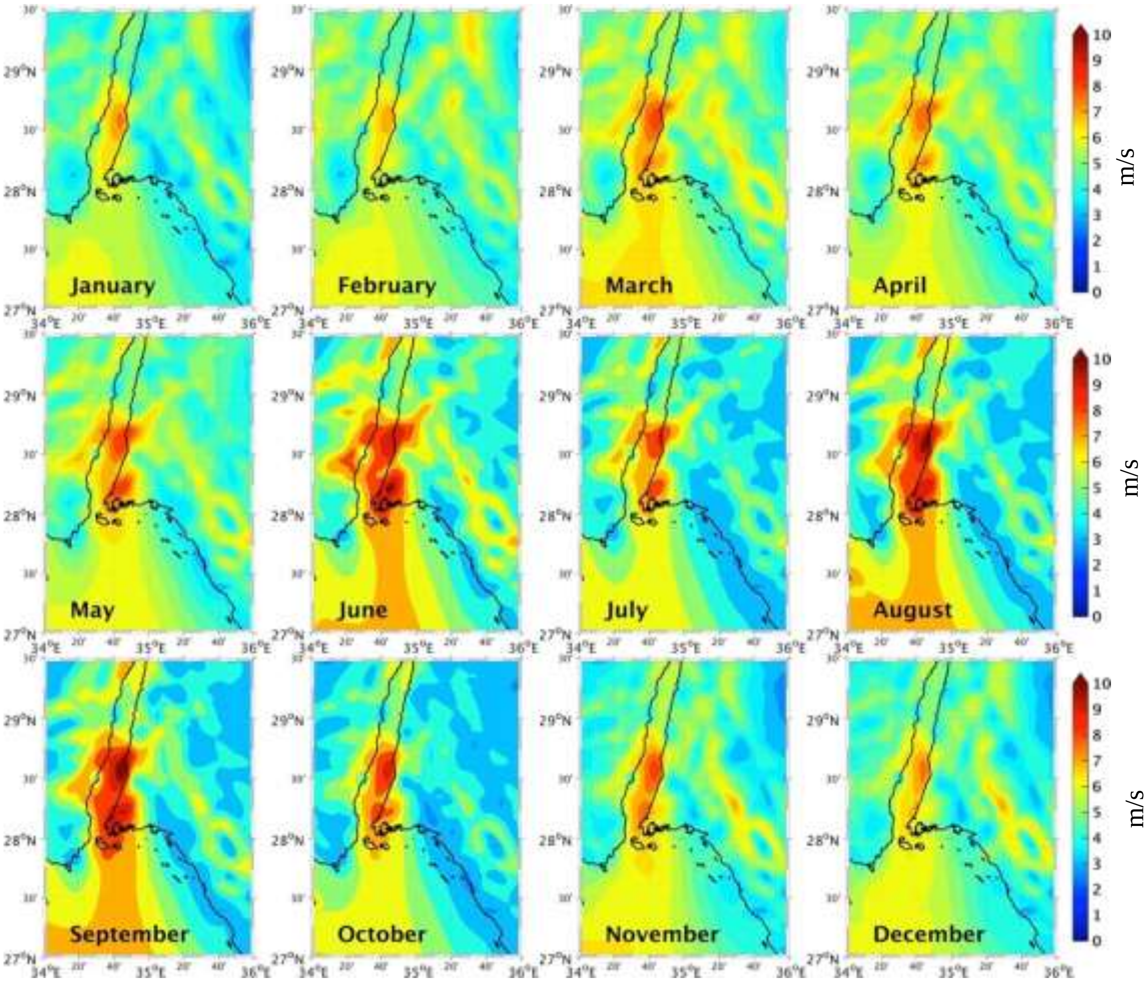


Figure 3.6 Monthly distribution of mean wind speed (m/s) using WRF simulations (2001–2015).

3.2.2 Wave Analysis

The study of wave conditions over the NEOM region was performed based on simulated waves using WAVEWATCH III forced with WRF model outputs. The simulation was performed on a regular grid of 100 m resolution, and outputs are available at hourly intervals: Figures 3.7 and 3.8 demonstrate the mean and maximum wave heights for year 2001, respectively.

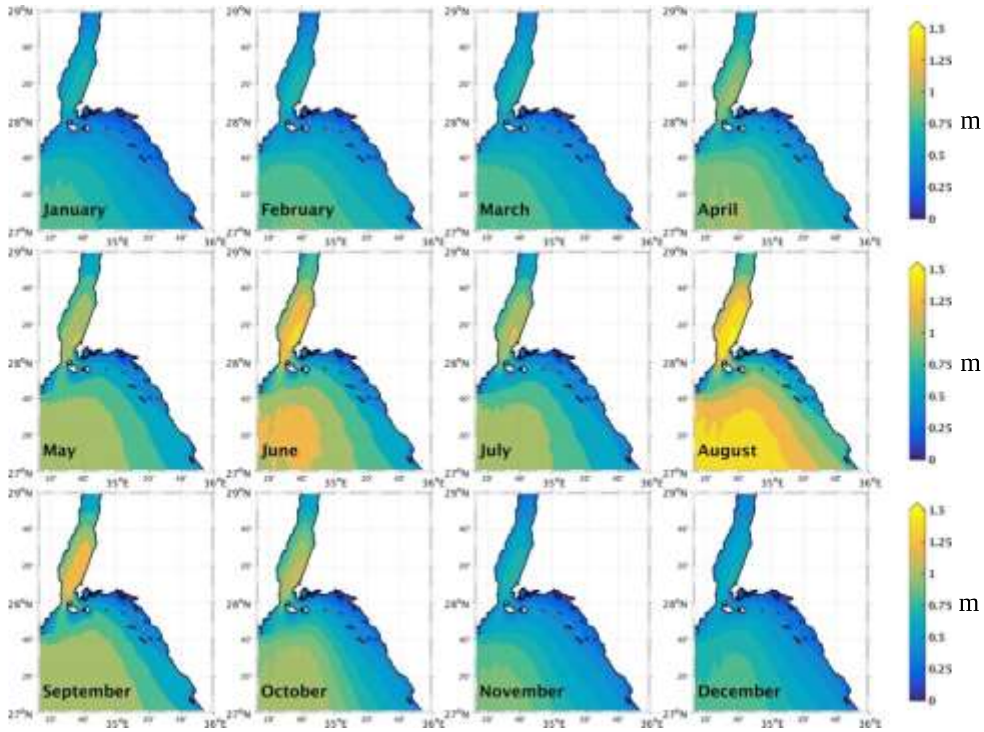


Figure 3.7 Monthly distribution of mean significant wave height (m) for the year 2001.

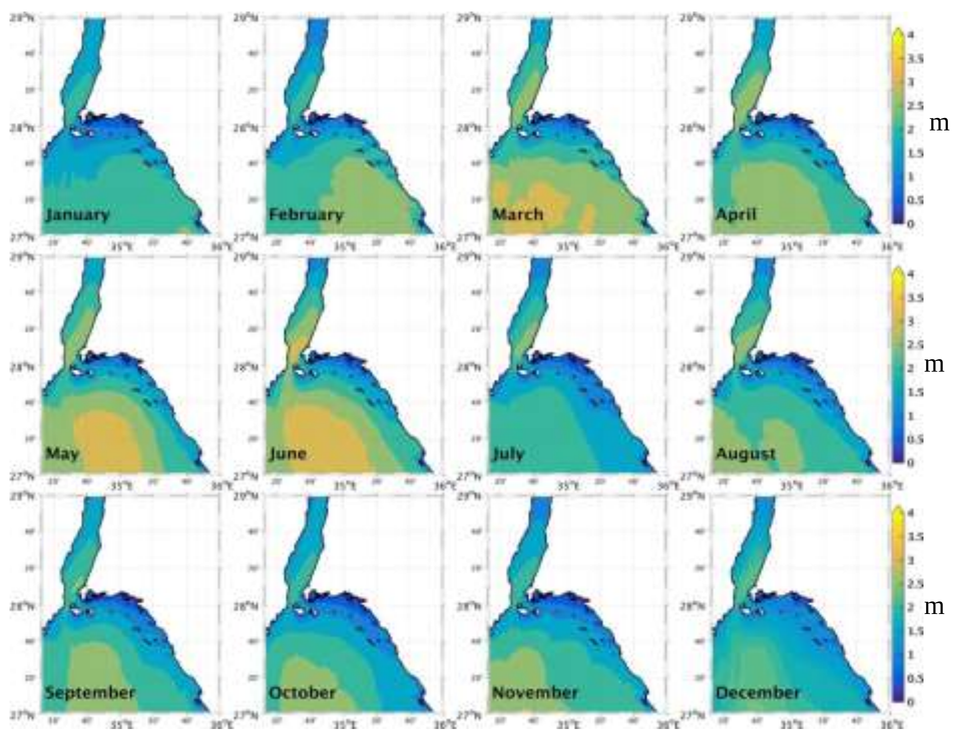


Figure 3.8 Monthly distribution of maximum significant wave height (m) for the year 2001.

Wave heights are generally low over the region and mostly dissipate after breaking close to the coast. Higher waves are noticeable throughout the summer months (mainly August) and are consistent over the period. In the 2001 simulation, the average wave height is less than 1.5 m along the coastline. The high waves are produced by occasional intense winds blowing in the northwest direction.

Although, the northwestern coast of the Red Sea has the greatest nearshore potential with 3 kW/m in wave power and 500 W/m in wind power, as shown in Figure 3.9.

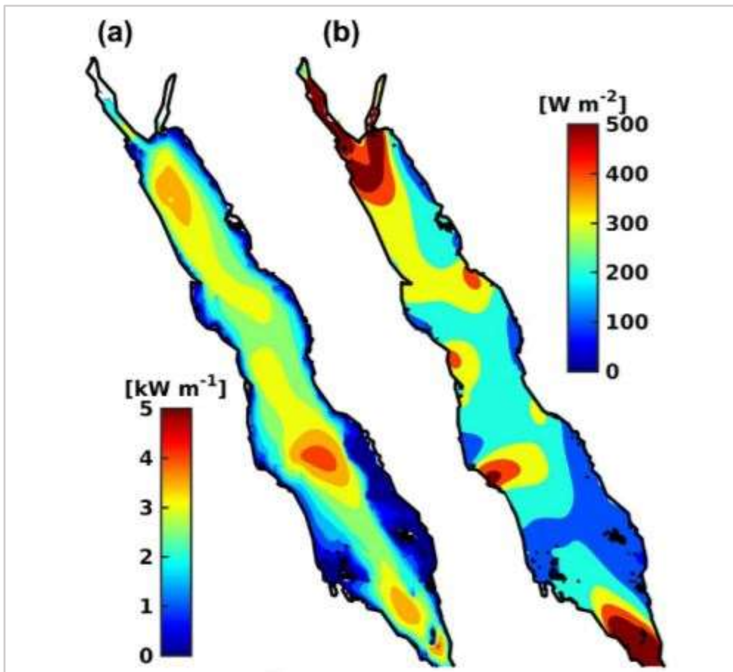


Figure 3.9 Annual mean power densities of (a) wind and (b) waves in the Red Sea [44].

Chapter 4: Wave Energy Converters

4.1 Definition of a Wave Energy Converter

Wave energy converter (WEC) is defined as a device that converts the kinetic and potential energy through the torque produced in a system associated with a moving wave motion between absorber and resistance point, which drives a working fluid through a generator mover into useful mechanical or electrical energy. Wave energy technologies consist of four main components as shown in Figure 4.1: 1) the structure which captures the wave energy, 2) the foundation or mooring to keep the structure in place, 3) the power take-off (PTO) system which converts the mechanical energy into electrical energy, and 4) the control systems to optimize performance in operating conditions.

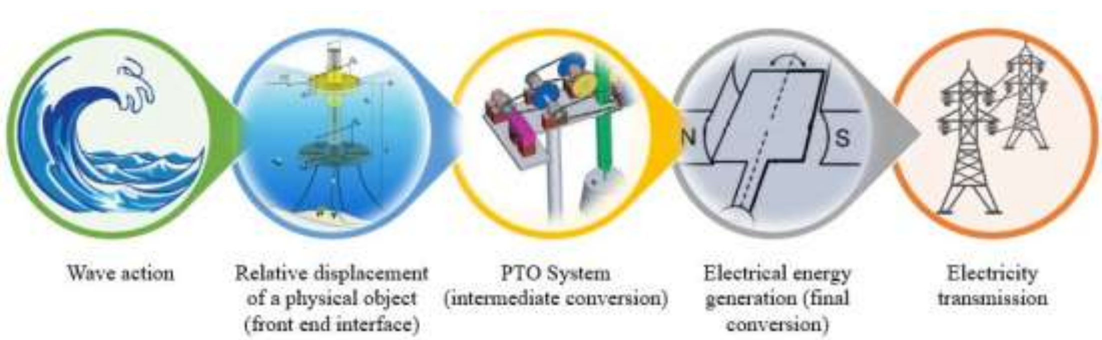


Figure 4.1 Stages of a typical wave energy converter.

Many countries, such as Ireland, Sweden, the United States, China, and Portugal, shown some interesting progress in the planning, installation, and operation of wave energy converters [6]. Although the quantity of those WECs is still low compared with other renewable energy sources, such as solar and wind. The below table presents the installation of Wave Energy Converters around the world. It shows that the understanding of the ocean wave energy sector is growing. The information in Table 2 applied during 2016, note that in this table, WECs are not yet commercialized, and the conceptualized designs are not included [6, 45].

Table 2. Wave Energy Converters Installations (kW) around the world [6, 45].

Country	Planned	Installed	Operational	Total
Canada	0	0	11	11
New Zealand	0	20	0	20
Denmark	39	12	1	52
Italy	0	150	0	150
Mexico	200	0	0	200
Ghana	0	0	450	450
Spain	0	230	296	526
Korea	0	0	665	665
Portugal	350	0	400	750
China	0	800	525	1325
United States	1335	500	30	1865
Sweden	0	0	3200	3200
Ireland	5000	0	0	5000

4.2 Classification of Wave Energy Converters

Due to the numerous numbers of WECs, there are several classifications based on the following criteria: 1) location of the device concerning the bathymetry and the distance to the coast, Figure 4.2. 2) position of the converter related to the sea level. 3) Size and orientation of the converter, Figure 4.3. 4) Energy captures principle, Figure 4.4 [40].

1) The first classification, WECs can be mounted either on the shoreline (typically adjacent to water depths < 15 m), on shallow water near the shore (typically water depths < 25 m), or in deeper offshore waters (typically water depths > 25 m) [16].

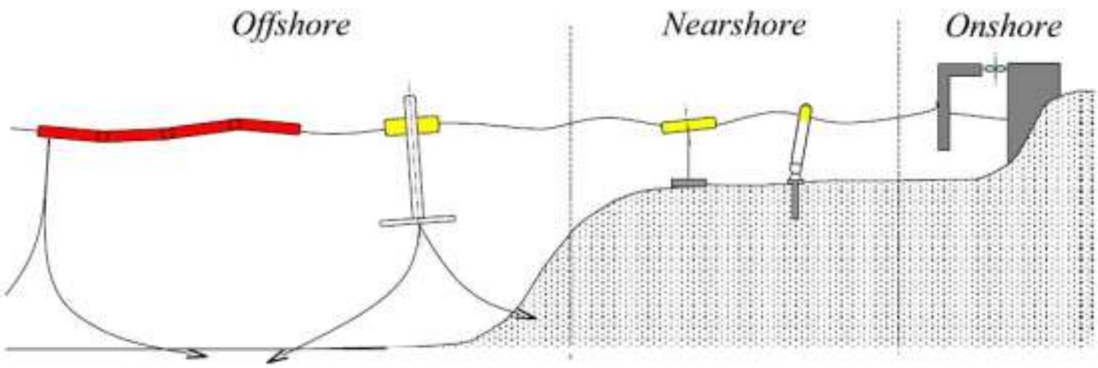


Figure 4. 2 Classification of wave energy converters according to the distance to the coast [16].

2) Regarding the second classifications, the position of the device related to the sea level distinguished between emerged, semi-submerged, and submerged. Also, depending on the type of support structure, it can be bottom-standing or floating with a mooring system.
3) The third classification of wave energy technologies is based on the device's size and orientation, the ratio of the total dimensions to the wavelength of the waves, and the relation between the orientation and propagation direction, as shown in Figure 4.3. Technologies are therefore categorized as terminators when considering wave-facing structures with dimensions greater than or equal to the order of wavelength magnitude. In contrast, attenuators are referred to as large-sized wave energy converters whose main dimension is aligned with waves. Such a device is known as a point absorber when the system is small compared to the waves.

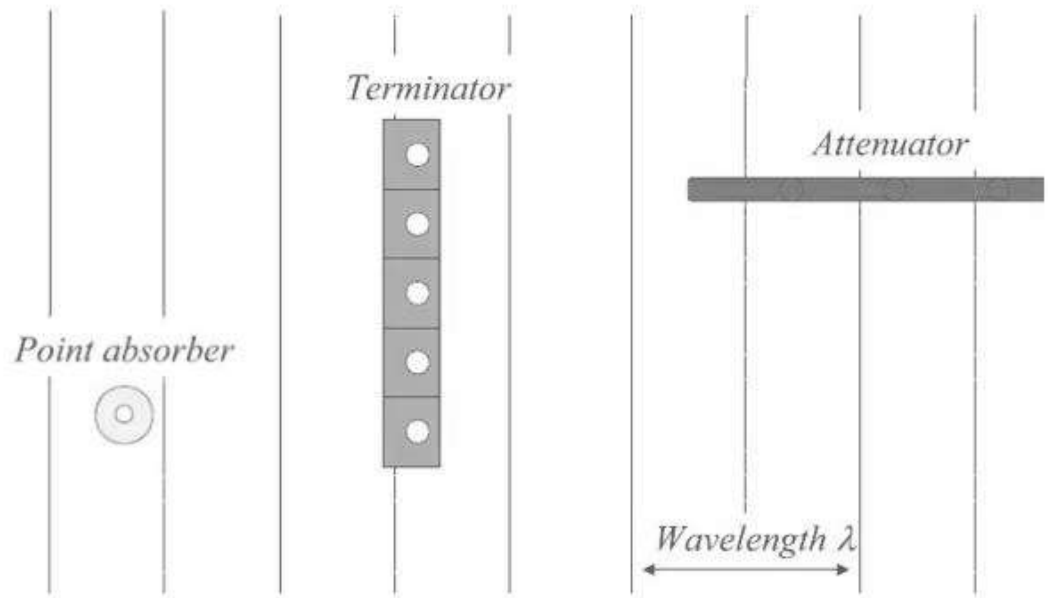


Figure 4.3 Classification of wave energy converters according to the wavelength and their orientation according to the main direction of propagation.

4) The fourth classification depends on the principles of catching energy, which we are going to use in this study: A) Wave Attenuator. B) Point Absorbers. C) Oscillating Water Columns. D) Overtopping Devices. Tables 2, 3, 4, and 5 present a brief description of the characteristics and examples of each category.

A. Wave Attenuator

An attenuator is a floating device that runs parallel to the path of the wave and rides the waves effectively. These instruments extract energy from the two arms relative motion as they move through the wave. Floating devices of this type, including Pelamis [46], Wave Star [47], Salter Duck [48], and Anaconda [49]. Table 3 present the characteristics of floating devices. Figure 4.4 shows examples of wave attenuator devices. More details can be founded in Appendix A.

Figure 4.4 Attenuator: Pelamis (top) [46] and Wave Star (bottom) [47].

Table 3. Characteristics of attenuator wave energy conversion systems [50].

Wave absorber	Type, water depth (m)	Mean wave power (kW/m)	Output power (kW)	Development Stage
Pelamis	Floating ocean surface 50-60	15-40	750-1000	Currently busy to install the world's first wave farm (Agucadura) with a capacity of 2.25MW
Wave Star	Floating in the ocean 2-30	24	500-6000	Early tests (1:10 scale model)
Salter Duck	Floating in the ocean 2-30	24	375	Early testing stage
Anaconda	Floating in the ocean 20	50	1000	Scale model testing in a wave tank

B. Point Absorbers

A point absorber is a floating object that absorbs energy from all directions by traveling to/near the surface of the water. Depending on the displacer/reactor configuration, the power take-off system can take several forms. Examples of this type of waver energy converters are the SEAREV [51], L10 [52], OPT power [53], AquaBuoy [54], Archimedes Buoy [55], Uppsala [56], WaveBob [57], WaveRoller [58], BioWave [59], and Pendulum [60] as shown in Table 4. AquaBuoy, Archimedes Buoy, WaveRoller, and Pendulum have the lowest mean wave power around 15 kW/m. while the highest mean wave power for wave energy converter is the WaveBob 70 kW/m. Figure 4.5 shows examples of wave point absorber devices. More details can be founded in Appendix A.

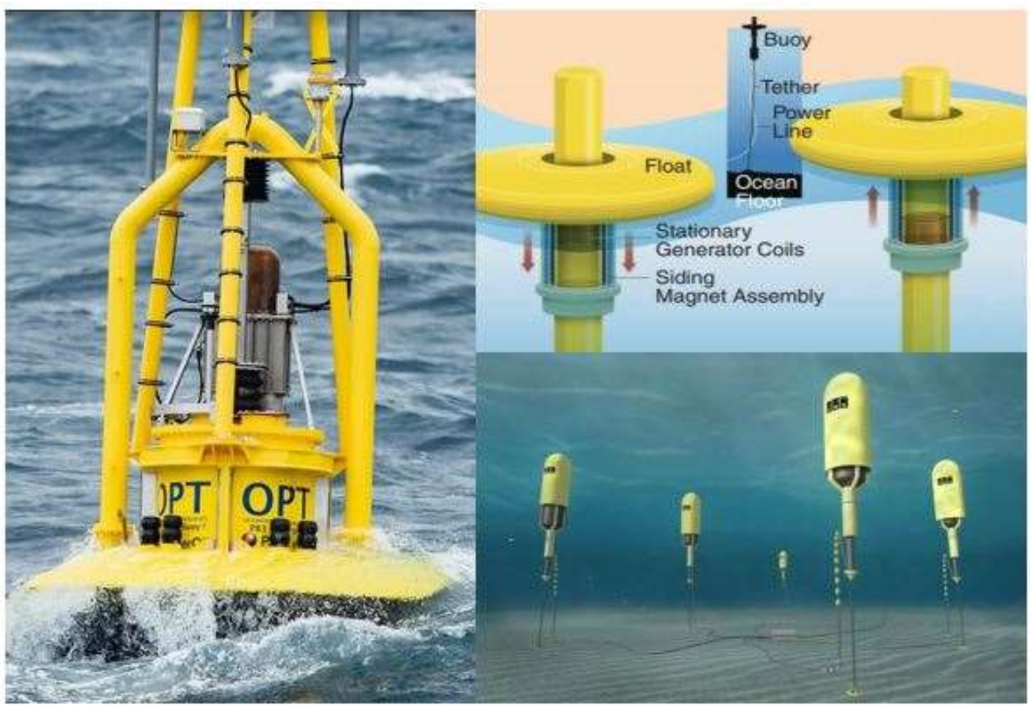


Figure 4.5 Point Absorber: OPT power (left) [53], L10 (top right) [52], Archimedes Buoy (bottom right) [55].

Table 4. Characteristics of point absorber wave energy conversion systems [50].

Wave absorber	Type, water depth (m)	Mean wave power (kW/m)	Output power (kW)	Development Stage
SEAREV	Floating ocean surface 50	40	500	1/12 prototype
L10	Floating in the ocean	20	10	Early testing stage
OPT power	Fixed in the ocean 30-60	50	40-500	Optimization
AquaBuoy	Fixed ocean surface 40-80	15-50	250	Early production
Archimedes Buoy	Fixed seabed 30-60	15	250	Full-scale tests
Uppsala	Fixed seabed	20	5	Concept
WaveBob	Fixed ocean surface over 50	20-70	500	Optimization
WaveRoller	Floating seabed 6-23	15	300	Concept
BioWave	Fixed seabed 6-23	50	250-1000	Unknown
Pendulum	Fixed shore	15	20-300	Concept

C. Oscillating Water Column

An oscillating column of water is a hollow structure that is partially submerged. It is exposed to the sea below the waterline, supporting an air column on top of a water column. Waves cause the column of water to rise and fall, compressing and decompressing the column of air in turn. The trapped air flows into and out of the atmosphere through a turbine, which can rotate regardless of airflow direction; the electricity is generated based on the turbine rotation. The rotation of the turbine is used to produce electricity. Fixed and floating examples of this type are OceanLinx [42], Limpet [61], Pico Plant [62], Osprey [63], and Mighty Whale [64]. Mean wave power, output power, and development stages are given in Table 5. Figures 4.6 and 4.7 show examples of wave oscillating water column devices. More details can be founded in Appendix A.

Figure 4.6 Oscillating Water Column: OceanLinx [42].

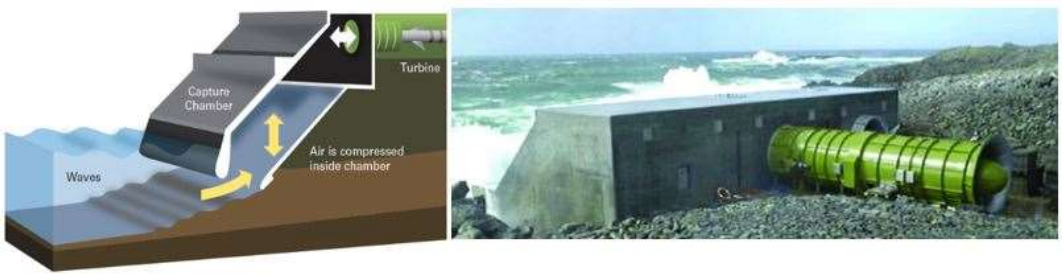


Figure 4.7 Oscillating Water Column: Limpet [61].

Table 5. Characteristics of oscillating water column wave energy conversion systems [50]

Wave absorber	Type, water depth (m)	Mean wave power (kW/m)	Output power (kW)	Development Stage
OceanLinx	Floater off-shore 5-50	50	200-1500	Sea trails
Limpet	Fixed on-shore 15	15	500	Production
Pico Plant	Fixed in the ocean 7	40	400	Production
Osprey	Fixed in the ocean 15-20	50	500	Production
Mighty Whale	Fixed ocean surface 40	15	110	Sea trails

D. Overtopping Device

This type of device captures water as waves break into a storage reservoir. Then, the water returns to the sea by passing through a conventional low-head turbine, generating power. To concentrate the energy of the wave, and the overtopping device may use ‘collectors’. Fixed and floating devices of this type are the Tapchan [64], Wave Dragon [65], and SSG [66] are shown in Table 6. Figure 4.8 shows examples of wave overtopping devices. More details can be founded in Appendix A.

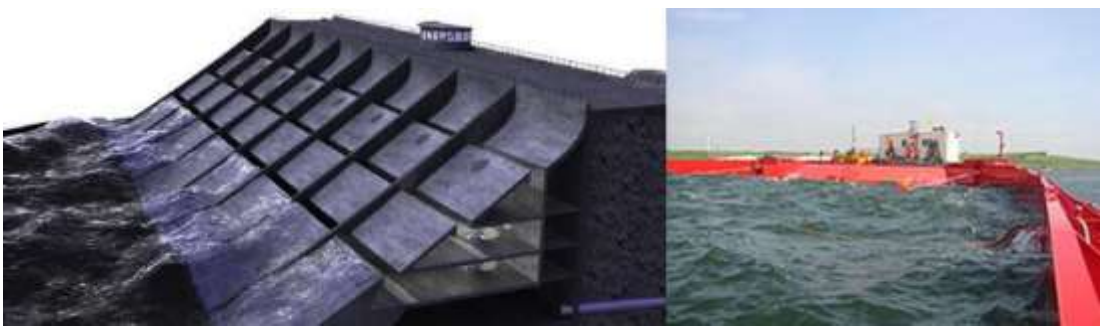


Figure 4.8 Overtopping Device: Tapchan (left) [64] and Wave Dragon (right) [65].

Table 6. Characteristics of overtopping wave energy conversion systems [50].

Wave absorber	Type, water depth (m)	Mean wave power (kW/m)	Output power (kW)	Development stage
Tapchan	Fixed shore 20	40	350	Unknown
Wave Dragon	Floating ocean surface 20-30	24	40	Plans to install a 7MW device during 2008 of the Wales coast
SSG	Fixed shore 15	19	150	Concept

There are other classifications considering all the mentioned criteria as per the European Marine Energy Centre, EMEC [46], they are using eight main types to classify converters: attenuator, point absorber, oscillating wave surge converter, oscillating water column, overtopping/terminator device, submerged pressure differential, bulge wave, rotating mass, and other presented in Figure 4.9.

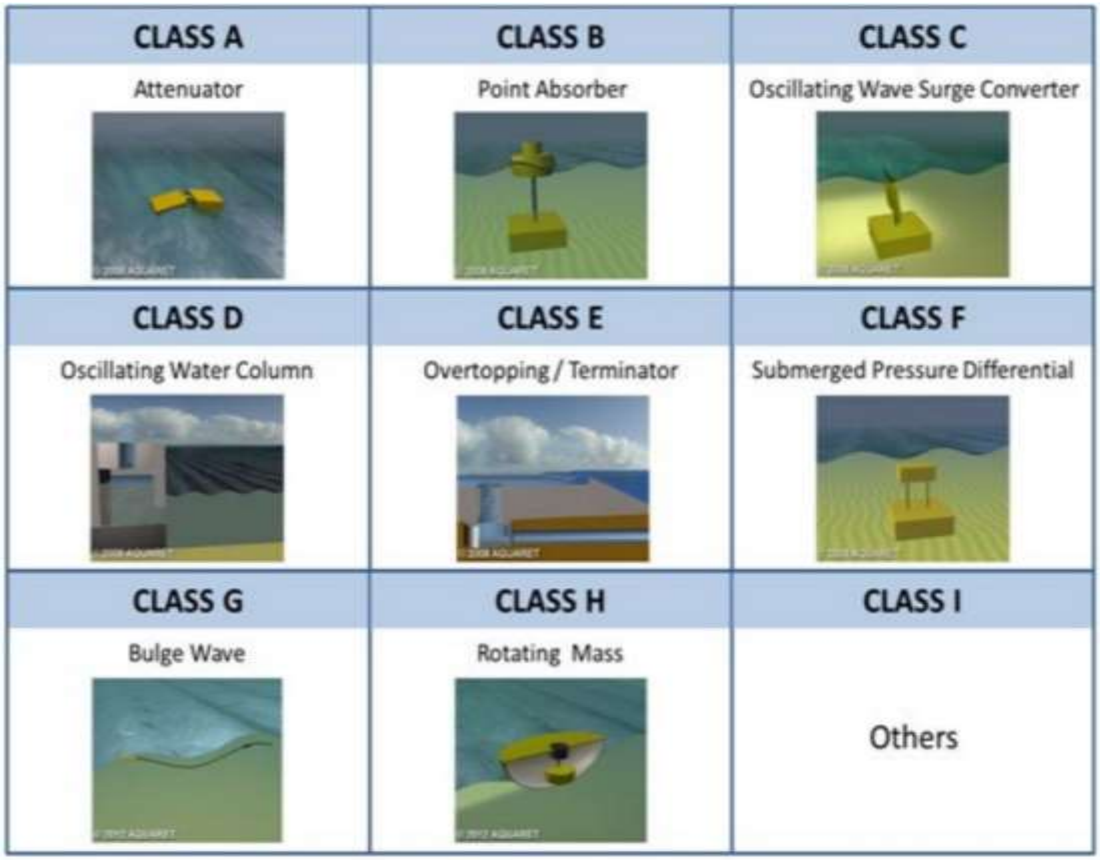


Figure 4.9 WECs classification by EMEC [46].

4.3 Testing and Commercialization

4.3.1 DEIM

A fixed point absorber device is proposed by the Department of Energy, Engineering Information, and Mathematical Models (DEIM) of the University of Palermo, Italy [67]. DEIM is an integration of wave and solar sources to produce electricity regularly during the year, and it has a rated power of 80kW. Figure 4.10 shows a representation of a Point Absorber currently in the design stage.

DEIM is able to transform wave energy into electrical energy, without the use of other devices such as toothed wheels, pressurized liquids (oils or water), transmission belts, etc. [68]. It is capable of transforming wave energy independently from its direction of propagation, which is a significant feature to increasing the electrical energy output. An interesting research on the modeling of a Point Absorber's hydraulic efficiency and its wave energy extraction is provided in [69], in which an effective conversion system is assessed as being rated at 100 kW. A useful method for transforming wave energy into electrical output is the use of linear generators, in which the magnetic field is generated by use of Permanent Magnets (PM). An interesting study on this Power Take-Off for a wave energy technology is presented in [70], which is referred to Archimedes Wave Swing (AWS) generating system.

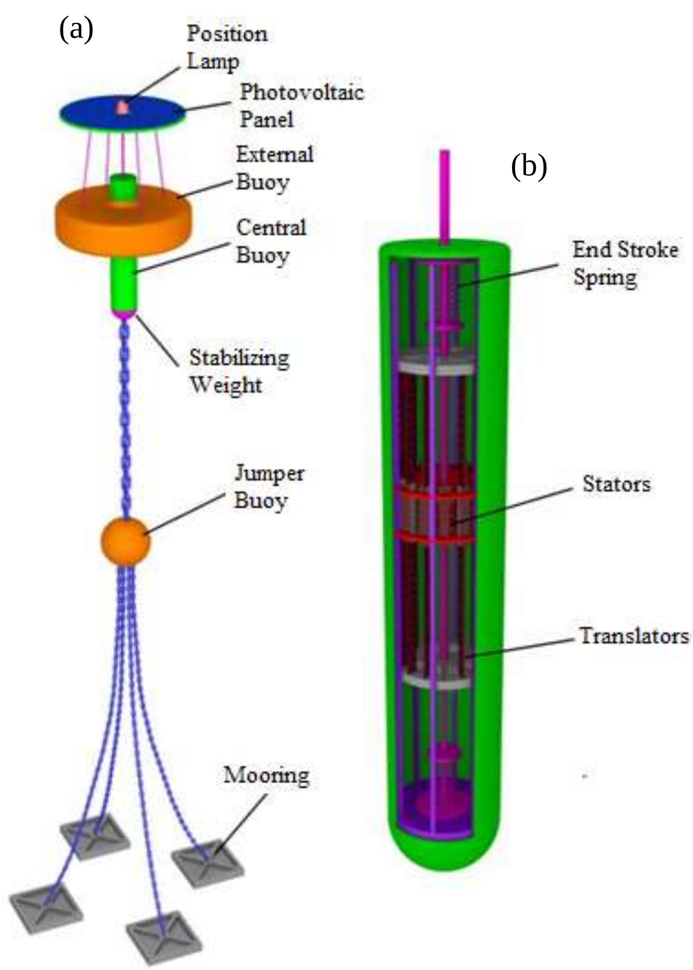


Figure 4.10 (a) External and (b) internal views DEIM [67].

The DEIM wave converter consists of two buoys, shown in Figure 4.11, which can float independently of one another. At different heights, an intermittent red light is mounted on top of the buoy, making the conversion system visible up to several nautical miles away. The outer one (yellow buoy) is 10 m in diameter, while the internal one (green buoy) is 2 m in diameter. The first one is able to intercept the wave energy and to transfer it to the second one due to the presence of connecting rods (pink rods). A hemispherical weight (red part) is located in the bottom part of the inner buoy, which ensures its correct vertical positioning and gives it greater inertia. The green buoy contains all eight linear generators, see Figure 4.12, which are based on a small-scale prototype built in the Department's laboratory [71]. These linear generators have a working stroke of 4 m, in order to use wave energy contained in the most energetic sea state too. In the upper and lower part of the inner case, there are two springs that prevent any damage to the inner buoy due to bad weather.

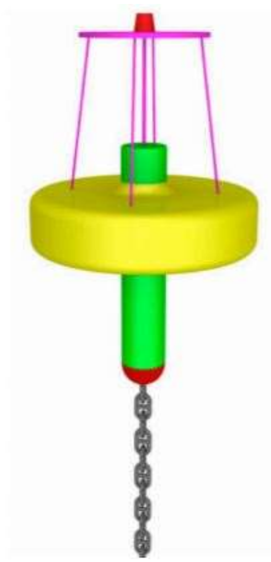


Figure 4.11 Graphical representation of the DEIM Point Absorber [71].

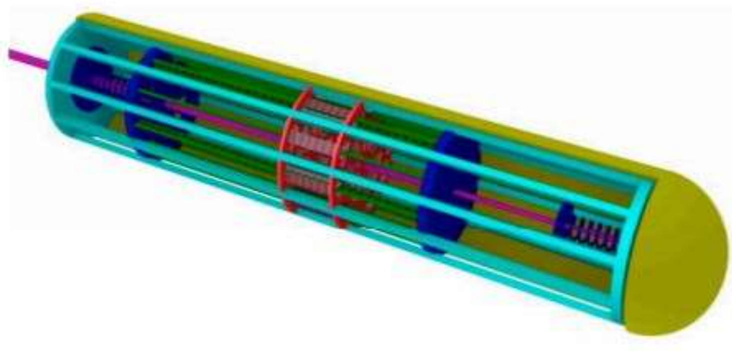


Figure 4. 12 Cross-section of the inner buoy of DEIM Point Absorber [71].

The linear generators are connected to electronic devices, which are used to correct the electricity waveform produced here. These are fundamental devices, because of the irregular frequencies of the incoming waves. To reduce scraping phenomena and interference in the seabed, the connection of the systems to the grid will be obtained through the use of submarine cables [71]. Moreover, DEIM can be used offshore, several kilometers away from the coasts, reducing the visual impact on the mainland.

Finally, in order to avoid mutual interference phenomena, these devices will be mounted in multiple arrays in a line that is normal to the direction of the main waves: in this way, it is possible to build several wave farms with an installed power of different MW in a very restricted area. The high performance of the linear generators constituting the Power Take-Off (PTO) and the high resistance of the construction materials, which make the useful life of the device is about 20 years.

Chapter 5: Research Methodology

5.1 Methodology of Wave Energy Modeling

The first task for achieving the objective of this study consists of the development of a methodology for site selection. This chapter presents the approach, which will seek to help decision-making by describing six phases. These stages relate to different levels of detail that will be requested by promoters when planning deployment at the Red Sea. The main stages are shown by the power flow diagram for selecting Wave Energy Converters in Figure 5.1. In the first stage, it is gathering general information about the Red Sea basin, such as wind speed and significant wave heights distribution in the Red Sea, derived from a long-term data set of 30-year (1985-2015) at 10-km and 5-km resolution, respectively. In the second stage, general information of wind speed at NEOM region will be collected from (2001-2015) at 5-km resolution in hourly intervals and collected data of significant wave height during (2001) at 100 m resolution, using simulations of WRF and WAVEWATCH III, respectively. In the third stage, further information gathering will begin. The methodology will list the necessary information on NEOM coastlines, including the Gulf of Aqaba and NEOM Bay, at a high-resolution data set of 1-km from (2007-2018), such as wave height, wave peak period, mean wave power, distance to shoreline, and wind speed. This will provide an accurate and convenient visual aid for choosing suitable study points as stage four. In stage five, the total wave energy resource generated at a point will be assessed, allowing the computation of the power average at each point using equations (5.13) and (5.14) at the eight study points. In addition to the amount of wave power and potentially available energy, another aspect to consider when selecting an appropriate site for WEC deployment is its temporal variability at the eight study points in different time scales (monthly and seasonal): the seasonal variability index (SV), the coefficient of variation (COV), and the monthly variability index (MV). Finally, the last stage is selecting a suitable WEC, which will be discussed in chapter 6.

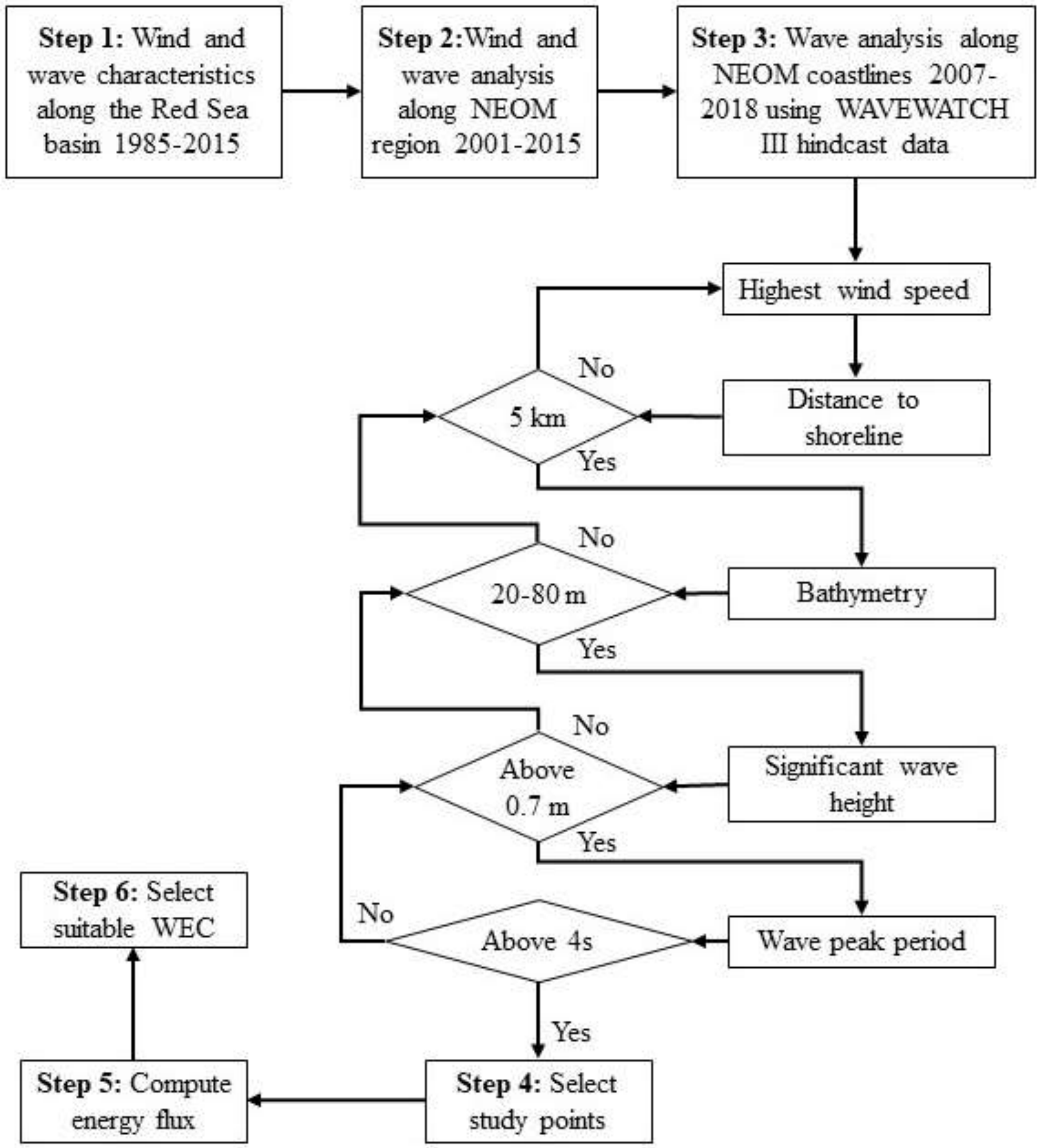


Figure 5. 1 Power flow diagram for selecting Wave Energy Converters (WECs).

5.2 Study Area

NEOM, located in southwestern Saudi Arabia at Tabuk Province, extends along the Gulf of Aqaba. 468 km of coastline with beaches and coral reefs, and mountains up to 2,500 m high. A total area of around 26,500 km^2. Figure 5.2 represents the location of the study area.

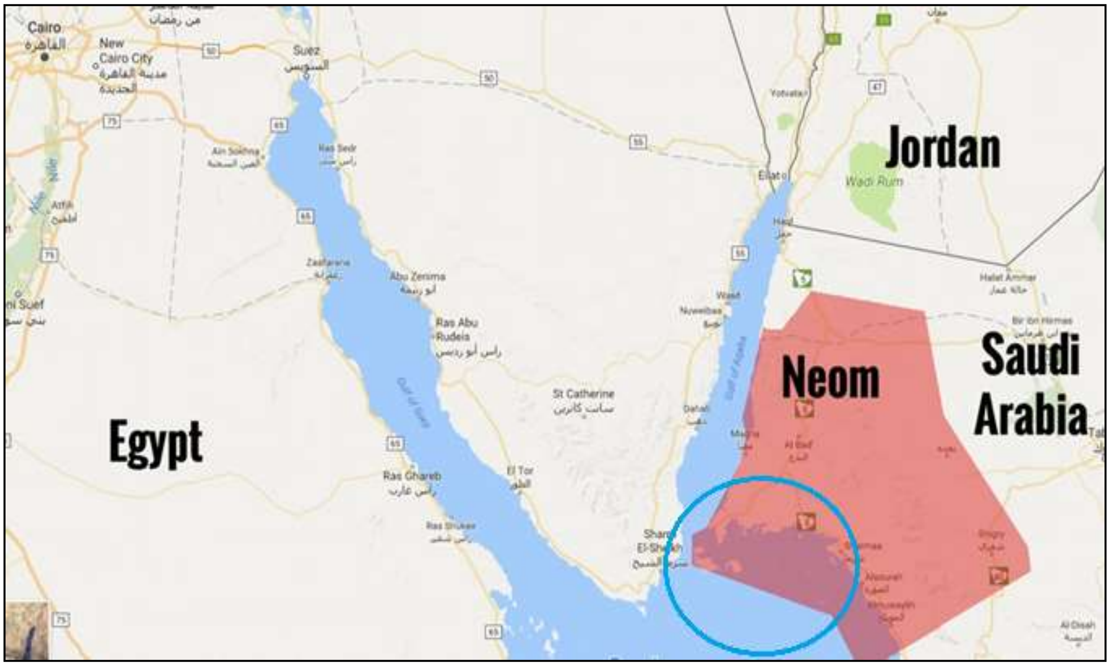


Figure 5.2 Study Area (NEOM Region) [72].

5.3 Selection of Study Points

Choosing a suitable location for WEC has been gone through different factors. Starting from studying and observing the mean wave height over NEOM region using the simulated waves using WAVEWATCH III model for one year (2001) on a regular grid of 100 m resolution at 1-hour intervals, shown in Figure 3.6, and the simulated winds using Weather Research Forecasting (WRF) from 2001–2015 at 5 km horizontal resolution at 1-hr intervals as shown in Figure 3.5. NEOM region has two coastlines; along the Red Sea, NEOM Bay located in Sharma and along the eastern coast of the Gulf of Aqaba, Figure 5.3.

Figure 5.3 NEOM Coastlines.

Based on the previous study and observations from Figure 3.5 and 3.6, the Gulf of Aqaba was considered as a suitable preliminary location for WEC, since the mean wave height is 1.5 m near shore and wind speed almost 8 m/s over Gulf of Aqaba which is stronger than over NEOM Bay.

The study points selected based on a hindcast was generated for wave height and peak wave period using WAVEWATCH III model based on 30-year (1985-2015) at 10-km resolution, power computed based on 12-year (2007-2018) at 1-km resolution grid of NEOM Bay and part of the Gulf of Aqaba, forced by the Red Sea reanalysis surface winds for 12 years, as shown in Figure 5.4 and 5.5 respectively. Table 7 present the collected data set as based on the steps from power flow diagram in Figure 5.1.

Table 7. Collected data sets of Wave and Wind

Location	Red Sea Basin		NEOM Region		NEOM Coastline	
Utilization	Wave Height	Wind Speed	Wave Height	Wind Speed	Wave Height	Peak wave period
Data set	1985-2015	2007-2018	2001	2001-2015	2007-2018	
years	30-year	12-year	1-year	15-year	12-year	
Spatial Resolution	10-km resolution	1-km resolution	100 m resolution	5-km resolution	1-km resolution	
Temporal Resolution	Hourly intervals					

It can be noticed that the wave height along the Gulf of Aqaba is 0.78 m and nearshore, while the average at NEOM Bay is around 0.58 m and far away from the shoreline. The peak wave period at the Gulf of Aqaba is 4 seconds, while it is lower in NEOM Bay. In the power flow diagram, the factor of mean wave peak period has to be more than 4 s, since the mean peak wave period at the selected region is ranging between 1.7 to almost 4 s nearshore, for the period 2007 to 2018 as shown in Figure 5.5.

The bathymetry of the region at a 1-km resolution grid is also considered for the selection of points. Locations with a depth range between 20-80 m were taking into consideration based on most wave energy converters specifications.

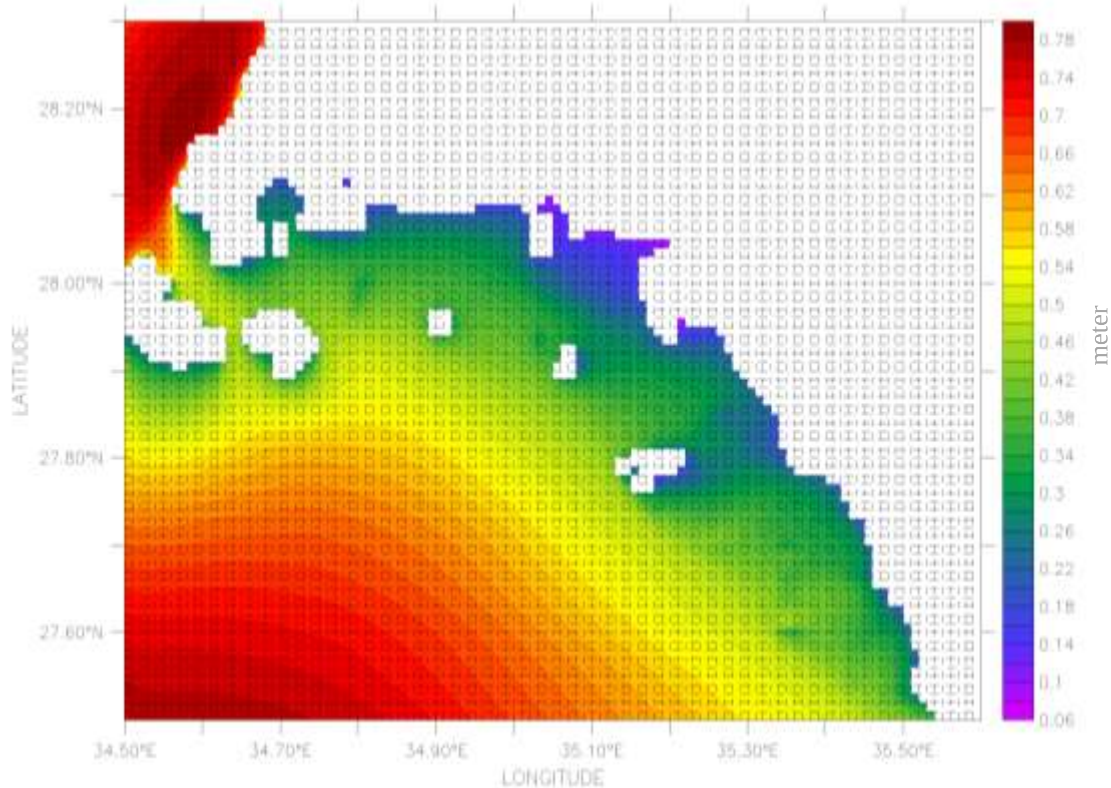


Figure 5.4 Mean significant wave height for the period 2007-2018.

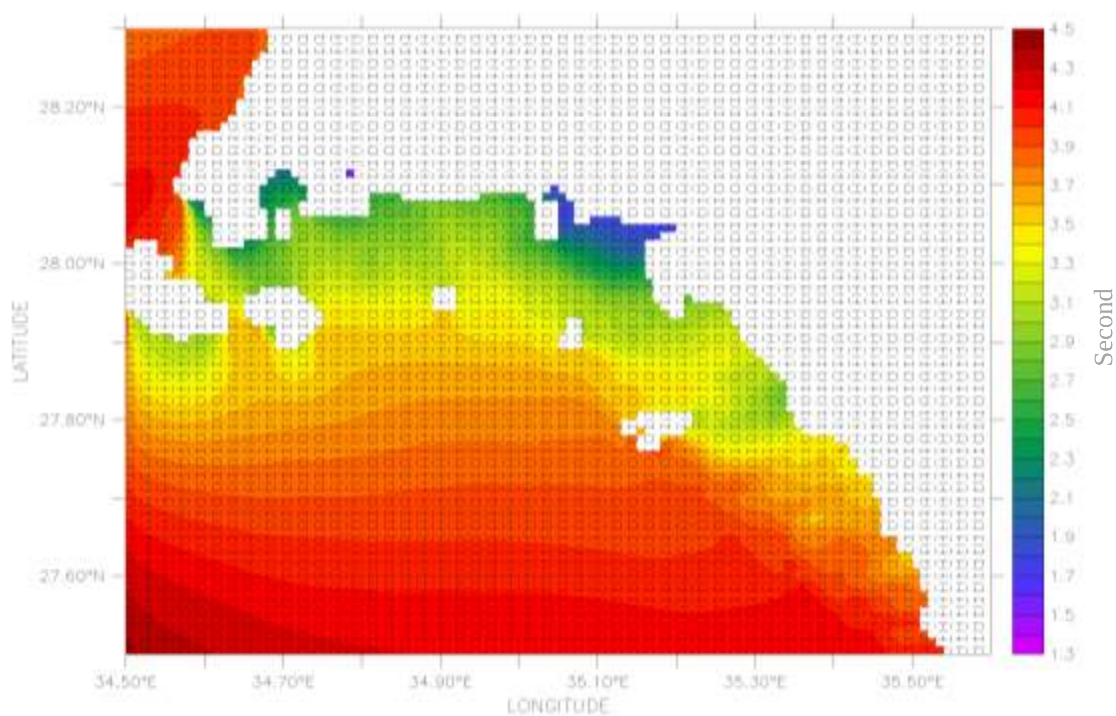


Figure 5.5 Mean peak wave period for the period 2007-2018.

A total of 8 points were selected to test the potential of wave energy at NEOM coastlines. The distribution of study points is presented in Figure 5.6 (denoted as P1 to P8), and their geographical coordinates, water distances, and distance to shore are listed in Table 8. P1 to P5 located in the Gulf of Aqaba and P6, P7, and P8 are located in NEOM Bay.

Table 8. Selection of study points.

Point	Latitude	Longitude	Depth (m)	Distance (km)
P1	28°10’N	34°54’E	40.30	3.55
P2	28°15’N	34°56’E	32.95	5.68
P3	28°20’N	34°59’E	21.50	7.49
P4	28°25’N	34°60’E	28.75	7.53
P5	28°28’N	34°62’E	46.57	6.97
P6	27°91’N	34°84’E	55.4	18.50
P7	27°92’N	34°82’E	51.60	18.96
P8	27°72’N	35°06’E	44.93	39.88

Figure 5.6 Selected Study Points P1 to P8 in the Gulf of Aqaba and NEOM Bay.

5.4 Wave Energy Modeling

A range of wave energy modeling methods based on hydrodynamics is available in the literature to analyze and estimate the potential wave power and locate the regions of rich wave energy generation [73–76]. Although the description of waves is relatively complex, the modeling is principally based on the definition of the total ideal constant wave energy that results from the sum of kinetic energy (E_k), which results for the movement of the water particles through the fluid, and potential energy (E_p), that results of the displacement of the free surface wave [77].

$$E_k = \frac{1}{2}mV^2 = \int_{volume}\frac{1}{2}(u^2+w^2)dm \quad (5.1)$$

$$= \int_{-h}^{\zeta}\int_0^{\lambda}\frac{1}{2}\rho(u^2+w^2)dxdz$$

$$= \int_{-h}^{0}\int_0^{\lambda}\frac{1}{2}\rho(u^2+w^2)dxdz + \cancel{\int_0^{\zeta}\int_0^{\lambda}\frac{1}{2}\rho(u^2+w^2)dxdz}$$

$$= \frac{1}{4}\rho g\zeta_a^2\lambda$$

$$E_p = mgh = \int_0^{\lambda}(\rho\zeta dx\, .\, g\, .\frac{1}{2}\zeta) \quad (5.2)$$

$$= \int_0^{\lambda}\frac{1}{2}\rho g\zeta^2 dx$$

$$= \frac{1}{2}\rho g\zeta_a^2\int_0^{\lambda}cos^2(kx-wt)dx$$

$$= \frac{1}{2}\rho g\zeta_a^2\, .\frac{1}{2}\lambda$$

$$= \frac{1}{4}\rho g\zeta_a^2\, .\, \lambda$$

Where m is the mass, V is the velocity of meters per second, w is the wave frequency, ζ is the wave elevation, h is the local water depth, λ is the wave length, ρ is the density of seawater (assumed to be 1025 kg/m3), g is the acceleration due to the gravitational force, and k is the wave number.

Total energy E is described by:

$$E = E_k + E_p = \frac{1}{2}\rho g\zeta_a^2 = \frac{1}{8}\rho g H_s^2 \quad (5.3)$$

The wave power (kW/m) transmitted at a specific location by a regular wave per unit of the crest is then approximate by the following relation [77, 78].
The wave power flux P can be obtained by:

$$P = EC_g = \frac{1}{8}\,\rho g H_s^2 C_g \tag{5.4}$$

Where C_g is the group velocity, or the speed of wave energy propagation. For deep waters, the energy is transmitted at only half the speed of the wave celerity. In our study, we are using deep water since WECs in deep water have more substantial generation potential than in shallow water. Also, deep water indicates that the highest orbits are on the surface of the water, having both the highest potential and kinetic energy. The deep waters of the central Red Sea exhibit high wave power, almost double of that found near the coast.
C_g defined as:

$$C_g = \frac{1}{2}\left(1 + \frac{2kh}{\sinh(2kh)}\right)\frac{L}{T} \tag{5.5}$$

where T is the wave period, L is the wavelength, $C = L/2$ which is the wave celerity, and k is the wave number given by $k = 2\pi/L$.

The wavelength, depth and period are related through the dispersion equation:

$$L = T\sqrt{\frac{g}{k}\tanh(kh)} \tag{5.6}$$

For a regular wave in deep water ($h > L/2$), $C = L/2 = 2C_g$, and $L = L_o = gT^2/2\pi$ [79]. Substituting these relations in equation (5.4), we get:

$$P = \frac{1}{32\pi}\rho g^2 {H_s}^2 T \tag{5.7}$$

Real sea states a summation of a large number of regular waves of varying frequencies, amplitudes, and directions [79]. The combination of amplitudes, frequencies, and directions is also represented by a variance spectral density function or 2D spectrum of waves, If the directional spectrum of sea state variance $S(f, \theta)$ is known with f the wave frequency (Hz) and θ the wave direction (rad), a more accurate formulation is used [80]:

$$P = \rho g \int_0^{2\pi} \int_0^{\infty} C_g(f, h) S(f, \theta) \mathrm{d}f\mathrm{d}\theta \tag{5.8}$$

To find $C_g(f, h)$, substitute (5.6) in (5.5) :

$$C_g(f, h) = \frac{1}{2}[1 + \frac{2kh}{\sinh(2kh)}]\sqrt{\frac{g}{k}\tanh(kh)} \tag{5.9}$$

Where k is the frequency-dependent wave number, and h is the local water depth. The wave power per unit width transmitted by irregular waves can be approximated as:

$$P \approx \frac{\rho g}{16} H_{m0}^2 C_g(T_e, h) \tag{5.10}$$

where $H_{m0} = 4\sqrt{m_0} = H_s$, it is the spectral wave height evaluated from the wave energy spectrum, whose spectral moments are defined as [81]:

$$m_i = \int_0^{2\pi} \int_0^{\infty} (f, \theta) f^i \mathrm{d}f\mathrm{d}\theta \tag{5.11}$$

T_e is known as the energy period. The energy period of a sea state is defined in terms of spectral moments as:

$$T_e = \frac{m_{-1}}{m_0} = \frac{\int_0^{2\pi} \int_0^{\infty} f^{-1} S(f) \mathrm{d}f\mathrm{d}\theta}{\int_0^{2\pi} \int_0^{\infty} S(f) \mathrm{d}f\mathrm{d}\theta} \tag{5.12}$$

In deep water where $\left(h > \frac{L}{2}\right), C_g(f, h = \infty) = \; g/4\pi f$ [82]. The approximate expression for wave power transmitted per unit width simplifies further from the previous equations to the final relation to find the power flux:

$$P = \frac{\rho g^2}{64\pi} H_s^2 T_e = 0.491 H_s^2 T_e \tag{5.13}$$

The database used in this study does not include details on the spectral shape or spectral moments, and sea states are specified in terms of significant wave height H_s and peak period T_p, so T_e must be calculated using other variables. When T_p is known, one approach is to make the following assumption [79]:

$$T_e = \alpha T_p \tag{5.14}$$

Where α is a coefficient depends on the shape of the wave spectrum; a conservative value of T_e = 0.9 T_p was used to assess the wave energy resource [83].

During the selection of a site for wave energy converter (WEC), another critical aspect that should be considered besides the amount of wave power and potentially available energy is its temporal variability at different time scales, namely: daily, monthly and seasonal. Sites with a steady wave energy flux are preferable to those with unstable wave conditions since they are more reliable and show higher efficiency. Among the coefficients proposed to assess the temporal variability in wave power at a specific location, as suggested by Cornett et al. [79]: the coefficient of variation (COV), the seasonal variability index (SV), and the monthly variability index (MV).

The COV is determined by dividing the standard deviation (σ) of the power time series (*P(t)*) by the average power (μ):

$$COV = \frac{\sigma[P(t)]}{\mu[P(t)]} \tag{5.15}$$

COV Values of 0.85-0.9 indicate that the resource is unsteady, while values higher than 1.2 denote considerable variability as reported in reference [83]. SV is defined by:

$$SV = \frac{P_{S1} - P_{S2}}{P_{year}} \tag{5.16}$$

Where $PS_{1,}$ is the mean wave power for the highest-energy season (winter) and PS_4 is the mean wave power for the lowest-energy season (summer), and P_{year} is the mean wave power over the year. Greater SV means more significant seasonal variability, values lower than 1, indicating moderate seasonal variability. MV is defined as follows:

$$MV = \frac{P_{M1} - P_{M12}}{P_{year}} \tag{5.17}$$

P_{M1} is the mean wave power for the highest-energy month, and P_{M12} is the mean wave power for the lowest-energy month. Since it is a monthly variation, the values of MV are higher than those of SV.

To estimate a WEC's electricity production at a particular site is to compare the power matrices that provide the wave operation for the respective location within a specified time period with the power matrices of each WEC, this operation can be performed [84] using the equation:

$$P_E = \frac{1}{100} \cdot \sum_{i=1}^{n_T} \sum_{j=1}^{n_H} p_{ij} \cdot P_{ij} \tag{5.18}$$

Where pij is the energy percentage corresponding to the bin defined by the line i and the column j, and Pij is the electric power corresponding to the same energy bin for the WEC (the power matrix is provided by each WEC manufacturer on an experimental basis, or they were designed using numerical models).

In the next chapter, mean wave power will be calculated using equation (5.13) and (5.14). The temporal variability at different time scale daily, monthly, and seasonally will be calculated at each study point.

Chapter 6: Results and Discussion

The potential of wave energy study was carried out for the Red Sea, considering the wave conditions over a long-term period from 2007 to 2018. The wave hindcast was generated using WAVEWATCH III – WW3, a third-generation wave model forced by Red Sea reanalysis surface winds from the advanced Weather Research and Forecasting model - WRF on a 1 km resolution grid. A detailed analysis of wave energy variation was performed at 8 locations (P1 to P8) along the Gulf of Aqaba and NEOM Bay, as shown in Figure 6.1. The results of wave power calculated in hourly intervals were averaged for different months, seasons, and years. The long-term mean provides the average distribution of wave power eliminating the inconsistencies due to the variability. There is a distinct amount of wave energy potential in the deep waters of NEOM coastlines, with the mean wave power ranges up to 1.98 kW/m. The highest mean wave power is obtained between 28.00_ N and 28.30_ N latitudes in the Gulf of Aqaba, followed by at around 27.50_ N latitude NEOM Bay.

In the following sections, we will analyze results obtained for the mean significant wave height, energy period, mean wave power, variability index, and the WECs and performance output.

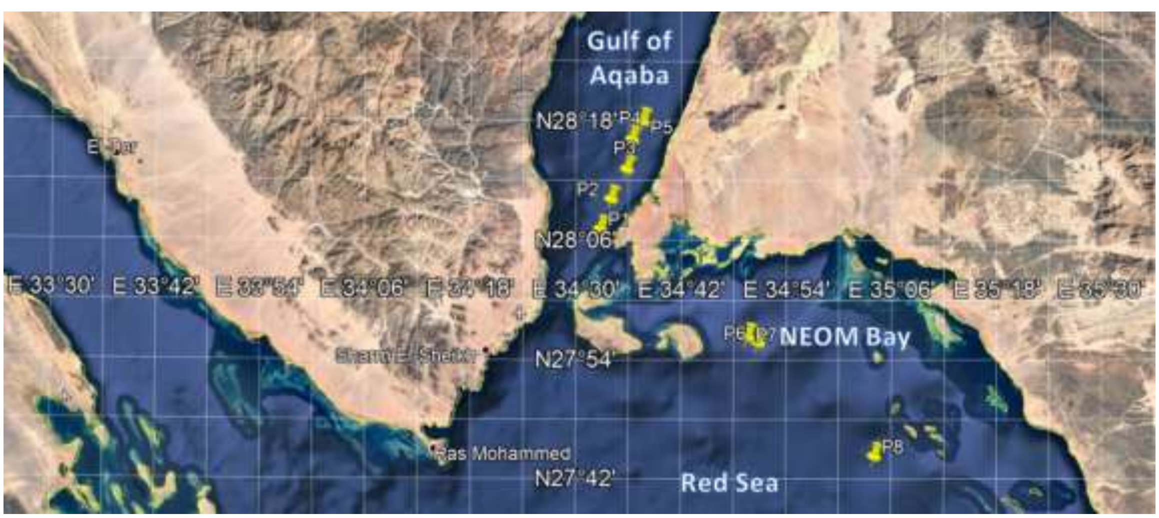


Figure 6.1 Gulf of Aqaba and NEOM Bay in the Red Sea.

6.1 Mean Significant Wave Height, Energy Period, and Mean Wave Power

Figure 6.2 shows the mean significant wave height Hs and the wave energy Te at the eight selected study points. It can be observed that significant wave heights are low in the Red Sea. However, the highest wave values are located in the Gulf of Aqaba (P1 to P5) up to 0.79 m, while in NEOM Bay, the wave height is considerably low in (P6 to P8) up to 0.54 m. while the wave energy period is ranging between 3.5 to 4 s in the Gulf of Aqaba and below 3.5 s along NEOM Bay.

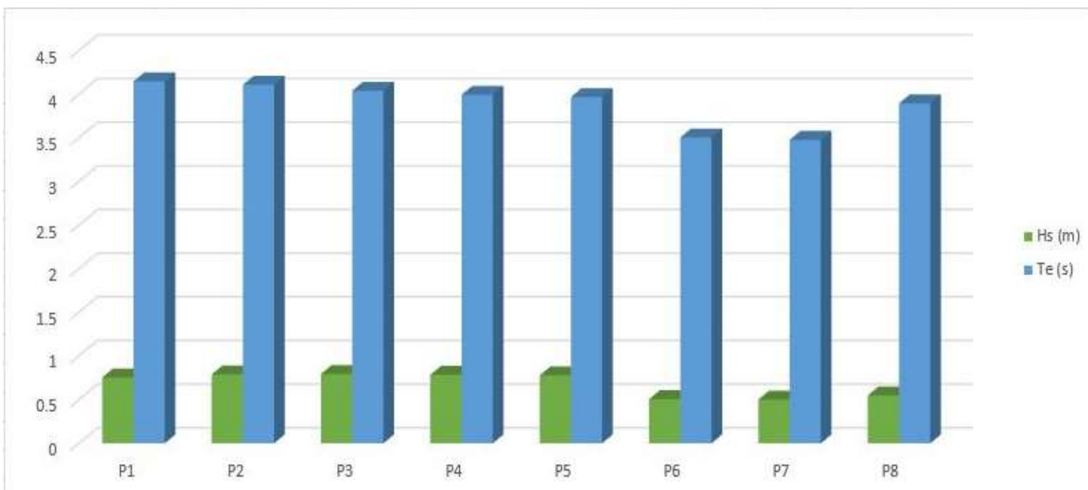


Figure 6.2 Values of the mean $\boldsymbol{Hs}$ and mean Te at the 8 studied points.

Figure 6.3 shows that the mean wave power is relatively low in the Gulf of Aqaba and very low in NEOM Bay. The standard deviations (SD) are below the magnitudes of mean wave power.

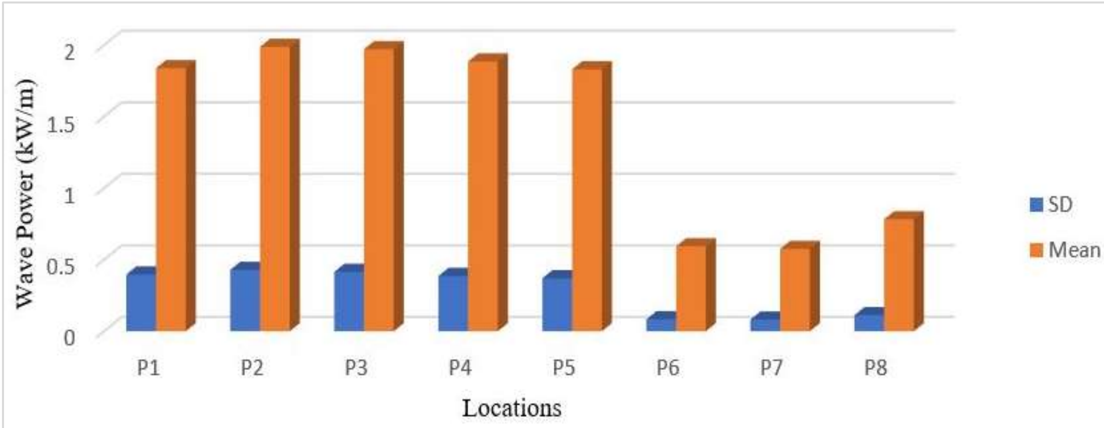


Figure 6.3 Mean wave power and standard deviation at locations P1 to P8 during 2007-2018.

6.2 Coefficient of variation, Seasonal Variability Index, and Monthly Variability Index

Figure 6.3 shows the annual mean wave power (kW/m) at selected locations in the Red Sea including NEOM Bay and Gulf of Aqaba (P1 to P8), the corresponding values are listed in Table 9 and Table 10. The annual mean wave power in the Gulf of Aqaba at the highest and lowest study points (P1 to P5) is 1.99 - 1.83 kW/m, respectively, and annual wave energies of 17.41 – 16.04 MW h/m. While the annual mean wave power at (P6 to P8) on NEOM Bay ranges between 0.59 – 0.78 kW/m and the annual wave energies are 5.21 – 6.86 MW h/m, which has relatively weak mean wave power and annual wave energies due to the sheltering effect on the waves. Since the winds blow from land, it does not have enough fetch to grow the waves. This indicates that NEOM Bay is not well suitable for the exploitation of wave energy on a large scale.

Table 9. Annual mean wave power during 2007-2018 at locations P1 to P8.

Locations	Mean Wave Power (kW/m)				
	Annual	Spring	Summer	Fall	Winter
P1	1.84	1.70	2.00	2.17	1.47
P2	1.99	1.83	2.19	2.33	1.59
P3	1.97	1.82	2.16	2.3	1.59
P4	1.89	1.74	2.06	2.19	1.54
P5	1.83	1.69	1.99	2.12	1.5
P6	0.59	0.53	0.63	0.59	0.61
P7	0.58	0.52	0.61	0.58	0.58
P8	0.78	0.72	0.79	0.71	0.89

The deep waters at the Gulf of Aqaba (P2 and P3) exhibit the highest mean wave power of 1.99 kW/m and 1.97 kW/m, respectively, almost double that found in NEOM Bay. Followed by (P4, P1, P5) ranges between 1.89 and 1.83 kW/m.

Table 10. Wave power and variability coefficients at the 8 study points.

Point	Mean Power (kW/m)	Annual Energy (MW h/m)	COV	SV	MV
P1	1.84	16.11	0.21	0.38	0.79
P2	1.99	17.41	0.22	0.37	0.80
P3	1.97	17.28	0.21	0.36	0.78
P4	1.89	16.52	0.20	0.35	0.75
P5	1.83	16.04	0.20	0.34	0.50
P6	0.59	5.21	0.14	0.16	0.43
P7	0.58	5.04	0.14	0.17	0.44
P8	0.78	6.86	0.14	0.23	0.44

It is interesting to analyze the temporal variability of the wave power at the selected study points. Figure 6.4 shows the seasonal mean wave power (kW/m) during four seasons; fall, summer, spring, and winter at the Gulf of Aqaba and NEOM Bay in the Red Sea during 2006 - 2018. The highest mean wave power at locations P1 to P5 is during fall, while at locations P6 and P7 are during summer, and at location, P8 is during winter. This indicates that the mean wave power during fall is stronger in the Gulf of Aqaba. At P1 to P5, the highest mean wave power during fall is up to 2.33 kW/m at P2 while the lowest mean wave power during fall located at P5, almost 2.12 kW/m, followed by summer, the highest mean wave power is 2.19 kW/m at P2 and the lowest mean wave power is 1.99 kW/m at P5. During spring, the mean wave power ranging between 1.69-1.83 kW/m at P2 and P5, respectively. While in the winter season, the highest mean wave power is at P2 up to 1.59 kW/m, and the lowest mean wave power is 1.50 kW/m at P5. From the results, P2 is the highest mean wave power at the Gulf of Aqaba, and the lowest study point is P5. The seasonal response of the wave power differs according to the locations, sheltering effect on the waves, wave attenuation caused by a large number of coral reefs and small islands. So, along the coast of NEOM Bay P6 and P7, the mean wave power during summer is 0.61-0.63 kW/m, while during winter is 0.58-0.61 kW/m, fall 0.58-0.59 kW/m and spring 0.52-0.53 kW/m. At P8, the mean wave power during winter is 0.89 kW/m, while that summer, spring, and fall are 0.79 kW/m, 0.72 kW/m, and 0.71 kW/m, respectively. Therefore, the seasonal variations of the wave energy resource at P1 to P5 during fall provides almost twice the wave energy potential as the winter, due to stormier conditions. Moreover, P1 to P5 among all seasons considers the highest study points in wave potential than P6, P7, and P8. Finally, P2 is the best study point at the Gulf of Aqaba, and P8 has the highest mean wave power from the selected study points at NEOM Bay.

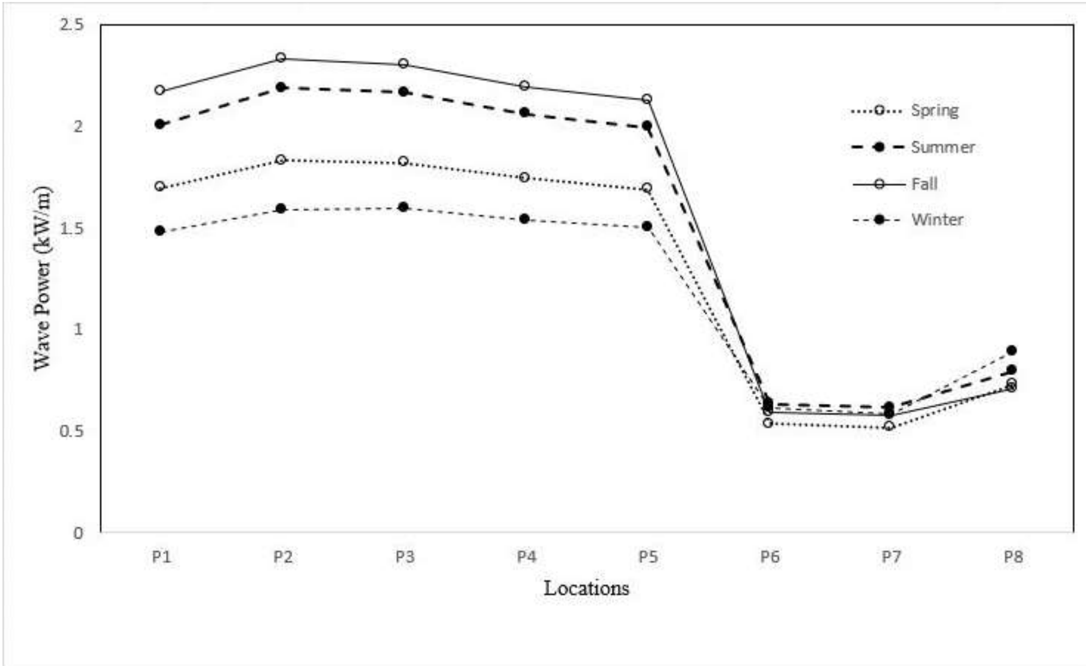


Figure 6.4 Seasonal mean wave power (kW/m) at locations P1 to P8.

Table 11 reports the monthly average value of Hs and Te for the study points (P1 to P8) in the Red Sea. These values are obtained by processing the data collected by WW3 during the period 2007-2018. The power flux of wave is evaluated using equation (5.13). The annual trends of power flux along the two coastlines are reported in Figure 6.3.

Table 11. Monthly average wave data in the Gulf of Aqaba (P1 to P5) and NEOM Bay (P6 to P8).

P1	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
H (m)	0.65	0.6	0.71	0.66	0.71	0.83	0.78	0.88	0.97	0.84	0.72	0.72
T (s)	3.94	3.8	4.08	3.9	4.01	4.31	4.25	4.47	4.61	4.31	4.01	4.07
(kW/m)	1.46	1.23	1.87	1.57	1.64	1.98	1.84	2.18	2.7	2.22	1.58	1.73
P2	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
H (m)	0.68	0.61	0.74	0.69	0.74	0.87	0.82	0.93	1.02	0.88	0.75	0.74
T (s)	3.88	3.74	4.03	3.87	3.98	4.28	4.22	4.44	4.58	4.28	3.97	4.02
(kW/m)	1.57	1.34	2	1.7	1.78	2.17	2.01	2.38	2.91	2.38	1.69	1.86
P3	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
H (m)	0.69	0.62	0.74	0.7	0.75	0.88	0.83	0.93	1.02	0.88	0.75	0.75
T (s)	3.79	3.65	3.93	3.81	3.93	4.23	4.17	4.39	4.53	4.21	3.91	3.92
(kW/m)	1.58	1.34	1.99	1.69	1.77	2.15	1.98	2.36	2.87	2.35	1.67	1.85
P4	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
H (m)	0.68	0.62	0.74	0.69	0.74	0.86	0.82	0.92	1	0.87	0.74	0.74
T (s)	3.74	3.6	3.87	3.77	3.89	4.18	4.13	4.35	4.48	4.17	3.86	3.87
(kW/m)	1.53	1.3	1.91	1.62	1.69	2.04	1.89	2.24	2.72	2.24	1.61	1.79
P5	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
H (m)	0.68	0.62	0.73	0.68	0.73	0.85	0.81	0.91	0.99	0.86	0.74	0.74
T (s)	3.71	3.57	3.83	3.74	3.87	4.17	4.1	4.33	4.46	4.14	3.84	3.84
(kW/m)	1.49	1.27	1.85	1.57	1.85	1.97	1.83	2.17	2.63	2.18	1.56	1.75
P6	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
H (m)	0.5	0.46	0.49	0.44	0.48	0.57	0.51	0.56	0.59	0.49	0.46	0.53
T (s)	3.85	3.85	3.63	3.24	3.14	3.28	3.55	3.42	3.33	3.3	3.57	3.88
(kW/m)	0.62	0.51	0.6	0.48	0.52	0.67	0.58	0.64	0.73	0.56	0.48	0.69
P7	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
H (m)	0.49	0.45	0.49	0.44	0.47	0.56	0.51	0.55	0.58	0.49	0.46	0.53
T (s)	3.83	3.84	3.61	3.22	3.11	3.24	3.52	3.39	3.28	3.26	3.55	3.87
(kW/m)	0.59	0.49	0.58	0.46	0.5	0.65	0.56	0.63	0.71	0.55	0.46	0.66
P8	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
H (m)	0.56	0.52	0.55	0.49	0.52	0.61	0.55	0.59	0.61	0.51	0.49	0.58
T (s)	4.11	4.05	3.88	3.58	3.58	3.8	4.04	4	3.93	3.79	3.83	4.15
(kW/m)	0.91	0.81	0.85	0.65	0.67	0.84	0.73	0.81	0.86	0.66	0.6	0.94

Figure 6.5 and Figure 6.6 show the monthly mean wave power at the Gulf of Aqaba and NEOM Bay in the Red Sea during 2007-2018 at location P1-P8. The mean wave power at (P1 to P5) in the Gulf of Aqaba follows the same pattern in all the months. The highest mean wave power is obtained during September (up to 2.9 kW/m), and it has consistently the larger wave heights (up to 1.02m) as shown in Table 11. The lowest mean wave power is during February (up to 1.2 kW/m), and it has the lowest wave height of 0.6m. During October, there was a slight decrease in the mean wave power to 2.2 kW/m, and it has been dropped considerably to 1.5 kW/m during November,

almost half the mean wave power during September. While it is slightly increasing again in December almost 1.8 kW/m. During January and February, the sharp decrease happens in those two months, and February considers the lowest. While in NEOM Bay, the highest mean wave, power is in September at (P6 and P7) is (up to 0.73 kW/m). during April and November, the wave power has been dropped to the lowest value around the year (up to 0.47 kW/m). During December and January, there is a significant increase in the mean wave power after the drop in November (up to 0.69 kW/m). a slight decrease in mean wave power is found during February. From the graphs, we can observe that the mean wave power values are fluctuating around all the months. In P8 at NEOM Bay, the highest mean wave power is obtained in December and January (up to 0.95 kW/m). while during November, there is a significant drop in the mean wave power almost 0 kW/m. The mean wave power and wave heights at the selected study points located at NEOM Bay are considerably low in all the months.

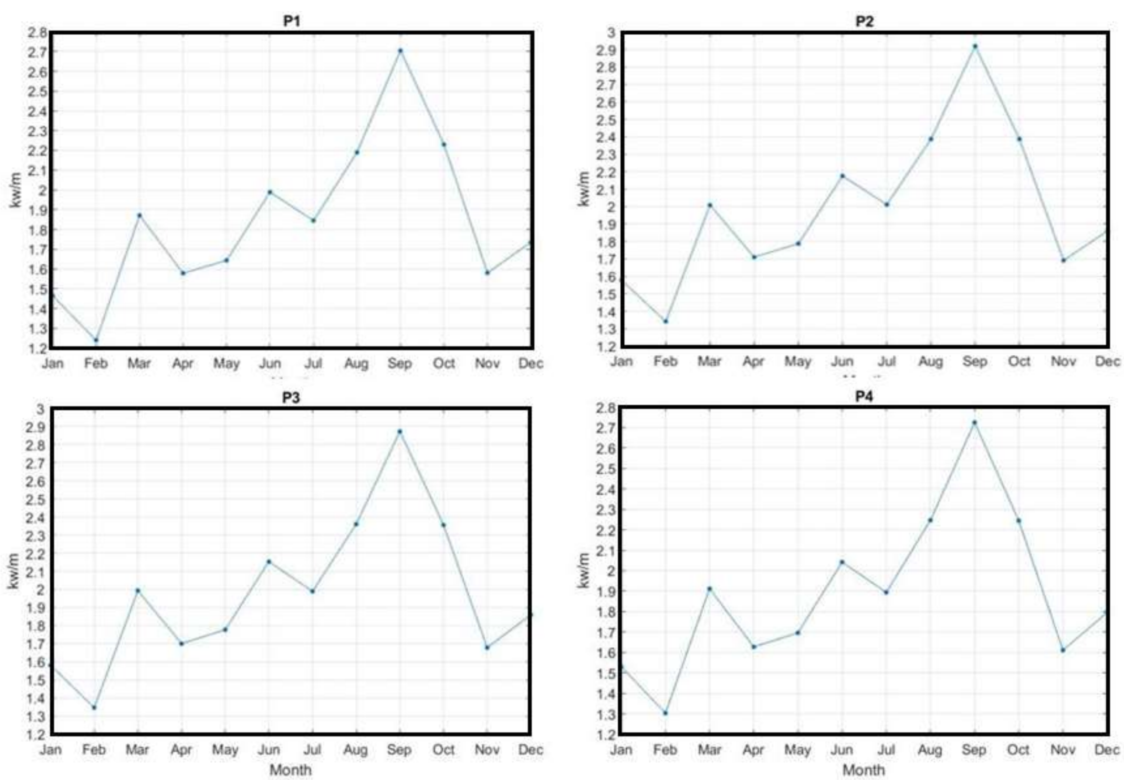


Figure 6.5 Average monthly values of the mean wave power per unit width at P1, P2, P3, and P4 (2007-2018).

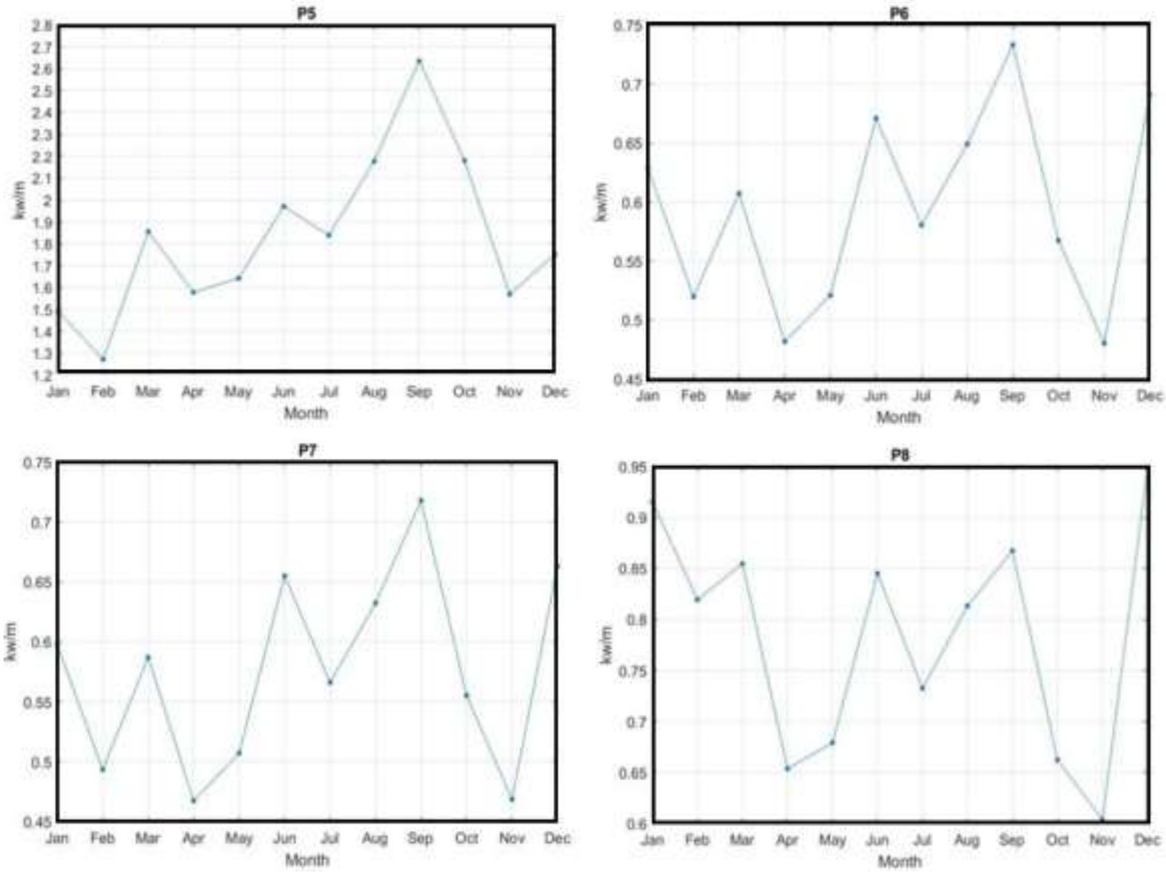


Figure 6.6 Average monthly values of the mean wave power per unit width at P5, P6, P7, and P8 (2007-2018).

To conclude the study and analysis of the temporal variability, the coefficients explained in chapter 6 have been calculated, and their values are presented in Table 10. The three coefficients, COV, SV, and MV, present a generally uniform trend across all of the study points. Referring to the points with the most significant wave energy potential, in the Gulf of Aqaba coastline between P1 and P5, the temporal variability is higher than the NEOM Bay, the COV varying between 0.22 and 0.20, SV between 0.37 and 0.34 and MV varying between 0.80 and 0.74. The points located in NEOM Bay present the lowest variability coefficients. However, they don't tend to offer as much energy potential as in (P6 to P8), COV of 0.14, SV of 0.16 and 0.23, and MV of 0.43 and 0.44, respectively. We can conclude that the greater the value of SV, the larger the seasonal variability, with values lower than 1 indicating moderate seasonal variability.

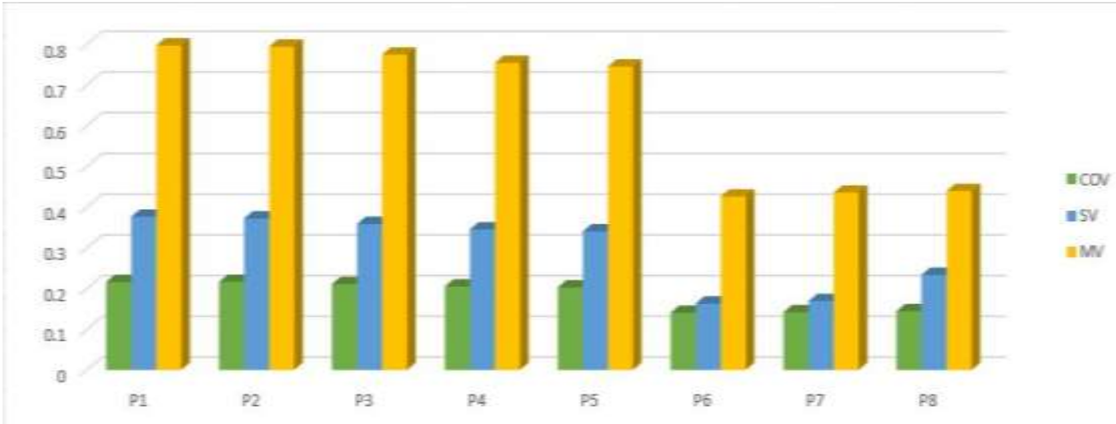


Figure 6.7 Variability coefficients at the 8 studied points

6.3 WEC Systems

Sea waves release their energy in either kinetic or potential form. Thus, WEC manufacturers use different approaches to utilize this resource in a way that is both dependable and efficient. The fixed-point absorber, DEIM wave converter system, is considered further in this current study to assess its performance in the selected locations along the Red Sea in the Gulf of Aqaba and NEOM Bay coastlines. Since it is one of the most wave energy converters that can be activated with a low value of mean wave power of 1.9 kW/m [67] as represented in Table 12 [71]. Table 10 presents the highest mean wave power we could find at NEOM coastlines in P2 is 1.98 kW/m. This system was designed to generate in offshore locations, where it is still under the design stage.

Table 12 Comparison of some WEC technologies [67, 71].

Wave Energy Converter	Operating Principle	Water Depth (m)	Mean Wave Power (kW/m)
SSG	OTD	6-18	14-16
OBREC	OTD	25	2-8
Wavestar	Floating bodies	10-20	2.8-5.2
Mutriku	OWC	5	26
LIMPET	OWC	6	20
Pico	OWC	8	37.9
REWEC3	U-OWC	15	4.67
DEIM	Fixed point absorber	30	1.9

6.4 WEC Output and Performance

Once the scatter diagrams have been obtained, the exact wave energy converter energy output can be computed. In this study, DEIM [67] has been considered since it has the lowest mean wave power among all the previous wave converters, the mean wave power is the lowest power to activate the wave converter. Unfortunately, the power matrix which is an important parameter to be used in equation (5.18) to find out the exact annual power output from DEIM, since it is still under design stage, the power matrix is not available yet. The power output will be estimated based on a theoretical calculation in the next section. The power matrix (PM) is a concise WEC representation, showing the WEC response. A way to estimate the electricity production of a WEC in a specific site is to associate with the power matrices of each WEC the matrices that give the wave activity for the respective location in a determined time interval [22]. As a function of two parameters describing the sea state, the significant wave height HS and the peak wave period Tp. The overall efficiency of 50% is considered, according to the experimental tests on a small-scale prototype in the laboratory [42]. The results can be used for further evaluation, which will be conducted as soon as there is the first data from a full-scale prototype.

6.4.1 DEIM Farm

Wave energy source and offshore photovoltaic technology farms are proposed in this scenario. Equation (6.1) is used to evaluate the rated power of all wave farms [85]:

$$P_{WF} = P_{C,Rated} \,.\, N_C . N_F \tag{6.1}$$

Where $P_{C,\ Rated}$ is the rated power of a single point absorber, N_C is the number of WEC installed in a single wave farm, and N_F is the number of wave farms.
Equation (6.2) estimate the annual electrical output [85]:

$$E_{WF} = \varphi_m . N_C . N_F . D_C . \varepsilon_C . h_{year} \tag{6.2}$$

Where φ_m is the wave power flux, D_C the external diameter of a single WEC, $N_C . N_F$ total number of installed devices, ε_C overall efficiency, and finally, h_{year} the number of hours per year.

All parameters are reported in Table 13. According to this simplified assessment, the installation of 12 wave farms based on the DEIM Point Absorber along the Gulf of Aqaba and NEOM Bay at the Red Sea, will generate from 27.4 to 94.135 MWh/year at different locations as indicated in Table 14, Figure 6.8 shows the annual productions variations at each point. The total capacity installed is 86 MW. Each wave farm will be comprised of three lines of 30 WEC. Figure 6.9 represents the layout of the wave farm.

Table 13. Wave farm parameters.

Parameter	Symbol	Value
Buoy diameter	D_C	10 m
Rated power of wave converter	$P_{C,Rated}$	80 kW
Average overall energetic efficiency	ε_C	50%
Number of buoys in a wave farm	N_C	90
Number of wave farms	N_F	12
Wave power flux	φ_m	1.99 kW/m
Overall installed power	P_{WF}	86.4 MW
Hours per year	h_{year}	8760 h/year

Table 14. Annual energy production $\boldsymbol{E_{WF}}$ at the 8 locations.

Point	Mean Power (kW/m)	Annual Energy Production (MWh/year)
P1	1.84	87.039
P2	1.99	94.135
P3	1.97	93.189
P4	1.89	89.405
P5	1.83	86.566
P6	0.59	27.909
P7	0.58	27.436
P8	0.78	36.897

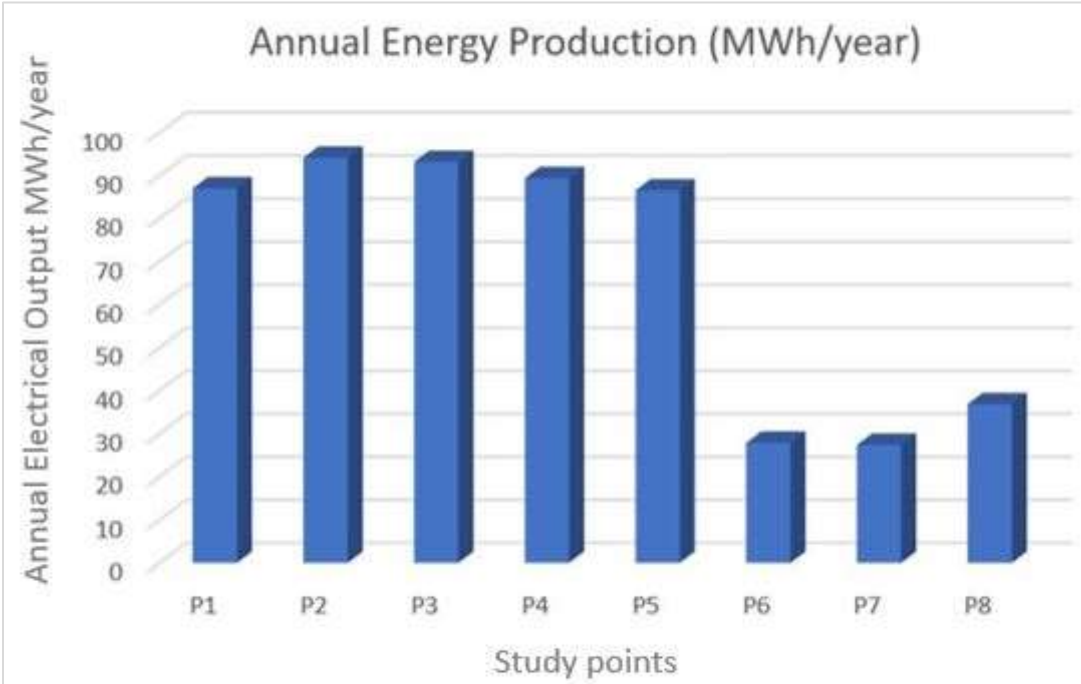


Figure 6.8 Annual electrical output $\boldsymbol{E_{WF}}$ at P1 to P8.

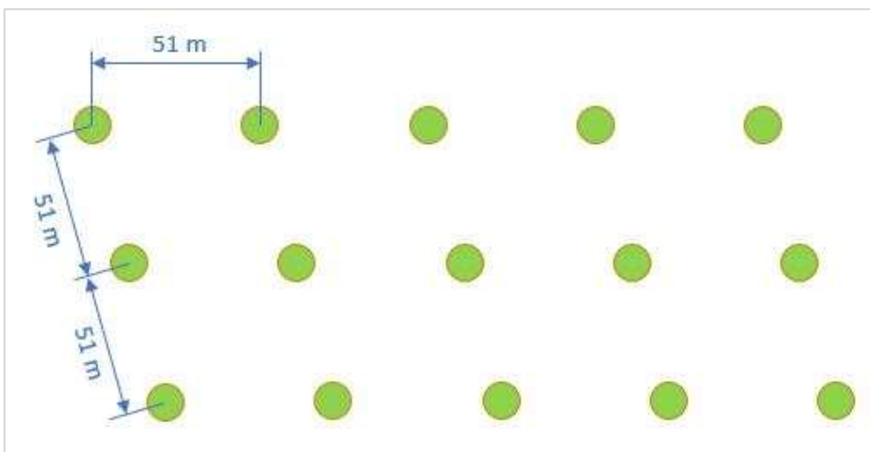


Figure 6.9 Wave farm layout.

The minimum distance between each WEC is set to 51 m, approximately ten times greater than the outer buoy radius. This length is chosen to minimize the interferences among the wave farm's buoys. Therefore, a single wave farm occupies an area of 1500 m long and 120 wide.

The integration of solar photovoltaic panels is also considered. The solar system could be installed in the upper part of the wave converter, increasing the electrical output of the device. Table 1 in Appendix B reports the Average daily total GHI data Wh/m2 for 44 stations across the country. The data collected from K.A.CARE was generated from one-year data for 44 installed stations from December 2015 to November 2016 [86]. In this study, we will consider Tabuk province, where NEOM city is located. The annual solar radiation, according to those data I_{year} in Tabuk, is equal to 75.77 kWh/m^2 [86].

The equation used to evaluate the global installed power by photovoltaic panels is given by [42]:

$$P_{PVF} = I_{PV,Std}.S_{PV}.N_C.N_F.\varepsilon_{PV} \tag{6.3}$$

Where $I_{PV,Std}$ is the standard solar radiation, S_{PV} is the surface of photovoltaic panels installed on a single wave converter, $N_C.N_F$ are the total number of wave converters, and ε_{PV} is the electrical efficiency of photovoltaic panels [85].

Equation (6.4) is used to find out the global electrical energy production by photovoltaic panels [42]. All solar parameters are reported in Table 15.

$$E_{PVF} = I_{year}.S_{PV}.N_C.N_F.\varepsilon_{PV} \tag{6.4}$$

Table 15. Parameters of solar panels installed on the wave farms

Parameter	**Symbol**	**Value**
Tabuk Annual solar radiation	I_{year}	75.77 kWh/m^2
Standard solar radiation	$I_{PV,Std}$	1000 W/m^2
Panel efficiency	ε_{PV}	17%
Panel surface per buoy	S_{PV}	52.12 m^2
Installed power	P_{PVF}	9.56 MW
Annual energy production	E_{PVF}	725 kWh/year

According to this analysis, the solar source can be used to increase the output of electrical energy by installing 9.56 MW, which will generate about 0.7 MWh per year.

In order to increase renewable energy output in the same region, this technology can be properly combined with other conversion devices, such as the offshore photovoltaic one, making wave farms much more efficient. Table 16 represents the total annual energy production of the wave source, and photovoltaic per year is about 94.860 MWh.

Table 16. Annual energy production from sea wave to solar photovoltaics at each study point.

Point	Total Annual Energy Production (MWh/year)
P1	87.764
P2	94.860
P3	93.914
P4	90.130
P5	87.291
P6	28.634
P7	28.161
P8	37.622

6.4.1.1 Household Power Consumption in Saudi Arabia

In 2018, King Abdullah Petroleum Studies and Research Center (KAPSARC) stated that the energy consumption of residential buildings is approximately 49% of the total electricity consumption in Saudi Arabia [87]. Figure 6.10 represents electricity consumption in residential, commercial, industrial, governmental, agricultural, and other facilities [88].

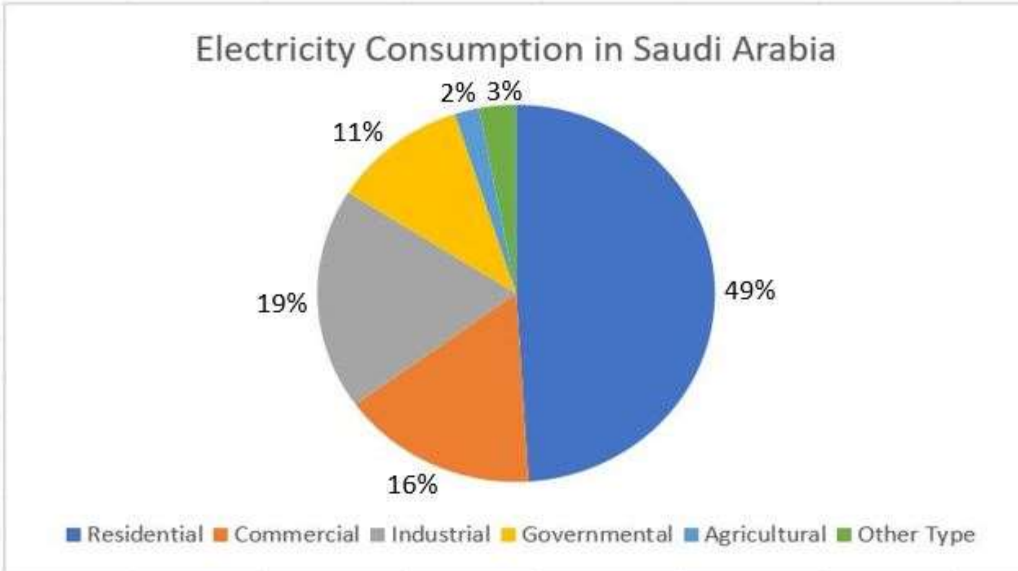


Figure 6.10 Electricity consumption in Saudi Arabia during 2018 reported by KAPSARC [88].

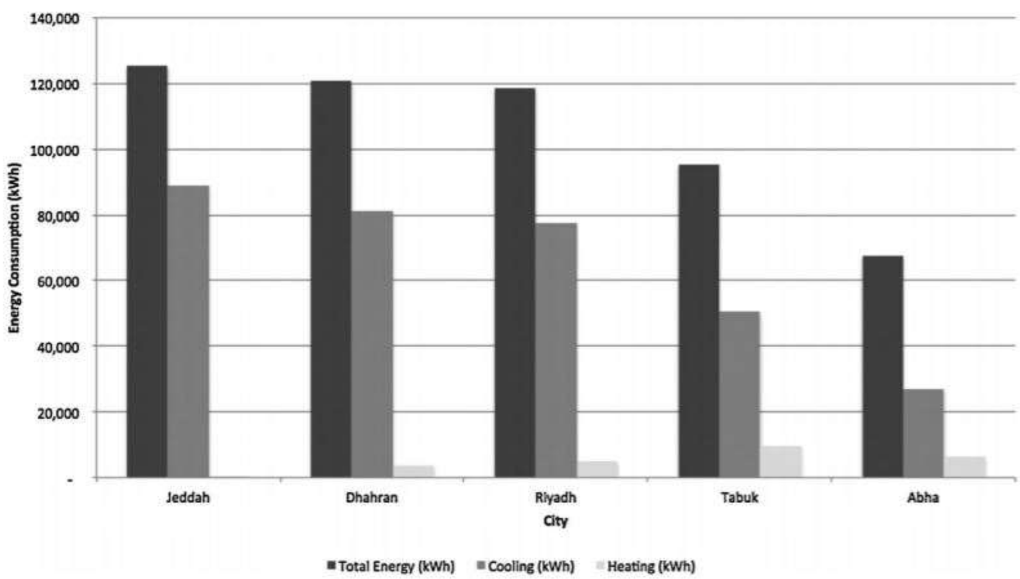


Figure 6.11 Total annual energy consumption for a villa located in five cities [88].

The electrical energy production of DEIM wave energy converter through the installation of 95.96 MW will generate about 94.860 MWh/year, as shown in Table 16, which represents the annual energy consumption of 10 villas energized by WEC in Tabuk city as per Figure 6.11.

6.5 Discussion

Before drawing conclusions based on this thesis work, a summary of the results found will be discussed. The main outcome of this thesis is to explore and investigate the potential of wave energy along the Red Sea in the Gulf of Aqaba and NEOM Bay, study the feasibility and impact of implementing wave energy converters in the Red Sea, and finally identify the most suitable system for extracting wave energy at this region. Generally, it can be observed that significant wave heights are low in the Red Sea. However, the highest wave values are located in the Gulf of Aqaba and were obtained during the month of September, while the lowest values were obtained during the month February. In NEOM Bay, the wave height is considerably low. The deep waters at the Gulf of Aqaba exhibit the highest mean wave power almost double that found in NEOM Bay. Also, the temporal variability of the Gulf of Aqaba is higher than the NEOM Bay. To conclude, the study point P2 is the most suitable for a possible installation of DEIM WEC device.

WEC system used in this study is DEIM. It has the lowest mean wave power among all the wave converters up to date. The mean wave power is the lowest power to activate the wave converter. DEIM is an integration of wave and solar photovoltaic converter, 12 wave farms consist of 3 lines, each with 30 WEC of DEIM along the Gulf of Aqaba and NEOM Bay. 94.860 MWh/year is the highest annual energy production that will be generated at P2. To compare the output with real-life energy consumption, a household power consumption in a villa located at Tabuk providence will consume almost 95,000 kWh/year, while DEIM is generating 94.860 MWh/year, which represents the annual energy consumption of around 1000 villas.

6.5.1 Cost Analysis

6.5.1.1 DEIM

The cost of wave energy is more expensive than other Renewable energy sources. Since DEIM is still under development, the author provided an initial estimated cost of DEIM, which is between 2,700 and 5,000 $/kW. The following table shows how far the WEC projects have proceeded and whether they are seemingly ongoing or not. Table 17 shows that DEIM is under research and simulation only.

Table 17. Current stages of WECs projects [89].

Concept	WEC	Research	Simulation	Test	Deployed	Company	Ongoing
3D & surge	WABRO	×	×	–	–	×	–
AaltoRO	WABRO	×	×	–	–	–	–
Buoy array	WABRO	×	×	–	–	–	–
CETO	WABRO	×	×	×	×	×	–
Delbuoy	WABRO	×	×	×	×	×	–
DEIM	WABRO	×	×	–	–	–	–
Duck	WABVC	×	×	–	–	–	–
ISWEC	WABRO	×	×	–	–	–	–
Odyssée	WABRO	×	×	–	×	–	×
Oyster	WABRO	×	×	–	–	–	–
SAROS	WABRO	×	×	×	×	×	×
Uppsala	WABRO	×	–	–	–	–	×
Vizhinjam	OWCRO	×	×	×	×	–	–
WaveCatcher	OWCRO	×	–	×	–	–	–
Wind/wave	WABRO	×	–	–	–	–	–

6.5.2 Environmental Challenges

Wave Energy is considered as a non-polluting and sustainable source of energy, especially concerning harmful emissions as wave energy devices do not produce pollutants and emissions of the atmospheric greenhouse gas type, such as carbon dioxide and nitrogen oxides associated with burning fossil fuels for electricity production [90]. Developing wave energy converters provides significant advantages. Emission-free electricity is the key advantage of course, but energy security is another significant benefit. Wave Energy is a clean source of energy that can naturally replenish itself within a short time, and it is less environmentally harmful than certain other types of renewable energy generation.

In 2015, the members of the United Nations states adopted the Sustainable Development Goals (SDGs), also known as the Global Goals. To install a wave converter in the sea, it is essential to take into consideration SDG#14 states that "Conserve and sustainably use the oceans, seas and marine resources for sustainable development [91]." The main objective here is to maintain and preserve marine and coastal ecosystems sustainably, while at the same time improving the protection and sustainable use of ocean-based resources. Due to the high abundance of birds, fish, tortoises, and corals and the already endangered biodiversity, WEC project deployment could have a cumulative impact and jeopardize marine and coastal ecosystem health and resilience.

Up to date, a little is known about the potential environmental impacts of wave energy systems since they are still in their experimental or early stages of implementation, most wave energy schemes build on lessons learned from more developed ocean-based projects for oil drilling and offshore wind power industries. In a recent publication, Alkhayyat et al. [92], pointed out that technical and social impacts were found to be deciding factors for the viability of wave energy exploitation. WEC project deployment could cause cumulative impacts and jeopardize marine and coastal ecosystem health and resilience.

A detailed overview of the most common environmental impacts of wave energy devices is given in Figure 6.13.

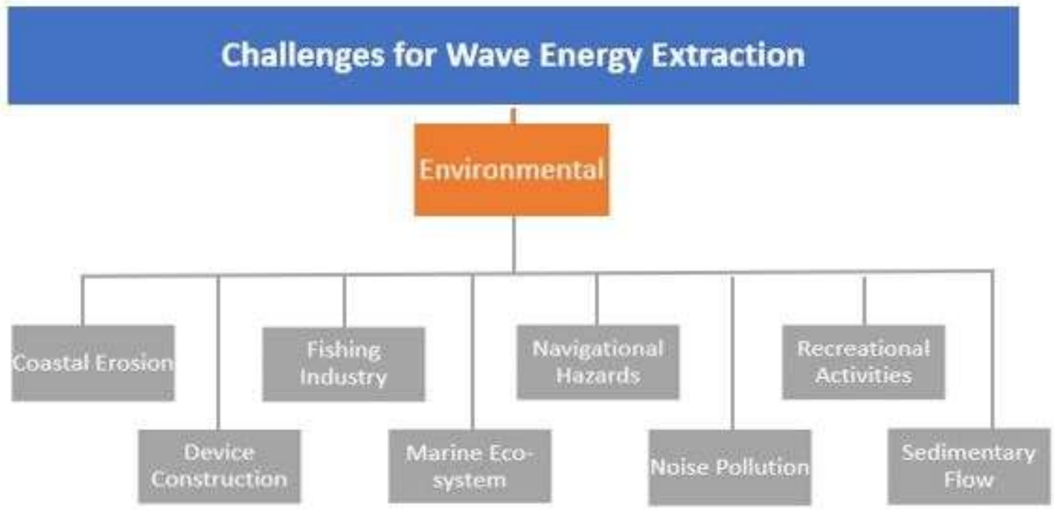


Figure 6. 12 Environmental challenges of wave energy extraction

- **Coastal Erosion** - Onshore and nearshore schemes can affect coastal erosion as a result of currents and wave alterations. Tidal velocities, wave amplitude, and flow of water can be altered with the array size.
- **Device Construction** - Possible effect of anchoring certain devices during deployment, using pilings, concrete blocks, anchors, and chains. Several wave energy devices are anchored or attached to the ocean floor. Preparation of the site may include dredging and scouring the seabed for installing electrical cables. An online self-administered interview about the NEOM region was conducted [93], a sample of 1000 people above 18 years, including 58% males and 42% females in Saudi Arabia. 10% of people liked to have pristine beaches, mountains & islands. The installation of WEC at sea could make it an environmental issue against them.
- **Marine Pollution** - Although wave energy does not emit greenhouse gasses or other pollutants in the environment when producing electricity, emissions occur from other stages of its construction, transportation, and life cycle. Potential impacts of releasing and leaking hydraulic fluids for hydraulic rams, power trains, lubricating oils and fluids, anti-corrosion and biofouling paints and coatings in the coastal oceans.

- **Fishing Industry** - Exclusion zones around offshore equipment may affect local fishing areas. Anchor lines, tethers, and power cables limit the use of nets. At the same time, WECs can establish protected environments that provide advantages for some aquatic species and ecosystems by limiting access and fishing at the site. However, as with marine reserves, the fishing activity will expand directly beyond the installation's boundary.
- **Marine Eco-system** - Marine mammals, might be vulnerable to floating structures or may serve as obstacles to marine movement and migration on the seabed that affect the fauna and flora. For some animals, particularly larger whales, most offshore wave energy devices are moored directly to the seafloor, and mooring lines may pose a threat of entanglement. WECs could be used as temporary roosts by sea birds.
- **Navigational Hazards** - Possible navigational risks to shipping because their low profile may cause them to be difficult to detect visually or by a radar ship. Potential shipping effect if the WECs are not illuminated at night or if their moorings break off during storms. Besides, water quality may be affected due to possible oil spills from increased boat traffic in the area.
- **Noise Pollution** - The constant noise from WECs, especially in rough waters, can disturb whales and dolphins that use echolocation for hunting. The operating noise levels can constitute a noise disturbance locally on the beach or shoreline for shoreline and nearshore devices.
- **Recreational Activities** – since NEOM will be an important tourist destination, WECs may affect certain types of recreational swimming and water sports. Sub-aqua diving and water skiing may benefit from these devices offering shelter, but sailing and windsurfing can suffer. Also, the visual effect of large-scale installations on tourism as the water depth required by nearshore WECs might only be a few hundred yards offshore. Back to the online survey [93], 6 in 10 claims that NEOM will be an even better touristic place than the top-ranked best cities in tourism in MENA: Dubai, Cairo & Riyadh. WEC installation might affect this concern about tourism in NEOM.

- **Sedimentary Flow** - Placing onshore and nearshore WECs such as system platforms, anchors, and cables may shift the water and sands flow around the structures immediately. Increases in water velocities can impact the movement of sediments, coastal erosion, and the deposition of coarse sediments such as pebbles and rocks. Slower or restricted flows of water may increase sediment deposition.

6.5.3 Social Challenges

Any installation of wave energy converters requires local community approval to be viable. Social acceptance of marine resources is linked to the level of involvement of stakeholders and public understanding of renewable energy [87]. Renewable energy itself does not resist deployment by individuals and organizations, but rather by the characteristics of the technology and the location of the installation. Opposition to WECs is associated with proximity to local stakeholders, due to noise and visual impacts. This is supported by Stefanovich et al. [94], Argue for increased risk of "Not In My Back Yard "-syndrome (NIMBY) as proximity decreases. NIMBY-syndrome results in a slower development transition process, which can continue to grow or potentially delay WEC implementation. Nonetheless, this is a location-specific problem, as NIMBY-syndrome is based on public perception of wave energy in various markets.

WECs may also lead to positive public relations and a way for luxury resorts and off-grid utilities to show their ability to adopt renewable technology with appropriate placement in cooperation with local stakeholders. The increased public resistance to near-shore construction has to be seen concerning the decreased monetary expense of bringing the WEC(s) closer to shore [89]. The size of the WEC farm is likely to coincide with public opposition too. Installing a larger farm would result in a greater NIMBY-syndrome than a small farm, regardless of the positive effects of green energy production. Figure 6.13 summarizes the main social challenges of wave energy extraction. However, there are benefits to society offered by wave energy as well [90] including:

- Offering a new, environmentally sustainable, and easily assimilated grid-connected option to meet the load growth. The online survey represented 15% of the sample consider it most unique/new to power up NEOM city by Renewable energy [93], which is a good social impact for implementing wave energy converters along NEOM coastlines.
- Avoiding aesthetic issues that plague other infrastructure projects.
  Wave energy converters are located several miles offshore and have a low profile over water (like an iceberg, most of the equipment is submerged). The submerged transmission cable is buried and uses horizontal directional drilling to reach under the beach.
- Reducing reliance on imported energy supplies, rising national security, and reducing the risk of potential volatility in fossil fuel prices.
- Reducing greenhouse gas emissions by displacing fossil-fuel generation.
  Carbon emissions constitute more than 40 percent of overall carbon emissions. Use emission-free ocean energy to generate electricity instead of traditional pulverized coal energy ensures 0.8 tons of carbon per MWh of electricity generated is not emitted into the atmosphere. Other contaminants are also limited, such as Sulphur oxides, nitrous oxides, mercury, and particulates.

There is a global acknowledgment for greenhouse effect and resulting global warming. Countries around the world are drawing up proposals to reduce carbon emissions by implementing sustainable forms of green energy. In addition, there is a parallel global race to establish free economic zones within countries to attract business and investment, namely, to diversify their economies and step away from fossil fuels [95]. NEOM plans to join the race in a big way; it will be a city bordering Saudi Arabia, Egypt, and Jordan with unparalleled sun and wind capacity. Neom is expected to rely heavily on renewable energy, which will be a significant factor in reducing greenhouse gas emissions at the NEOM region.

- Promoting local job creation and economic development.

  The economic opportunities are significant. The harvesting of this indigenous resource would create jobs and boost the local economies. Building and running wave energy plants will have major positive economic impacts for coastal states. As a result [93], 75% of the people who represent the majority believe that NEOM will be a source of pride for Saudi Nationals, improving the image of Saudi Arabia around the world, and will open doors for new job opportunities.
- The provision of renewable energy, such as marine energy, is stated as the 7th of the United Nations Sustainable Development Goals (SDG#7) " Affordable and Clean Energy, Ensure access to affordable, reliable, sustainable and modern energy for all [91]". Marine renewable energy has the potential to improve access to electricity, mainly because NEOM is a newly built city.

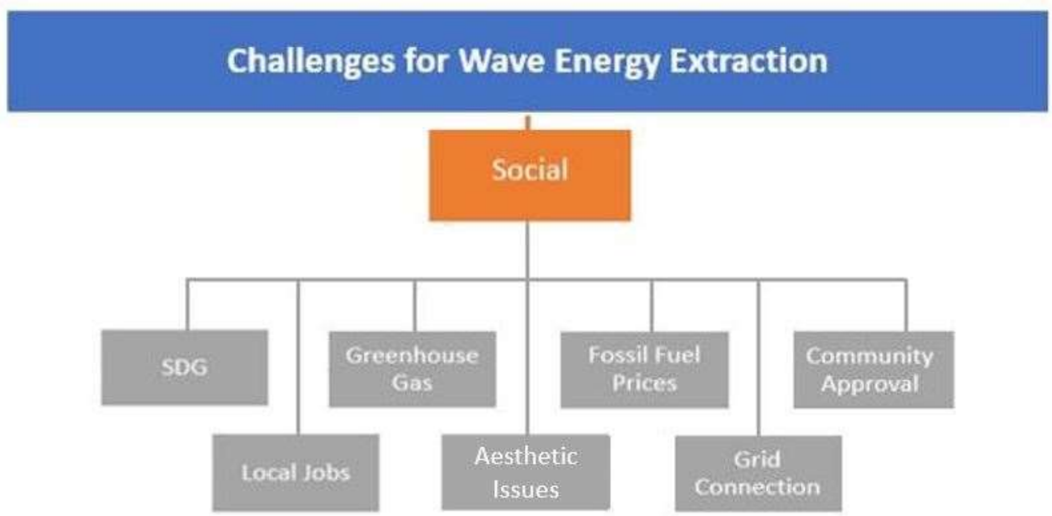


Figure 6.13 Social challenges of wave energy extraction

6.5.4 Constraints and Limitations

One of the limitations of installing wave converters at the NEOM region is the coral reefs in the north of the Red Sea, as it must be protected since it is a global focus due to its remarkable resilience to climate change, Figure 6.13. The Ministry of Culture has been working with UNESCO, as a member of the World Heritage Convention since 1978, to classify coral reefs in the Red Sea and other unique sites in the Red Sea as UNESCO sites protected and listed as a World Heritage Site, to preserve them as valuable natural assets for future generations [91].

Figure 6.14 Red Sea coral reefs [91].

Another factor to be considered is the location of Sharma Palaces owned by the Saudi royal family located along NEOM Bay.

6.5.5 Operation and Maintenance

The operation and maintenance stages of wave energy converter projects refer to their performance and survivability. Preventive maintenance should be done rather than costly corrective maintenance. That may also prevent damage to the environment. WECs marine structures should be with moving parts such as joints or cables, and structural fatigue is a major concern. Periodic inspections are required to check the conditions of electrical and mechanical components, and to ensure that moving components are lubricated, thus preventing friction between them. Regions with high temperatures can speed up the spread of aquatic microorganisms inside the devices, so biofouling-induced component degradation is a very serious threat [93].

6.5.6 Design and Development

One of the significant challenges facing the design and implementation of WEC is that technology is still in its maturity stage compared to other developed renewable energy technologies such as wind and solar [94, 96] despite several prototypes and patents published in so many literatures. Different technologies are considered for harvesting wave energy, which means that the wave conversion technology has not been converted yet. Hence, anticipating the challenges and addressing them at the design stage of a WEC is difficult.

6.5.7 Performance Improvement

One of the most complex issues in wave energy extraction is the conversion of the erratic waves into a smooth electrical output, applicable to the electrical grid, requiring a certain kind of energy storage device. Wave converters not only need to adjust to changes in wave height and time, but they also need to be able to align themselves on the wave fronts [97]. The WECs are made up of several components: 1) the structure which captures the energy of the wave, 2) foundation or mooring keep the structure in place, 3) the power take-off (PTO) system, it converts the mechanical energy into electrical energy, and 4) the control systems to optimize performance in operating conditions. In an analysis of wave energy in the Red Sea region, Alkhayyat et al. [92] found that technically represent a deciding factor for the viability of wave energy exploitation.

The current research and development are focused on enhancing the device components to make them more resistant to storms and enhancing the amount of energy extraction possible. Technological improvements include the efficiency of the appliances, their subsystems and components, and cost reduction. Many devices have already been tested at sea, but research is still needed to improve the devices ' durability, make the materials they are made of more durable, etc. Improved techniques of installation and recovery impact these areas, as well as improved operability and service access, which decreases mean repair times.

6.5.8 Cost Reduction

To ensure that ocean energy is efficient, cost reduction is the most critical element for improvement. In the future, wave technology could have a cost reduction in power take-off costs by 22%, and installation by 18%, operation, and maintenance by 17%, Whereas the cost of foundation and mooring and grid connection, could fall by 6% and 5% respectively [11]. Another interesting cost-saving solution is to share the facilities of existing offshore wind parks or existing breakwaters with WECs.

6.5.9 Adverse Environmental Conditions

WEC systems must be able to withstand harsh weather, or it will lead to costly maintenance operations and expensive moorings. WECs must have some sort of mechanism that helps them to withstand hurricanes or have cheap, easy-to-replace components. Another idea is that such devices can be submersible as the storm passes or can be towed to a protected area. WEC anchoring must be strong enough to withstand the currents that may be produced during a cyclone to avoid losing the full device.

Chapter 7: Conclusions and Recommendations

7.1 Conclusions

In this study, wind and wave energy in the Red Sea region has been investigated using a data series based on a hindcast was generated for wave height and peak wave period using the WAVEWATCH III model based on 30-year (1985-2015) at 10-km resolution. Power computed based on 12-year (2007-2018) at 1-km resolution grid of NEOM Bay and part of the Gulf of Aqaba, forced by the Red Sea reanalysis surface winds for 12 years, as shown in Table 6. The goal was to select the most suitable area for the installation of WECs. The wave power has been analyzed using the data from 8 study points by incorporating wind and wave data between 2007 and 2018. The highest peak period and the significant wave height selected in the present study are based on the wave hindcast generated on a 1-km resolution grid. The wave power per unit of crest length (kW/m) is calculated in the selected areas. Based on the results, the Gulf of Aqaba, with a mean wave height of 1.5 m, is a good candidate for a WEC. Potential environmental and social challenges should be considered as an important deciding factors for the viability of wave energy exploitation. At NEOM coastlines, we must take into consideration the coral reef at the shorelines. Coral reefs in the north of the Red Sea are a global focus for their remarkable resilience to climate change. Based on this study, a fixed-point absorber integrating wave and solar sources (DEIM) could be installed at P2 and P3 in the Gulf of Aqaba since they have the highest energy flux among the study points at NEOM Bay. This is the best WEC to use along the Red Sea since it has the lowest mean wave power, which is the power that needs to activate the converters at the study points.

7.2 Recommendations

Since the government of the kingdom of Saudi Arabia has set an initial target of vision 2030 to generate 9.5 gigawatts of renewable energy, solar, and wind power. They are seeking to localize an important portion of the renewable energy value chain in the

Saudi economy, including the research stage, development stage, and manufacturing stage. Implementing wave energy converters to generate electricity will be a new concept to the market in Saudi Arabia. This solution requires research on WECs that operate with low wave height and energy period to install it in different sites along the Red Sea and the the development of a mechanical wave converters suitable to the Red Sea conditions. A hybrid wind-wave system might be a good solution to implement, too, since the wind speed along the Red Sea is moderate. It is recommended to find out the cost of DEIM converter once it reaches to commercialization stage to be installed along NEOM coastlines. The government could add the ocean wave energy into the energy mix of solar and wind by commissioning studies to perform resource assessments, provided laboratories, and test sites for the design and testing of wave energy converters. We also recommend the private organizations, universities, research centers, and individuals to participate in bringing ocean wave energy into the mainstream of the renewable energy industry. To encourage research into ocean wave energy systems, we could have a public design-build-test competition for the best wave energy converter development. Finally, there is one more wave converter, OBREC that have the potential to be installed at NEOM coastlines based on the fact that that it could be used in areas with relatively low mean wave power of 2-8 kW/m [67]. OBREC output is typically measured via the power matrix, but since OBREC testing has just started, there is no definitive power matrix available for calculations. Also, the ARRECIFE wave converter is designed for the most typical waves from 1 to 5m high waves [44], which meets the range of the wave height at NEOM coastlines, while most WECs offer as a nominal electric power that is related to wave height between 5 to 8 m. Unfortunately, the power matrix for ARRECIFE is not available yet, as declared from developers. So, the cost of DEIM is still unknown, the technique is new, and still under research and simulation stage. A brief of initial cost analysis of suggested wave converters ARRECIFE and OBREC are added to appendix C.

References

[1] World Energy Resources 2016 | World Energy Council.” [Online]. Available: https://www.worldenergy.org/publications/entry/world-energy-resources-2016. [Accessed: 20-Jan-2020].

[2] R. Cascajo, E. García, E. Quiles, A. Correcher, and F. Morant, “Integration of Marine Wave Energy Converters into Seaports: A Case Study in the Port of Valencia,” Energies, vol. 12, no. 5, p. 787, 2019.

[3] G. Lavidas, “Energy and socio-economic benefits from the development of wave energy in Greece,” Renewable Energy, vol. 132, pp. 1290–1300, 2019.

[4] Iea, “Tracking Power – Analysis,” IEA. [Online]. Available: https://www.iea.org/reports/tracking-power-2019. [Accessed: 27-Mar-2020].

[5] D. Greaves and G. Iglesias, Wave and tidal energy. Hoboken, NJ: John Wiley & Sons Inc, 2018.

[6] T. Aderinto and H. Li, “Ocean Wave Energy Converters: Status and Challenges,” Energies, vol. 11, no. 5, p. 1250, 2018.

[7] T. Brahimi, “Using Artificial Intelligence to Predict Wind Speed for Energy Application in Saudi Arabia,” Energies, vol. 12, no. 24, p. 4669, Sep. 2019.

[8] (2020). SAUDI ARABIA’S RENEWABLE ENERGY, Detailed Value Proposition [PowerPoint slides]. Available: https://Investsaudi.Sa/Media/1323/Saudi-Arabia-S-Renewable-Energy-Detailed-Value-Proposition.Pdf.

[9] “Towards Saudi Arabia’s Sustainable Tomorrow”. [Online]. Available: https://sustainabledevelopment.un.org/content/documents/20230SDGs_English_Report972018_FINAL.pdf. [Accessed: 15 Spetember-2019].

[10] A. Babarit, “Energy Performance of Wave Energy Converters,” Wave Energy Conversion, pp. 153–198, 2017.

[11] N. Dickmann, Energy from water: hydroelectric, tidal, and wave power. St. Catharines, Ontario: Crabtree Publishing Company, 2016.

[12] E. Rusu and F. Onea, “A review of the technologies for wave energy extraction,” Clean Energy, vol. 2, no. 1, pp. 10–19, Jul. 2018.

[13] R. E. Phillips, “Harvesting Ocean Wave Energy: A Proposed System for Conversion Into Electrical Power,” *Natural Gas & Electricity*, vol. 36, no. 2, pp. 9–15, 2019.

[14] S. Qiu, K. Liu, D. Wang, J. Ye, and F. Liang, “A comprehensive review of ocean wave energy research and development in China,” *Renewable and Sustainable Energy Reviews*, vol. 113, p. 109271, 2019.

[15] I. R. Young, “Regular, Irregular Waves and the Wave Spectrum,” Encyclopedia of Maritime and Offshore Engineering, pp. 1–10, 2017.

[16] N. M. A. Rasul, The Red Sea: the formation, morphology, oceanography and environment of a young ocean basin. Heidelberg: Springer, 2015.

[17] D. Magagna and A. Uihlein, “Ocean energy development in Europe: Current status and future perspectives,” International Journal of Marine Energy, vol. 11, pp. 84–104, 2015.

[18] S. Sannasiraj and V. Sundar, “Assessment of wave energy potential and its harvesting approach along the Indian coast,” Renewable Energy, vol. 99, pp. 398–409, 2016.

[19] M. Shadman, C. Silva, D. Faller, Z. Wu, L. D. F. Assad, L. Landau, C. Levi, and S. Estefen, “Ocean Renewable Energy Potential, Technology, and Deployments: A Case Study of Brazil,” Energies, vol. 12, no. 19, p. 3658, 2019.

[20] Z. Wang, C. Duan, and S. Dong, “Long-term wind and wave energy resource assessment in the South China sea based on 30-year hindcast data,” Ocean Engineering, vol. 163, pp. 58–75, 2018.

[21] C. Alaoui, “Review and assessment of offshore renewable energy resources in morocco’ coastline,” Cogent Engineering, vol. 6, no. 1, 2019.

[22] E. Rusu and C. G. Soares, “Wave Energy Assessments in the Coastal Environment of Portugal Continental,” Volume 6: Nick Newman Symposium on Marine Hydrodynamics; Yoshida and Maeda Special Symposium on Ocean Space Utilization; Special Symposium on Offshore Renewable Energy, Jan. 2008.

[23] M. M. Nezhad, D. Groppi, and G. Piras, “Nearshore Wave Energy Assessment of Iranian Coastlines,” Proceedings of the 4th World Congress on New Technologies, 2018.

[24] A. Metwally and A. G. Abul-Azm, 2007: The Red Sea wind-wave ATLAS. Proc. 17th Int. Offshore and Polar Engineering Conf., Lisbon, Portugal, International Society of Offshore and Polar Engineers, 1850–1854.

[25] D. K. Ralston, H. Jiang, and J. T. Farrar, “Waves in the Red Sea: Response to monsoonal and mountain gap winds,” Continental Shelf Research, vol. 65, pp. 1–13, 2013.

[26] V. Aboobacker, P. Shanas, M. Alsaafani, and A. M. Albarakati, “Wave energy resource assessment for Red Sea,” Renewable Energy, vol. 114, pp. 46–58, 2017.

[27] S. Langodan, Y. Viswanadhapalli, H. P. Dasari, O. Knio, and I. Hoteit, “A high-resolution assessment of wind and wave energy potentials in the Red Sea,” Applied Energy, vol. 181, pp. 244–255, 2016.

[28] S. Langodan, L. Cavaleri, A. Pomaro, J. Portilla, Y. Abualnaja, and I. Hoteit, “Unraveling Climatic Wind and Wave Trends in the Red Sea Using Wave Spectra Partitioning,” Journal of Climate, vol. 31, no. 5, pp. 1881–1895, 2018.

[29] S. Langodan, L. Cavaleri, Y. Vishwanadhapalli, A. Pomaro, L. Bertotti, and I. Hoteit, “The climatology of the Red Sea - part 1: the wind,” International Journal of Climatology, vol. 37, no. 13, pp. 4509–4517, Dec. 2017.

[30] S. Langodan, L. Cavaleri, A. Pomaro, Y. Vishwanadhapalli, L. Bertotti, and I. Hoteit, “The climatology of the Red Sea - part 2: the waves,” *International Journal of Climatology*, vol. 37, no. 13, pp. 4518–4528, Sep. 2017.

[31] K. Gunn and C. Stock-Williams, “Quantifying the global wave power resource,” Renewable Energy, vol. 44, pp. 296–304, 2012.

[32] R. Alamian, R. Shafaghat, S. J. Miri, N. Yazdanshenas, and M. Shakeri, “Evaluation of technologies for harvesting wave energy in Caspian Sea,” Renewable and Sustainable Energy Reviews, vol. 32, pp. 468–476, 2014.

[33] MacCormick, M. E. (1981). Ocean wave energy conversion. New York: Wiley..

[34] Study on Lessons for Ocean Energy Development | European Commission.” [Online]. Available: http://publications.europa.eu/resource/cellar/03c9b48d-66af-11e7-b2f2-01aa75ed71a1.0001.01/DOC_1. [Accessed: 12-Feb-2020].

[35] A. F. D. O. Falcão, “Wave energy utilization: A review of the technologies,” Renewable and Sustainable Energy Reviews, vol. 14, no. 3, pp. 899–918, 2010.

[36] A. Falcão, “Developments in oscillating water column wave energy converters and air turbines,” Renewable Energies Offshore, pp. 3–11, Jul. 2015.

[37] A. F. Falcão and J. C. Henriques, “Oscillating-water-column wave energy converters and air turbines: A review,” Renewable Energy, vol. 85, pp. 1391–1424, 2016.

[38] H. Polinder, M. E. C. Damen, and F. Gardner, “Design, modelling and test results of the AWS PM linear generator,” European Transactions on Electrical Power, vol. 15, no. 3, pp. 245–256, 2005.

[39] A. Babarit, A. H. Cle´ment, and J.-C. Gilloteaux, “Optimization and Time-Domain Simulation of the SEAREV Wave Energy Converter,” 24th International Conference on Offshore Mechanics and Arctic Engineering: Volume 2, Jan. 2005.

[40] G. Mattiazzo, "State of the Art and Perspectives of Wave Energy in the Mediterranean Sea: Backstage of ISWEC," Frontiers in Energy Research, vol. 7, 2019.

[41] "Oceanlinx 1MW Commercial Wave Energy Demonstrator - Australian Renewable Energy Agency (ARENA)," Australian Renewable Energy Agency. [Online]. Available: https://arena.gov.au/projects/oceanlinx-1mw-commercial-wave-energy-demonstrator/. [Accessed: 12-Jan-2020].

[42] V. Franzitta, D. Curto, D. Milone, and D. Rao, "Assessment of Renewable Sources for the Energy Consumption in Malta in the Mediterranean Sea," Energies, vol. 9, no. 12, p. 1034, Aug. 2016.

[43] "Waves power: Spain: Arrecife Systems," Arrecife. [Online]. Available: https://www.arrecifesystems.com/. [Accessed: 12-Dec-2019].

[44] S. Langodan, L. Cavaleri, Y. Viswanadhapalli, and I. Hoteit, "The Red Sea: A Natural Laboratory for Wind and Wave Modeling," *Journal of Physical Oceanography*, vol. 44, no. 12, pp. 3139–3159, 2014.

[45] "Annual report 2016 wave energy," *Docsity*. [Online]. Available: https://www.docsity.com/en/annual-report-2016-wave-energy/2271897/. [Accessed: 31-Mar-2020].

[46] "EMEC: European Marine Energy Centre," EMEC European Marine Energy Centre. [Online]. Available: http://www.emec.org.uk/marine-energy/wave-devices/. [Accessed: 28-Nov-2020].

[47] "Wave Star - Unlimited Clean Energy," Wavestar. [Online]. Available: http://wavestarenergy.com/. [Accessed: 28-Mar-2020].

[48] The Salter Duck. [Online]. Available: http://www.technologystudent.com/energy1/tidal7.htm. [Accessed: 28-Mar-2020].

[49] "Anaconda Wave Energy Converter Concept," Sustainable Energy Research Group. [Online]. Available: http://www.energy.soton.ac.uk/anaconda-wave-energy-converter-concept/. [Accessed: 28-Mar-2020].

[50] "Course Modules," Centre for Renewable and Sustainable Energy Studies | Home. [Online]. Available: https://www.crses.sun.ac.za/. [Accessed: 28-Mar-2020].

[51] J. Cordonnier, F. Gorintin, A. D. Cagny, A. Clément, and A. Babarit, "SEAREV: Case study of the development of a wave energy converter," Renewable Energy, vol. 80, pp. 40–52, 2015.

[52] "From Blue to Green [Ask the Experts]," IEEE Control Systems, vol. 31, no. 5, pp. 18–24, 2011.

[53] "PB3 PowerBuoy®," Ocean Power Technologies. [Online]. Available: https://oceanpowertechnologies.com/pb3-powerbuoy/. [Accessed: 28-Mar-2020].

[54] A. Weinstein, G. Fredrikson, M. Parks, and K. Nielsen, "AquaBuOY - the offshore wave energy converter numerical modeling and optimization," Oceans 04 MTS/IEEE Techno-Ocean 04 (IEEE Cat. No.04CH37600).

[55] M. G. D. S. Prado, F. Gardner, M. Damen, and H. Polinder, "Modelling and test results of the Archimedes wave swing," Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, vol. 220, no. 8, pp. 855–868, 2006.

[56] E. Hultman, M. Linder, and M. Leijon, "Robotized Stacking of the Uppsala University Wave Energy Converter Generator Stator," Volume 9A: Ocean Renewable Energy, Aug. 2014.

[57] M. P. Kazmierkowski and M. Jasinski, "Power electronics for renewable sea wave energy," 2010 12th International Conference on Optimization of Electrical and Electronic Equipment, 2010.

[58] J. Hakulinen, "AW Energy Oy," AW Energy Oy, 16-Jan-2020. [Online]. Available: https://aw-energy.com/. [Accessed: 28-Mar-2020].

[59] "bioWAVE concept," BPS. [Online]. Available: http://bps.energy/biowave. [Accessed: 28-Mar-2020].

[60] P. Nicola, B. Giovanni, P. Biagio, S. S. Antonello, V. Giacomo, M. Giuliana, and S. Gianmaria, "Wave Tank Testing of a Pendulum Wave Energy Converter 1:12 Scale Model," International Journal of Applied Mechanics, vol. 09, no. 02, p. 1750024, 2017.

[61] T. Heath, "The Development and Installation of the Limpet Wave Energy Converter," World Renewable Energy Congress VI, pp. 1619–1622, 2000.

[62] A. Brito-Melo; F. Neuman ; Sarmento, A.J.N.A. Full-scale data assessment in OWC Pico plant. In Proceedings of the Seventeenth International Offshore and Polar Engineering Conference, Lisbon, Portugal, 1–6 July 2007.

[63] W. Kingston, "Examining the Effectiveness of Support for UK Wave Energy Innovation since 2000. Lost at Sea or a New Wave of Innovation?," Prometheus, vol. 35, no. 2, pp. 145–158, Mar. 2017.

[64] H. Osawa, T. Miyazaki, and S. Miyajima, "Characteristics of Hydrodynamics and Generating Output of the Offshore Floating Wave Energy Device 'Mighty Whale,'" Journal of Offshore Mechanics and Arctic Engineering, vol. 135, no. 1, Jan. 2013.

[65] E. Mehlum, "Commercial Tapered Channel Wave Power Plants in Australia and Indonesia," OCEANS 91 Proceedings.

[66] S. Parmeggiani, J. Kofoed, and E. Friis-Madsen, “Experimental Update of the Overtopping Model Used for the Wave Dragon Wave Energy Converter,” Energies, vol. 6, no. 4, pp. 1961–1992, Mar. 2013.

[67] V. Franzitta, P. Catrini, and D. Curto, “Wave Energy Assessment along Sicilian Coastline, Based on DEIM Point Absorber,” Energies, vol. 10, no. 3, p. 376, 2017.

[68] V. Boscaino, G. Cipriani, V. D. Dio, V. Franzitta, and M. Trapanense, “Experimental Test and Simulations on a Linear Generator-Based Prototype of a Wave Energy Conversion System Designed with a Reliability-Oriented Approach,” *Sustainability*, vol. 9, no. 1, p. 98, Nov. 2017.

[69] M. Vantorre, R. Banasiak, and R. Verhoeven, “Modelling of hydraulic performance and wave energy extraction by a point absorber in heave,” *Applied Ocean Research*, vol. 26, no. 1-2, pp. 61–72, 2004.

[70] H. Polinder, M. Damen, and F. Gardner, “Linear PM Generator System for Wave Energy Conversion in the AWS,” *IEEE Transactions on Energy Conversion*, vol. 19, no. 3, pp. 583–589, 2004.

[71] V. Franzitta and D. Curto, “Sustainability of the Renewable Energy Extraction Close to the Mediterranean Islands,” *Energies*, vol. 10, no. 3, p. 283, 2017.

[72] M. -, By, -, and Meo, “MEO,” *The Middle East Observer*, 14-Jan-2018. [Online]. Available: https://www.meobserver.org/?p=14600. [Accessed: 04-Apr-2020].

[73] A. M. Rizal, N. S. Ningsih, I. Sofian, F. Hanifah, and I. Hilmi, “Preliminary study of wave energy resource assessment and its seasonal variation along the southern coasts of Java, Bali, and Nusa Tenggara waters,” *Journal of Renewable and Sustainable Energy*, vol. 11, no. 1, p. 014502, 2019.

[74] R. Manyala, *Energy harvesting*. London, United Kingdom: IntechOpen, 2018.

[75] A. Khaligh and O. C. Onar, “Energy Harvesting,” 2017.

[76] G. Thomas, “The Theory Behind the Conversion of Ocean Wave Energy: a Review,” *Green Energy and Technology(Virtual Series) Ocean Wave Energy*, pp. 41–91.

[77] “Offshore Hydromechanics: Dr. ir. Pepijn de Jong,” Scribd. [Online]. Available: https://www.scribd.com/document/319049701/7-OffshoreHydromech1-Waves-pdf. [Accessed: 15-May-2020].

[78] C. Chen, “Determination of the right wave by empirical statistics: The wave energy resource assessment and the investigation of existing marine and coastal potential compatibility,” Journal of Ocean Engineering and Science, vol. 1, no. 4, pp. 284–288, 2016.

[79] A. M. Cornett, “A global wave energy resource assessment,” Sea Technol. 50(4), 59–64 (2008).

[80] “Wave energy converters in coastal structures,” *Wave energy converters in coastal structures - MarineSpecies Introduced Traits Wiki*. [Online]. Available: http://marinespecies.org/introduced/wiki/Wave_energy_converters_in_coastal_structures. [Accessed: 11-May-2020].

[81] A. López-Ruiz, R. J. Bergillos, J. M. Raffo-Caballero, and M. Ortega-Sánchez, “Towards an optimum design of wave energy converter arrays through an integrated approach of life cycle performance and operational capacity,” *Applied Energy*, vol. 209, pp. 20–32, 2018.

[82] “Wave energy resource off the French coasts: the ANEMOC database: Manualzz,” *manualzz.com*. [Online]. Available: https://manualzz.com/doc/36264098/wave-energy-resource-off-the-french-coasts--the-anemoc-da... [Accessed: 12-May-2020].

[83] J. Sierra, C. Martín, C. Mösso, M. Mestres, and R. Jebbad, “Wave energy potential along the Atlantic coast of Morocco,” Renewable Energy, vol. 96, pp. 20–32, 2016.

[84] E. Rusu and F. Onea, “Estimation of the wave energy conversion efficiency in the Atlantic Ocean close to the European islands,” *Renewable Energy*, vol. 85, pp. 687–703, 2016.

[85] L. Ciabattoni, M. Grisostomi, G. Ippoliti, and S. Longhi, “Fuzzy logic home energy consumption modeling for residential photovoltaic plant sizing in the new Italian scenario,” *Energy*, vol. 74, pp. 359–367, 2014.

[86] A. Awan, M. Zubair, P. P., and A. Abokhalil, “Solar Energy Resource Analysis and Evaluation of Photovoltaic System Performance in Various Regions of Saudi Arabia,” *Sustainability*, vol. 10, no. 4, p. 1129, Oct. 2018.

[87] “King Abdullah City For Atomic And Renewable Energy: Gensler - RTF: Rethinking The Future,” *RTF | Rethinking The Future*, 07-Aug-2019. [Online]. Available: https://www.re-thinkingthefuture.com/gada-2018-runner-up/king-abdullah-city-for-atomic-and-renewable-energy-gensle /#e59828e911d32f140b03a6666de2eaf72af5a4e4#27336. [Accessed: 28-Mar-2020].

[88] A. Felimban, A. Prieto, U. Knaack, T. Klein, and Y. Qaffas, “Assessment of the Current Energy Consumption of Residential Buildings in Jeddah, Saudi Arabia,” 2019.

[89] J. Leijon and C. Boström, “Freshwater production from the motion of ocean waves – A review,” *Desalination*, vol. 435, pp. 161–171, 2018.

[90] Administrator, “Environmental Impact of Wave Energy Devices,” Alternative Energy Tutorials, 01-Jan-1970. [Online]. Available: http://www.alternative-energy-tutorials.com/energy-articles/environmental-impact-of-wave-energy.html. [Accessed: 28-Mar-2020].

[91] “Sustainable Development Goals,” *UNDP*. [Online]. Available: https://www.undp.org/content/undp/en/home/sustainable-development-goals.html. [Accessed: 28-Mar-2020].

[92] M. Alkhayyat, T. Brahimi, T, S. Langodan, Hoteit, “Wave Energy in the Red Sea Region: Perspectives and Analysis", accepted for publication,999993333 ENERGYCon 2020, 6th IEEE International Energy Conference, 28 September - 1st October 2020, Tunisia.

[93] Minawi, M., 2019. Saudi Arabia’S Mega-City: THE NEOM PROJECT. Overview Of Public Perceptions Towards “The Worlds Most Ambitious Project” [PowerPoint slides]. Available: https://www.ipsos.com/sites/default/files/ct/news/documents/2019-01/saudi_arabias_mega-city_-_the_neom_project.pdf.

[94] M. Stefanovich; J.F. Chozas. Toward best practices for public acceptability in wave energy: Issues developersneed to address. In Proceedings of the ICOE 2010 3rd International Conference on Ocean Energy, Bilbao, Spain, 6–8 October 2010.

[95] H. Albalawi, A. Eisa, and E.-H. M. Aggoune, “Energy Warehouse - A New Concept for NEOM Mega Project,” 2019 IEEE Jordan International Joint Conference on Electrical Engineering and Information Technology (JEEIT), 2019.

[96] P. A. Bonar, I. G. Bryden, and A. G. Borthwick, “Social and ecological impacts of marine energy development,” *Renewable and Sustainable Energy Reviews*, vol. 47, pp. 486–495, 2015.

[97] A. Sandberg, E. Klementsen, G. Muller, A. D. Andres, and J. Maillet, “Critical Factors Influencing Viability of Wave Energy Converters in Off-Grid Luxury Resorts and Small Utilities,” *Sustainability*, vol. 8, no. 12, p. 1274, Jul. 2016.

[98] “Pelamis Wave Power Ocean Power Delivery Ltd,” Pelamis Wave Power Ocean Power Delivery Ltd | Open Energy Information. [Online]. Available: https://openei.org/wiki/Pelamis_Wave_Power_Ocean_Power_Delivery_Ltd. [Accessed: 05-Apr-2020].

[99] *Pico OWC*. [Online]. Available: http://www.pico-owc.net/en/. [Accessed: 05-Apr-2020].

[100] D. Vicinanza, L. Margheritini, J. P. Kofoed, and M. Buccino, “The SSG Wave Energy Converter: Performance, Status and Recent Developments,” *Energies*, vol. 5, no. 2, pp. 193–226, 2012.

[101] P. Contestabile, E. D. Lauro, M. Buccino, and D. Vicinanza, “Economic Assessment of Overtopping BReakwater for Energy Conversion (OBREC): A Case Study in Western Australia,” Sustainability, vol. 9, no. 1, p. 51, 2016.

[102] P. Contestabile, G. Crispino, E. D. Lauro, V. Ferrante, C. Gisonni, and D. Vicinanza, "Overtopping breakwater for wave Energy Conversion: Review of state of art, recent advancements and what lies ahead," *Renewable Energy*, vol. 147, pp. 705–718, 2020.

[103] P. Contestabile and D. Vicinanza, "Coastal Defence Integrating Wave-Energy-Based Desalination: A Case Study in Madagascar," Journal of Marine Science and Engineering, vol. 6, no. 2, p. 64, Jan. 2018.

[104] P. Contestabile, F. Vincenzo, E. D. Lauro, and D. Vicinanza, "Full-Scale Prototype Of An Overtopping Breakwater For Wave Energy Conversion," *Coastal Engineering Proceedings*, no. 35, p. 12, 2017.

[105] "IRENA. Ocean Energy Technology Brief 4. 2014," Available online: https://www.irena.org/documentdownloads/publications/wave-energy_v4_web.pdf [accessed: 15-Apr-2020].

Appendices

Appendix A: WECs

1. Pelamis [98]

A semi-submerged structure consists of multiple cylindrical parts connected to hinged joints (made from steel). Hydraulic pumps are used to make use of the bending motion within the joints induced by the waves that travel. The high-pressure oil is used in a hydraulic system to produce electricity.

Within the framework is installed the electricity generation network, as well as the rectification circuit. Many modules can be linked in parallel, and a single cable network can feed the electricity into the grids.

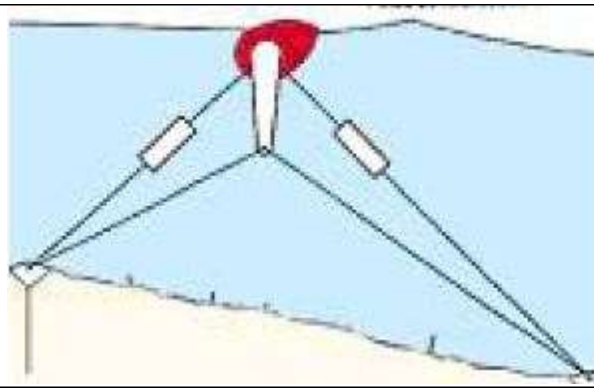
Classification	• Above waterline WEC with hydraulic PTO. • Far offshore (5-10 km). • Development stage: Currently busy installing the world's first wave farm (Agucadura) with a capacity of 2.25MW.
Generation capacity	30 MW farm (square kilometer).
Device capacity	750 kW.
Size	150m long and 4.63m diameter.
Cost for a single device	\$2 to \$3 million (estimated in 2004).
Environmental impact	Low. The device will have a small impact, and that of the anchor is also very small. The hydraulic system further uses biodegradable fluid.
Maintenance	Low. The system uses proven technology, and components are easily accessible.
Manufacturability	Good. It is made from steel, and it can be built in almost any shipyard then towed to the desired site.

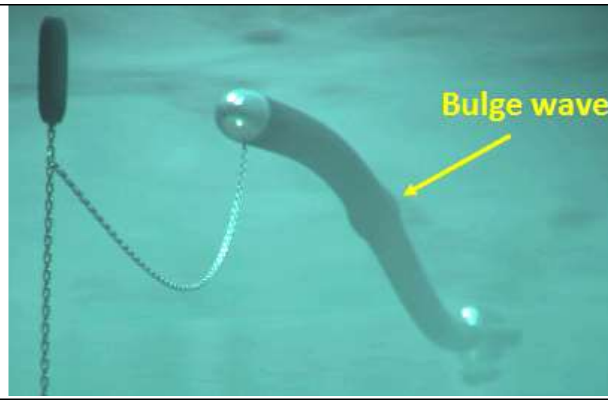
2. Wave Star [47]

The Wave Star consists of 20 hemisphere shaped floats partially submerged, each driving a hydraulic pump. The incoming wave moves the floats up in order of sequence. The compressed oil (at approximately 200 bar) is collected from each pump and fed into each accumulator.

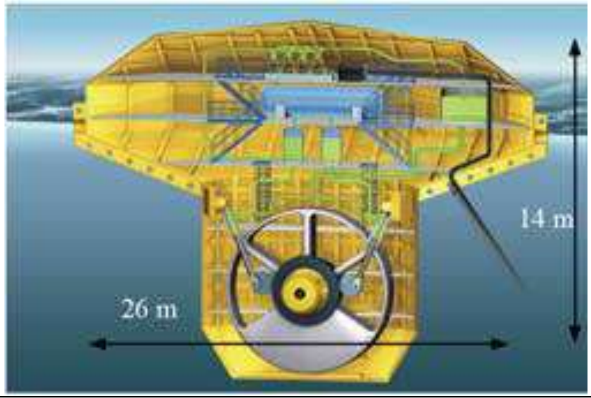
The entire frame is fixed onto two steel pillars in such a way that the incoming waves are placed at right angles. This implies that the device can not align itself with waves from any other direction, thus restricting its performance.
The floats are pulled up and secured as a protective measure during rough weather.

Classification	• Above waterline WEC with hydraulic PTO. • Multi-point absorber. • Development stage: early tests.
Generation capacity	3 MW estimated.
Environmental impact	Low.
Maintenance	Low. Components will be above the waterline and inside a protected cover, protecting them from the harsh ocean environment. The device will be loosened from the base and tugged to shore when extensive maintenance needs to be performed.
Manufacturability	Medium. The device will be premanufactured and then towed to the location and then bolted onto the stand.

3. **Salter Duck** [48]	
	
In a nodding motion, the moving waves cause the Duck to rotate; this motion is used to pump fluid or to compress air. If the hydraulic principle is used, the fluid will drive a hydraulic motor which in turn drives an electrical generator to produce electricity. Still, the compressed air will drive a turbine if air is used. It was planned in the 1980s, but production was delayed after estimates showed that it had too high operating costs. A recent analysis, however, showed that the operating costs are around ten times lower than originally expected.	
Classification	• Above waterline WEC with hydraulic PTO. • Line absorber. • Development stage: Early testing stage.
Environmental impact	Low. Slow rotating structure with no sharp rotating parts that pose no threat to marine life.
Maintenance	Medium. Components are protected and are accessible from a boat, but It is a complicated system. Still, the critical component is not only protected by the structure but also easily accessible with a boat.
Manufacturability	Medium to poor. It will use a complicated hydraulic system.

4. Anaconda [49]	
	
The Anaconda has a single principle of function. The system absorbs the energy of the wave in the form of a "bulge wave" that falls in the water contained inside the system. A turbine is then used to collect and transform the energy from the water into electricity (the turbine powers an electric generator). Rubber is used as the element of the base structure. The front end is a 150 m long rubber tube with a diameter of 5 m (inside this section, the bulge wave is induced). The rear is bigger than the front end (it's bigger because it houses the turbine and therefore requires a lot of inertia) and it's made of rubber, too.	
Classification	• Above waterline with a hydraulic PTO. • Development stage: Scale model testing in a wave tank.
Generation capacity	1MW (expected).
Size	150m long with a 7m diameter.
Environmental impact	Low environmental impact since it does not have any components that pose a threat to marine life.
Maintenance	Low. The system uses proven technology, and all the critical components are easily accessible. If it's necessary, the device can be towed to a nearby harbor to be serviced.
Manufacturability	Medium. The device will use very little off the shelf components, but the manufacturing techniques for the concerned materials is common.

5. SEAREV [51]



SEAREV, an offshore device of the second generation, includes a sealed, watertight floater with a charged wheel, acts as an embedded pendulum. The upper half of the 9-meter-diameter horizontal axis wheel is spare. Weight is concentrated in the lower half filled with concrete, which explains the pendulum effect. Sea swell and waves cause the oscillation of the SEAREV floater, allowing the pendulum wheel to swing back and forth. Since the floater and the pendulum both have their motion, the relative floater-wheel movement triggers a hydroelectric mechanism that transforms mechanical energy into electricity. Hydraulic connected to the pendulum wheel charge the high-pressure accumulators which discharge their energy into hydraulic motors driving electric generators. An undersea cable transmits electricity to shore. Several floaters from SEAREV can be anchored offshore, forming a park or farm.

Classification	• Floating device, similar to Salter Duck • Development stage: 1/12 prototype • 500 kW full scale 2009
Environmental impact	Low. The device has a small footprint.
Maintenance	Medium. It can be towed to the nearest port for maintenance work.
Manufacturability	Medium.

6. AquaBuoy [54]

A cylindrical buoy as a displacer which houses the impulse turbine and generator. The reactor is a mass of water under the buoy that is surrounded by a long vertical cylinder. The hose pump is powered by a large neutrally buoyant disk inside the cylinder. When the moving waves cause the system to travel up and down, the disk remains relatively. Still, this allows the upper or lower pipe to expand (diminishing its displacement volume), forcing the water through a high-pressure accumulator, respectively. The water is fed to a turbine from the accumulator, which, in turn, drives a generator. The electricity is fed to shore through a cable. The device's output will be reduced because it can not easily adapt to the frequency of the wave.

Classification	• Above waterline WEC. • Point absorber. • Development stage: early production
Rated power	250kW per buoy.
Average output	56kW.
Size	6m diameter buoy.
Total cost	$3million for four units.
Environmental impact	Low. Minimal obstruction for marine life. The material composition is by the Kyoto Protocol standards; therefore, the materials only environmentally friendly are used.
Maintenance	Low. Components are housed inside the buoy where they are protected and also easily accessible. It can be towed to the nearest harbor if major maintenance needs to be performed.
Manufacturability	Good. The buoy can be premanufactured and, after that, towed to the desired location.

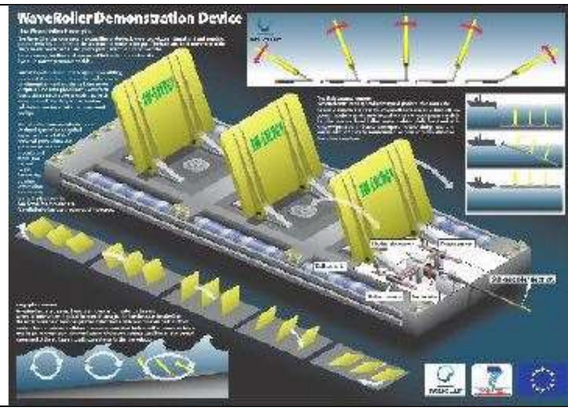
7. Archimedes Buoy [55]

The lower device is fixed to the seabed, and the upper one is allowed to push swell. Within the upper cylinder is trapped in an air pocket; the pocket is compressed as the wave peak passes. This forces the float down, compressing the gas, as the trough passes through the compressed air pushes the float back up. This causes the float to waver.
The generation of electricity is through a linear generator. The magnets are connected to the float's internal (upper cylinder) and produce electricity as they pass relative to the inner coil.

Classification	• Bottom mounted, linear-generator as PTO. • Point absorber. • Far from shore. • Development stage: full-scale tests.
Generation capacity	>1.2 MW.
Size	9.5m diameter.
Cost estimate	$4-6 million.
Environmental impact	Medium. It uses a larger piece of ocean floor than the buoy type concepts, but it will not influence the sensitive beachfront. It doesn’t use hydraulic oils, thereby lowering pollution risks.
Maintenance	Medium. The system is submerged, making maintenance difficult, but this also protects it during storms. The device will have to be floated to perform extensive maintenance.
Manufacturability	Medium. Large structure, and difficult to transport the structure to the desired location.

8. WaveBob [57]	
	
The WaveBob is a free-floating point absorber that uses a hydraulic system to convert the wave energy into electricity (there is very little information available about the system). In case a spill occurs, the hydraulic system uses biodegradable fluids to avoid contamination. It has an onboard control system that adjusts the device's natural frequency according to the predominant frequency of the wave. This also has an overload protection system that protects the device under severe weather.	
Classification	• Above waterline WEC. • Point absorber. • Depth: >50m • Development stage: Optimization.
Rated power	1 MW.
Size	15m diameter.
Environmental impact	Low. The mooring system will have an environmental impact, and this should below.
Maintenance	Unknown. Too little information is available.
Manufacturability	Unknown. The structure made out of steel; this will ease manufacturing.

9. WaveRoller [58]



WaveRoller is an appliance that transforms ocean waves into electricity and oil. The system works at depths of between 8 and 20 meters in nearshore areas (approx. 0.3-2 km from the shore). It is fully submerged and grounded on the seabed. A single WaveRoller unit (one panel) ranges from 500kW to 1000kW, with a capacity factor of 25-50 percent depending on project site wave conditions.

The hydraulic piston attached to the panel pumps the hydraulic fluids inside a closed hydraulic circuit, while the WaveRoller panel shifts and absorbs the energy from ocean waves. All of the hydraulic circuit components are enclosed inside a hermetic system inside the unit and are not exposed to the marine environment. There is also no chance of leaching into the water. The high-pressure fluids are pumped into a hydraulic engine driving an electric generator. The electric output from this renewable wave power plant is then connected via a subsea cable to the electrical grid.

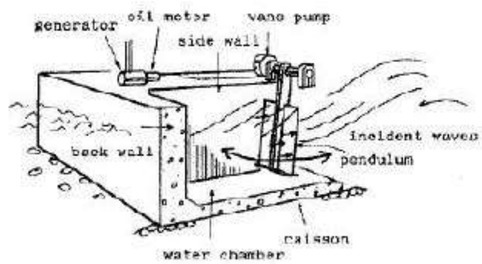
Classification	Full scaled testing.
Capacity	0.5 to 1 MW depending on waves.
Environmental impact	invisible sits on the sea bed

10. bioWAVE [59]

When a wave moves, the unit is said to be moving in the same way as an ocean plant. The specially designed O DRIVE TM, which is located at the hinge point at the bottom of the system, transforms this swaying motion into electricity.
The unit can defend itself by lying flat on the seabed when a storm approaches.
The Oyster and the WaveRoller are very close in method. The biggest difference between their devices is the PTOs.

Classification	• Bottom mounted, water-pump serving as PTO. • Development stage: unknown.
Generation capacity	500kW, 1000kW and 2000kW.
Environmental impact	Low. There are no fast-moving parts that can harm marine creatures, and the anchor will also have a very small impact.
Maintenance	Medium. The generator near the bottom of the ocean; this will make maintenance more difficult.
Manufacturability	Medium. The device itself is easily manufactured.

11. Pendulum [60]



The Pendular consists of a pendulum and a broad vane pump, which is part of it mounted on the pendulum shaft. Incident waves are standing waves in the water chamber from which water flows to be at the node vice versa. The flow drives the pendulum, and the pendulum motion drives a generator by the combination of the pump and two oil motors.

Classification	Shore mounted.
Environmental impact	Medium
Maintenance	Medium
Manufacturability	Medium

12. OceanLinx [42]	
	
A parabolic wall is used to track the waves. A chamber is situated above the parabola's focal point; this chamber reaches deeper into the water than others would be experienced through it. This chamber is packed with air, and it narrows to the top where there is an air turbine with a variable speed pitch edge. To drive a generator, the turbine uses the oscillating air (the waves cause the air to oscillate. To maximize output, the turbine will be easily tuned to the wave frequency. It would be improved by the soft-started machine ability to pull in speed quicker (grid energy can be used to drive the generator, enabling it to work as a motor).	
Classification	• Above the waterline, OWC PTO system. • Development stage: sea trails.
Generation capacity	321 kW.
Size	20 m x 40 m x 5 m.
Environmental impact	Medium. The wall will increase its environmental impact.
Maintenance	Low. All critical components are outside of the water.
Manufacturability	Medium. The greater energy density is a great reward, and it allows the use of less energy extracting equipment. Most of the structure will be built out of steel; this will ease manufacturing.

13. **Limpet** [60]

The limpet is built by Wavegen, a device located in Islay (an island off the west coast of Scotland) where it supplied power to the national grid. The limpet operates on the owc (waves cause an air pocket to oscillate, trapped behind a wall), and it uses a Wells turbo generator, which drives an induction generator to convert the extracted energy into electricity. The device may be viewed as an integral part of the breakwater. This would result in a much lower cost of deployment.

Classification	• Shore-based, preferable water depth is 15m, with OWC PTO. • Development stage: production
Generation capacity	500 kW.
Environmental impact	High. The system occupies the beach; therefore, its use will probably be limited to breakwaters and other special places. However, the system might have a small environmental impact if it is stalled in a breakwater.
Maintenance	Low. All critical components will be housed outside of the water, and also, it’s accessible from the beach.
Manufacturability	Medium. It requires a solid structure, which will increase installation costs.

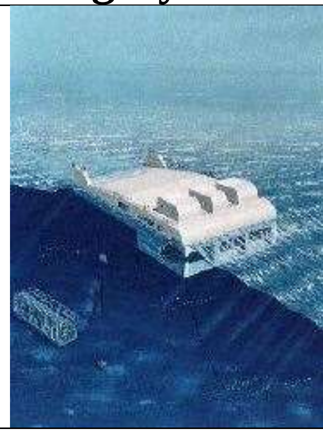
14. Pico Plant [99]

A 400kW rated OWC power plant was constructed on the shoreline of Pico Island in the Azores. The plant uses a concrete frame, installed on the seabed/shoreline, and uses a Wells turbine for power takeoff. Various problems originally developed in 1995-1999 forced the project to stop testing. Testing began in 2005, with much of the original equipment (notably the generator and turbine) still intact, and the plant was connected to the local power grid. Unfortunately, the existence of mechanical resonances inside the system prevented the plant from working at optimum power levels, restricting it to 20-70kW range power output.

Classification	Shorebased OWC
Generation capacity	500 kW.
Environmental impact	Medium.
Maintenance	Medium.
Manufacturability	Medium.

15. Osprey [63]	
	
Osprey is a steel structure system of 2 MW Nearshore OWC. During installation, the device was destroyed before it could be secured to the seafloor.	
Classification	Nearshore OWC
Generation capacity	2 MW.
Environmental impact	Medium.
Maintenance	Medium.
Manufacturability	Medium.

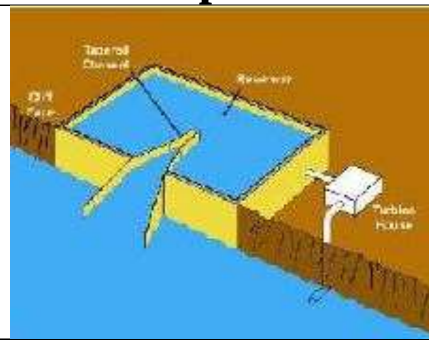
16. Mighty Whale [64]



The Mighty Whale works based on the OWC (oscillating column of water). It has three front-facing chambers containing trapped air pockets. The waves cause the air to oscillate; this motion is used to power air turbines that power electrical generators in turn. The idea has been in the making since the 1940s. The plan is to use a number of these machines in a line to build calm seas behind them and power generation.

Classification	• Above the waterline, OWC PTO system. • Development stage: sea trails.
Generation capacity	110 kW (prototype).
Size	50m x 30m x 12m
Environmental impact	Low.
Maintenance	Low. Easy to perform maintenance since its critical components are above the waterline. The structure can be towed to a nearby harbor when major maintenance needs to be performed or when a storm approaches.
Manufacturability	Medium. It is made out of steel, and it can be built in almost any shipyard before it's towed to the appropriate location.

17. Tapchan [65]



The device has a tapered channel, which leads to an elevated tank. The channel focuses the waves when it gets narrower; this effect allows the waves to flow into the elevated reservoir. If it is allowed to flow back into the ocean, the elevated water can be used to drive a traditional hydropower plant. This is a desirable device since it can provide energy on demand (it stores the water in the reservoir until it is needed), but its use is restricted to coastlines with deep water near shore and high fallacies. It also needs less than 1 m of tidal length.

Classification	• Shore-based. • Development stage: Unknown.
Environmental impact	Medium. It is a large structure, but it will not have too a great effect on the suitable places where it can be installed.
Maintenance	Low. It uses well-proven and readily available technology. All critical components are protected from storms and also easily accessible.
Manufacturability	Medium. It requires a large structure, and it is limited to only a few suitable locations.

<table>
<tr><th colspan="2">18. Wave Dragon [66]</th></tr>
<tr><td colspan="2"></td></tr>
<tr><td colspan="2">The Wave Dragon is a massive, floating structure with its reservoir and two reflector arms as its main components. The reflectors are used to concentrate the waves on the central section; hence, their amplitudes are increased. The dispersed waves are pushed into the elevated reservoir to flood up a specially shaped path. Kaplan turbines are used to transfer mechanical energy to the low heat of the water. The turbines drive permanent generators of magnets, thereby producing electricity on the same basis as traditional hydropower plants built on the land. This is one of the heaviest (if not the largest) devices used by ocean waves to produce electricity.</td></tr>
<tr><td>Classification</td><td>• Above waterline.
• More than 40 m.
• Development stage: Planing to install a 7MW device during 2008 of the Wales coast.</td></tr>
<tr><td>Rated power</td><td>10 MW.</td></tr>
<tr><td>Estimated cost</td><td>13.5 mill. Euros.</td></tr>
<tr><td>Environmental impact</td><td>Low. It needs a large anchoring system due to its sheer size, but it will need a much smaller anchor than several buoy-like WECs with the same combined output.</td></tr>
<tr><td>Maintenance</td><td>Medium to low. The sheer size of the device will make it very stable during storms; hence survivability should not be a problem. The size will prevent it from being retrieved for extensive maintenance.</td></tr>
<tr><td>Manufacturability</td><td>Medium to poor. A large structure will be very difficult to transport and install.</td></tr>
</table>

19. SSG [100]

The SSG definition is based on the theory of overtopping. It uses three reservoirs mounted on top of each other to absorb the incoming wave crest and a specially built multi-stage turbine to transform the head into mechanical energy (the system would work very close to a traditional hydropower station). To produce electricity for the grid, or to produce hydrogen, the turbine must be connected to an electric generation system.

Classification	• Shore-based with an overtopping type PTO. • Development stage: concept.
Environmental impact	High. if it is built offshore (will completely occupy the beach it's installed on).
Maintenance	Low. It will use well-proven hydro technology, and all the components will be easily accessible.
Manufacturability	Medium to poor. It will require a large structure. It is limited to sites with steep beachfront facing deep water.

Appendix B: Daily GHI across the KSA

Table 18. Daily total GHI data Wh/m2 for 44 stations across the country [86].

Station \ Month	December	January	February	March	April	May	June	July	August	September	October	November	Average Daily Total
Al Baha	4223.4	5070.6	6012.5	6591.5	6059.1	6705.1	7496	6798.5	6535.4	6462.6	6673.5	5533.8	6180.2
Al Jouf	3576.5	4213.8	5347.5	5948.5	7395.3	8115.6	8536.2	8453.7	7474.4	6718.2	5355.4	4137	6272.7
Abha	4382	4443.6	6304.7	7063.6	5620.9	6656	6928.4	5808.7	6086	6106.8	6740	5512.5	5971.1
Al Farshah	4675.5	4775.1	6013.9	6540.5	5483.1	6733.4	6396.2	5290.1	5831.2	5985.6	6538.4	5404.1	5805.6
Al Ahsa	3938.9	4301.5	5306.3	5333.2	6294.6	7453.5	7881.4	7623.2	7239	6594.9	5798.4	4401.5	6013.9
Al Dhahran	3372.4	3829	4866	4869.8	6110.4	7067.9	7548.6	7134	6657.1	6086.6	5182	3787.1	5542.6
Al Damam	3576.7	4081.6	5285	5248.1	6403.9	7434.1	7966.8	7557.4	7035.4	6546.2	5505.8	4005.1	5887.2
Hafar Al Batin	3238.3	3738.1	5090.2	5373.2	6927.2	7943.1	8240.1	8278.9	7491.3	6618.7	5601.5	4071.6	6051
Al Jubail	3303.6	3946.3	5158.3	5232.4	6536.5	7343.5	7835.6	7405.3	6870.2	6327.5	5290.4	3843.4	5757.7
Al Khafji	3139.4	3794.7	4999.2	5130.7	6579.8	7395.3	7745.7	7535.4	7022	6333.9	5186.6	3750.9	5717.8
Hail	3758.8	4217.2	5427.8	5794.1	6860.2	8047.6	8423.9	8393.4	7434.7	6720.4	5655.3	4304.2	6253.1
Farasan Island	4152.5	4190.3	5270.4	6143	6501.1	6512.5	6381.7	5615.9	5871.3	5966.7	5937.9	4823.2	5613.9
Jazan	4218.6	4235.5	5312	6044.4	6345.3	6515	6228.3	5356.4	5858.1	5986.7	5986.5	4942	5585.7
Al Hanakiyah	4035.4	4631.2	5625	5820.5	7143.3	7936.4	8066.3	7897.7	7040.3	6728.5	5894.3	4954.3	6314.4
Al Madinah	4028.	4523.5	5526.2	5727.6	6767	7868.4	7865.4	7847.6	7077.9	6520.7	5666.9	4840.6	6188.3
Yanbu	4234.1	4603.1	5635.1	5790.3	7261.2	7949.1	7829.2	7612.5	7001.8	6455.4	5458.7	4860.8	6224.3
Hada Al Sham	3618.6	4255.7	5279	6068.4	6687.3	7445	7498.2	6974.6	6517.7	6098.9	5723.7	4795.6	5913.6
Jeddah	3769.1	4295.1	5262.7	5906.9	6825.4	7375.7	7235	6776.9	6267.6	6132.4	5452.1	4578.8	5823.1
Rania	4316.3	4839	5862.7	6030.7	5990.8	7311.7	7679.3	7206.3	7089.5	6638.8	6483.3	5313	6230.1
Makkah	3901.2	4282.6	5375.6	6185.1	6718	7421.1	7510	6936.1	6461.4	6003.9	5778.5	4782.2	5946.3
Osfan	3909.7	4306.9	5352	5972.8	6987	7530.2	7368.4	6923.7	6418.1	6071.6	5525.2	4648.7	5909.5
Al Qunfudhah	4007.6	4440.9	5305.2	6228.4	6540.1	6707.4	6526.9	6143.1	6057.8	5890.7	5548.7	4917	5667.8
Thuwal	3840.6	4414.8	5339.1	6040.3	6923.1	7541.1	7365.2	6869	6498.6	6099.4	5491.9	4731.8	5929.6
Najran	4979.2	5358.7	6569.4	6892	6318.5	7646.9	7765.3	6958.8	7062.7	6960.6	6977.1	5990.8	6623.3
Sharurah	5088.4	5368.9	6383.1	6898.6	6639.4	7768.4	7642.5	7167	7106.1	7104.1	6862.1	5825.4	6654.5
Arar	3307.9	3819.5	5121.6	5858.8	7190.8	8008.5	8357.9	8472	7303.8	6663.9	5204.4	3974.8	6106.9
Qassim	3422	4250.7	5510.9	5637.6	6867.8	7839.4	8155.3	8182.6	7395.5	6606.2	5856.9	4392.2	6176.4

Appendix C: OBREC and ARRECIFE Wave Converters

OBREC

Overtopping Breakwater for Energy Conversion (OBREC) developed by a research team from the Second University of Naples [101]. The device has a reservoir that is filled with water from waves running up a slope located above the sea level, as shown in Figure 1. A hydraulic turbine is powered with the energy of water flowing back to the sea. OBREC is integrated into a traditional breakwater and can be considered an innovative non-conventional breakwater. It is considered as traditional breakwaters with the added value of power generation. The potential energy of the stored water in the reservoir is converted into kinetic energy, flowing through low-head turbines installed behind the reservoir in an engine room [102]. A specially designed concrete structure, consisting of an impermeable sloping front ramp, leads the overtopping waves into a reservoir that is directly behind it. The energy is extracted by low head turbines, using the difference in water levels between the reservoir and the mean water level at sea.

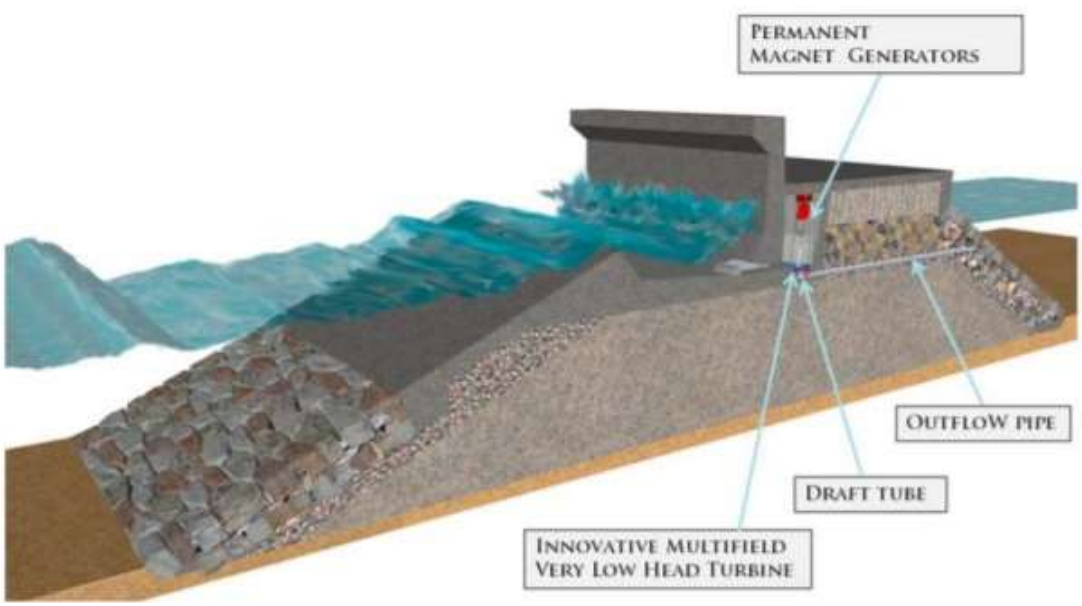


Figure 1. OBREC working principle [102].

Wave energy converters output is typically measured via the power matrix. As OBREC testing has just started, there is no definitive power matrix available. Consequently, the power output parameters are determined using a particular numerical model, called OBRECsim, a numerical model designed to simulate OBREC energy generation. The software provides detailed modeling of the OBREC hydrodynamics because a well-specified overtopping flow rate formula provided by an OBREC small-scale laboratory test [103], has been implemented. Moreover, the preliminary results obtained during a two-year monitoring campaign of the full-scale OBREC prototype were used to calibrate the code.

The prototype was implemented in the Port of Naples in 2015 [101]. It is the first wave converter that integrated into an existing breakwater, as shown in Figure 2. There is no definitive power matrix available since the monitoring has just begun [2].

Figure 2. OBREC implementation in Port of Naples [101].

Wave energy converters embedded in breakwater will provide a new form of energy source, especially in the core of coastal cities, contributing to the reduction of city pollution. In Chile [104] the installation of OBREC along 500 m of a breakwater could provide more than 2500 MWh of the expected average annual electricity consumption. While in Madagascar [103], the estimated power production is 115.5 kW, corresponding up to about 1010 MWh/year, as shown in Table 19.

Table 19. OBREC results in Madagascar [2].

Parameter	Value
Length of breakwater	500 m
Effective module average power	2.31 kW
Number of OBREC modules	50
Mean wave power	6.27 kW/m
Rated Capacity	115.5 kW
Annual energy production	1012.5MWh/year

ARRECIFE

Manufacturers WECs offer as a nominal electric power that is related to wave height between 5 to 8 m. ARRECIFE is designed for the most typical waves from 1 to 5m high waves [43], which means greater productivity in both production and power generation, operating at maximum capacity for more hours. Nevertheless, there are different models depending on the sizes and powers. **ARRECIFE 75kW** Designed for small applications. For example, islands, Isolated places, or to charge the batteries of solar panels. **ARRECIFE 440kW** Designed to operate all over the world through its standardized design. **ARRECIFE 2MW** Built for big power and production. It is the best model for harnessing marine energy in strong power areas from 70 kW/m [43]. It has an immersion feature which will be operated in storms. The machine is partially submerged, which avoids being destroyed by any harsh weather. ARRECIFE is 100% offshore as it can be adapted to any mooring: single anchor, dead weight, chain, jackets, or pilots, among others. This wave converter shown in Figure 4.12 can be transported by a tugboat, which enables that revisions and reparations can be done in yards. Thus, Operation and Maintenance costs are reduced [43]. Similarly, to an anchored boat, the system is guided by the direction of the waves. The rotating system of turbines allows for transforming the mentioned movement into electricity through electric generators.

A 75kW system tested at the open sea, Figure 3. It was carried out in the Cantabrian sea on a 1:10th scale. The results confirm the system works in real conditions as it is stable, simple anchor mooring worked correctly, all the turbines rotate constantly, waves break over the turbines, recovering its potential energy partially. Also, the system is a strong, robust, and the mechanical resist real waves, being designed to 0.5m waves, and it survives the impact of high waves.

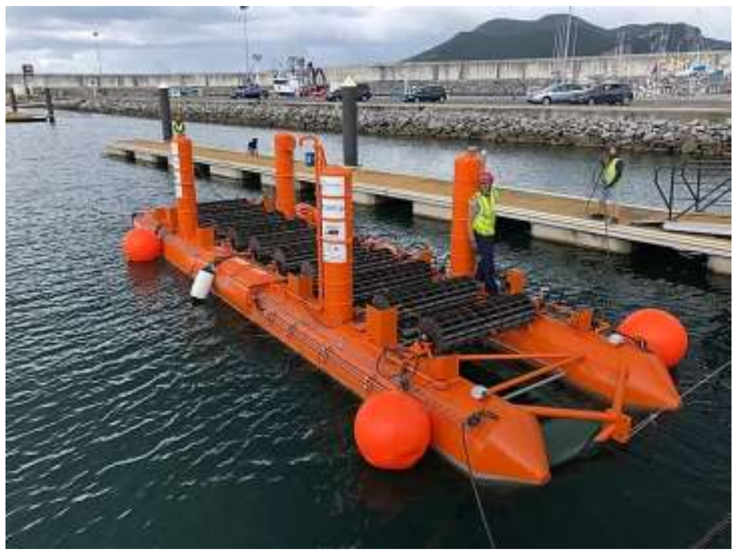


Figure 3. ARRECIFE Energy Systems [43].

Cost Analysis:

6.5.1.2 OBREC

The added cost of implementing a WEC would be lower when constructing a new breakwater system, given that the project is built at once compared with installing a WEC in an existing breakwater [2].

The estimated LCOE (Levelized cost of energy) for wave energy farms (i.e., 10 MW) that is in the range of 330–630 € / MWh [105], is higher than other marine renewable energy sources. In fact, this result is not surprising because the wave technologies are still in the initial stage of development. This impacts directly on economies of scale, including the assumptions considered for estimating current and expected costs of projects. These LCOE values correspond to those obtained by other studies.

However, due to learning rates and economies of scale in the industry, the costs are estimated to drop by a net amount of 70 percent by 2030. As we expand the level of growth reached with other marine energy sources, i.e. offshore wind, there would be a transfer of knowledge to other technologies and hence the costs will be changed accordingly. By 2030, this would mean an average LCOE of around €150–180/MWh.

When evaluating the productivity of a wave power plant, we must ensure that maintenance costs are minimized by providing the necessary tools for a proactive maintenance system to improve the maintenance planning.

6.5.1.3 ARRECIFE

As per the CEO Inigo Doria feedback, the estimated LCOE of ARRECIFE converter for 1kW only will be around 2,000 € per unit as an initial cost estimation.

Appendix D: Publications

International Conference on Industrial Engineering and Operations Management
Dubai, UAE, March 10-12, 2020
IEOM Society Venue: Hyatt Regency Dubai

February 11, 2020

Tayeb Brahimi
Energy Research Lab,
College of Engineering
Effat University, Jeddah, Saudi Arabia

ID 384: Wave Energy Converters: Barriers and Drivers

Subject: Acceptance Letter for ORAL PRESENTATION at the 10th International Conference, Dubai.

Dear Tayeb:
On behalf of the IEOM Society International's organizing and program committee, it is our pleasure to inform you that your paper for the above title has been accepted for Oral Presentation and publication for the 10th International Conference on Industrial Engineering and Operations Management (IEOM) to be held at Hyatt Regency Hotel in Dubai during March 10-12, 2020. Each paper was subject to anonymously peer reviewed by at least two referees. Accepted full papers will be published in the Proceedings and indexed in SCOPUS. Attending the conference and presentation of the paper is required.

IEOM Society International, a 501(c)(3) nonprofit organization has become a premier international platform and forum for academics, researchers, scientists and practitioners to exchange ideas and provide insights into the latest developments and advancements in the fields of Industrial Engineering and Operations Management. After having successfully organized previous international conferences in Dhaka (2010), Kuala Lumpur (2011), Istanbul (2012), Bali (2014), Dubai (2015), Orlando (2015), Detroit (2016), Kuala Lumpur (2016), Rabat (2017), Bristol, UK (2017), Bogota (2017), Bandung (2018), Paris (2018), Washington DC (2018), South Africa (2018), Bangkok (2019), and Pilsen (2019) is now organizing the 10th Annual International Conference in Dubai, United Arab Emirates.

Minimum one author must register to include the paper in the program and proceedings. You can check out recommended hotels, visa information, and other travel details in the following links: http://ieomsociety.org/ieom2020/travels/ and http://ieomsociety.org/ieom2020/.

IEOM is expecting another exciting event in Dubai. Some of the events and activities that are planned include: outstanding keynote speakers, global engineering education track, industry solutions track, more than 400 technical presentations, women in industry and academia track, undergraduate and graduate student paper competitions, panel sessions, recognition and awards, and exhibition. More than 400 participants are expected to join from more than 50 countries with a diverse background.

You will see the Dubai Conference as a great value-added event. Your participation is highly appreciated. If you have any question, please contact info@ieomsociety.org.

We look forward to seeing you in Dubai, UAE.

Regards,

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Wave Energy Converters: Barriers and Drivers

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Abstract

Wave energy has the most important renewable energy sources with many advantages compared to other types of renewable energies. The objective of this study is to provide an up-to-date investigation of the wave energy harvesting technology with emphasis on the main barriers and drivers of the wave energy converters development and utilization. The goal is to locate the best spot for wave energy converter (WEC) in the Red Sea region. The outcome of this study is to identify the most suitable converter system to harvest wave energy based on the most important criteria, including wave depth, amplitude, wavelength, and frequency of the waves. These parameters, along with environmental factors, sustainability development goals (SDG#14), and site constraints, have been assessed to develop a WEC device site-specific screening. Technical and social impacts were found to be deciding factors for the viability of wave energy exploitation.

Keywords
Wave Energy Converter, Wave Energy, Ocean Energy, Drivers, Barriers

1. Introduction

To shorten greenhouse gas discharge and to safe admissible for all countries, it is visible that renewable power sources will assume a key job. Universally, fossil fuel utilization is ~78.3% of the all-out part energy utilization, trailed by sustainable power sources with 19.2%. Customary biomass represents 8.9%, while the current sustainable power source has a level of 10.3%, controlled by sunlight and air. Internationally, the sustainable energy division between 2004 and 2013 (barring hydropower) expanded from 85 to ~560 GW. Representing the division was the wind industry with development from 48 to 318 GW, trailed by the photovoltaic segment from 2.6 to 139 GW (Rusu & Onea, 2018). Globally, the renewable energy sector between 2004 and 2013 (excluding hydropower) increased from 85 to ~560 GW. Leading the sector was the wind industry, with growth from 48 to 318 GW, followed by the photovoltaic sector from 2.6 to 139 GW (Swenson, 2020). The growth in the renewable sector was due to several factors, including political support, financial incentives, and reduction in the costs of technology, making renewable energy cost-competitive. As the name implies, wave energy is the energy of the waves, collected and transformed into useful energy. It is considered as one of the promising renewable energy options with great potential in reducing CO_2 emission (CCR, 2018; Crus, 2008). However, wave power needs explicit ecological conditions to be made. The energy is similarly distributed between (i) the potential energy part, where the water is constrained against gravity from the wave trough and peaks, and (ii) the active vitality segment, that is, the water swaying speed. To utilize this power, it is imperative to draft a structure that can productively catch and collect the energy transmitted by the waves (Aderinto & Li, 2019, Ilyas et al., 2014). Another important factor is that the structure must have the option to endure the marine atmosphere; specifically, storm occasions wherein the wave power fundamentally increments. The present study attempts to locate the best spot for wave energy converter (WEC) in the Red Sea region by identifying the most suitable converter system to harvest wave energy. Besides, the study considers the social and environmental factors, as well as site constraints.

2. Literature Review

In a report by the World Energy Council (WEC, 2016), it has been reported that there is a potential of 32,000 TWh per year, including 1300 TWh/year in the Mediterranean Sea and Atlantic Archipelagos (Cascajo et al., 2019). In 2019, the International Energy Agency (IEA, 2019) reported that marine development electricity generation increased by an estimated 16% in 2018. In the sustainable development scenario, 2000-2030, it is expected that ocean power generation reached 15 TWh (IEA, 2019). With the first WEC patent issued in 1799, the first WEC system was developed in France (Alamian et., 2014). Yoshio Masuda created the predecessor to modern wave energy systems in Japan in 1940 with the integration of the first floating oscillating water column into a navigation buoy (Masuda, 1986). Since then, more than 1000 patents have been issued; each project is described by different design and power take-off device (air, hydraulic, electrical, mechanical), describing the mechanism that absorbs and converts wave energy into electricity (Swenson, 2020). Wave energy converter research and development began in Great Britain in 1975 through several programs (MacCormick, 1981). Sweden constructed one of the world's largest commercial wave energy at Sotenäs, including 42 devices and producing a power of 1.05 MW. Another project was also installed in Ghana, including six devices with a capacity of 400 kW (WEC, 2016). The Norwegian government then adopted these policies. In 1985, on the coast near Bergen, Norway, significant efforts were made to build two real-size converters with a rated power of 350 kW and 500 kW (MacCormick, 1981). Activities in this field remained largely at the academic level in Europe until the early 1990s (Falcão, 2010). A small-scale, oscillating water column (OWC) built-in Islay, Scotland, in 1991, is the most notable achievement of this era (Falcão, 2015). Two OWCs were installed in Asia around the same time, including a 60-kW converter combined with a breakwater in the port of Sakata, Japan, and a 125-kW bottom-standing power plant in Trivandrum, India (Falcão, 2016). One of the failed devices of the time is the 2-MW converter in Scotland, destroyed by the waves. A 400-kW OWC was installed in Portugal in 1999, followed in Scotland in 2000 by a 300-kW Limpet ((Falcão, 2016; Polinder et al., 2005). The floating-point absorber SEAREV was first published in France in 2003 (Babari, 2009). Two years later, in Port Kembla, Australia, a new version of this absorber was developed, and a semi-industrial 1:5 scale prototype, named Wave Dragon, was dropped into Denmark's water (Cascajo et al., 2019). Several converters were launched later in 2008, including a Pelamis in northern Portugal, 16 OWC systems in Mutriku, Spain, and an Oregon State University floating system. A floating system of 25 kW and an Osprey in the UK were also designed in Denmark (Alamian et., 2014).

In 2010, the Ocean Linx was launched in Australia with eight air chambers and two engines, followed by PSFROG in the UK (Oceanlinx, 2019). Among other devices that have been deployed to date are salter energy converters (UK), point absorbers (Norway), tapered channels (Norway), energy-absorbing pedals (Japan), and Archimedes boys (Portugal) (Aderinto & Li, 2019; Cascajo et al., 2019; Alamian et., 2014).

3. Wave Energy Converters

Waves have the ability to provide a sustainable source of energy, which can be captured and converted to electricity by wave energy converter (WEC) machines (Aderinto & Li, 2019; Cascajo et al., 2019). These WECs were designed to extract energy from the shoreline to the deeper offshore waters. There are currently about 80 wave energy conversion technologies available. The WEC chosen will depend on the physical characteristics of the specific location, the types of local waves, and their working principles. WECs can be divided into four groups.

3.1 Attenuator

An attenuator is a floating device that runs parallel to the path of the wave and rides the waves effectively. These instruments extract energy from the two arms relative motion as they move through the wave. Floating devices include the Pelamis (Alamian et., 2014, 2014), Wave Star (Masuda, 1986), Salter Duck (McCormick, 1981), and Anaconda (Falcão, 2010) are shown in Table 1.

Table 1. Characteristics of attenuator wave energy conversion systems

Wave absorber	Type, water depth (m)	Mean wave power (kW/m)	Output power (kW)	Generator position
Pelamis	Floating ocean surface 50-60	15-40	750-1000	Within the body
Wave Star	Floating in the ocean 2-30	24	500-6000	Overwater surface
Salter Duck	Floating in the ocean 2-30	24	375	In water
Anaconda	Floating in the ocean 20	50	1000	Out of water

3.2 Point Absorber

A point absorber is a floating object that absorbs energy from all directions by traveling to/near the surface of the water. Depending on the displacer/reactor configuration, the power take-off system can take several forms. Examples of this type of WEC such as the SEAREV Anaconda (Falcão, 2015), L10 Anaconda (Falcão, 2016), OPT power (Babarit, 2009), AquaBoy (Cascajo et al., 2019), Archimedes Buoy (AREAN, 2019), Uppsala (Bahaj, 2011), WaveBob, WaveRoller (Alamian et al., 2014), BioWave (Kassem, 2015), and Pendulum (OPT, 2008) are shown in Table 2.

Table 2. Characteristics of point absorber wave energy conversion systems

Wave absorber	Type, water depth (m)	Mean wave power (kW/m)	Output power (kW)	Generator position
SEAREV	Floating ocean surface 50	40	500	On the ocean surface – inside the body
L10	Floating in the ocean	20	10	In water – inside the body
OPT power	Fixed in the ocean 30-60	50	40-500	In water – inside the body

AquaBuoy	Fixed ocean surface 40-80	15-50	250	On the ocean surface – inside the body
Archimedes Buoy	Fixed seabed 30-60	15	250	In water
Uppsala	Fixed seabed	20	5	In water
WaveBob	Fixed ocean surface over 50	20-70	500	In water
WaveRoller	Floating seabed 6-23	15	300	shore
BioWave	Fixed seabed 6-23	50	250-1000	In water
Pendulum	Fixed shore	15	20-300	Out of water

3.3 Oscillating Water Column

An oscillating column of water is a hollow structure that is partially submerged. It is exposed to the sea below the waterline, supporting an air column on top of a water column. Waves cause the column of water to rise and fall, compressing and decompressing the column of air in turn. The trapped air will flow through a turbine into and out of the atmosphere, which typically can rotate regardless of airflow direction. The rotation of the turbine is used to generate electricity. Floating and fixed examples of this type such as OceanLinx (Weinstein et al., 2004), Limpet (Polinder et al., 2005), Pico Plant (Joubert et al., 2009), Osprey (Breslin, 2005), and Mighty Whale (López et al., 2013) are shown in Table 3.

Table 3. Characteristics of oscillating water column wave energy conversion systems

Wave absorber	Type, water depth (m)	Mean wave power (kW/m)	Output power (kW)	Generator position
OceanLinx	Floater off-shore 5-50	50	200-1500	Above free-surface
Limpet	Fixed on-shore 15	15	500	On-shore
Pico Plant	Fixed in the ocean 7	40	400	Above free-surface
Osprey	Fixed in the ocean 15-20	50	500	Above free-surface
Mighty Whale	Fixed ocean surface 40	15	110	Above free-surface

3.4 Overtopping Device

Overtopping converters capture water as waves break into a storage reservoir. The water is then returned to the ocean, passing through a conventional low-head turbine, which generates power. An overtopping converter may use ‘collectors’ to concentrate the wave energy. Floating and fixed converters of this type are the Tapchan (bioWAVE, 2020), Wave Dragon (Kofoed, 2006), and SSG (Vicinanza, 2012).

Table 4. Characteristics of overtopping wave energy conversion systems

Wave absorber	Type, water depth (m)	Mean wave power (kW/m)	Output power (kW)	Generator position
Tapchan	Fixed shore 20	40	350	Out of water
Wave Dragon	Floating ocean surface 20-30	24	40	In water
SSG	Fixed shore 15	19	150	Out of water

4. Barriers and Drivers

4.1 Identification of Site

To choose a suitable location for WEC, it depends on many factors. In our research focusing on the Red Sea with emphasizing to NEOM city. The monthly distribution of mean wave height is shown in Figure 1. Gulf of Aqaba is to be considered, since the mean wave height has been found to be 1.5m, and it is near shore. Also, according to the monthly distribution of mean wind speed, winds are stronger over the Gulf of Aqaba, as shown in Figure 2. A total of 8 points were selected to test the potential of wave energy at the NEOM coastline. The distribution of study points is presented in Figure 3 (denoted from P1 to P8).

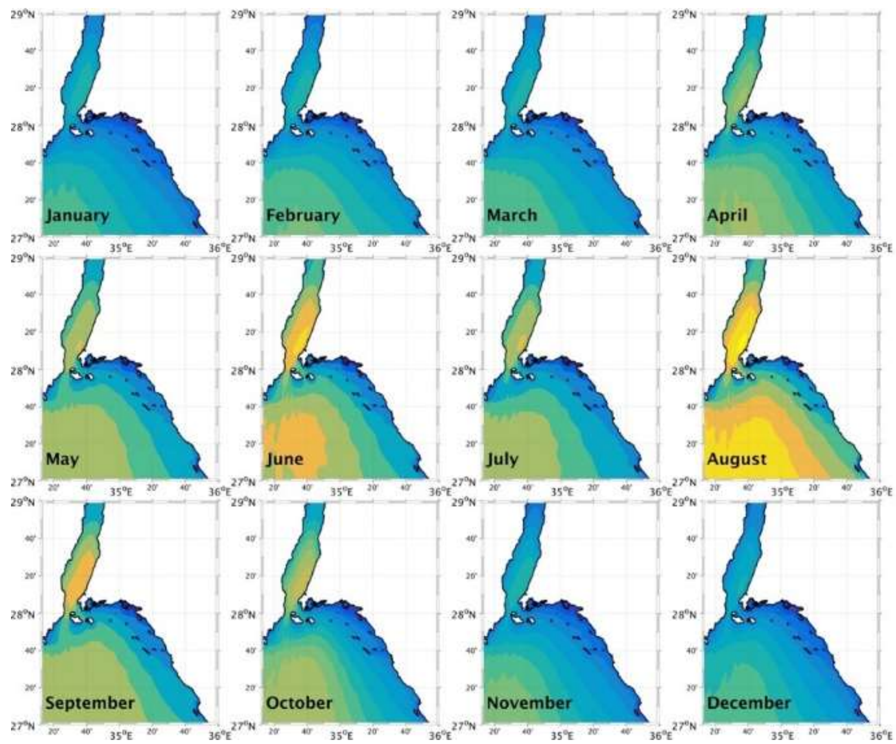

Figure 1. Monthly distribution of mean wave height from one year of shallow water wave simulation (2001)

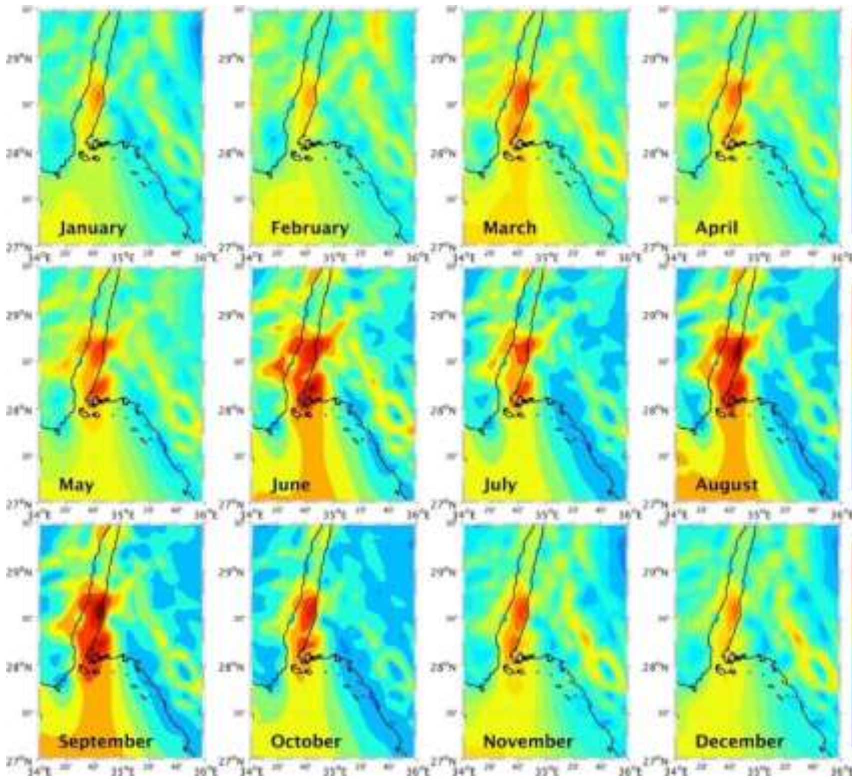

Figure 2. Monthly distribution of mean wind speed from the 15 years of WRF simulations (2001-2015).

Figure 3. Selected Study Points

4.2 WEC Selection

Based on Table 5**,** the minimum mean wave power necessary to activate a WEC is 2.8–3.4 kW/m. "Fixed- and floating-point absorber devices" indicate that Point absorber devices might present a power output of 4 kW.

Table 5. Summary of operating depths, mean wave power ranges and output power ranges for wave energy converter (WEC) devices

WEC Concept	Type	Depth Range (m)	Mean Wave Power Range (kW/m)	Output Power Range (kW)
Wave activated body	Floating	2-75	10-70	68-2250
	Fixed	1-40	10-50	5-100
Point absorber	Floating	10-2500	3.4-80	4-500
	Fixed	10-43	2.8-40	221-600
Oscillating water column	Floating	5-50	4-50	153-1500
	Fixed	4-14.5	20-60	31.7-2000
overtopping	Floating	20-40	60	625-940
	Fixed	6-20	14-30	49-350

4.3 Social Challenges and Environmental Challenges

The Sustainable Development Goals (SDGs), known as the Global Goals, were adopted by all United Nations Member States in 2015 as a universal call to action to end poverty, protect the planet and ensure that all people have peace and prosperity by 2030. The 17 SDGs are integrated, they recognize that action in one area will affect outcomes in others and that development should balance social, economic, and environmental sustainability. Implementing the ocean wave energy to produce electricity will achieve SDG #7: Affordable and Clean Energy, Ensure access to affordable, reliable, and modern energy for all. On the other hand, for wave energy converter installation, it is important to take into SDG#14 that states, "Conserve and sustainably use the oceans, seas and marine resources for sustainable development." The main goal here is to sustainably manage and protect marine and coastal ecosystems while enhancing the conservation and the sustainable use of ocean resources.
Due to the high abundance of birds, fish, tortoises, and corals and the already endangered biodiversity. WEC project deployment could cause cumulative impacts and jeopardize marine and coastal ecosystem health and resilience. As coastal communities are highly dependent on the goods and services provided by these ecosystems, such as fishing and beach safety, any changes to these habitats could have serious social implications. On the other hand, setting up WECs could produce environmental benefits, such as setting up fishing exclusion zones where endangered fish populations could recover. Here SDG #14: Life Below Water, Conserve, and sustainably use the oceans, seas, and marine resources for sustainable development will be achieved. At the coasts of NEOM, we have to take the coral reef at the shoreline into account. Coral reefs in the Red Sea north are a regional focal point for their exceptional resistance to climate change. Given the importance of the Red Sea coral reefs and other distinct marine structures and ecosystems in Saudi Arabia, As a member of the World Heritage Convention since 1978, the Ministry of Culture has been collaborating with UNESCO to recognize coral reefs in the Red Sea and other unique sites in the Red Sea as UNESCO protected sites and classified as World Heritage Sites, with the goal of protecting them as important natural assets for future generations (Saudi, 2019). Also, another consideration to take into account is the location of Sharma Palace along the coast located in the southwest of the NEOM region.

4.5 Operation and Maintenance Challenges

The operation and maintenance stages of wave energy converter projects refer to their performance and survivability. Preventive maintenance is required to avoid corrective maintenance of the devices.

4.6 Performance Improvement

- One of the most challenging issues in wave energy harvesting is the transformation of the irregular waves into a smooth electrical output, acceptable to the electrical grid, requiring some type of energy storage system or a reactive compensation means. The WECs need not only to adapt to changes in wave height and period, but they also need to be able to align themselves on the wavefronts. The

WECs are composed of a number of components: (1) the structure and the primary mover collecting the wave energy, (2) the base or mooring that holds the structure and the primary mover in place, (3) the power take-off (PTO) system that transforms mechanical energy into electrical energy, and (4) the control systems that safeguard and maximize operating efficiency (Felix et al., 2019).

- **Cost Reduction**

Cost reduction is the most critical element for improvement, to ensure that ocean energy becomes competitive. Stated that improvements in the next generation of wave technology could reduce the costs of power take-off by 22%, installation by 18%, and operation and maintenance by 17%, while costs in foundations, mooring, and grid connection could fall by 6% and 5%, respectively (Rusu et al., 2018). Another provided option to cut costs is by WECs sharing the infrastructure of existing offshore wind parks.

5. Results & Discussion

5.1 Selection of suitable WEC

Fixed- and floating-point absorber devices and floating oscillating water column devices operate with 2.8–3.4 kW/m and 4 kW/m, respectively, as shown in Table 5. Indicates that Point absorber devices might present a power output of 4 kW, whereas the floating oscillating water column devices might yield 153 kW. Regarding the mean wave power at the study points, as shown in Figure 4, P2 presents the heights mean wave power 1.98 kW/m.

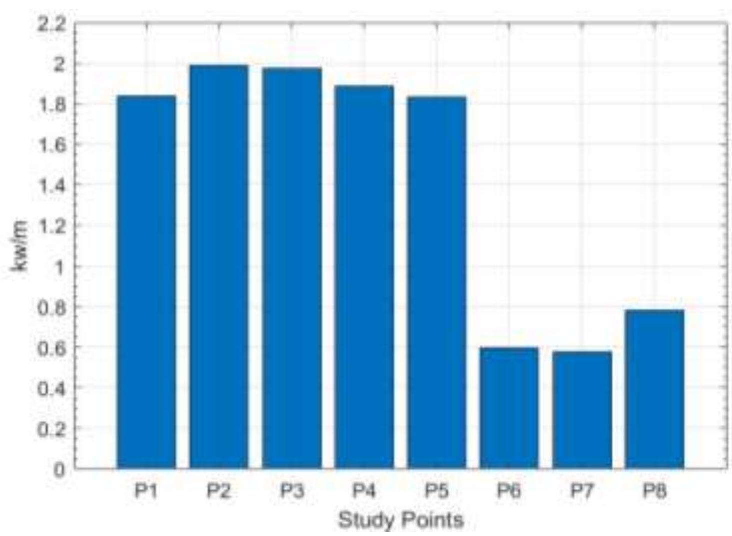

Figure 4. Annual mean wave power calculation for 12 years (2006 – 2018)

Build a new infrastructure that combines a breakwater and a wave energy converter (Mustapha et al., 2017; Arricife, 2020). It called Overtopping Breakwater for wave Energy Conversion (OBREC) Figure 5. Overtopping Devices (OTDs) has a reservoir that is filled with water from waves running up a slope located at a higher level than the surrounding sea. The energy of water returning back to the sea is used to power a hydraulic turbine, as shown in Figure 5. With the deployment of the OBREC device along 500 m of the breakwater in Madagascar, considering a breakwater of 500 m, estimated a total power of 115.5 kW, corresponding up to about 1010 MWh/year, Table 6.

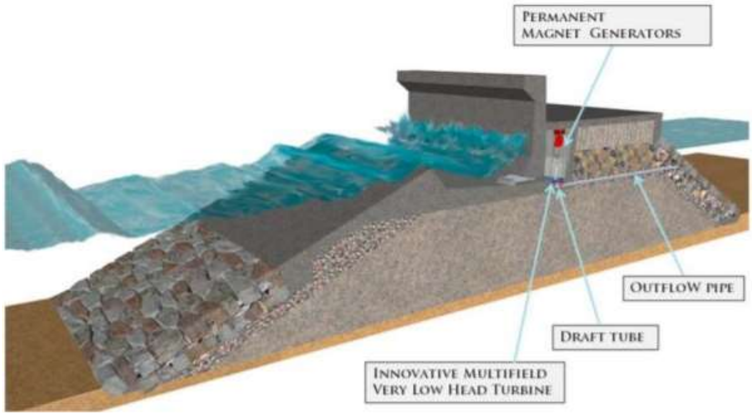

Figure5. OBREC working principle (Arrecife, 2020)

Table 6. Comparison of some WEC technologies

Wave Energy Converter	Operating Principle	Water Depth (m)	Mean Wave Power (kW/m)
SSG	OTD	6-18	14-16
OBREC	OTD	25	2-8
Wave Star	Floating bodies	10-20	2.8-5.2
LIMPET	OWC	6	20
Pico	OWC	8	37.9

ARRECIFE Energy Systems (Arrecife, 2020) Figure 6, a new wave energy converter designed to operate at low wave heights between 1 and 5 m, while other WECs needed 5 to 8 m waves for activity, Figure 6. The ARRECIFE specification considered the first operating system that directs turbines, opposes the wave, which absorbs more energy; it obtains energy from waves, currents, and tidal flows, installed offshore, away from the coast and at great depths, low O&M cost, Transportable system and fixable onshore.

Figure 6. ARRECIFE Energy Systems (Arrecife, 2020)

6. Conclusion

In this study, wind and wave energy in the Red Sea region have been investigated using a data series that has been developed via numerical modeling over 12 years. The goal was to select the most suitable area for the installation of WECs. The wave power has been analyzed using the data from 8 study points by incorporating wind and wave data between 1985 and 2015. The highest peak period selected in the present study is based on the wave hindcast generated on a 10-km resolution grid. The wave power per unit of crest length (kW/m), the significant wave height, is calculated in the selected areas. Based on the preliminary results, the Gulf of Aqaba, with a mean wave height of 1.5 m, is a good candidate for a WEC. Technical and social impacts were found to be deciding factors for the viability of wave energy exploitation. At NEOM coastline, we must take into consideration the coral reef at the shoreline. Coral reefs in the north of the Red Sea are a global focus for their remarkable resilience to climate change. Based on this preliminary study, a fixed-point absorber could be installed at P2 and P3; however, it will provide a power output during September. A hybrid system wind-wave might be another solution; however, to install wind turbines, it should be on a fixed surface/substructure, which is not going to work with the selected WEC above. Other solutions are being investigated, and more work in underway to complete this part of the thesis and include an economic study.

Acknowledgments

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References

Aderinto, T., Li, H., (2019), Review on Power Performance and Efficiency of Wave Energy Converters, *Energies* 2019, 12(22), 4329; https://doi.org/10.3390/en12224329

Alamian, R., Shafaghat, R., Miri, S. J., Yazdanshenas, N., & Shakeri, M. (2014). Evaluation of technologies for harvesting wave energy in Caspian Sea. *Renewable and Sustainable Energy Reviews*, *32*, 468–476. doi: 10.1016/j.rser.2014.01.036.

AREAN, Oceanlinx wave of success, (2019). Australian Renewable Energy Agency (ARENA). (2019, August 11). Retrieved from https://arena.gov.au/news/oceanlinx-wave-of-success/

Babarit, A.,Mouslim, H., Guglielmi,M., and Clément, A. H. Simulation of the SEAREV wave energy converter with a by-pass control of its hydraulic power take off. In Proceedings of the TenthWorld Renewable Energy Congress (WREC X), Glasgow, UK, July 2009, pp. 1004–1009.

Bahaj, A.S. Generating electricity from the oceans. Renew. Sustain. Energy Rev. 2011, 15, 3399–3416.

bioWAVE concept. (n.d.). Retrieved from http://bps.energy/biowave.

Breslin, J. (2015, May 20). Wavebob: Generating Power from the Movement of Waves. Retrieved from https://technologyvoice.com/2011/01/13/wavebob-generating-power-from-the-movement-of-waves/

Brito-Melo, A.; Neuman, F.; Sarmento, A.J.N.A. Full-scale data assessment in OWC Pico plant. In Proceedings of the Seventeenth International Offshore and Polar Engineering Conference, Lisbon, Portugal, 1–6 July 2007.

Cascajo, R., García, E., Quiles, E., Correcher, A., & Morant, F. (2019). Integration of Marine Wave Energy Converters into Seaports: A Case Study in the Port of Valencia. *Energies*, *12*(5), 787. doi: 10.3390/en12050787.

CCR, Construction Climate Challenge, (2018). Wave energy set to become a key renewable and reduce emissions. Retrieved from https://constructionclimatechallenge.com/2018/05/08/wave-energy-set-become-key-renewable-reduce-emissions/ (Accessed 20 January, 2020).

Crus, J. Ed., (2008). Ocean Wave Energy: Current Status and Future Perspectives. Springer, Berlin.

Falcão, A. (2015). Developments in oscillating water column wave energy converters and air turbines. *Renewable Energies Offshore*, 3–11. doi: 10.1201/b18973-3

Falcão, A. F. D. O. (2010). Wave energy utilization: A review of the technologies. *Renewable and Sustainable Energy Reviews*, *14*(3), 899–918. doi: 10.1016/j.rser.2009.11.003

Falcão, A. F., & Henriques, J. C. (2016). Oscillating-water-column wave energy converters and air turbines: A review. *Renewable Energy*, *85*, 1391–1424. doi: 10.1016/j.renene.2015.07.086

Felix, Hernández-Fontes, Lithgow, Mendoza, Posada, Ring, & Silva. (2019). Wave Energy in Tropical Regions: Deployment Challenges, Environmental and Social Perspectives. *Journal of Marine Science and Engineering*, *7*(7), 219. doi: 10.3390/jmse7070219.

Fredriksen, A. E. (2013, November 17). Tapered Channel Wave Power Plants. Retrieved from https://www.sciencedirect.com/science/article/pii/B9780080334233500290.

He, F.; Huang, Z.; Law, A.W.K. An experimental study of a floating breakwater with asymmetric pneumatic chambers for wave energy extraction. Appl. Energy 2013, 106, 222–231.

Heath, T. (2000). The Development and Installation of the Limpet Wave Energy Converter. *World Renewable Energy Congress VI*, 1619–1622. doi: 10.1016/b978-008043865-8/50334-2.

Heller, V.; Chaplin, J.; Farley, F. Physical model tests of the anaconda wave energy converter. In Proceedings of the 1st IAHR European Congress, Edinburgh, UK, 4–6 May 2000; Volume 1, pp. 3–8.

IEA (2019), "Tracking Power", IEA, Paris https://www.iea.org/reports/tracking-power-2019, (accessed on 15 January 2020).

Ilyas, A., Kashif, S. A., Saqib, M. A., & Asad, M. M. (2014). Wave electrical energy systems: Implementation, challenges and environmental issues. *Renewable and Sustainable Energy Reviews*, *40*, 260–268. doi: 10.1016/j.rser.2014.07.085

JAMSTEC JAMSTEC JAPAN AGENCY FOR MARINE-EARTH SCIENCE AND TECHNOLOGY. (n.d.). Retrieved from http://www.jamstec.go.jp/e/

Joubert, J.R.; Niekerk, J.L. Van recent developments in wave energy along the coast of southern Africa. In Proceedings of the 8th European Wave and Tidal Energy Conference, Uppsala, Sweden, 7–10 September 2009; pp. 1096–1100.

Kassem, A. M., Besheer, A. H., & Atawi, I. E. (2015). Kalmen estimator as a robust solution for output power maximization of wave energy converter. *IEEJ Transactions on Electrical and Electronic Engineering*, *10*(4), 390–395. doi: 10.1002/tee.22098.

Kofoed, J.P.; Frigaard, P.; Friis-Madsen, E.; Sørensen, H.C. Prototype testing of the wave energy converter wave dragon. Renew. Energy 2006, 31, 181–189.

López, I.; Andreu, J.; Ceballos, S.; De Alegría, I.M.; Kortabarria, I. Review of wave energy technologies and the necessary power-equipment. Renew. Sustain. Energy Rev. 2013, 27, 413–434.

MacCormick, M. E. (1981). *Ocean wave energy conversion*. New York: Wiley.

Masuda Y (1986) An experience of wave power generator through tests and improvement. In: Evans DV and Falcão AFDO (eds) Hydrodynamics of Ocean Wave-Energy Utilization. Berlin, Heidelberg: Springer, pp. 445–452.

Mustapa, Muhammad Adli & Yaakob, Omar & Ahmed, Yasser & Rheem, Chang-Kyu & Koh, Kho & Adnan, Faizul. (2017). Wave energy device and breakwater integration: A review. Renewable and Sustainable Energy Reviews. 77. 433-58. 10.1016/j.rser.2017.03.110.

Oceanlinx 1MW Commercial Wave Energy Demonstrator - Australian Renewable Energy Agency (ARENA). (n.d.). Retrieved from https://arena.gov.au/projects/oceanlinx-1mw-commercial-wave-energy-demonstrator/

OPT Powerbuoy. Available from http://tinyurl.com/ oceanpt/ (access date 2 July 2008).

Polinder, H., Damen, M. E. C., & Gardner, F. (2005). Design, modelling and test results of the AWS PM linear generator. European Transactions on Electrical Power, 15(3), 245–256. doi: 10.1002/etep.56

Rusu, E., & Onea, F. (2018). A review of the technologies for wave energy extraction. *Clean Energy*, *2*(1), 10–19. doi: 10.1093/ce/zky003.

Saudi aims to preserve Red Sea's coral reefs. (2019, September 10). Retrieved from https://filipinotimes.net/global-news/2019/09/10/saudi-aims-preserve-red-seas-coral-reefs/

Swenson, A. (2020, January 30). Building the sustainable energy future with renewable energy. Retrieved from https://www.ren21.net/

Vicinanza, D.; Margheritini, L.; Kofoed, J.P.; Buccino, M. The SSG wave energy converter: Performance, status and recent developments. Energies 2012, 5, 193–226.

Waves power: Spain: Arrecife Systems. (n.d.). Retrieved from https://www.arrecifesystems.com/

WEC, World Energy Council, (2016). World Energy Resources 2016. Available online: https://www.worldenergy.org/wp-content/uploads/2016/10/World-Energy-Resources-Full-report-2016.10.03.pdf (accessed on 20 January, 2020).

Weinstein, A., Fredrikson, G., Parks, M., & Nielsen, K. (n.d.). AquaBuOY - the offshore wave energy converter numerical modeling and optimization. *Oceans 04 MTS/IEEE Techno-Ocean 04 (IEEE Cat. No.04CH37600)*. doi: 10.1109/oceans.2004.1406425

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Dr. Ibrahim Hoteit, an associate professor in the Earth Sciences and Engineering program and the Applied Mathematics and Computational Sciences program at KAUST. He is currently the associate director of the Saudi Aramco-KAUST Center for Marine Environmental Observations (SAKMEO) and the PI of the Virtual Red Sea Initiative, a joint project with MIT/SIO/PML. Before joining KAUST in 2009, he worked as a research scientist at Scripps Institution of Oceanography of the University of California, San Diego. Dr. Hoteit's research interests are in modeling and simulation of ocean and atmospheric systems on supercomputers, with a specific interest in data assimilation and inverse problems and associated uncertainty quantification. Dr. Hoteit co-authored more than 150 scientific papers and is a co-recipient of five best conference paper awards. He is a member of the American and European Geophysical Unions, the Society of Industrial and Applied Mathematics, and an elected member of the UNESCO Center of Pure and Applied Mathematics. Dr. Hoteit earned his M.S. (1998) and Ph.D. (2002) in applied mathematics from the University of Joseph Fourier, France.

Dr. Sabique Langodan, Dr. Langodan's research focuses on modeling and understanding ocean processes in the Red Sea, especially those related to ocean waves. He is currently investigating the variability and trends of wind and waves in the Red Sea, and their relationship to the climate processes. Ph.D., Earth Science, and Engineering, King Abdullah University of Science and Technology (KAUST), Thuwal, KSA, 2016. He earned his M.S., Ocean Technology, Cochin University of Science and Technology (CUSAT), India, 2010. And M.S., Physics, Aligarh Muslim University (AMU), India, 2008. His B.S. in Physics from University of Calicut, India, 2006.

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Acceptance Letter

Date: 08 April 2020

Dear Dr. Tayeb Brahimi,

Congratulations!

On behalf of the ENERGYCON 2020 Technical Program Committee, we are pleased to inform that your paper:

Paper: *245*

Title: *Perspectives and Analysis of Wave Energy in the Red Sea Region*

Authors: *Tayeb Brahimi and Misaa Alkhayyat*

has been accepted for presentation at the 6th IEEE R8 International ENERGY Conference to be held on 13-16 April 2020, in Ramada Plaza Hotel, Gammarth – Tunis, Tunisia.

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Thank you very much for your contribution. We are looking forward to seeing you in Tunisia.

Sincerely,

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Wave Energy in the Red Sea Region: Perspectives and Analysis

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Abstract—**The main purpose of this study is to investigate the feasibility of the installation of Wave Energy Converters (WECs), and to evaluate and compare the potential of wave energy at selected locations in the Red Sea near the region of NEOM using available wind and wave model data provided by KAUST. The study is based on the soft seashore, wave depth, amplitude, wavelength, frequency of the waves, and bed and shore conditions. Due to its two distinct and opposing wave structures, caused by reverse winds converging at its middle, the Red Sea represents a challenge in wave modeling and analysis. By incorporating wind and wave data between 1985 and 2015 in the Advanced Research Weather and Forecasting model and WAVEWATCH III, it has been found that three major wind systems are creating waves. Several attempts were made to locate the best WECs; a total of 8 points were selected and analyzed. Based on the preliminary results, the Gulf of Aqaba, with a mean wave height of 1.5 m, is a good candidate for a WEC. Based on this study, a fixed point absorber could be installed at P2 and P3; however, it will provide a power output during September. A hybrid system wind-wave might be another solution; however, the installation of wind turbines should be on a fixed surface/substructure. Other solutions are being investigated, and more work is underway to suggest alternative solutions. The outcome of this study was the identification of the most suitable converter system to harvest wave energy in a given site based on the most important criteria. Technical and social impacts were found to be deciding factors for the viability of wave energy exploitation.**

Keywords-wave energy, Red Sea, analysis, wave converters, perspectives

I. Introduction

In 2016, a report by the World Energy Council [1] (WEC, 2016) reported that there is a potential of 32,000 TWh of wave power per year, including 1300 TWh/year in the Mediterranean Sea and Atlantic Archipelagos [2]. More recently, in 2019, the International Energy Agency [3] reported that marine development electricity generation increased by an estimated 16% in 2018. In the sustainable development scenario, 2000-2030, it is expected that ocean power generation reached 15 TWh [2]. Wave energy has the most important renewable en[1]ergy sources with many advantages compared to other types of renewable energies. However, wave power needs the existence or creation of particular ecological conditions. To utilize this power, it is imperative to draft a structure that can catch and collect the energy transmitted by the waves to use it productively. Despite the recent interest in marine energy, wave energy technology is just at the beginning stage of improvement, being focused primarily on wave power. Wave energy is distributed between (i) the potential energy part, where the water is constrained against gravity from the wave trough and peak and (ii) the active vitality segment, that is, the water's fluctuating speed., it is imperative to draft a structure that can catch and collect the energy transmitted by the waves to use it productively. Another important factor is that the structure must have the capability to endure the marine atmosphere, specifically stormy weather, wherein the wave power fundamentally increments [4-6]. This paper explores and investigates the potential of wave energy in the Red Sea region by studying the feasibility and impact of implementing wave energy converters in the Red Sea, focusing on the NEOM region and identifying the most suitable wave energy converter system for extracting energy from the waves. Besides, the study considers the social and environmental factors as well as site constraints.

II. Problem Statement

In its national transformation program and Vision 2030 plan, Saudi Arabia recently set ambitious goals for moving away from oil dependence, and redirecting efforts to other higher-value uses, chiefly meeting 10% of its energy demand through renewable energy sources. This goal is being accomplished by creating a roadmap for the energy supply of 10% of the country's energy demand from renewable energy sources, mainly solar and wind energy, with an initial target of generating 3.45 GW of renewable energy by 2020 and 9.5 GW by 2023 [7]. The energy that comes from resources that are naturally replenished, such as solar, wind, geothermal, biomass, wave, and tidal energy is defined as renewable energy. The potential of electric power generation from marine renewable energy is enormous, and it is recognized as a resource for sustainable electrical power generation yet to be exploited. To the best of the authors' knowledge, no research has been conducted to investigate the potential of wave energy in the NEOM region. In this study, several attempts were made to identify the best location for WECs based on NEOM's monthly distribution of mean wave height and the mean wind.

The projected outcomes of this study were the possibility of identifying the best converter system to harvest wave energy in the Red Sea, site-specific screening for installing a WEC device, and understanding the effect of social and environmental factors on the viability of wave energy exploitation.

III. Literature Review

Wave energy is an abundant energy source all over the world [1, 8]. It is an unconventional renewable energy source that is of interest due to its wide prevalence and density across the globe. Waves are mainly produced by the interaction between the wind and the sea surface, where the wind is continuously acting as a tangential force contributing to the formation of waves. Waves are also caused by the gravitational pull of sun and moon in the earth, creating what is known as tide waves. Universe. The flux of wave energy is contained in waves as both kinetic energy and potential energy. The amount of energy transmitted, and thus the size of the resulting waves depends largely on the wind speed, the length of time it blows for, and the distance through which it blows over the water [9, 10].

There has been an important increase in interest in wave energy over recent decades because of the requirement to decrease the emission of greenhouse gas. Most of technology developments in wave energy is particularly in Northern European countries where different wave energy conversion technologies are applied, such as in the United Kingdom and Norwegian Sea [11]. An assessment of wave energy potential and its harvesting approach along the Indian coast has been conducted by Sannasiraj et al. [12]. 73 locations have been selected on the Indian coast, where the maximum power found reached 20 to 25 kW/m. Shadman et al. [13] investigated wave energy generation along the Brazilian coastline using numerical models and conclude that there is a great potential of wave energy resources reaching 91.8 GW. Wang et al. [14] performed a long-term wind and wave energy resource assessment in the South China sea based on 30-year hindcast data. Results showed that the maximum power generated may reach 65 kW/m. Alaoui et al. [15] highlighted the existence of a significant ocean wave energy located in the region between Essaouira and Agadir in Morocco. In assessing the potential of wave energy in some location in Portugal, Rusu et al. [16] found the selected location present a great potential of wave energy resources. Nezhad et al. [17] showed that wave energy near Qeshm, Chabahar, and Anzali of the Iranian coastlines present the best potential of wave energy generation. In the Red Sea region, only a few studies have investigated the assessment of wave energy. Metwally et al. [18] generated a wave atlas, Ralston et al. [19] presented a two-year simulation summary of wave conditions in the Red Sea. Aboobacker et al. [20] used a long term assessment for wave energy in the Red Sea using numerical simulation. Langodan al. [21-22] conducted an extensive assessment of harvesting wave and wind energy with a detailed analysis of northern, central, and southern parts of the Red Sea using the Advanced Weather Research Forecasting model. Langodan et al. [23, 24] were able to develop an extensively wind and wave behavior that leads to the estimation of the wind and wave potential in the red Sea region. Four main wind and wave systems have been found to be the most dominant in the climate of the Red Sea, as discussed in [23]. With this great amount of research on wave energy, it can be anticipated that wave energy will have a larger role in the coming years in the supply systems of energy, as reported by World Energy Council [1] and the International Energy Agency [8]. Based on different government and non-government research studies, interest in wave power has been progressively increasing. In regions such as Australia, South America, Canada, and the South Coast of Africa have been recognized as high wave energy generation areas [25]. Fig. 1, adapted from [26], illustrates the total wave power distribution for various coastal environments based on the National Oceanic and Atmospheric Administration's WaveWatch III data. By analyzing the graph in Fig. 1, Australia, USA, and Chile, have more significant wave power resources compared to countries in Europe.

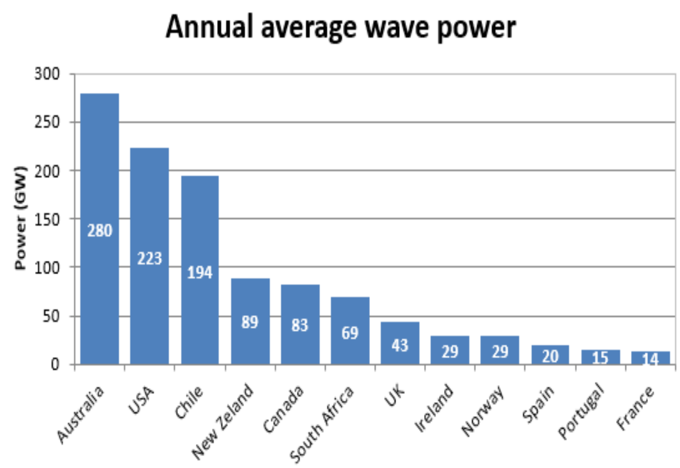

Fig. 1 Estimation of the total annual average wave power by countries.

On the wave energy converters (WECs) research activities, the first WEC patent issued in 1799 was developed in France [27]. Wave energy converter research and development began in Great Britain in 1975 through a number of programs [28]. Sweden constructed one of the world's largest commercial wave energy at Sotenäs, including 42 devices and producing a power of 1.05 MW [1]. In 1985, on the coast near Bergen, Norway, significant efforts were made to build two real-size converters with a rated power of 350 kW and 500 kW [29]. Activities in this field remained largely at the academic level in Europe until the early 1990s [30]. A small-scale, oscillating water column (OWC) built-in Islay, Scotland, in 1991, is the most notable achievement of this era [31]. Two OWCs were installed in Asia around the same time, including a 60-kW converter combined with a breakwater in the port of Sakata, Japan, and a 125-kW bottom-standing power plant in Trivandrum, India [32]. One of the failed devices of the time is the 2-MW converter in Scotland, destroyed by the waves. A

400-kW OWC was installed in Portugal in 1999, followed in Scotland in 2000 by a 300-kW Limpet [32, 33]. The floating-point absorber SEAREV was first published in France in 2003 [34]. Two years later, in Port Kembla, Australia, a new version of this absorber was developed, and a semi-industrial 1:5 scale prototype, named Wave Dragon, was dropped into Denmark's water [35]. Mattiazzo [36] analyzed the possibilities of using the wave energy in the Mediterranean Sea by focusing on the Inertial Sea Wave Energy Converter (ISWEC) technology. Several other converters were launched later in 2008, including a Pelamis in northern Portugal, 16 OWC systems in Mutriku, Spain, and an Oregon State University floating system [37, 38]. A floating system of 25 kW and an Osprey in the UK were also designed in Denmark.

IV. Wind and Wave Characteristics of the Red Sea

The Red Sea is a seawater inlet linking the Suez Canal, Aqaba Gulf, and the Sinai Peninsula to its north with the Indian Ocean via the Bab el Mandeb Strait and the Aden Gulf. The total surface of the Red Sea is roughly 438,000 km2, with 2,000 km along the coast with a maximum width of 355 km [39]. Figure 2 shows that the Red Sea has three distinct depth zones: a shallow shelf with a depth of fewer than 50 meters, a deep zone between 500 and 1,000 meters, and a central axis between 1,000 and 2,900 meters. In figure 6b, it is necessary to point out that eddies of the Red Sea basin drive coastal flows. The Red Sea is a challenge in wave modeling and analysis due to its two distinct and opposing wave configurations, driven by reverse winds and converging in the center. Through incorporating wind and wave data in the Advanced Research Climate and Forecasting model between 1985 and 2015, and using KAUST's WAVEWATCH III, simulations for wind and wave dynamics of the entire period have been created. It has been found that that three major wind systems were generating waves: blowing from the north, the south, and in summer from the central Tokar gap on the Sudanese coast. These results represent the first study of wind and wave trends in the Red Sea region [22-24].

Figure 3 demonstrates the statistical climate analysis and wind movement, including the wind is distributed through three different zones [23]. The graph shows the northern winds are more powerful due to the strong storm effect relative to the central and southern zones. While the northern and southern zones have the same wind speed and intensity, the distribution of the northern and southern winds is slightly different. Figure 4 indicates the waves' maximum and minimum height during the summer and winter seasons [24]. The colors reflect the height of waves over the course of 30 years in different seasons. The highest mean values in summer indicate that the winds driven by the Tokar Gap jets produce the largest waves, and the lowest waves are in winter, being the product of the monsoon winds.

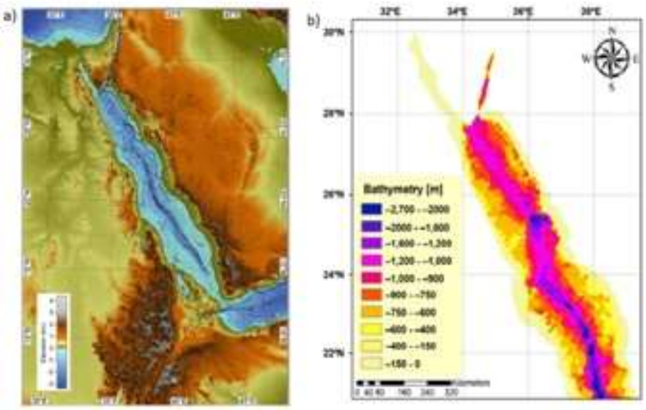

Fig. 2 a) Topography and bathymetric map. Bathymetric contours are at 500 m intervals; b) Bathymetric chart.

In deep water (h > L/2), the approximate expression for wave power transmitted per unit width simplifies further to

$$P = \frac{\rho g^2}{64\pi} H_s^2 T_e = 0.491 H_s^2 T_e \qquad (1)$$

here P is the wave power per unit of crest length (kW/m) Hs is the significant wave height, Te is the energy period, ρ is the density of seawater (assumed to be 1025 kg/m3), and g is the gravitational acceleration. T is important to note that Te *is* estimated using

$$T_e = \alpha\, T_p \qquad (2)$$

where α is a coefficient whose value depends on the shape of the wave spectrum; a conservative value of Te = 0.9Tp was used to assess the wave energy resource.

Fig. 3 Mean (panels a, c) and maximum (b, d) wind speeds in the Red Sea. Left panels for summer, right ones for winter.

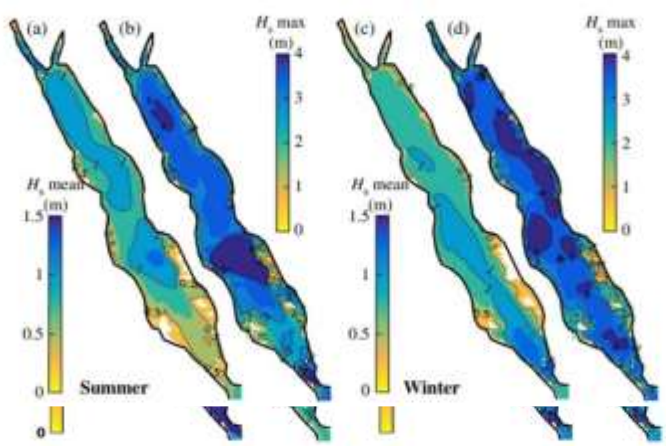

Fig. 4. Mean (panels a, c) and maximum (b, d) significant wave heights distribution in the Red Sea. Left and right panels are for summer and winter, respectively.

One way to estimate a WEC's electricity production at a particular site is to compare the matrices that provide the wave operation for the respective location within a specified time period with the power matrices of each WEC.

This approach yields the following formula for the estimation of the average electric power that might be expected in the time interval associated with the matrix that gives the wave activity:

$$P_E = \frac{1}{100} \cdot \sum_{i=1}^{n_T} \sum_{j=1}^{n_H} p_{ij} \cdot P_{ij} \qquad (3)$$

Where: p_{ij} is the energy percentage corresponding to the bin defined by the line i and the column j. Pij is the electric power corresponding to the same energy bin for the WEC.

V. Results and Discussion

Choosing a suitable location for WEC depended on many factors. Based on NEOM's monthly distribution of mean wave height, the Gulf of Aqaba was considered because the mean wave height is 1.5m, and it is near shore. Also, according to the monthly distribution of mean wind speed at NEOM, the winds are stronger over the Gulf of Aqaba. Figures 5 and 6 show the distribution of the monthly mean and maximum significant wave height (m) from one-year shallow water wave simulation (2001).

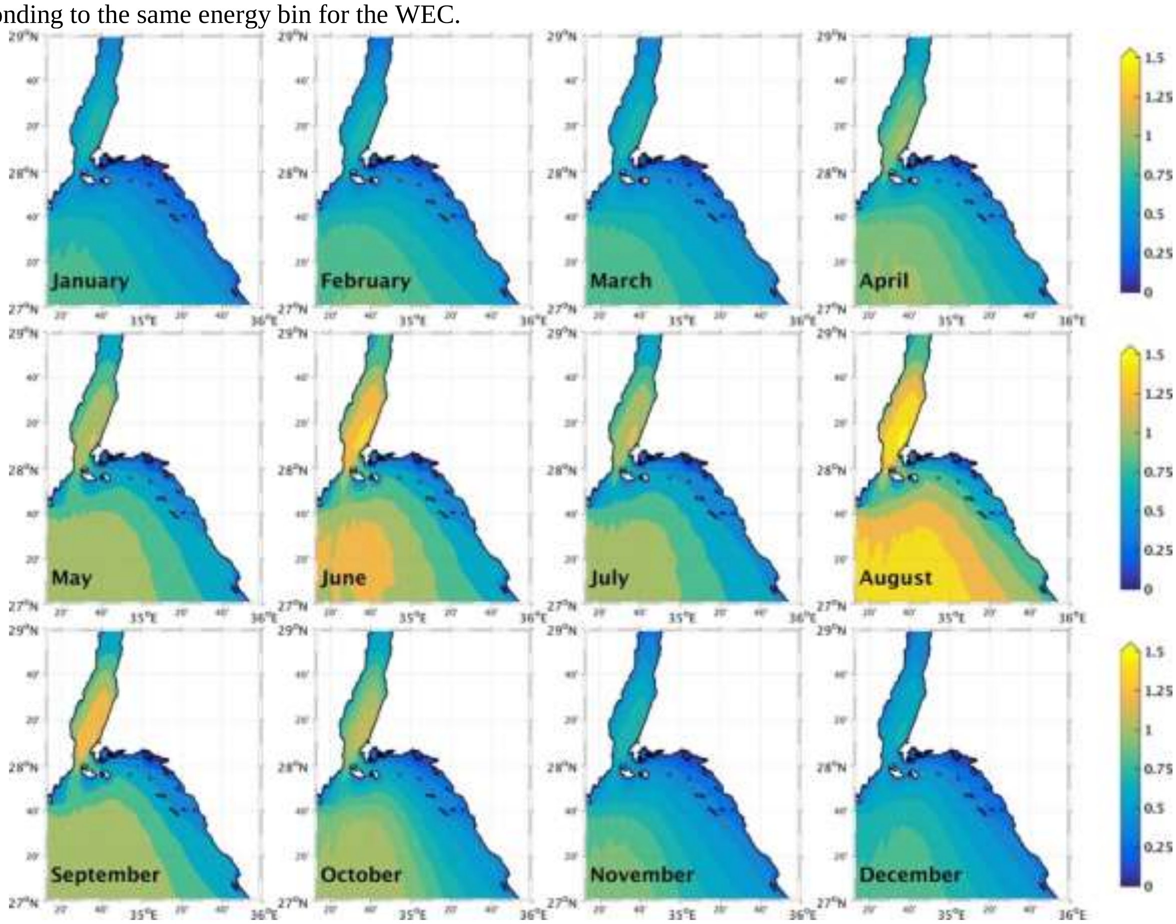

Fig. 5. Monthly distribution of mean significant wave height (m) from one-year shallow water wave simulation (2001).

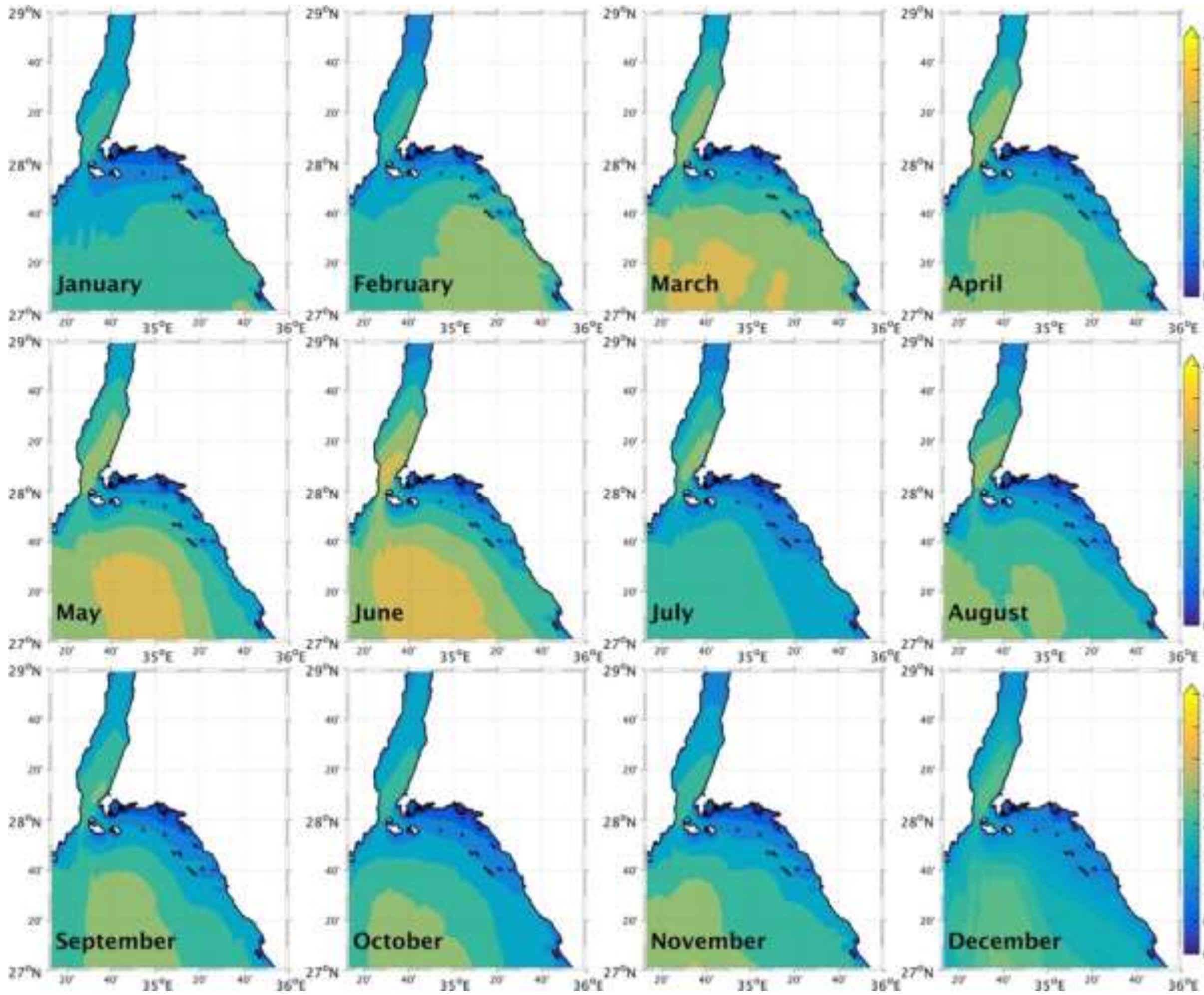

Fig. 6. Monthly distribution of maximum significant wave height (m) from one-year shallow water wave simulation (2001)

Wave heights are generally low over the region and mostly dissipate after breaking close to the coast. Higher waves are noticeable in the summer months (mainly August) and are consistent throughout the period. The highest wave height in the simulation period in 2001 is less than 1.5 m along the coastline. The high waves are created by occasional intense winds blowing in the northwest direction. The Significant height of wind and swell waves is illustrated in Figure 7. The highest spots with the highest wave were picked through the hindcast, which was generated using WAVEWATCH III on a 1-km resolution grid, forced by the Red Sea reanalysis surface winds for 12 years, as shown in Figure 8. Then the highest peak period was selected also based on the wave hindcast generated using WAVEWATCH III on a 1-km resolution grid, as shown in Figure 6. Then, water depth within the range of 20-80 m was selected based on the generated data implemented at 1-km horizontal resolution, taking into consideration the highest wave and peak period.

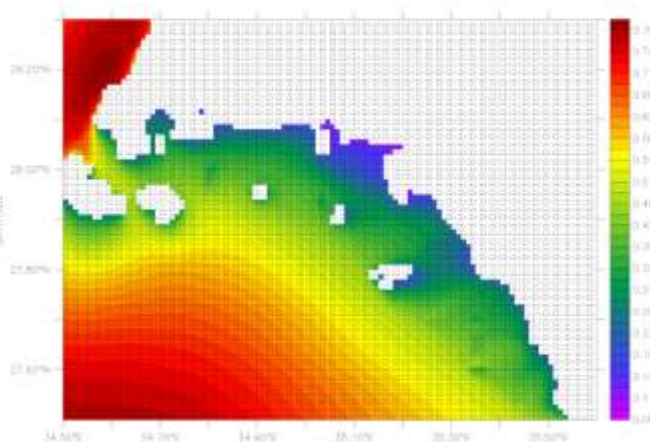

Fig. 7 Significant height of wind and swell waves (m)(T=31-DEC-2006 23:30:31-DEC-2018 23:30@AVE)

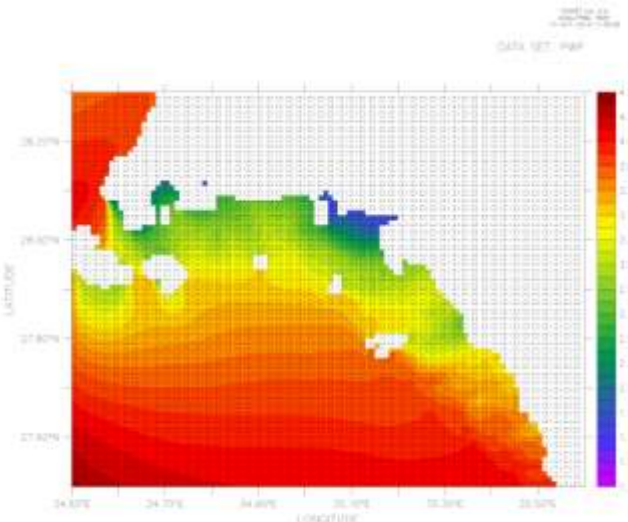

Fig. 8 Peak wave period (T=31-DEC-2006 23:30:31-DEC-2018 23:30@AVE)

A total of 8 points were selected to test the potential of wave energy at the NEOM coastline. The distribution of study points is presented in Figure 9 (denoted from P1 to P8). The geographical coordinates, water distances, and distance to shore for each point are listed in Table 1.

Waves energy can be captured and converted into electricity by wave energy converter (WEC) machines [40]. These WECs were designed to extract energy from the shoreline to the deeper offshore waters. There are currently about 80 wave energy conversion technologies available. Table 2 gives a summary of operating depths, mean power ranges, and output power ranges for wave energy converter (WEC) devices.

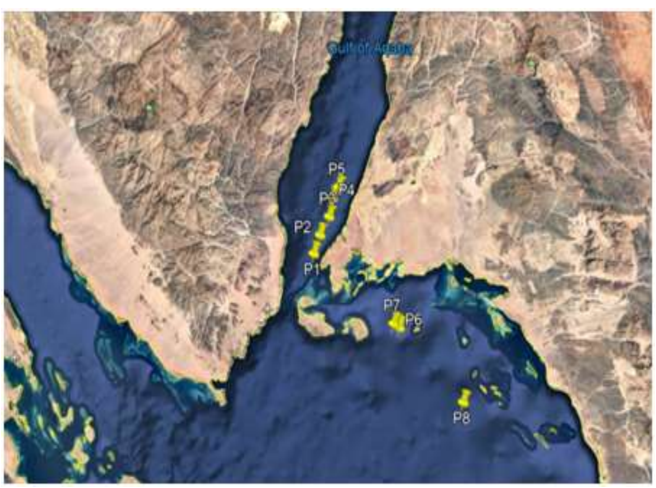

Figure 9. Selected Study Points, P1 to P8.

TABLE I
Characteristics of the Selected Points

Point	Latitude	Longitude	Depth (m)	Distance (km)
P1	28°10'E	34°54'N	40.30	3.55
P2	28°15'E	34°56'N	32.95	5.68
P3	28°20'E	34°59'N	21.50	7.49
P4	28°25'E	34°60'N	28.75	7.53
P5	28°28'E	34°62'N	46.57	6.97
P6	27°91'E	34°84'N	55.4	18.50
P7	27°92'E	34°82'N	51.60	18.96
P8	27°72'E	35°06'N	44.93	39.88

TABLE 2
WECs Characteristics and Performance

WEC Concept	Type	Depth Range (m)	Mean Wave Power Range (kW/m)	Output Power Range (kW)
Wave activated body	Floating	2-75	10-70	68-2250
	Fixed	1-40	10-50	5-100
Point absorber	Floating	10-2500	3.4-80	4-500
	Fixed	10-43	2.8-40	221-600
Oscillating water column	Floating	5-50	4-50	153-1500
	Fixed	4-14.5	20-60	31.7-2000
overtopping	Floating	20-40	60	625-940
	Fixed	6-20	14-30	49-350

Fixed and floating point absorber devices and floating oscillating water column devices operate with 2.8–3.4 kW/m and 4 kW/m respectively as shown in Table 3, indicating that point absorber devices might present power output of 4 kW, whereas the floating oscillating water column devices might yield 153 kW. Regarding the mean wave power at the study points, P2 presents the heights' mean wave power, 1.98 kW/m.

A fixed point absorber could be installed at P2 and P3, and it will provide a power output during September only, which will present a power output of 4 kW. A hybrid system wind and wave were taken into consideration so that the wind turbines operate during the rest of the year. But to install wind turbines, it should be on a fixed surface/substructure, as shown in Figure 10 [40], which is not going to work with the selected WEC above.

TABLE 3
Wave Power Calculation at 8 Selected Locations

Point	Mean Power (KW/m)	Annual Energy (MW h/m)	P_E (MWh)
P1	1.838	16.11	1.11
P2	1.987	17.41	1.203
P3	1.972	17.28	1.193
P4	1.885	16.52	1.141
P5	1.830	16.04	1.108
P7	0.594	5.21	1.036
P7	0.575	5.04	1.035
P8	0.782	6.86	0.118

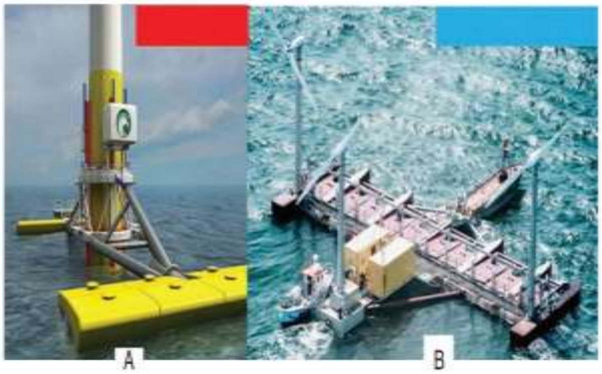

Figure 10. Hybrid wind-wave platforms: (a) Wave treader, (b) Floating power plant.

On the NEOM coastline, we must take into consideration the coral reef, at the shoreline, and other distinct marine systems and environments in Saudi Arabia [41]. Coral reefs in the north of the Red Sea are a global focus for their remarkable resilience to climate change. With the help of state-of-the-art technology and in cooperation with worldwide specialists and experts, the Kingdom is intensively working to preserve the Sea coral reefs. Besides that, there is a high abundance of birds, fish, tortoises, and corals, and their rich biodiversity might completely disappear. WEC project deployment could have a cumulative impact and jeopardize marine and coastal ecosystem health and resilience. As a member of the World Heritage Convention since 1978, the Ministry of Culture in the Kingdom has been collaborating with UNESCO to recognize coral reefs in the Red Sea and other unique sites in the Red Sea as UNESCO protected sites and classified as World Heritage Sites [42, 43].

VI. Conclusion

In this study, wind and wave energy in the Red Sea region have been investigated using a data series that has been developed via numerical modeling over 12 years. The goal was to select the most suitable area for the installation of WECs. The wave power has been analyzed using the data from 8 study locations by incorporating historical wind and wave data between 1985 and 2015. The highest peak period selected in the present study was based on the wave hindcast generated on a 10-km resolution grid. The wave power per unit of crest length (kW/m), the significant wave height, was calculated in the selected areas. Based on the preliminary results, the Gulf of Aqaba, with a mean wave height of 1.5 m, is a good candidate for a WEC. Technical and social impacts were found to be deciding factors for the viability of wave energy exploitation. On the NEOM coastline, we must take into consideration the coral reef at the shoreline. A fixed point absorber could be installed at P2 and P3; however, it will provide a power output during September. A hybrid system wind-wave might be another solution; however, the installation of wind turbines should be on a fixed surface/substructure, which is not going to work with the WEC selected above. Other solutions are being investigated, and more work is underway to complete this part of the thesis and includes an economic study.

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References

[1] WEC, World Energy Council, (2016). World Energy Resources, 2016. Available online: https://www.worldenergy.org/wp-content/uploads/2016/10/World-Energy-Resources-Full-report-2016.10.03.pdf (accessed on 20 January 2020).

[2] R. Cascajo, E. García, E. Quiles, A. Correcher, F. Morant. "Integration of Marine Wave Energy Converters into Seaports: A Case Study in the Port of Valencia." Energies, 12(5), 787, 2019. doi: 10.3390/en12050787.

[3] (2018) G. Lavidas. Energy and socio-economic benefits from the development of wave energy in Greece. Retrieved from https://www.sciencedirect.com/science/article/pii/S096014811831070X

[4] (2019) The International Energy Agency website. Tracking Power, Paris. [Online]. Available https://www.iea.org/reports/tracking-power-2019.

[5] D. Greaves, G. Iglesias. Wave and tidal energy. Hoboken, NJ: John Wiley & Sons, Inc. 2018.

[6] T. Aderinto, H. Li. Ocean Wave Energy Converters: Status and Challenges. Energies, 11(5), 1250, 2018. doi: 10.3390/en11051250

[7] Brahimi, T. (2019). Using Artificial Intelligence to Predict Wind Speed for Energy Application in Saudi Arabia. Energies, 12(24), 4669. doi: 10.3390/en12244669

[8] IEA (2019), "Tracking Power", IEA, Paris https://www.iea.org/reports/tracking-power-2019, (accessed on 15 January 2020).

[9] Babarit, Aurelien. Wave Energy Conversion: Resource, Technology and Performance. Elsevier, 2017.

[10] Dickmann, N. (2016). Energy from water: hydroelectric, tidal, and wave power. St. Catharines, Ontario: Crabtree Publishing Company.

[11] Magagna, D., & Uihlein, A. (2015). Ocean energy development in Europe: Current status and future perspectives. International Journal of Marine Energy, 11, 84–104. doi: 10.1016/j.ijome.2015.05.001

[12] Sannasiraj, S., & Sundar, V. (2016). Assessment of wave energy potential and its harvesting approach along the Indian coast. Renewable Energy, 99, 398–409. doi: 10.1016/j.renene.2016.07.017

[13] Shadman, M., Silva, C., Faller, D., Wu, Z., Assad, L. D. F., Landau, L., … Estefen, S. (2019). Ocean Renewable Energy Potential, Technology, and Deployments: A Case Study of Brazil. Energies, 12(19), 3658. doi: 10.3390/en12193658

[14] Wang, Z., Duan, C., & Dong, S. Long-term wind and wave energy resource assessment in the South China sea based on 30-year hindcast data. Ocean Engineering, 2018, 163, 58–75. doi: 10.1016/j.oceaneng.2018.05.070

[15] Alaoui, C. (2019). Review and assessment of offshore renewable energy resources in morocco' coastline. Cogent Engineering, 6(1). doi: 10.1080/23311916.2019.1654659

[16] Rusu, Eugen, and Guedes Soares, C. "Wave Energy Assessments in the Coastal Environment of Portugal Continental." Proceedings of the ASME 2008 27th International Conference on Offshore Mechanics and Arctic Engineering. Volume 6: Nick Newman Symposium on Marine Hydrodynamics; Yoshida and Maeda Special Symposium on Ocean Space Utilization; Special Symposium on Offshore Renewable Energy.

Estoril, Portugal. June 15–20, 2008. pp. 761-772. ASME. https://doi.org/10.1115/OMAE2008-57820
[17] Nezhad, M. M., Groppi, D., & Piras, G. (2018). Nearshore Wave Energy Assessment of Iranian Coastlines. Proceedings of the 4th World Congress on New Technologies. doi: 10.11159/icepr18.180
[18] Metwally, A., and A. G. Abul-Azm, 2007: The Red Sea wind-wave ATLAS. Proc. 17th Int. Offshore and Polar Engineering Conf., Lisbon, Portugal, International Society of Offshore and Polar Engineers, 1850–1854.
[19] Ralston DK, Jiang H, Farrar JT. 2013. Waves in the Red Sea: response to moonsonal and mountain gap winds. Cont Shelf Res. 65:1–13.
[20] Aboobacker, V. M., P. R. Shanas, M. A. Alsaafani, and M. A. Albarakati, 2016: Wave energy resource assessment for Red Sea. Renew. Energy, 114, 46–58, https://doi.org/10.1016/ j.renene.2016.09.073.
[21] Langodan, S., Viswanadhapalli, Y., Dasari, H. P., Knio, O., & Hoteit, I. (2016). A high-resolution assessment of wind and wave energy potentials in the Red Sea. Applied Energy, 181, 244–255. doi: 10.1016/j.apenergy.2016.08.076
[22] Langodan, S., Cavaleri, L., Pomaro, A., Portilla, J., Abualnaja, Y., & Hoteit, I. (2018). Unraveling Climatic Wind and Wave Trends in the Red Sea Using Wave Spectra Partitioning. Journal of Climate, 31(5), 1881–1895. doi: 10.1175/jcli-d-17-0295.1
[23] Langodan, S., Cavaleri, L., Vishwanadhapalli, Y., Pomaro, A., Bertotti, L., & Hoteit, I. (2017). The climatology of the Red Sea - part 1: the wind. International Journal of Climatology, 37(13), 4509–4517. doi: 10.1002/joc.5103
[24] Langodan, S., Cavaleri, L., Pomaro, A., Vishwanadhapalli, Y., Bertotti, L., & Hoteit, I. (2017). The climatology of the Red Sea - part 2: the waves. International Journal of Climatology, 37(13), 4518–4528. doi: 10.1002/joc.5101
[25] Rusu, E., & Onea, F. (2018). A review of the technologies for wave energy extraction. Clean Energy, 2(1), 10–19. doi: 10.1093/ce/zky003
[26] Gunn K, Stock-Williams C. Quantifying the global wave power resource. Renew Energy 2012; 44:296–304.
[27] Alamian, R., Shafaghat, R., Miri, S. J., Yazdanshenas, N., & Shakeri, M. (2014). Evaluation of technologies for harvesting wave energy in the Caspian Sea. Renewable and Sustainable Energy Reviews, 32, 468–476. doi: 10.1016/j.rser.2014.01.036.
[28] MacCormick, M. E. (1981). Ocean wave energy conversion. New York: Wiley.
[29] European Commission, Study on Lessons for Ocean Energy Development. Final Report, April 2017. EUR 27984, DOI 10.2777/389418.
[30] Falcão, A. F. D. O. (2010). Wave energy utilization: A review of the technologies. Renewable and Sustainable Energy Reviews, 14(3), 899–918. doi: 10.1016/j.rser.2009.11.003
[31] Falcão, A. (2015). Developments in oscillating water column wave energy converters and air turbines. Renewable Energies Offshore, 3–11. doi: 10.1201/b18973-3
[32] Falcão, A. F., & Henriques, J. C. (2016). Oscillating-water-column wave energy converters and air turbines: A review. Renewable Energy, 85, 1391–1424. doi: 10.1016/j.renene.2015.07.086
[33] Polinder, H., Damen, M. E. C., & Gardner, F. (2005). Design, modelling and test results of the AWS PM linear generator. European Transactions on Electrical Power, 15(3), 245–256. doi: 10.1002/etep.56
[34] Babarit, A.,Mouslim, H., Guglielmi,M., and Clément, A. H. Simulation of the SEAREV wave energy converter with a by-pass control of its hydraulic power take off. In Proceedings of the TenthWorld Renewable Energy Congress (WREC X), Glasgow, UK, July 2009, pp. 1004–1009.
[35] Cascajo, R., García, E., Quiles, E., Correcher, A., & Morant, F. (2019). Integration of Marine Wave Energy Converters into Seaports: A Case Study in the Port of Valencia. Energies, 12(5), 787. doi: 10.3390/en12050787.
[36] Mattiazzo, G. (2019). State of the Art and Perspectives of Wave Energy in the Mediterranean Sea: Backstage of ISWEC. Frontiers in Energy Research, 7. doi: 10.3389/fenrg.2019.00114
[37] Alamian, R., Shafaghat, R., Miri, S. J., Yazdanshenas, N., & Shakeri, M. (2014). Evaluation of technologies for harvesting wave energy in Caspian Sea. Renewable and Sustainable Energy Reviews, 32, 468–476. doi: 10.1016/j.rser.2014.01.036.
[38] Oceanlinx 1MW Commercial Wave Energy Demonstrator - Australian Renewable Energy Agency (ARENA). (n.d.). Retrieved from https://arena.gov.au/projects/oceanlinx-1mw-commercial-wave-energy-demonstrator/
[39] Rasul, N. M. A., & Stewart, I. C. F. (2016). *The Red Sea — The formation, morphology, oceanography and environment of a young ocean basin*. Berlin: Springer Berlin
[40] Rusu, E., & Onea, F. (2018). A review of the technologies for wave energy extraction. *Clean Energy*, *2*(1), 10–19. doi: 10.1093/ce/zky003.
[41] Bruckner, A. (2011) Khaled bin Sultan Living Oceans Foundation Habitat Mapping and Characterization of Coral Reefs of the Saudi Arabian Red Sea: 2006-2009. Final Report Part II, Ras Qisbah, Al Wajh, Yanbu, Farasan Banks and Farasan Islands. Panoramic Press, Arizona, 248 pp.
[42] Saudi aims to preserve Red Sea's coral reefs. (2019, September 10). Retrieved from https://filipinotimes.net/global-news/2019/09/10/saudi-aims-preserve-red-seas-coral-reefs/
[43] Tesfamichael, D., & Rossing, P. (2016). Saudi Arabia. *Coral Reefs of the World The Red Sea Ecosystem and Fisheries*, 79–91. doi: 10.1007/978-94-017-7435-2_6