SCHOOL OF SCIENCE AND ENGINEERING

Potential of a Hybrid Wind Wave Energy System in Morocco

Capstone Design Project

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Capstone Report

Student Statement:

"I, Aâwatif Mounkid, affirm that I applied the ethics to the design process and the selection of the final proposed design. And that, I have held the safety of the public to be paramount and I have addressed this in the presented design wherever may be applicable."

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Nomenclature

WEC Wave energy converter

OCW Oscillating water column

COV Coefficient of variability

SV Seasonal variability

MV Monthly variability

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Abstract

Ocean renewable energy systems are one of the most profitable sources of energy in our planet and exploiting it will help answer the energy needs of the population with less cost and damage to the environment.

Offshore wind energy is one the promising sources of energy and it has been exploited in different parts of the globe. With its high energy production, the offshore wind farms are considered more efficient than the onshore ones due the high speed of the wind and the size of the wind turbines used.

Wave energy is yet another promising energy sector that has been targeted by different countries, but still under research for different designs. Water, which is denser than wind, is a great source of energy when exploited adequately through maximizing the output and minimizing the cost.

The purpose of this capstone research project is to investigate the potential of these two sources of energy in the Moroccan ocean. The study focuses on analyzing the combined potential of both offshore wind and wave energy. The potential site was mainly deduced from previous work done in the Moroccan region using wind and wave data and the combination and analysis of these studies led to the choice of Essaouira as the most promising location for the implementation of the energy farm. The next step consisted of deciding about the best hybrid wind wave energy system from the highest power output and availability of information criteria. This was done through comparing different under research hybrid projects.

The data used in this capstone project was extracted from an open-source satellite through gathering 7 years data of both offshore wind and wave speeds for the same region in the western Essaouira offshore. This data was analyzed using excel to deduce the extreme weather that needs to be handled by the firm as well as the estimation of the yearly power output.

An economic analysis was run at the end of the project to study its feasibility from an investment point of view.

1. Introduction

The purpose of this capstone research project is to investigate the potential of offshore wind and wave energy systems in the Moroccan ocean. The study aims at analyzing the potential of combining these two sources of renewable energy, with a focus on Essaouira as the most promising location for the implementation of an energy farm. The project compares different under-researched hybrid projects to decide on the best hybrid wind-wave energy system based on the highest power output and availability of information criteria. The data analysis part consisted of extracting the wind and wave data from an open-source satellite and analyzing it using excel to deduce the extreme weather conditions that need to be handled by the farm and to estimate the yearly power output. In this final part, the project conducts an economic analysis to determine the feasibility of the project from an investment point of view. The findings of this project will provide valuable insights into the potential of offshore wind and wave energy systems and their feasibility as sources of sustainable energy in the Moroccan ocean.

1.1 Literature review

1.1.1 Wave energy

a. Initial introduction to wave energy

The first idea of wave energy utilization returns to 1799 with the application of a Frenchman named Girard for a wave energy technology patent. In the 20th century, and more precisely in 1910, Busso Belasek, a Frenchman, created a wave energy driven power station. This helped generate 1000 watts of electricity [1]. The concept of the wave energy station consisted of a pneumatic device that helped generate electricity through air compression and drain resulting from the power created by the fluctuation of waves. This power pushes a piston embodied in the system to allow the conversion of the wave power into electrical one through the rotation of a turbine [2].

b. Initial commercialization of wave energy

Back in the 1940s, Yoshio Masuda, a Japanese researcher did different research related to the wave energy implementation and created a new type of device. This consisted of an oscillating water column meant to generate power for buoys of navigation. The concept of the device consisted of using the wave energy through the absorption and compression of the air to boost the electricity production of the generator. In 1965, the types of buoys that are charged using wave energy started being commercialized. They started being popular in the Japanese market then to other countries, with a power that range between 60 to 500 watts. This was the first aspect of the commercialization of wave energy devices in the world [3].

c. Wave energy research in 1970s

During the 1970s, the oil crisis affected energy production all over the world, and different research started focusing on analyzing the potential use of renewable energies which led to the discovery of the great potential of wave energy. The very first studies were run by the Scottish Stephen Salter, the Norwegian Kjell Budal from Norway, and the American Michael E. McCormick. Stephen Salter published an article in 1974, "Wave Energy in the Nature magazine", which gained the attention of worldwide scientific research organizations regarding wave energy and its development [4]. Different countries around the world such as UK, Japan, and Norway have a huge amount of wave energy, which gave them the possibility to exploit it as a solution to the crisis of energy. Their investment was significantly important when it came to wave energy research. In the 1970s, the "Hamming", a wave energy ship for testing was able to produce 190,000 kWh/year and succeeded in attaining a small-scale transmission of power from offshore power plants to the land. During 1976, more research was conducted by Yoshio Masuda to combine different types of wave energy converter devices. However, the efficiency did not improve significantly, which indicated the need for further research in the domain to develop the wave power technology [2].

d. Wave energy in the late 20th century

In the 1980s, the investments in wave energy reduced significantly due to the fall in oil prices. In 1982, the energy department of the UK stopped sponsorship in technology. Yet, other researchers continued their experiments on prototyping and sustaining projects related to wave energy [3]. During 1985, Norway researchers run trials of a prototype of 350 kW power, and a second one of 500kW. In 1989, an oscillating water column of 75kW was installed in Scotland. Japan also installed wave energy convertor with a power of 60kW. This is also the case of India with a 125kW wave energy device. In the 1990s, more funding was allocated to the wave energy sector after realizing its potential, especially in Europe through the establishment of "wave energy thematic Network" [5].

e. Wave energy in the 21st century

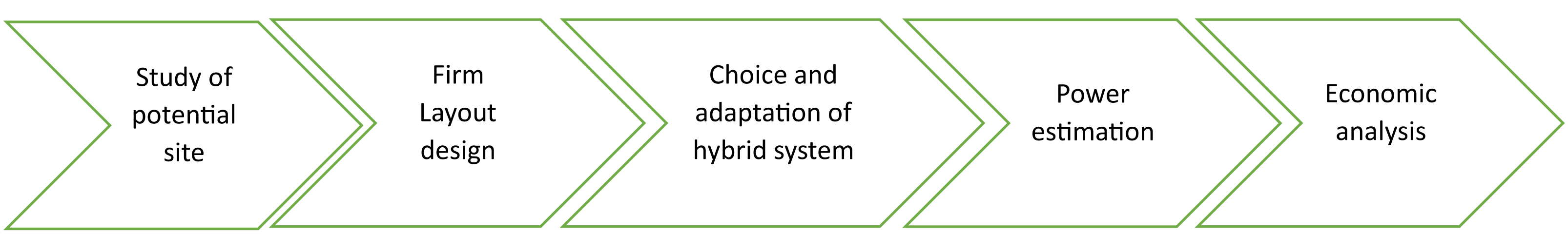
Wave energy developed more in the 21st century. The interest in wave energy noticed a significant increase starting in 2000, which increased the sponsorship allocated to the wave energy sector. A concrete example is the one of Scotland and Cornwall that have established marine energy centers to facilitate research in the domain. During 2007, Aqua Buoy, a wave energy station in Canada showed after trials that it has the capacity to have a high energy efficiency. In the present time, Pelamis in the UK is considered the most powerful wave energy generation station [2].

1.1.2 Offshore wind energy

Wind power has been acknowledged as a significant renewable energy source, primarily through the establishment of onshore wind farms, with only 2000 offshore wind megawatts installed by the end of 2009. The first offshore wind turbine was installed in Sweden in 1990, which was a single 220 kW wind turbine situated 350m away from the coast and supported by a tripod structure anchored 6m deep on the seabed. From 1991 to 1998, low-rating experimental projects were carried out to test different models of wind turbines and foundation types. Wind turbines rated between 450-600 kW were utilized, with distances of up to 4km from the coast and depths of up to 6m being achieved [6]. Despite initial doubts, these projects demonstrated good profitability and reliability indices. Later, multi-megawatt wind turbines were introduced during a second experimental phase, with the Utgrunden project in Sweden being the first project with those characteristics. Several commercial wind farms, such as Blyth, Middelgrunden, and Yttre Stengrund, were initiated by these facilities. The Horns Rev and Nysted facilities on Danish coasts further confirmed the adaptability of this type of facility to the marine environment [6].

1.2 Methodology

The methodology followed in this capstone project consists of running a literature review for both technologies, the offshore wind and the wave energy. The following step consist of studying the best location for the installation of a firm that will exploit both energies in the Moroccan region. A comparison between hybrid systems was made afterwards and led to the choice the best in terms of power output and availability of design information. The design chosen was then adapted to ensure the best power output of the system. A potential layout of the hybrid firm was suggested in order to maximize the offshore wind power generated by the system. The next step was gathering data about wind and wave speed for the same region chosen using open-source satellite to deduce the extreme weather conditions and estimate the yearly power output. The final step in the capstone project is the economic analysis to study the feasibility of the firm from a cost perspective.

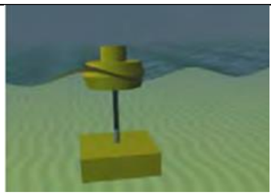
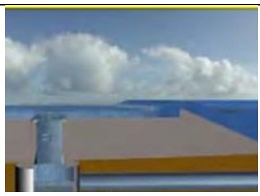
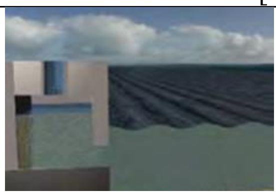
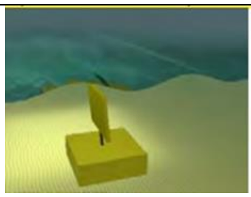


2. Description of technologies

2.1 Type of wave converters

Wave energy converters are designed to harness the power of ocean waves and convert it into usable energy. There are several types of WECs currently being developed and tested, each with its own unique advantages and disadvantages. In this paragraph, we will discuss some of the most common types of WECs and their basic operating principles.

Table 2.1 Types of wave energy converters

Types		description
Point absorber	 [7]	Floating structures that use the motion of waves at one point.
Attenuator	 [7]	Structure that is installed parallel to the direction of the waves and generate energy from the flexing of the structure's joints [7].
Overtopping device	 [7]	Structures that generate energy through the difference in potential through moving water at a higher level than the one of the ocean surfaces [7].
Oscillating water column	 [7]	It is an L shaped design that generates energy through trapping air in a chamber allowing the rotation of a turbine when the air leaves it [7].
Oscillating wave surge	 [7]	This design uses the surge motion with the waves allowing it to switch back and forth.

2.2 Existing wave energy technologies

Wave energy converters have been implemented in various locations around the world, with the goal of harnessing the power of ocean waves to generate renewable energy. As a relatively new technology, there are still relatively few commercially operational WECs, but several experimental and demonstration projects have been deployed over the past several decades. In this paragraph, we will explore some examples of already implemented WECs.

Table 2.2 existing technologies of wave energy converters

Technology	Image	Description	Type	configuration	Depth
Pelamis Wave Energy Converter	 [7] Source: https://www.ecosources.org/	It consists of a series of cylindrical sections linked by hinged joints, which allows the device to flex and generate electricity as it moves with the waves. A prototype Pelamis device was installed off the coast of Portugal in 2008, but the company that developed it went bankrupt in 2014 [7]	Attenuator	Floating	offshore
LIMPET	 [8] Source: https://www.sciencephoto.com	it was installed on the Scottish island of Islay in 2000. The device is connected to the island's electrical grid and can generate up to 500 kilowatts of power, enough to meet the needs of about 300 homes [8]	Oscillating water column	Fixed	Nearshore

Wave Dragon	 [9] Source: https://tethys.pnnl.gov	It uses two arms to capture wave energy and funnel it to a central turbine. A 237-kilowatt Wave Dragon device was installed off the coast of Denmark in 2003, and a 4-megawatt device was planned for installation in Wales, but the project was cancelled in 2014 due to financial issues [9].	Overtopping device	Floating	Offshore
CETO	 [10] Source: https://www.herox.com/	It is a submerged buoy that captures wave energy and uses it to drive a hydraulic pump. The pump sends pressurized water to an onshore facility, where it is used to generate electricity. A 3-megawatt CETO system was planned for installation off the coast of Western Australia in 2020 [10].	Submerged pressure differential	Submerged	Nearshore
Oyster	 [11] Source: https://www.oleoinc.com/	It uses a hinged flap to capture wave energy. A 2.4-megawatt Oyster device was installed off the coast of Scotland in 2009, but the project was	Oscillating water surge	Submerged	Nearshore

		ultimately cancelled due to technical issues and financial difficulties [11]			

2.3 Offshore wind turbine platforms

In this section, we will be giving a brief description of the most popular platforms for the offshore wind turbine. We will be describing the semi-submersible, tension leg, and spar buoy.

Table 2.3 offshore wind turbine platforms

Platform	Image	Description
Semi-submersible	[12] Source: https://www.bpp-renewables.com/	These are floating structures that have a submerged section below the waterline and are anchored to the seabed. Semi-submersibles are commonly used in offshore wind farms and can also be adapted for wave energy conversion [12].
Tension-leg	[12] Source: https://www.bpp-renewables.com/	These are also floating structures, but they are anchored to the seabed using tension cables. Tension-leg platforms are often used for deep-water offshore wind farms and can also be suitable for wave energy conversion [12].
Spar buoys		These are cylindrical floating structures that are anchored to the seabed and have a central spar that extends below the

	[12] Source: https://www.bpp-renewables.com/	waterline. Spar buoys are typically used for wave energy conversion and can also be combined with offshore wind turbines [12].

3. Potential site for farm implementation

This chapter of the capstone consists of studying the potential of wave energy in the Moroccan coastline based on previous data and research done in this context.

Morocco has a coastline that is 3500 km long, which create a great opportunity to invest in wave energy and benefit from the wave energy resources. However, a deep understanding of this potential is a must to study benefit the most out of the technology.

A previous study done in this sense consisted of gathering a 44-year series of wave data from 23 points among the Moroccan coastline based on hindcasting. The study focused on determining the annual wave energy and wave power in the different locations, the shadow effects of the nearby locations, as well as their variability across seasons [13].

3.1 Potential wave energy site

a. Data of the research

The 23 points are in the Atlantic Moroccan coastline and the 44-year series (1958-2001) data have been taken from the HIPOCAS project [14]. The HIPOCAS project database is a reliable one and it has been used in different other studies to investigate the potential of wave and wind energy. The data provided does not represent extreme scenarios (storms) accurately, but it provides reliable mean values [13].

The source of the waves of the Atlantic coastline are the Azores islands. These areas are characterized by large intensity winds, which forms large waves that propagate until reaching the Moroccan coastline. These waves, however, reach the coastline with a reduced power since they deviate and become nearly perpendicular when arriving.

The following table summarizes the data about the 23 locations, including both their depth and distance from the coast which was taken from nautical charts [15].

Table 3.1.1: Data about wave and ocean in the Moroccan coast [15]

Point	Longitude (W)	Latitude (N)	Depth (m)	Distance (km)
P1	6°00’	35°45’	60	5
P2	6°15’	35°30’	110	18
P3	6°30’	35°00’	130	21.5

P4	7°00’	34°53’	200	38
P5	7°30’	34°00’	140	31.5
P5	8°00’	34°00’	200	52
P7	8°30’	33°30’	60	22
P8	9°00’	33°00’	90	16.5
P9	9°30’	32°30’	60	20
P10	10°00’	32°00’	500	45
P11	10°00’	31°30’	70	17.5
P12	10°00’	31°00’	80	16
P13	10°00’	30°30’	120	16.5
P14	10°00’	30°00’	125	23.5
Pl 5	10°30’	29°30’	120	33
P16	11°00’	29°00’	60	21.5
P17	11°30’	28°30’	35	13
P18	12°00’	28°30’	50	37
P19	12°30’	28°30’	95	52
P20	13°00’	28°00’	40	9
P21	13°30’	28°00’	350	47
P22	13°30’	27°30’	85	24
P23	14°00’	27°00’	350	49

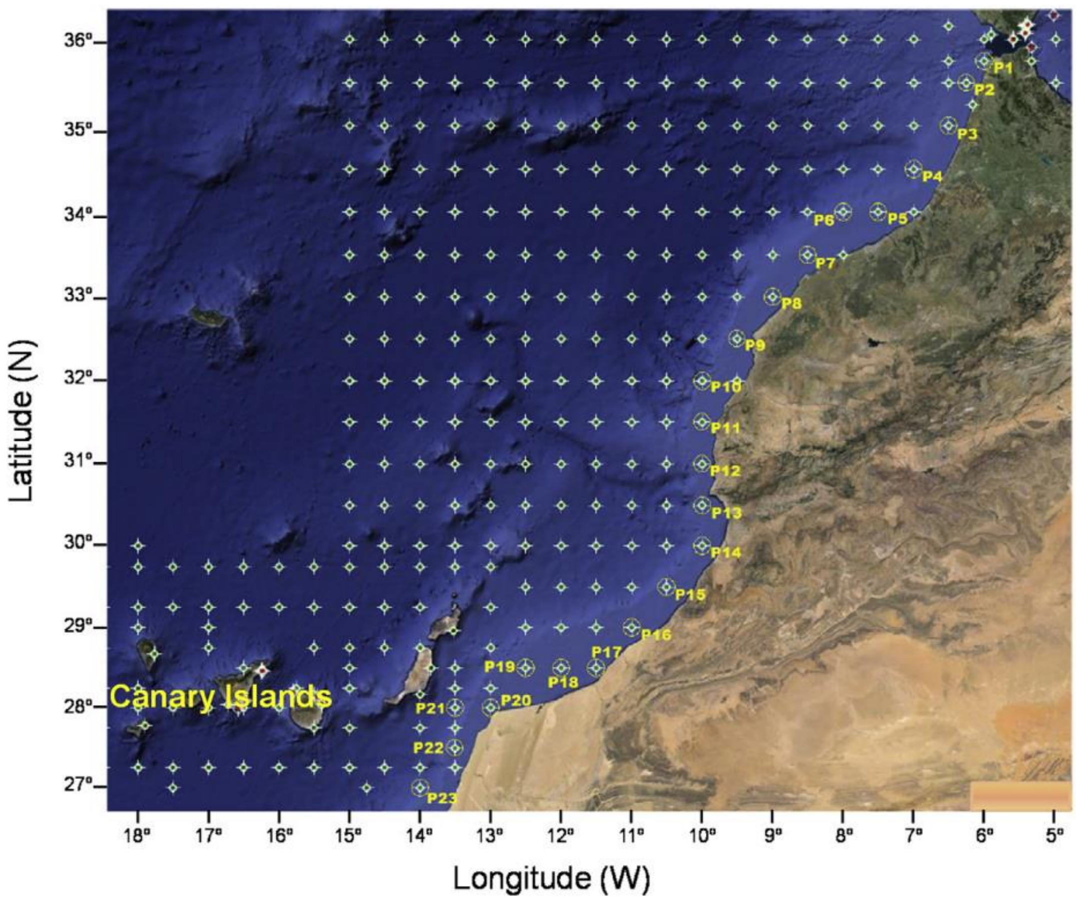


Figure 3.1.1: Location of the 23 points in the Moroccan Map [15]

b. Methodology

The methodology followed during the previous research consists of calculating the wave power and studying its variability. The wave power is obtained through applying the following formula:

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

Where:

P: wave power
Hs: wave height
T_e: energy period
ρ: density of sea water
g: acceleration

T_e: $\frac{m-1}{m_0}$ = $0.9T_p$ since there is no information about the spectral moment

Besides the wave power in the different locations, an analysis of the variability of this power output is a must also be considered when deciding about the most adequate regions. The main coefficient that will be used to analyze the wave energy flux is the coefficient of variation (COV), which is expressed by the ratio of the standard deviation of the series of power and the mean power [15].

$$C_v = \frac{\sigma}{\mu}$$

The seasonal variability index is also used and is expressed as the following

$$S_v = \frac{P_{s.max} - P_{s.min}}{P_{Year}}$$

Where:

$P_{s.max}$: mean of wave power during the season with high energy levels

$P_{s.min}$: mean of power during the low energy season

P_{year}: annual power mean.

Another measurement is the monthly variability which is expressed as the following:

$$M_v = \frac{P_{M.max} - P_{M.min}}{P_{Year}}$$

Where:

$P_{M.max}$: mean of power in the season with the highest energy level

$P_{M.min}$the mean during the low energy level season

The following tables summarize the findings of the research based on the 44-year series of data.

Table 3.1.2: Mean power, energy, and variability of wave power in 23 sites [15]

Point	Mean power(kW/m)	Annual energy MW h/m	COV	SV	MV
P1	9.25	81	2.03	1.75	1.79
P2	12.66	110.91	1.93	1.75	1.81
P3	17.61	154.29	1.76	1.71	1.8

P4	21.49	188.29	1.67	1.67	1.77
P5	23.2	203.21	1.57	1.62	1.71
P5	26.08	228.47	1.54	1.6	1.69
P7	25.69	225.03	1.46	1.52	1.62
P8	27.33	239.45	1.41	1.48	1.57
P9	28.62	250.68	4.43	1.47	1.56
P10	29.94	262.31	1.36	1.38	1.45
P11	28.76	251.97	1.33	1.35	1.44
P12	27.4	239.99	1.35	1.36	1.46
P13	26.29	230.34	1.35	1.37	1.46
P14	24.97	218.7	1.36	1.39	1.49
Pl 5	25.95	227.33	1.29	1.29	1.37
P16	23.08	202.17	1.26	1.2	1.27
P17	19.12	167.48	1.27	1.17	1.23
P18	20.11	176.2	1.25	1.11	1.19
P19	19.41	170.03	1.2	1.04	1.13
P20	12.7	111.28	1.13	0.84	0.96
P21	7.83	68.56	1.2	0.39	0.57
P22	8.14	71.3	1.03	0.62	0.84
P23	14.39	126.04	1.21	1.18	1.31

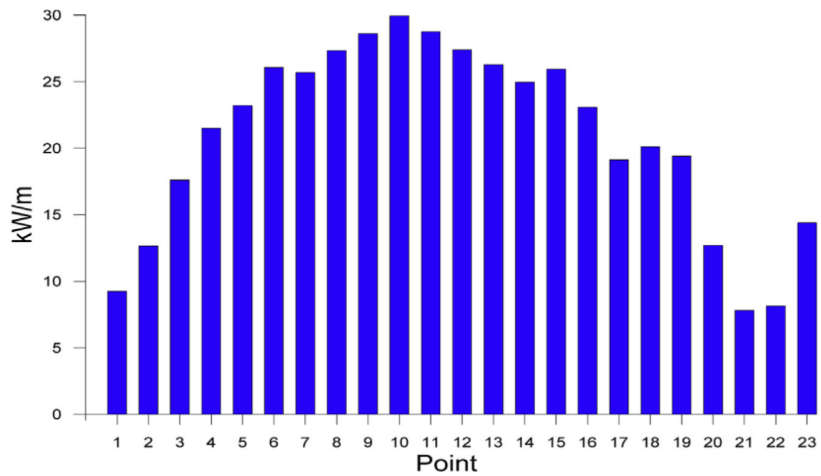


Figure3.1.2: Power per unit width in the 23 sites [15]

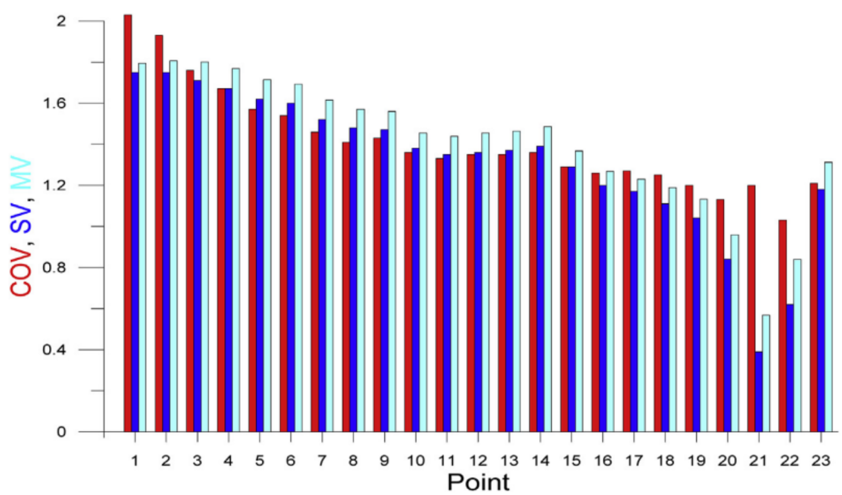


Figure 3.1.3: coefficients of variability in the 23 sites [15]

From this previous analysis, we can see that the sites that are more likely to be suitable for the implementation of a wave energy firm are the ones with moderate to high wave power and moderate to low variability. This being said, the best regions are the ones between P8 and P13, excluding P10 seen its depth (500m), and its big distance from the coast (45km) [15].

3.2 Potential of offshore wind energy in the Moroccan coastline

The assessment of the potential offshore wind energy was concluded from a previous capstone project of the student Yassin Charouif. The Data used in the research was gathered on site for the period 2019-2021 which was provided by the Direction National de Meteorologie, satellite data from the Advanced Scatterometer tool for the period 2010-2021, as well as data from the European marine observation and data network [16]. The study consisted of calculating the wind power density of the locations through the wind power density index which is expressed as the following.

$$E = 0.5 \times \rho \times V^3$$

E refers to the energy, pho is the air density, and V is the speed of the wind at the chosen location. However, the data that can be obtained through the satellites is of height of 10m above sea level. This being said, an extrapolation was used to get the speed at different heights (e.g., 50m => 80m) in which the wind speed is higher, and thus the potential wind energy is higher as well [16]. The technique used consists of calculating the natural logarithmic value of the needed altitude following the formula:

$$A = \ln\left(\frac{h}{\tau}\right)$$

τ is the surface roughness parameter, and it is equal to 0.0002m. The next step is to calculate the natural logarithmic value for the given heigh, which is 10 through the formula:

$$B = \ln\left(\frac{10}{\tau}\right)$$

The following step will be to calculate the desired speed based using the ration of the two previous values though the following:

$$V = v_0 \left(\frac{A}{B}\right)$$

Different parameter were taken into account when deciding about the optimal location including technical ones (depth of water, volcanic activity, …), Socio economic ones (Distance from the shore, shipping density), as well as environmental one focusing in the bird migration phenomena.
After studying all these different aspects, the research helped conclude that one of the best sites that are characterized by the highest values of wind speed are between Al Jadida and Agadir. This was in accordance with present facts which are the already existing 5 on shore wind plant the region. Another main windy region is the one from Tan Tan to Lagouira, in which other 9 wind farms are operating [17],[18],[19].

An In-depth simulation was run using all the previously mentioned variables to decide upon the precise and most accurate clusters for the implementation of the offshore wind energy farm. The result of the simulation shows three potential sites which are Dakhla, Boujdour, and Essaouira [16].

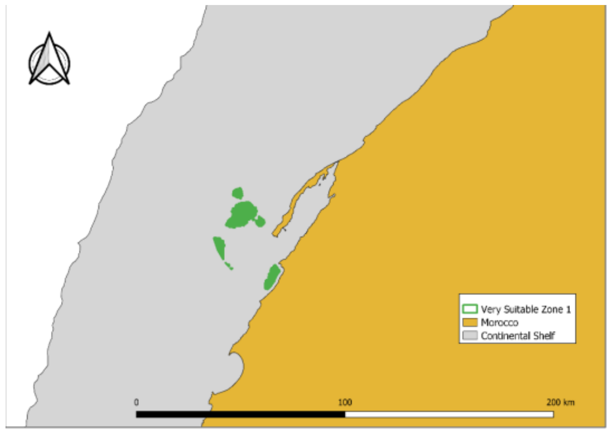


Figure 3.2.1: Cluster in the Dakhla region [16]

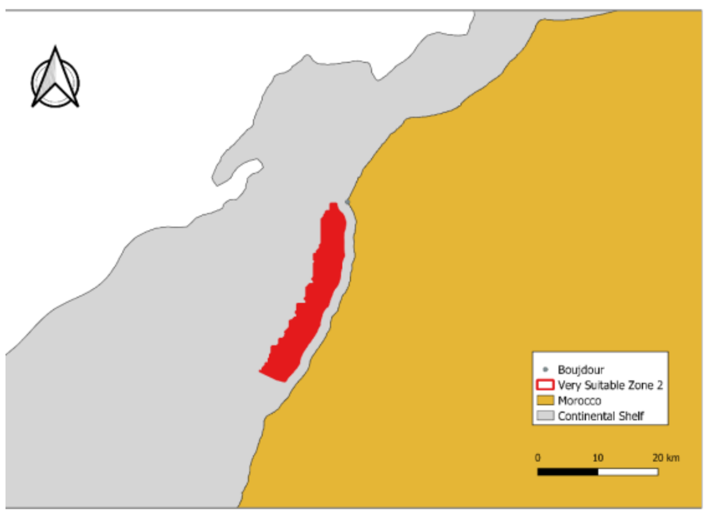


Figure 3.2.2: Cluster in the Boujdour region [16]

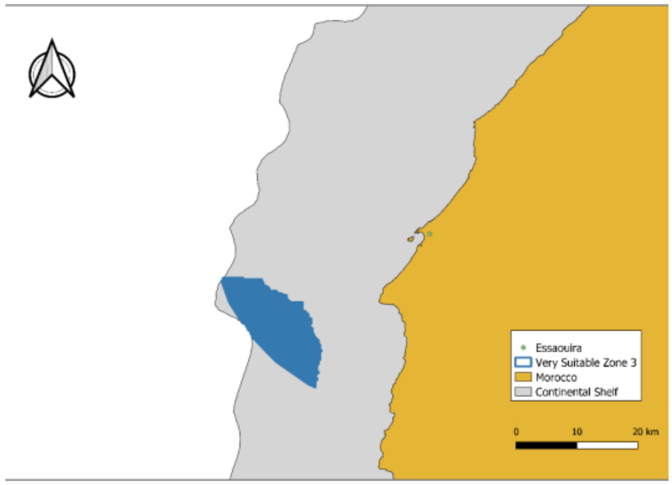


Figure 3.2.3: Cluster in the Essaouira region [16]

4. Farm layout design

The firm layout plays an important role in the energy production of the hybrid system. In our study, we base the layout choice according to the wind energy production, as the wave converter will be suitable for any layout and will work independently of the direction of the waves.
The research used in this regard was done using genetic algorithm along with satellite MERRA-2 Reanalysis data in 2019 [20].

The result of this research showed that the optimal size of an offshore wind farm located in Essaouira will have a size of 3200m×5000m and it will be located in a way that will ensure its connection to the Essaouira onshore wind farm.

Figure 4.1: Location of the firm in the Essaouira region [20]

The decision about the firm layout was based on a cost analysis that has as a goal to minimize the cost per unit energy. The study consisted of developing a MATLAB code using Multi population genetic algorithm in order to deduce the best layout. The final result consisted of having 27 offshore wind turbines that need to be placed in a perpendicular way to the common wind direction. The following figure shows the layout of the firm [20].

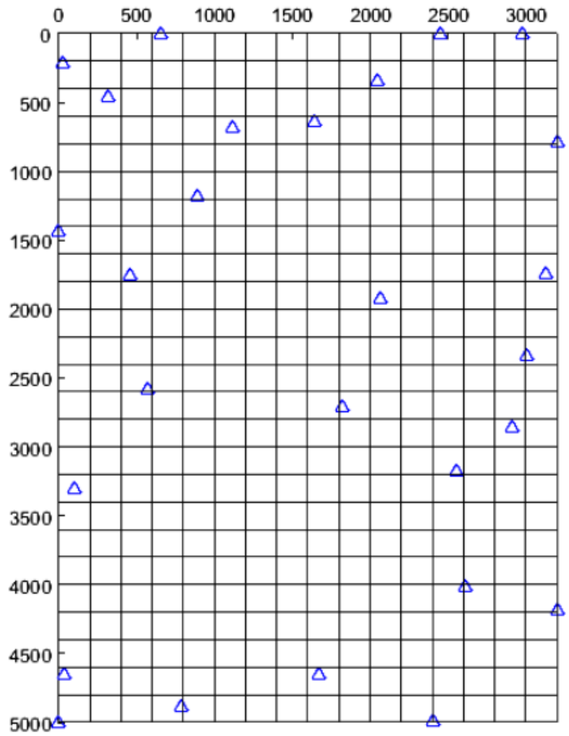


Figure 4.2: Layout chart of the energy convertors in the firm [20]

Figure 4.3: Layout of the firm using google maps [20]

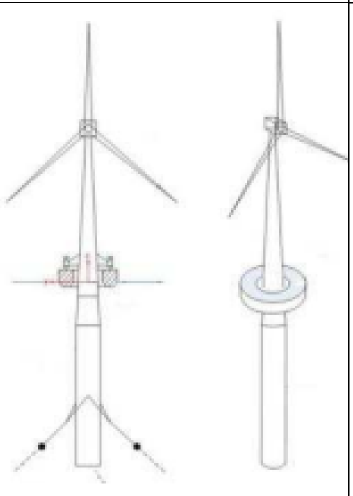
This layout will be the one to base on for the hybrid wind wave energy firm, since the wave energy converters that will be used will be totally independent from the direction of the waves.

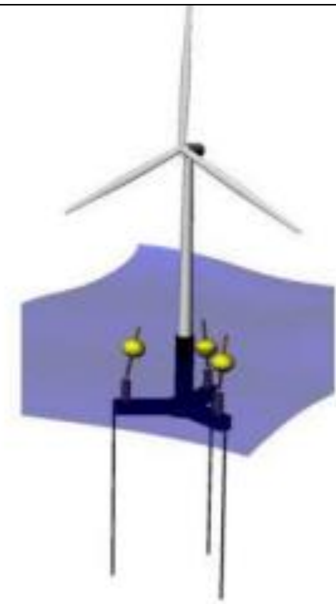
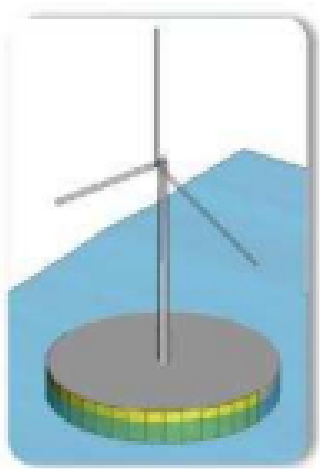
5. Hybrid system choice for implementation in the farm

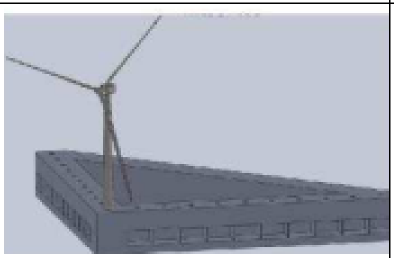
5.1 Hybrid wind wave technologies

In this chapter, we will be comparing different hybrid systems under research from different aspects. The following table summarizes this through comparing nine systems based on the types of platform used, types of wave energy converters, and power output.

Table 5.1: description and comparison of hybrid wind wave energy systems

Technology	Image	Description	Wind power (MW)	Wave power (MW)	N° of WECs
Semi-submersible combination	 [21]	The system includes a partially submerged 5MW floating wind turbine with flap-type wave energy converters attached to each of its underwater beams. The turbine is situated in the middle of the platform [21]	5	0.5	2 or 3
Spar torus combination	 [22]	The plan involves using a cylindrical 5MW floating wind turbine anchored by a spar, with a donut-shaped wave energy converter placed at the water's surface around the turbine tower. The donut-shaped converter is capable of vertical motion in response to waves	5	1	1

		around the tower's axis [22]			
TLP with 3-point absorbers	 [23]	The configuration involves using a tension leg platform to hold a 5MW wind turbine, with three-point absorbers on each of its underwater beams. Two-point absorber designs were evaluated. The first type could only move vertically (heave) relative to the platform's hull, while the second type featured a hinge below the water surface that enabled the buoy to move in both vertical (heave) and horizontal (surge/pitch) directions in response to waves [23]	5	0.9	3
Circular Hybrid platform		The platform is made up of a circular floating base that is 100m in diameter, with a 5MW WT mounted at the center. The semi-section of the barge that faces the waves is divided into 20 oscillating wave surge converters, which	5	5	20

	[24]	are attached to the platform via hinges [24]			
Truss Hybrid platform	 [25]	The system is made up of a partially submerged platform with five columns, and a 5MW wind turbine is located on the central column at the top-middle of the structure. The wave-facing sections of the platform have pitching wave energy converters, which are connected to the beams that link the front three columns [25]	5	5	12
Delta oscillating wave column hybrid platform	 [26]	The combination includes a sizable triangular floating platform made up of 20 oscillating water columns (OWCs), with a 5MW wind turbine located at the front of the platform. The oscillating water columns (OWCs) are positioned along the two beams that face the waves, with 10 OWCs on each side [26]	5	5	20

P80 Floating power plant	 [27]	The setup comprises of a buoyant platform that has four flap-type wave energy converters (WECs) and a 5MW wind turbine (WT) installed on its top. The size of the WECs Is optimized for the wave conditions at the deployment location, but there is only limited information available about the design characteristics due to confidentiality reasons [27]	5	5	4
W2Power	 [28]	The structure comprises of a vast triangular base with three pillars that are linked together by flat structural beams. The point absorber type wave energy converters are installed on these beams. Additionally, two 3MW wind turbines are situated on top of two of the three primary pillars [28]	6	3	-

WindWave float	 [29]	Semisubmersible platform adaptable for different types of wave energy converters: Point absorbers, wave surges, and OWC [29]	5	Variab le	Variab le

5.2 Hybrid system choice

Based on the comparison of the previous hybrid system, the P80 design is the one with higher energy production. However, and due to confidentiality matters, information about the system could not be determined. This being said, this system will be neglected in the choice of the most suitable energy converter. The following design that will be considered is the WindWave float, and a comparison between all its technologies is detailed in the following chapter.

5.2.1 General description

The WindWave float is a hybrid wind wave energy convertor platform designed to capture wind energy in high water depths (45m>). It is a three column semi-submersible design among which one column is designed to carry the wind turbine and suitable for different types of offshore horizontal axis wind turbines. In this study, the NREL 5 MW wind turbine is considered. The WindWave float platform was designed in a way that will be suitable for different wave energy converters among which three principal ones: The oscillating water column, single point energy absorber, and oscillating wave surge converter. More details about the concepts mentioned above are explained in the following section [29].

Figure 5.2.1 WindWave semisubmersible platform [29]

5.2.2 Design types

Oscillating water column

As stated previously, the oscillating water column is a design that allows water to go into an air chamber via a subsurface entry. The motion of the wave creates a rise and fall in the level of water, which then compresses and decompresses air like a piston. The air moves through a bidirectional turbine allowing its motions, and thus energy generation. In the case of the WindWave float platform, the chamber of the oscillating water column was external and linked to two columns that are not used for the wind turbine [29].

Figure 5.2.2.1: WindWave float with OWC [29]

Point energy absorber

The point absorber system helps capture energy from waves from all directions according to its floating motion with respect to the waves and surface water. This design is developed in a way that will help it resonate to reach the maximum power generation. For the WindWave float, a spherical point absorber was placed at the center of the platform. Many point absorbers can be placed on the platform.

Figure 5.2.2.2: WindWave float with single point absorber [29]

Oscillating plates

The oscillating wave surge converter or the flaps is a system that consists of a pivoting rectangular arm that moves back and forth to capture energy. In our case, the flaps are fixed on the beams of the platform, above water. This design has the advantage of stopping the flaps in big storms since the beams are meant to be dry and flaps can be fixed at a certain position [29].

Figure 5.2.2.3: WindWave float with oscillating plates [29]

5.2.3 Design choice and adaptation

a. Description

After researching the three different types of wave energy converters associated with the windwave float platform, using the single point absorber was the final choice. As stated in the previous system description, single point absorber a system that is totally independent from the direction of the wave, which will facilitate the process of the choice of the firm layout. Moreover, it is one of the most developed systems under research. On another hand, the number and the shape of the point absorbers to be used will be different from the one provided by the Windwave float company, and the purpose is to increase the efficiency of the system and thus the power output.

The shape of the point absorber that will be used in this project is a cone. According to [30], cone shape point absorbers absorb from 3% and up to 10% more wave energy than the spherical ones, which makes them more efficient. The number of cone-shaped point energy absorbers to be used will be fixed to three, as it is the most optimal one given in the company's report. The design of this energy converter will be the same as the cylindrical one provided in the picture below, but with an added cone shape at the bottom.

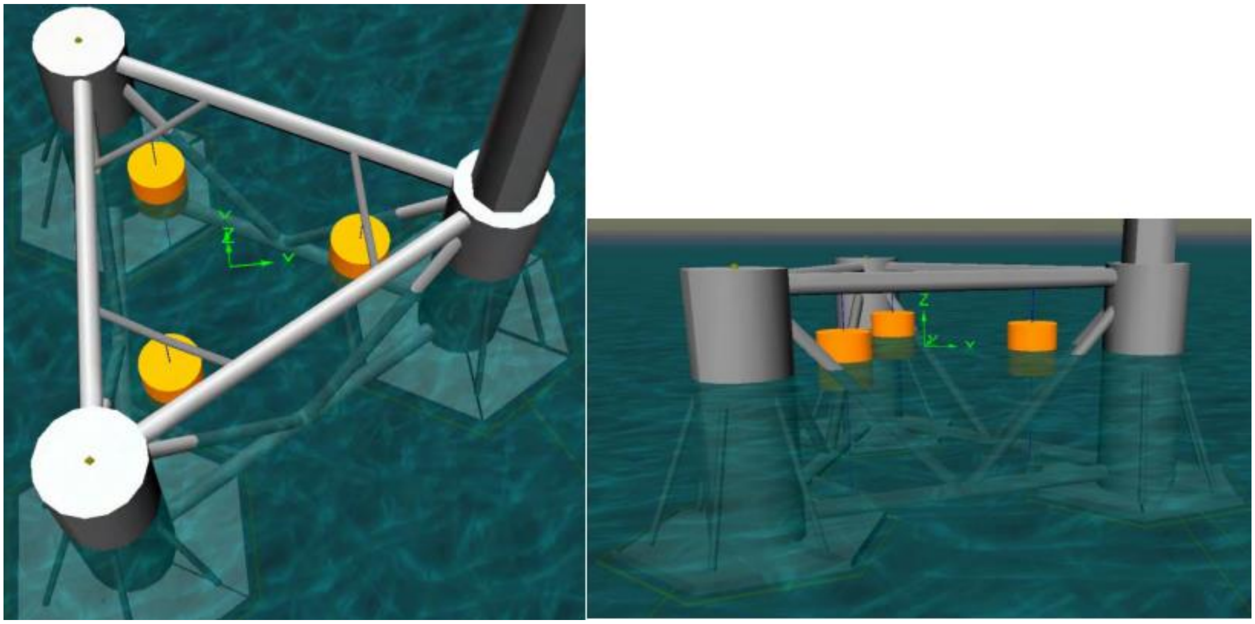


Figure 5.2.3.1: WindWave float with 3 cylindrical point absorbers [29]

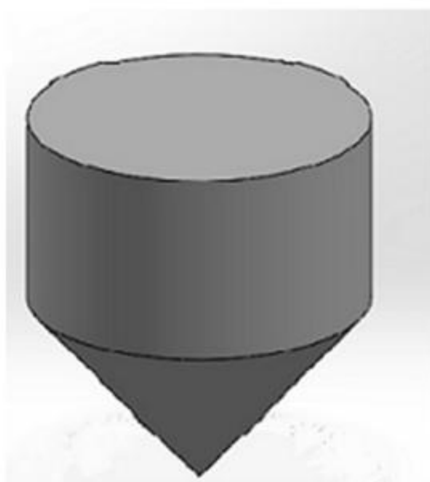


Figure 5.2.3.2: Conical point absorber chosen for the design [30]

b. Power take off system

The wave energy is converted into mechanical energy through the oscillations of the point absorber through the mechanical conversion system. The latter includes gear boxes and cables that generate mechanical energy to drive a rotary electrical generator. The following figure is a simple illustarion of the power take off system [31]

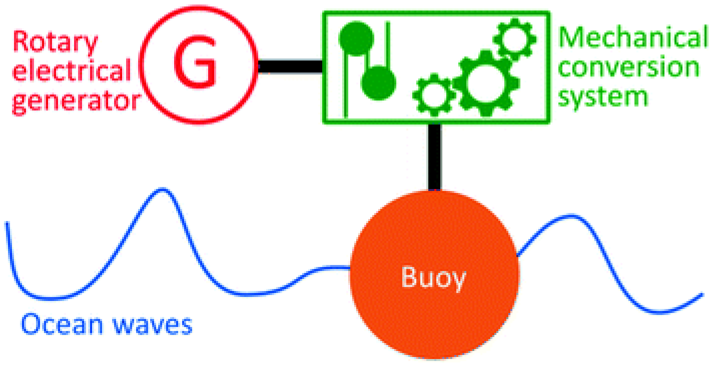


Figure 5.2.3.3: Power take off system of point absorber [31]

c. The platform dimensions:

Table 5.2.3.1 Dimensions of the WindWave float platform [29]

Column diameter	10 m
Length of water entrapment plate edge	15 m
Column center to center	46 m
Pontoon diameter	2.1 m
Operating draft	17 m
Airgap	10 m
Bracing diameter	1.5 m
Displacement	4832 tones

d. Conical floater characteristics

Table 5.2.3.2 Dimensions of the point absorber [29]

Radius	3m
Height	6m
Draft	3m

The draft suggested for the cylindrical shape is the same that will be used for the cylindrical cone shape. The power absorption is lower in higher draft, so we stick to the one with the best output.

6. Data analysis

6.1 Data gathering techniques

The data used for this capstone research was accessed through the open-source satellite AVISO using radar altimetry. The data extracted was the wind speed and the wave height in the offshore region of Essaouira. The data is of the following range: 14-september-2013 to 14-september-2019. However, for complete yearly estimation, only full years were considered which are 2014-2015-2016-2017-2018. The data was first extracted using the CSV data file type and it was then converted to excel for analysis. The data of the two parameters were extracted in a way that will ensure a compatibility in date and time for more accurate results.

Before using the wind data provided by the satellite, we had to extrapolate it to the height that will correspond to our system. The data provided by the satellite is 10 m over the surface of the ocean. The turbine that will be used in our system is the NREL 5MW, with a hub of 90m height. The following technique will be followed to get the speed of the wind at 90m.
The first chapter will consist of taking the natural logarithmic value of the targeted altitude:

$$A = \ln\left(\frac{h}{\tau}\right)$$

h corresponds to the targeted height, and τ is the surface roughness parameter. $\tau = 0.0002m$

The next step is to take the natural logarithmic value of the height at which the measurements were done, which is 10m.

$$B = \ln\left(\frac{10}{\tau}\right)$$

Finally, to obtain the desired speed, we use the following formula:

$$V = \mathrm{V0} \times \left(\frac{A}{B}\right)$$

6.2 Yearly power estimation

The first step in the data analysis will consist of analyzing the power generated by both the turbine and the wave energy converter. For this purpose, the following equations were used:

6.2.1Wind power estimation

$$P = 0.5 \times Cp \times \rho \times \pi \times R^2 \times V^3$$

Where Cp is the performance factor of the wind turbine, which in the case of the NREL 5MW is 52%.

ρ is the air density, which we will take as 1.293 kg/m^3

R is the blade radius, which has a value of 63m

V is the wind speed in m/s.

6.2.2 Wave power estimation

The equation that will be used for the wave power is given by the airy wave theory, which gives estimation of the power in regular wave ocean. This being said, the equation provides only an estimation, and it is expressed as the following:

$$P = \frac{\rho \times g^2 \times T \times H^2}{32\pi}$$

Where ρ is the seawater density, which will have a value of 1025Kg/m^3.

g is the gravitational acceleration and is given a value of 9.81 m/s^2.

T is the wave period, which we will assume to be constant with a value of 14s.

H is the wave height is meters.

This is the general equation to get power from ocean waves, it is in Watt/m. In our case, we estimate that the wave energy converter has an efficiency of C=0.44 as stated in earlier chapters. The diameter of the point energy absorber is 6m, and each system has 3 points absorbers. This will lead to the deduction of the following formula in the power calculation:

$$P = \frac{\rho \times g^2 \times T \times H^2}{32\pi} \times C \times 3 \times D$$

Where C is the efficiency of the wave energy converter.

D is the diameter of the point energy absorber.

6.3 Results

The wind power estimation was done in two cases to highlight the added value of the system chosen. The first calculations were done using a fixed platform for the wind turbine, which is the result that we can get from the equation mentioned above. The second calculations considered the motion of the platform, which goes with the design we are studying in this capstone project. According to [1], the power output of offshore wind turbines is affected by the motion of the platform in two ways: 1. The reduction of the power output due to the rotor pitch angle resulting from the pitch of the platform. 2. The motion of the rotor up wind and downwind which contributes to an increase in the power. The combination of these two effects lead to an increase in the power output of turbines in semisubmersible structures by a range of 0.1%-0.2% [32]. In our case, we take the average increase to be 0.15% of the overall power generation.

The following table gives the results of the yearly power generation of from the wind and wave sources for the whole firm, with the 27 hybrid systems.

Table 6.3.1: Yearly wind energy comparison for floating and fixed structures (2014-2018)

Year	Yearly wind energy produced for a floating platform in GWh	Yearly wind energy produced for a fixed platform in GWh	difference in kWh
2014	607	606	909,632
2015	555	554	831,280
2016	581	580	870,640
2017	436	436	654,426
2018	522	521	782,191

For the wave power generation, a comparison between the two systems was made to know the impact of the design of the point absorber. As stated earlier, the conical design will have an efficiency of 0.44, whereas the cylindrical one will have an efficiency of 0.4. This will help consolidate our choice from a power generation perspective.

Table 6.3.2: Yearly wave energy comparison for conical and cylindrical structures (2014-2018)

Year	Yearly energy produced for Conical absorber	Yearly energy production for cylindrical absorber	difference in GWh
2014	149	135	13
2015	115	104	10
2016	121	110	11

2017	107	98	9
2018	134	122	12

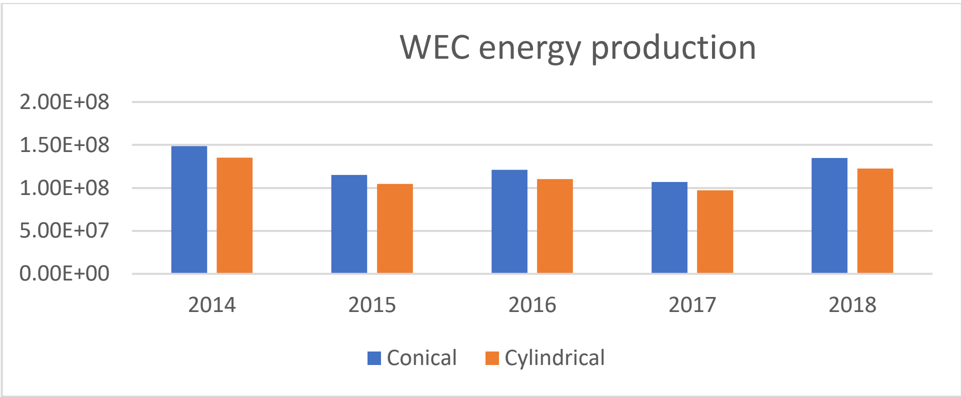


Figure 6.3.1: Wave energy converter power output: Cylindrical Vs Conical

The combined power output of the hybrid system is then calculated by summing up the values of both the wind power output for floating platform and the wave power output for the conical shape point energy absorber. The following table summarizes the results.

Table 6.3.3: Yearly energy production for chosen design (2014-2018)

Year	Yearly energy production in GWh
2014	755
2015	670
2016	702
2017	544
2018	658

Table 6.3.4: Percentage of wave power for the hybrid system (2014-2018)

Year	percentage of wave energy
2014	19.66%
2015	17.20%

2016	17.26%
2017	19.68%
2018	20.52%

The data found in this section is of the most optimistic scenario where the offshore wind turbines are operating at any speed. However, the NREL 5 MW turbine starts rotating at 2m/s and start producing energy at 4m/s. Moreover, the wind turbines do not operate 24 hours a day. An optimistic estimation is done in this regard and a total of 20 hours is being considered as the operating time of the turbine per day. The following data is a give an idea of a realistic scenario.

Table 6.3.5: Yearly energy produced for a floating platform in GWh (Realistic scenario)

Year	Yearly energy produced for a floating platform in GWh
2014	504
2015	461
2016	483
2017	362
2018	434

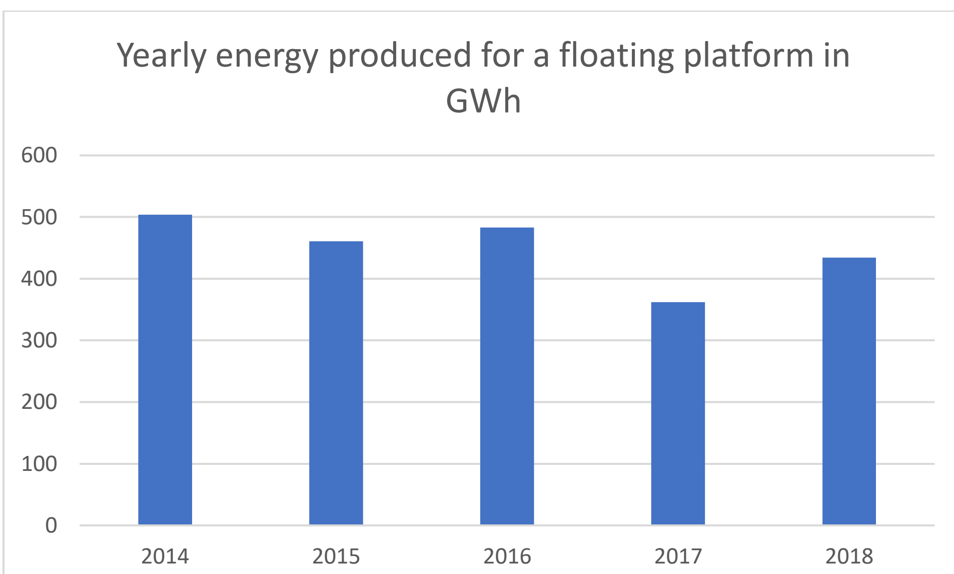


Figure 6.3.2: Realistic power output from the wind source

Table 6.3.6: Average energy produced by the entire farm

Average wind energy in GWhs	450
Average wave energy in GWhs	125
Average Percentage of wave energy	28%
Farm energy production in GWhs	575

7. Cost analysis

For the cost analysis chapter, we are assuming the cost using accurate pricing, except for the point absorbers since they are not being commercialized yet, and no exact price has been attributed to them.

7.1 Capex cost

CAPEX cost: it is the capital investment cost, and it is associated with the money that needs to be invested to purchase the fixed assets

General costs [33], [34], [36], [37]

Cost of the turbine NREL 5MW: $ 6.5 million

Cost of the WindWave float platform: $ 125 million

Cost of the wave energy converter: $ 1,131,750

Cost of installation [33], [34], [36], [37]

Wave energy convertor: $ 471,562

Platform: $ 1,300,000

Wind turbine: $ 650,000

Cost of connections and transmission [33], [34], [36], [37]

Wave converter: $ 396,112

Turbine: $ 6,173,300

Exporting cables: $ 1,690,000

Array Cables: $ 455,000

Cable protection: $ 26,000

Cable burial: $ 260,000

Cable pull-in: $ 97,500

Electrical testing: $ 84,500

Cable laying system: $ 485,000

Route clearance: $ 325,000

Onshore/ offshore cables: $ 2,950,000

Moorings: $ 37,725

Cost of the offshore station [33], [34], [36], [37]

Structure: $ 845,000

Electrical system: $ 780,000

Installation: $ 500,500

Cost of the onshore station [33], [34], [36], [37]

The offshore station will be connected to the already existing onshore station of Essaouira, so we assume no cost will be allocated to it.

7.2 OPEX cost

OPEX cost: it is the cost associated with the annual amount that is needed for maintenance and operation [34], [36], [37].

Cost of the turbine maintenance: $ 53,000

Cost of the wave converter maintenance: $ 72,621

Cost of logistics maintenance: $ 2,050

7.3 DECEX cost

DECEX cost: (decommissioning cost) it is the cost associated with the amount needed when taking down the plant at the end of its lifetime [33], [34], [36], [37]

Decommission cost of the turbine: $ 5,850,000

Decommission cost of the platform: $ 9,750,000

Decommission cost of the wave energy converter: $ 396,113

Decommission of cables and connections: $ 20,665,000.

7.4 DEVEX cost

DEVEX cost: it is the cost associated with research and development that needs to be carried out before projects [34] [36] [37].

Cost of project management: $ 910,000+169,762

Cost of environmental surveys: $ 52,000

Resources and ocean assessment: $ 52,000

Geological surveys: $ 50,000

Engineering consultancy: $ 50,000

7.5 Total cost for the whole firm

CAPEX COST: $ 340,048,224

OPEX COST: $ 127,671

DEPEX COST: $ 3,666,113

DEVEX COST: $ 1,283,762

The results show that the project is feasible from an economic point of view with a payback period of 12 years approximately. The results are logical since the average payback period for an offshore farm is 8 to 10 years. The calculation of the payback period was done through estimating the Yearly revenue from the average of the years 2014-2018.

8. STEEPLE analysis

Social implications:

Social factors will play a critical role in the success of the hybrid wind wave energy farm project in Morocco. The local community's support, especially those living near the proposed site of the energy farm, will be essential. Renewable energy is widely accepted in Morocco, and the government has set a target of 52% of electricity from renewables by 2030. The project also has the potential to create job opportunities in the community, particularly in construction, maintenance, and operations.

Technological implications:

Technological advancements will be key to the project's success. The wind and wave energy sectors are rapidly improving, leading to more efficient and cost-effective systems. Morocco's significant wind and wave resources make the country a favorable location for the hybrid energy farm. However, integrating the energy produced by the hybrid farm into the grid effectively is crucial to ensuring a stable energy supply.

Economic implications:

Economic factors, such as funding and cost-effectiveness, will also be critical to the project's success. Financing the construction and maintenance of the energy farm will require significant funding. The project, if successful, has the potential to bring economic benefits to Morocco, such as increased employment opportunities and reduced dependence on fossil fuels. To be competitive in the market, the hybrid wind wave energy farm must also be cost-effective in comparison to other energy sources.

Environmental implications:

Environmental considerations must also be taken into account. The construction and operation of the energy farm may have an impact on local wildlife, particularly marine life. However, the project will contribute to reducing carbon emissions and improving the environment. The project must also comply with environmental regulations to ensure that it is carried out in a sustainable manner.

Political implications:

Political factors, including government support, international relations, and political stability, will also be crucial to the project's success. The Moroccan government has shown a commitment to renewable energy, and this project may receive government support. Morocco's relationship with international organizations and foreign governments may also impact the project's success. Political instability in Morocco may impact the project's development and financing.

Legal implications:

Legal considerations, including regulations and permits, contractual agreements, and intellectual property, must also be addressed. The project must comply with all necessary regulations and obtain permits before construction can begin. Agreements must also be made with suppliers, contractors, and other stakeholders involved in the project. Legal agreements must be in place to ensure that intellectual property rights are protected since the hybrid wind wave energy farm will involve the use of patented technology.

Ethical implications:

Ethical considerations, such as social responsibility and transparency must also be considered. The project must be carried out in a socially responsible manner, taking into account the impact on the local community and the environment. All stakeholders must be kept informed and involved in the project's development and progress. The project must also adhere to ethical business practices, including fair labor practices and transparent financial reporting.

9. Engineering standards

When conducting the capstone project focused on the potential of a hybrid wind wave energy system in Morocco, adhering to engineering standards is crucial for ensuring safe, efficient, and reliable systems. The project must follow ISO 13588, which is related to the performance and safety of wave energy converters (WEC). This standard provides guidelines for the design, testing, and operation of WECs, ensuring that they are safe and efficient. Additionally, IEC/TS 62600-100:2012, related to the assessment of the electrical power production performance of WEC, should be considered when designing the electrical system. This standard provides guidelines for measuring the electrical output of WECs, ensuring that they are operating as intended. Finally, ISO 19030, related to the evaluation of the performance of WEC, should be used to evaluate the performance of the WEC. This standard provides guidelines for measuring the energy output of WECs and assessing their efficiency, enabling the project team to determine if the system is operating as expected. By following these standards, the project team can develop a safe, efficient, and reliable hybrid wind wave energy system that demonstrates the potential of renewable energy in Morocco.

Future work

The potential for a hybrid wind wave energy farm in Morocco is promising, and there are several areas of future work that can be explored. One such area is simulation, where computer models can be developed to simulate the performance of the farm under various conditions, such as changing wind and wave patterns. These simulations can help optimize the farm layout and improve the design of the energy converters, leading to greater energy production and profitability. Another area is hydrodynamic analysis, where the behavior of the wind and waves can be studied in greater detail to better understand the energy transfer mechanisms involved. This information can be used to further optimize the farm layout and design, and also to develop more advanced energy converters that can take advantage of specific hydrodynamic features. Besides, further research can be done on the potential environmental impact of the farm, particularly on marine ecosystems, to ensure that any negative effects are minimized.

Conclusion

To conclude, this capstone project aimed at studying the potential of Hybrid wind wave energy farm in Morocco. The first chapter of the research, which consisted of studying the best geographical location of the farm, led to the choice of Essaouira offshore region as the most adequate to exploit both the offshore wind and wave energy. This conclusion was made from previous work done using 44 years series data from the HIPOCAS project for studying the wave energy potential in 23 points along the Moroccan coastline. The wind energy location assessment was deduced from the work of the student Yassine Charouif related to his capstone project on analyzing the potential of offshore wind energy using satellite data. After the choice of the best location, the following step was the study of the best farm layout in order to maximize the energy production. This focused mainly on the direction of the wind with respect to the turbines. The wave converter choice will then be based on its independence on the wave direction. After this, the next chapter was about studying different designs and power take off systems. This includes different types of wave energy converters and platforms for offshore wind turbines. The next section compared between under research hybrid wind wave energy systems from power production and availability of information criteria. This comparison led to the choice of the WindWave float platform as the most profitable design in terms of power output. The WindWave float platform is adaptable to three different types of energy converters: Point absorbers, oscillating water column, and wave surge. The design chosen was 3 points absorbers since they will produce more energy compared to one and will be independent of the direction of the wind, which will not require any modification in the layout of the farm. The point absorber that will be used is a conical one to ensure a higher energy production (+3%) compared to the cylindrical one suggests in the WindWave float original design. The next step consisted of gathering wind and wave data from an open-source satellite to estimate the yearly power output of the firm. The data used was for the years 2014, 2015, 2016, 2017, and 2018. The final chapter of the research was the cost analysis that shows the feasibility of the farm with a payback period of approximately 5 years.

References

[1] Falcão AFDO (2010) Wav energy utilization: A review of the technologies. Renewable & Sustainable Energy Reviews, 14: 899-918

[2] H. Li, X. Sun, and H. Zhou, "Wave energy: History, implementations, environmental impacts, and economics," presented at the 2nd International Conference on Materials Chemistry and Environmental Engineering (CONF-MCEE 2022), Preprint, 2022. [Online]. Available: https://doi.org/10.1117/12.2646119.

[3] Peake, S. (2012) Renewable Energy: Power for a Sustainable Future, Oxford University Press, Oxford.

[4] Falnes J. (2007) A review of wave-energy extraction[J]. Marine Structures, 20(4): 185-201. [4] Yanjun Liu, Tongtong He. (2007) Development history and key technologies of wave energy utilization [J]. JOURNAL OF OCEAN TECHNOLOGY, 36(4)

[5] Walker, S.L. (2012) "Can the GB feed-in tariff deliver the expected 2% of electricity from renewable sources," *Renewable Energy*, 43, pp. 383–388. Available at: https://doi.org/10.1016/j.renene.2011.12.023.

[6] Esteban, M.D. *et al.* (2011) "Why offshore wind energy?" *Renewable Energy*, 36(2), pp. 444–450. Available at: https://doi.org/10.1016/j.renene.2010.07.009.

[7] Drew, B., Plummer, A.R. and Sahinkaya, M.N. (2009) "A review of Wave Energy Converter Technology," *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, 223(8), pp. 887–902. Available at: https://doi.org/10.1243/09576509jpe782.

[8] *Oceanlinx Tethys*. Available at: https://tethys.pnnl.gov/organization/oceanlinx (Accessed: March 20, 2023).

[9] Kofoed, J P, et al, (1998). "Wave Dragon – a Slack Moored Wave Energy Converter", Third European Wave Energy Conference, Patras, Greece, September 1998.

[10] Energy, Carnegie Clean. Carnegie Clean Energy. Available at http://carnegiewave.com/projects/ceto-6/. (Accessed: March 20, 2023).

[11] Aquamarine Power Oyster. Available at http:// tinyurl.com/cn9k4k/ (Accessed: March 20, 2023).

[12] *Floating platforms for Offshore Wind* (no date) *BPP Renewables*. Available at: https://www.bpp-renewables.com/floating-wind-farms/floating-platforms-for-offshore-wind/ (Accessed: April 10, 2023).

[13] Sierra, J.P. *et al.* (2016) "Wave energy potential along the Atlantic coast of Morocco," *Renewable Energy*, 96, pp. 20–32. Available at: https://doi.org/10.1016/j.renene.2016.04.071.

[14] Guedes Soares, C. (2008) "Hindcast of dynamic processes of the ocean and coastal areas of Europe," *Coastal Engineering*, 55(11), pp. 825–826. Available at : https://doi.org/10.1016/j.coastaleng.2008.02.007.

[15] Sierra, J.P. *et al.* (2016) "Wave energy potential along the Atlantic coast of Morocco," *Renewable Energy*, 96, pp. 20–32. Available at: https://doi.org/10.1016/j.renene.2016.04.071.

[16] Charouif, Y. (2022) "Assessment of the Off-Shore Wind Potential in the Kingdom of Morocco", Capstone Report

[17] Benazzouz, A., Mabchour, H., el Had, K., Zourarah, B., & Mordane, S. (2020). Offshore Wind Energy Resource in the Kingdom of Morocco: Assessment of the Seasonal Potential Variability Based on Satellite Data. Journal of Marine Science and Engineering, 9(1), 31. https://doi.org/10.3390/jmse9010031

[18] AZEROUAL, M., el MAKRINI, A., el MOUSSAOUI, H., & el MARKHI, H. (2018). Renewable Energy Potential and Available Capacity for Wind and Solar Power in Morocco Towards 2030. Journal of Engineering Science and Technology Review, 11(1), 189–198. https://doi.org/10.25103/jestr.111.23

[19]. E.O. Straume, C. Gaina, S. Medvedev, K. Hochmuth, K. Gohl, J.M. Whittaker, et al. Updated total sediment thickness in the world's oceans Geochem Geophys, 20 (4) (2019), pp. 1756-1772, 10.1029/2018GC008115

[20] Hassoine, M.A. *et al.* (2019) "A novel evaluation of wind energy potential in Essaouira offshore wind farm, using genetic algorithm and merra-2 reanalysis data," *2019 5th International Conference on Optimization and Applications (ICOA)* [Preprint]. Available at: https://doi.org/10.1109/icoa.2019.8727669.

[21] Luan, C. *et al.* (2014) "Modeling and analysis of a 5 MW semi-submersible wind turbine combined with three flap-type wave energy converters," *Volume 9B: Ocean Renewable Energy* [Preprint]. Available at: https://doi.org/10.1115/omae2014-24215.

[22] Wan, L., Gao, Z. and Moan, T. (2014) "Model test of the STC concept in survival modes," *Volume 9A: Ocean Renewable Energy* [Preprint]. Available at: https://doi.org/10.1115/omae2014-23213.

[23] Bachynski, E.E. and Moan, T. (2013) "Point absorber design for a combined wind and wave energy converter on a tension-leg support structure," *Volume 8: Ocean Renewable Energy* [Preprint]. Available at : https://doi.org/10.1115/omae2013-10429.

[24] Soulard, T. *et al.* (2013) "C-hyp: A combined wind and wave energy platform with balanced contributions," *Volume 8: Ocean Renewable Energy* [Preprint]. Available at: https://doi.org/10.1115/omae2013-10778.

[25] Soulard, T. *et al.* (2013) "C-hyp: A combined wind and wave energy platform with balanced contributions," *Volume 8: Ocean Renewable Energy* [Preprint]. Available at: https://doi.org/10.1115/omae2013-10778.

[26] O'Sullivan, M.G., Supple, B. and McCarthy, M. (2019) "Cross cultural experiences of Chinese students studying Food Science in Ireland," *Learning Connections 2019: Spaces, People, Practice* [Preprint]. Available at: https://doi.org/10.33178/lc2019.10.

[27] Floating Power Plant AS. Available at (http://www.floatingpowerplant.com/).

[28] Pelagic Power AS. Available at (http://www.pelagicpower.no/)

[29] Weinstein, A., Roddier, D. and Banister, K. (2012) *Windwavefloat (WWF): Final scientific report, WindWaveFloat (WWF): Final Scientific Report (Technical Report) | OSTI.GOV*. Available at: https://www.osti.gov/servlets/purl/1057931 (Accessed: April 24, 2023).

[30] Khojasteh, D. and Kamali, R. (2016) "Evaluation of wave energy absorption by heaving point absorbers at various hot spots in Iran Seas," *Energy*, 109, pp. 629–640. Available at: https://doi.org/10.1016/j.energy.2016.05.054.

[31] Têtu, A. (2016) “Power take-off systems for wecs,” *Ocean Engineering & Oceanography*, pp. 203–220. Available at: https://doi.org/10.1007/978-3-319-39889-1_8.

[32] M. Johlas, H. *et al.* (2020) “Review for ‘Floating platform effects on power generation in Spar and semisubmersible wind turbines.’” Available at: https://doi.org/10.1002/we.2608/v2/review1.

[33] *Cost modeling of floating wind farms - questfwe.com*. Available at: https://questfwe.com/wp-content/uploads/2018/02/Cost-Modeling-of-Floating-Wind-Farms-ECN-2016.pdf (Accessed: April 14, 2023).

[34]. *Cost estimations - analysis of cost reduction opportunities in the wave energy industry*. Available at: https://www.esru.strath.ac.uk/EandE/Web_sites/14-15/Wave_Energy/cost-estimations.html (Accessed: April 14, 2023).

[35] Guard, W. (2021). Wind Turbine Cost: Worth The Million-Dollar Price In 2022? Weather Guard Lightning Tech. https://weatherguardwind.com/how-much-does-wind-turbine-cost-worth-it/

[36]. BVG Associates. (2021). Wind farm costs – Guide to an offshore wind farm. https://guidetoanoffshorewindfarm.com/wind-farm-costs

[37]. BIGGAR Economics & Beatrice Offshore Wind Farm Ltd. (2019). Economic Impact of Beatrice Offshore Windfarm Limited.

[38] *Las Ui*. Available at: https://las.aviso.altimetry.fr/las/UI.vm (Accessed: April 4, 2023).