إقرار

أنا الموقع أدناه مقدم الرسالة التي تحمل العنوان:

Measuring the Efficiency of the Eastern Mediterranean Sea for Production of Electrical Power

أقر بأن ما اشتملت عليه هذه الرسالة إنما هي نتاج جهدي الخاص، باستثناء ما تمت الإشارة إليه حيثما ورد، وإن هذه الرسالة ككل، أو أي جزء منها لم يقدم من قبل لنيل درجة أو لقب علمي أو بحثي لدى أية مؤسسة تعليمية أو بحثية أخرى.

DECLARATION

The work provided in this thesis, unless otherwise referenced, is the researcher's own work, and has not been submitted elsewhere for any other degree or qualification

Student's name: Sameh S. Abu Zer — اسم الطالب: سامح سليم عبد أبو زر

Signature — التوقيع:

Date: — التاريخ: 7/6/2015

The Islamic University of Gaza
Research and Graduate Affairs
Faculty of Engineering
Electrical Engineering Department

Measuring the Efficiency of the Eastern Mediterranean Sea for Production of Electrical Power

By:
Sameh Saleem Abu zer

Supervisor:
Dr. Hatem A. ELaydi

"A Thesis is submitted in Partial Fulfillment of the Requirements for the Degree of Master in Electrical Engineering"

Islamic University of Gaza, Palestine

1436هـ - 2015م

بسم الله الرحمن الرحيم

الجامعة الإسلامية – غزة
The Islamic University - Gaza

مكتب نائب الرئيس للبحث العلمي والدراسات العليا هاتف داخلي 1150

الرقم...ج س غ/35/........ Ref

التاريخ 2015/04/26 ....Date

نتيجة الحكم على أطروحة ماجستير

بناءً على موافقة شئون البحث العلمي والدراسات العليا بالجامعة الإسلامية بغزة على تشكيل لجنة الحكم على أطروحة الباحث/ **سامح سليم عبد أبو زر** لنيل درجة الماجستير في **كلية *الهندسة*** قسم **الهندسة الكهربائية – أنظمة التحكم** وموضوعها:

قياس كفاءة شرق البحر الأبيض المتوسط لإنتاج الطاقة الكهربائية

Measuring the Efficiency of the Eastern Mediterranean Sea for Production of Electrical Power

وبعد المناقشة العلنية التي تمت اليوم الأحد 07 رجب 1436هـ، الموافق 2015/04/26م الساعة الثانية عشرة ظهراً بمبنى القدس، اجتمعت لجنة الحكم على الأطروحة والمكونة من:

د. حاتم علي العايدي	مشرفاً ورئيساً	....
د. باسل محمود حمد	مناقشاً داخلياً	....
د. محمد حاتم مشتهى	مناقشاً خارجياً	....

وبعد المداولة أوصت اللجنة بمنح الباحث درجة الماجستير في **كلية *الهندسة*/ قسم الهندسة الكهربائية – أنظمة التحكم.**

واللجنة إذ تمنحه هذه الدرجة فإنها توصيه بتقوى الله ولزوم طاعته وأن يسخر علمه في خدمة دينه ووطنه.

والله ولي التوفيق،،،

مساعد نائب الرئيس للبحث العلمي وللدراسات العليا

أ.د. فؤاد علي العاجز

Research & Graduate Affairs

P.O. Box 108, Rimal, Gaza, Palestine fax: +970 (8) 286 0800 فاكس Tel: +970 (8) 286 0700 هاتف ص.ب. 108 الرمال، غزة، فلسطين
public@iugaza.edu.ps www.iugaza.edu.ps

ABSTRACT

Generating electrical power from renewable sources is receiving great attention over the past decades where many industrialized countries are focusing on building this type of technologies. Indeed, many technologies have become effective and widely used, but the mystery that the world seeks to resolve is the effectiveness of wave energy technology compared to the challenges of reducing its very high cost. The world is still experimenting with models and locations. Encouragingly, this potential energy in the seas and oceans cover vast areas of the earth's surface, and many countries are characterized by a long coastal beaches.

During the last few decades, a lot of ideas were put forward and devices were designed to convert wave energy into electrical power; everyone has its advantages and difficulties. This motivated us in the Gaza Strip, which suffers from a severe energy crisis and is distinguished from many areas in that it is located on the coastline along it western borders on the southeastern corner of the Mediterranean, to conduct research on this topic.

This thesis, is investigating the feasibility of wave electricity production in the Eastern Mediterranean sea using the point absorber technology. WEC-Sim, a Matlab tool, is used to simulate reference model 3, (RM3) a two point absorber device, which simulates the behavior of the WEC under irregular waves of different wave heights during different times in the year in the study area.

The simulation results is tabulated in the power matrix and analyzed according to the four seasons. The results show that there is a potential to produce electrical power out of the Eastern Mediterranean waves.

The results also indicate that the offshore point absorber device is better than the onshore device tested in the study area which lifts sea water upward to a suitable head then is fed through a turbine (and a generator) to produce a specific amount of electricity.

ACKNOWLEDGEMENT

At the beginning, all my thankfulness are to Allah the almighty for facilitating this work and for granting me the opportunity to contribute to the benefit of Muslims, especially here in my homeland Palestine Gaza Strip.

I would like to extend my thanks and appreciation to the first deserves always to honor, my father, who is always keen to see us where we are today and gave all his life for us, and to affectionate heart, my mother who always calls us good luck and success. I will never forget her prayer and calls in midnight.

I would like to express my deepest thanks to my thesis supervisor Dr. Hatem A. Elaydi for his support, encouragement, and guidance. Also to extend my gratitude and appreciation to thesis committee, both Dr. Basil Hamad and Dr. Mohammed Mushtaha for their suggestions and recommendations that helped me in the enriching and development of this thesis, ask Allah the almighty to make it in the balance of their good deeds.

There are no words that describe how grateful I am to my wife sincere Helen, who was and still help me on religious matters and worldly affairs and they encourage me to do good, as well as my daughter Malak for her patience during my busy schedule.

I would like to express my thanks and appreciation to my family, my brothers and sisters and to my brothers in the mosque and work.
Finally, I wish to thank anyone who helped me in completing this work.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATION

Wave Energy Converter	WEC
Wave Energy Converter- Simulation	WEC-Sim
Reference Model 3	RM3
Reference Model Project	RMP
Oscillating Wave Column	OWC
Power Take Off	PTO
Land Installed Marine Powered Energy Transformer	LIMPET
Gaza Power Generation Company	GPGC
Archimedes Wave Swing	AWS
Degrees of freedom	DOF
National Renewable Energy Laboratory	NREL
Sandia National Laboratories	SNL
Wave Analysis At Massachusetts Institute of Technology	WAMIT
Computer-Aided Design	CAD
Rhinoceros 3D program	Rhino
Bretschneider Spectrum	BS
Israel Marine Data Center	ISRAMAR
Department of Energy (in the US)	DOE
S.D.E. Energy LTD, Israeli wave energy company	SDE

CHAPTER ONE
INTRODUCTION

1.1 Introduction

From time to time, various international bodies are concerned with the preservation of the environment reports, such as the eco-system and its changes. Those bodies often publish reports warning of changes in the eco-system as a result of various pollution factors, notably waste power plants that should be mitigated in order to preserve the integrity of the atmosphere.

This led to a global movement towards green energy and the exploitation of renewable energy. The last decades have seen a number of actions to develop new technologies and scientific methodologies in order to support clean forms of energy.

Currently, there are several types of renewable energy which varies in terms of the process of the study, development and practical application, and efficiency. Among the most prominent of these techniques are hydroelectric, biomass, wind, geothermal, solar and ocean/sea technologies.

There are many techniques that are used for extracting energy from the ocean/sea such as, tidal energy, ocean thermal energy, marine currents energy and ocean/sea wave energy which has the highest potential to produce electricity.

The wave energy is the energy that can be produced by ocean or sea waves. Wave energy is characterized by abundance, since the areas of water covers about 70% of the Earth's surface.

Many techniques exist for converting wave energy to electric power. Several devices have been developed to be situated on or offshore.
In general, there are four general forms of wave energy harvesting techniques. Two are floating or sea-based (point absorbers, attenuators) and two are stationary or land-based (oscillating wave column (OWC) terminators, overtopping terminators).

Point absorbers and attenuators capture wave energy as they are placed in the path of the wave. Point absorbers are moored to the sea bed or float near the surface to convert the

heaving and surging motions of waves to electric energy. In other words, the wave gives rise to motions in the point absorbing buoy which is directly transmitted to a Power Take Off (PTO) which might be hydraulic or electric.
The early scientific work on point absorbers was carried out by several people in the mid- and late Seventies of the last century.

Over the past decades, many countries focused on wave power resources and supported several research programs with government and private support, mainly in the United Kingdom, Portugal, Ireland, Norway, Sweden and Denmark. Research in other countries has spread, especially those located on the Coastal areas such as some of European countries and U.S.A.

However, Ocean/sea energy is untapped source of renewable energy. There was never any doubt about the magnitude of the renewable energy, the challenge was always in harnessing them. So it is now still under the significant research and development.

In November, 2000, the world's first commercial wave power plant began generating electricity. The small plant, called LIMPET 500 kW, is located in Islay, a small island off the west coast of Scotland. The plant was constructed at a cost of about 1.6 millions dollars [1].

In this thesis, the proposed device is a point absorber. It's a buoy floating on the water surface that is referenced to a fixed system. The device motion is due to the heave displacement caused by a passing wave and the relative heave motion between the two bodies is used to extract power.

1.2 Problem statement and motivation

In fact, there are many reasons that motivated me to investigate the theoretical performance of two-body-point absorber device using wave energy, among the most prominent of those reasons my vision that there is a need to carry out scientific research in Palestine, especially the Gaza Strip in this field.
The fact that it is relatively recent field compared with other renewable energy sources, as well as the geographic location of the Gaza Strip, which is located on the Mediterranean Sea along its western facade length of about 40 km.

Over the last 10 years, Gaza Strip has been suffering from electrical power shortage. The production does not meet the demand. The power demand ranges from 350 MW to 400 MW. Gaza receives electricity from three different sources: Gaza power generation (60MW), Israel electric company (120MW) and Egypt (28MW).
Moreover, the lack of fuel to the GPGC as a result of the Israeli Siege causes the Gaza power station to shut down several times.
Recent studies focused on using solar energy to solve Gaza power problem. Gaza costal border on the Mediterranean Sea is a great reservoir for energy and should be utilized. Very few studies exist to investigate the eastern Mediterranean area as site for electricity power production. This thesis presents a feasibility study to investigate the possibility of using Gaza costal area as a site for electrical power production based on wave energy.

1.3 Research objectives and methodology

The main goal of this thesis is to measure the efficiency of the Eastern Mediterranean Sea for production of electrical power from two body point absorber device. Therefore, this study will be useful for all countries which lies on the eastern Mediterranean such as Palestine, Syria, Lebanon…etc.
The procedure of this thesis is to achieve the desired goal as follows:

1. Conduct initial research about wave energy technologies and the extent of their applicability in the study area.
2. Choose a type of wave energy converter and the suitable tool to simulate a prototype.
3. Collect data about the nature and characteristics of waves in the eastern Mediterranean.
4. Simulate two body point absorber device by using WecSim tool.
5. Test the device to determine the amount of energy that can be obtained through the application of this technique in the study area and analyze the results.

1.4 Literature review

Several researches were proposed in this field as shown below:

- In 2008 Kimoulakis et al. [2] modeled and designed a special coupled electromechanical system, to be used in sea wave energy extraction applications. The system consisted of a specific linear permanent magnet generator combined with a cylindrical floating buoy moving due to the sea wave incidence. The system analysis required particularly electromagnetic-mechanical-hydraulic simulation models. The proposed models suitability was checked through measurements in a 16 kW prototype power plant.

- In 2009 El-Zaza [3] Developed Shoreline WEC device in Gaza Strip. The main theme of the prototype is based on converting the kinetic and potential energies, that exist in moving sea waves, into potential energy as the water is stored in an elevated reservoir. The stored water can then be fed through a turbine (and a generator) to generate electricity.

  Based on assumed electrical-power requirement (1.5 kWh per day) and available conditions, the model was designed, analyzed, fabricated, and finally tested on Gaza shoreline for few days. Several modifications were introduced whenever needed.

  The device produced average filling rates, at 15-m head, that would generate about 55% of the assumed power.

- In 2011 Foster [4] presented the undergoing development of a wave energy conversion device at the University of Hawaii Manoa. The device consisted of a three part point absorber with two buoys, one floating and absorbing incoming waves; the other maintaining tension on the third mechanism, the submerged power-take-off unit. This design was presented as three concept configurations for WEC construction. The analytical solution was developed, and the buoys response was computed based on a selected and analyzed sea-state.

- In 2012 Leclerc et al. [5] presented the recent advances of a sea wave energy conversion system into electrical energy both in modeling and control strategy techniques. The simulation model was improved in order to better represent the impact of the drag force due to the friction of water on the cylindrical buoy.

- In 2012 Song et al. [6] introduced a new type of the wave energy converter belonging to a point absorber type. The floating system convert the hydro kinetic energy of the sea waves to usable mechanical energy.

- In 2013 Bozzi et al. [7] investigated the feasibility of wave electricity production in Italian seas by the deployment of the Sea-based wave energy converter (WEC). A numerical model of the coupled buoy-generator system was presented, which simulated the behavior of the wave energy converter under regular waves of different wave heights and periods. The hydrodynamic forces, including excitation force, radiation impedance and hydrostatic force, were calculated by linear potential wave theory, and an analytical model was used for the linear generator. Two buoys of different radii were considered to explore the effect of buoy dimension on energy conversion and device efficiency. The power output was maximized by adding a submerged object to the floating buoy, in order to bring the system into resonance with the typical wave frequencies of the sites. The simulation results showed a very good agreement with the published data on the Sea-based WEC. The model was used to estimate energy production at eight Italian offshore locations.

- In 2013 Nazari et al. [8] analyzed and designed a point absorber wave energy converter for Asaluyeh coastal on Persian Gulf. The geographical conditions of this region have some local short waves. The buoy parameters were optimized using simulations in order to absorb maximum energy, to reduce damping and slamming effects and to increase the chance of heave resonance. Using resonance, the average heave amplitude of the buoy increases by 51% and the average achievable power rised to more than twice. The frequencies of the buoy were affected by changing the buoy shapes and sizes. This caused an increase in average amplitude heave and as results it increased the amount of power to around 45 watts. Finally, using resonance and decreasing damping effects caused a 7% increase in the amplitude of vibration of the buoy with respect to the average wave height in the region (0.582 meter).

- In 2014 Faizal et al. [9] proposed a design outline for floating point absorber wave energy converters. The wave characteristics were used to calculate the wavelength using an appropriate wave theory.

1.5 Contribution

This research presents a feasibility study on renewable energy, more specifically on wave energy. It investigates producing electricity from sea waves in the Eastern Mediterranean area. It present a modeling technique and design a system to convert wave energy to electricity. It presents recommendations based on simulation results.

1.6 Thesis outline

There are six chapters in this thesis; Chapter 2 presents the study of sea waves and wave energy. Chapter 3 general background about wave energy conversion and famous converters. Chapter 4 presents the model design and the specified input parameters values which used in WEC-Sim tool. Chapter 5 demonstrates results for the device of a point absorber WEC with the presence of uncertainty in system parameters. Finally chapter 6 ends up with conclusion and future work.

CHAPTER TWO
SEA WAVES

2.1 Introduction

The exploitation of one of the largest renewable sources on the planet, namely water for the production of energy is old. Most notably the exploitation of natural waterfalls. However, the geographical nature of the Earth's surface and other factors do not allow that there will be waterfalls in every place where there are water. Thus, the exploitation of the potential energy in the waves of the oceans and seas, which hit the coast of dozens of countries, may be one day an important source of alternative energy sources, especially in terms of preserving the environment.

In this chapter, some of the concepts and terminologies are clarified with detailed information on the sea waves. A visualization mechanism of wave energy converter is presented with details on extracting energy from sea waves.

2.2 Sea wave phenomenon

The sea surface is in continual motion. Waves are the result of disturbance of the water surface [10]; In the open sea, the friction moving the waves generates energy within the water. This energy is then passed between water molecules in ripples called waves of transition. When the water molecules receive the energy, they move forward slightly and form a circular pattern [11].

In short, due to the oscillation of water molecules, it moves in the form of orbital motion.
Figure (2.1) shows the orbital motion for water molecules.

The standard example is the rock-in-the-pond scenario. The rock provides the disturbing force, and generates waves that radiate outward, eventually losing their momentum and dissipating their energy so that the pond returns to calm [10]. But the movement of the waves in this example are going in all directions, while the sea waves are unidirectional waves.

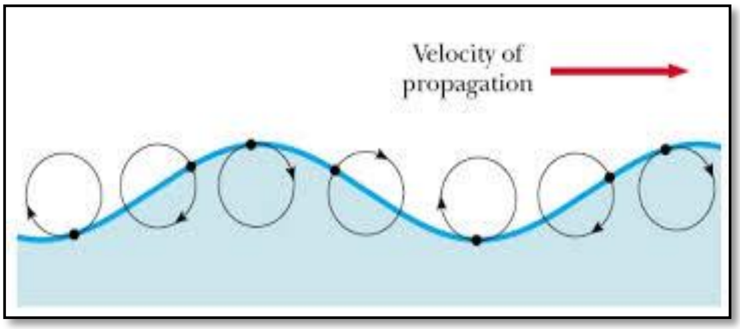

Figure (2.1): The movement of water molecules.

When studying waves, it is important to note that while it appears the water is moving forward, only a small amount of water is actually moving. Instead, it is the wave's energy that is moving and since water is a flexible medium for energy transfer, it looks like the water itself is moving [11].

2.3 Sea wave generation

Waves are considered the most powerful water movements. It cannot be compared with any factor leading to the water movements. In general, the waves of the sea can be classified into several different categories based on their generating and behavior…etc.

Most waves are caused by wind, but many other waves are created by releases of energy in the ocean, including internal waves, splash waves, tsunami, tides, and human- induced waves [1].

In this thesis, we want to talk about the usual cause for generating waves, namely wind.
The sun produces temperature differences across the globe, causing winds that blow over the ocean surface. These cause ripples, which grow into swells [12]. These waves move quite easily from one place to another through the oceans, with a speed proportional to their wavelength [13].

The waves increase in size if wind gets stronger. If heavy winds from tropical storms blow, they can create ocean swells that are capable of traveling long distances. Ocean swells are defined as mature undulations occurring in open ocean waters [13].

In other words, the size of the resulting waves, depends on the wind force and speed. It should be noted here that the waves of the sea are irregular. There is no perfect regularity in waves, as this affects the extent of benefit from the inherent power, because the energy varies randomly through the year.

2.4 Wave motions

There are five types of wave motions, which are used in the working principles for wave energy converters, WEC. This motions depend on the Six degrees of freedom (6DoF) refers to the freedom of movement of a rigid body in three-dimensional space (translation in three perpendicular axes, combined with rotation about three perpendicular axes).

The WEC's can use those motions alone or in combination to provide energy. The wave motions and the details are as follows:

- **Heaving Motion:** is one of the six degrees of freedom of a rigid body at sea. It can be defined as the vertical (up/down) translation motion. Typically, systems that principle is based on this motion contains a floating body moves vertically such as point absorber device as shown in Figure (2.2).

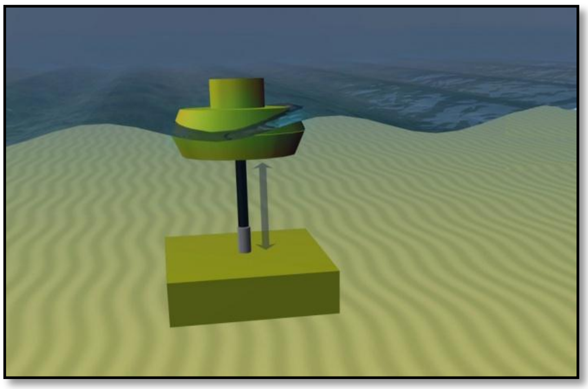

Figure (2.2): Point absorber device.

- **Pitching Motion:** is one of the six degrees of freedom of a rigid body at sea. It can be defined as the tilts forward and backward. In other words, is an up-or-down movement of the bow of the body. The pitching motion is rotational, unlike heaving motion, where it is the rotation of a body about its transverse (side-to-side) axis. Such as the Irish McCabe wave pump, the pitching motion of the two floating pontoons pumps hydraulic fluid back and forth motion that is used to drive a generator. Figure (2.3) shows the McCabe wave pump. Floats move up and down as the waves move past.

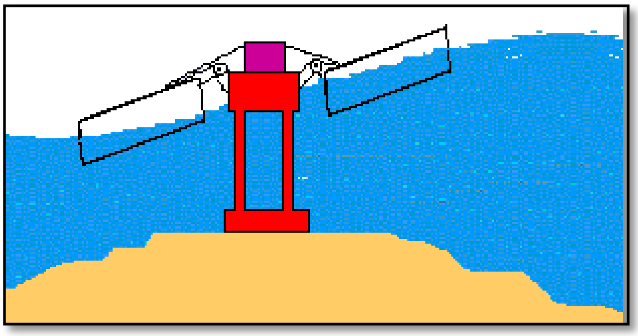

Figure (2.3): The McCabe wave pump.

- **Pneumatic Principles (oscillating water columns):** this type is on the beach where the waves breaking. The oscillating water is used for air pressure inside the chamber, which is blown out then pulled in through a Wells turbine. The clearest example of this type is Limpet device. Figure (2.4) shows a schematic of an oscillating water column.

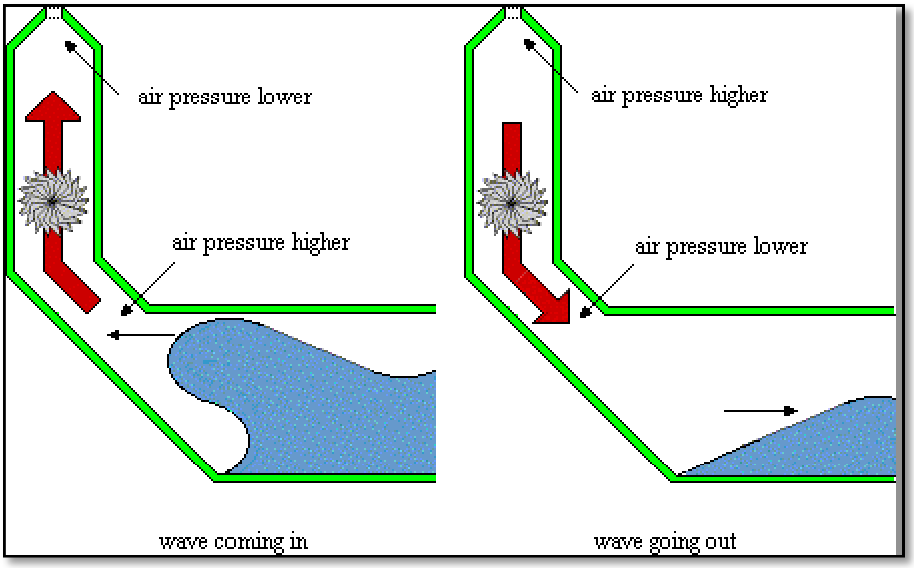

Figure (2.4): A schematic of an oscillating water column.

- **Surging motion:**

  The waves get over a concrete barrier (only the biggest waves do so). They fill a reservoir. The water in the reservoir flows back to the ocean through a turbine, as shown in Fig. (2.5), an example of this motion "tapchan" device.

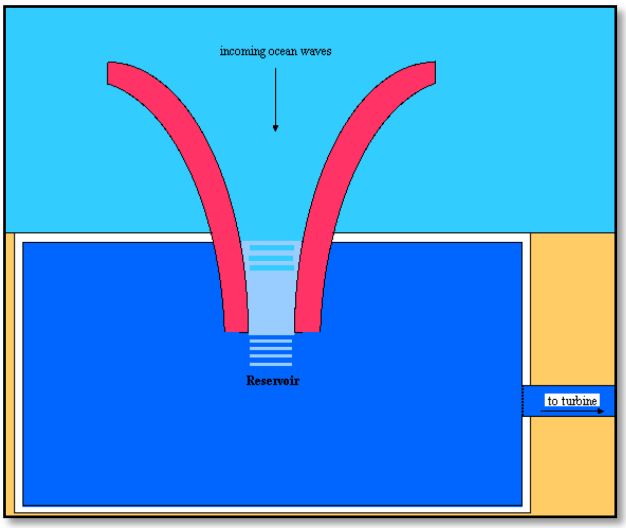

Figure (2.5): A schematic of a Surging motion.

- **Underwater Pressure Variations:** it is known that the pressure under the sea ratios varies. The pressure at the surface is not as it is at the bottom, and the transient waves at the surface produces changes in pressure underwater

  The Bristol cylinder is moored at the surface, just submerged. Surface waves rotate it in only one direction; energy can then be taken off, as shown in Figure (2.6).

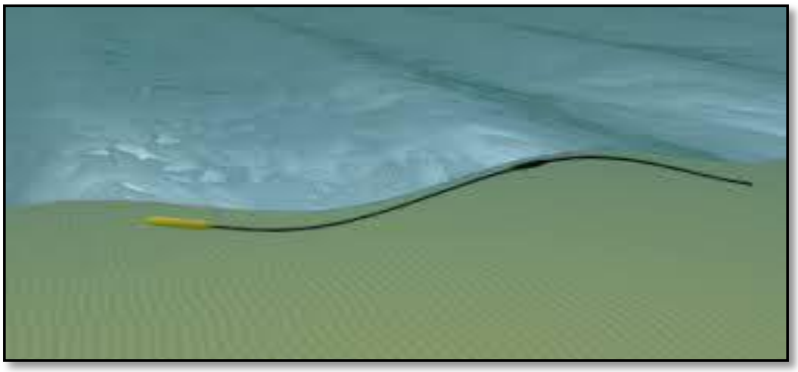

Figure (2.6): Bristol cylinder for wave energy extraction.

- **Hybrid Motion:** the Previous five types of wave motions used to design many of wave energy converters, also can be used together to design other converters, such as Pelamis Wave Energy Convertor known as "Sea Snake" project which combines heaving and pitching techniques. Figure (2.7) shows a principle of operation of Pelamis wave technology.

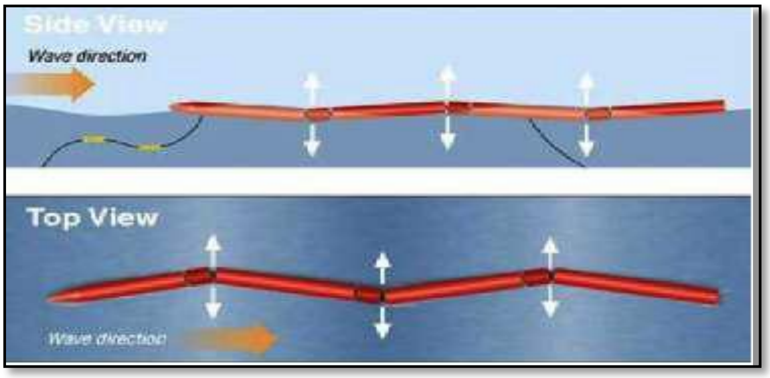

Figure (2.7): Principle of operation of Pelamis wave technology.

2.5 Sea wave power

2.5.1 Fundamentals of wave power

The waves propagate on the sea surface, and the wave energy is also transported horizontally with the group velocity (that is, the speed at which a wave packet travels). The mean transport rate of the wave energy through a vertical plane of unit width, parallel to a wave crest, is called the wave energy flux (or wave power, which must not be confused with the actual power generated by a wave power device) [14].

Wave power is a form of renewable energy. It's the transport of ocean/sea surface waves energy, and the capture of that energy to do useful work such as electricity generation, desalination and the pumping of water.

2.5.2 Basic sea wave parameters

Since we are going to exploit the potential energy in the waves, it's important that we know some of their parts, as described below [15]:
Figure (2.8) shows the most prominent sea wave parameters.

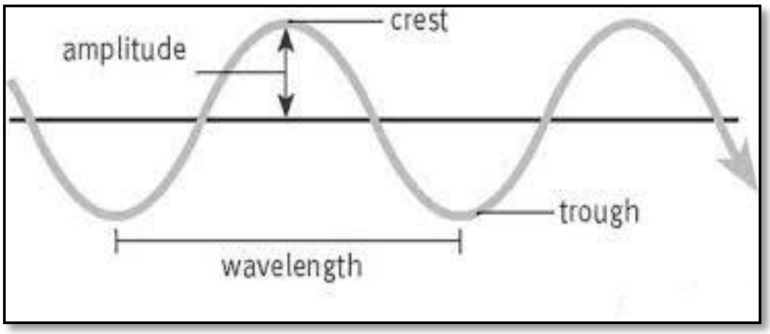

Figure (2.8): The most prominent sea wave parameters.

- **Crest (CR):** the very top of the wave.
- **Trough (TR):** the hollow between two crests.
- **Wave height (H):** the vertical distance between the top of one wave crest and the bottom of the next trough.

$$Height = 2\,a \quad (m) \qquad (2.1)$$

- **Amplitude (a):** the maximum vertical displacement of the sea surface from still water level (half the wave height).

$$Amplitude = \tfrac{1}{2} H \quad (m) \qquad (2.2)$$

- **Wavelength (λ):** the horizontal distance between any one point on one wave and the corresponding point on the next.
- **Wave steepness**: the ratio of height to length.
- **Period (T)**: the time it takes for one complete wavelength to pass a stationary point.
- **Wave speed (c)**: the velocity with which waves travel.

$$wave\ speed = \frac{distance\ between\ peaks}{time\ between\ peaks}$$

$$c = \frac{\lambda}{T} \qquad (2.3)$$

- **Wave frequency (F):** the number of waves passing a fixed point in a specified period of time. Frequency has units of waves per second or cycles per second. Another unit for frequency is the Hertz (abbreviated Hz) where 1 Hz is equivalent to 1 cycle per second.

$$F=\frac{1}{T} \quad (Hz) \qquad (2.4)$$

- **Deep water waves**: waves that are in water that is deeper than half their wavelength.
- **Shallow water waves**: waves that are in water that is shallower than 1/2 their wavelength (the important difference on these last two is whether or not the sea floor influences the motion of the wave).

2.5.3 Wave energy basic formulation

In a sea state, the average(mean) energy density per unit area of gravity waves on the water surface is proportional to the square of wave height, according to linear wave theory [14].

$$E = \frac{1}{8}\rho g H_{m0}^2 \qquad (2.5)$$

Where E is the mean wave energy density per unit horizontal area in (J/m^2), ρ is the sea water density per unit area in (kg/m^3), g is the gravity in (m/s^2), and H_{mo} is the significant wave height in (m).

E is the sum of kinetic and potential energy density per unit horizontal area. The potential energy density is equal to the kinetic energy, both contributing half to the wave energy density E, as can be expected from the equipartition theorem [14].

As the waves propagate, their energy is transported. The energy transport velocity is the group velocity. As a result, the wave energy flux, through a vertical plane of unit width perpendicular to the wave propagation direction, is equal to [14]:

$$P = E\,c_g \qquad (2.6)$$

with C_g the group velocity in (m/s). Due to the dispersion relation for water waves under the action of gravity, the group velocity depends on the wavelength λ, or equivalently, on the wave period T. Further, the dispersion relation is a function of the water depth h. As a result, the group velocity behaves differently in the limits of deep and shallow water, and at intermediate depths [14].

A wave is travelling along the water surface with phase speed, which is well approximated by equation (2.7):

$$c = \sqrt{\frac{g\lambda}{2\pi}\tanh\left(\frac{2\pi d}{\lambda}\right)} \qquad (2.7)$$

Where c is the wave phase speed in (m/s), λ is the wavelength in (m), measured from crest to crest, and d is the water depth in (m).

Generally, in the case of linear plane waves, the particles movement on or near the surface and the phase velocity of group waves vary depending on the depth of the water. Thus, the wave power in deep water (typically more than 40 m water depth) differs from shallow water (typically 10 to 25 m water depth). The oscillatory motions are highest at the surface and diminish exponentially with depth.

Deep water: where the depth is larger than half the wavelength, particles on or near the surface move in circular paths in oscillatory motions through a combination of longitudinal, back and forth, and transverse, up and down wave motions. As the depth below the free surface increases, the radius of the circular motion decreases. Figure (2.9) shows a particle motion in a wave at deep water [16].

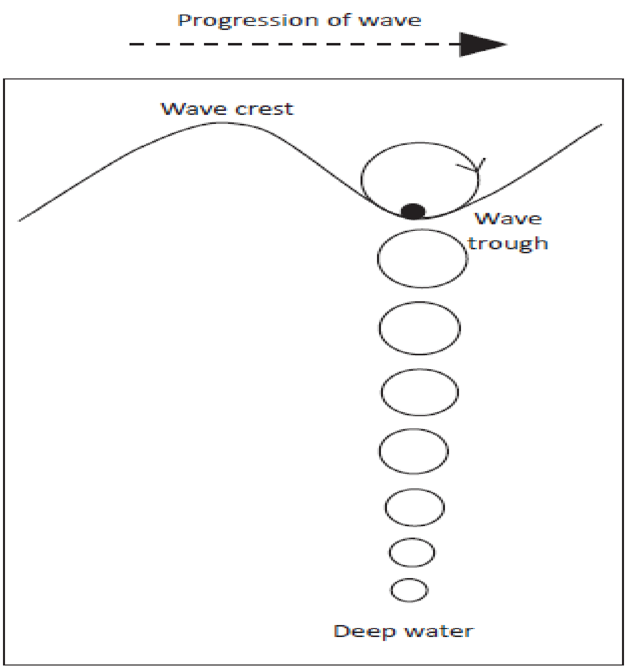

Figure (2.9): A particle motion in a wav at deep water.

In deep water, where $d \geq \frac{1}{2}\lambda$, so $\frac{2\pi d}{\lambda} \geq \pi$ and the hyperbolic tangent approaches 1, the speed c approximates by equations (2.8-2.9):

$$c_{\text{deep}} = \sqrt{\frac{g\lambda}{2\pi}} \qquad (2.8)$$

$$c_{\text{deep}} \approx 1.25\sqrt{\lambda} \qquad (2.9)$$

This means that in deep water, the wave speed is hardly influenced by water depth, but is mostly dependent on the actual wave wavelength [16].

Since several waves are travelling together in groups, as is always the case in nature, the waves are characterized by group speeds. The group speed of a wave is the speed with which the overall shape of the wave's amplitudes, known as the modulation or envelope of the wave, propagates through space. The group speed Cg is considered to be the speed at which wave energy is conveyed and transported horizontally along a wave. In deep water, the group speed is approximated as being half of the actual wave phase speed. Wave power in deep water is provided by the following equation (2.10):

$$P = \frac{\rho g^2 \, T H_{mo}^2}{64\pi} \qquad (2.10)$$

Where P is the wave power in (kW/unit length) of crest length, ρ is the sea water density in (kg/m^3), g is the acceleration due to gravity in (m/s^2), T is the period of the wave in (s), and Hmo is the significant wave height in (m), defined as the average wave height, trough to crest.

Equation (2.10) shows that the power in the wave depends on several factors, but it is mainly proportional to the square of the height and to the period of its motion.

This means that whenever the wave height and period has increased as in large storms, will be a larger amount of power.

Shallow water: where the depth is less than half the wavelength. The particle trajectories are compressed into ellipses. As the depth below the surface increases, the radius of the elliptical motion decreases; therefore, the elliptical movement flattens significantly. Therefore, the pressure fluctuations at greater depth are too small to be interesting from the point of view of wave power and this is why any wave power device or converter to exploit pressure fluctuations has to be located at the surface. Figure (2.10) shows a particle motion in a wav at shallow water [16].

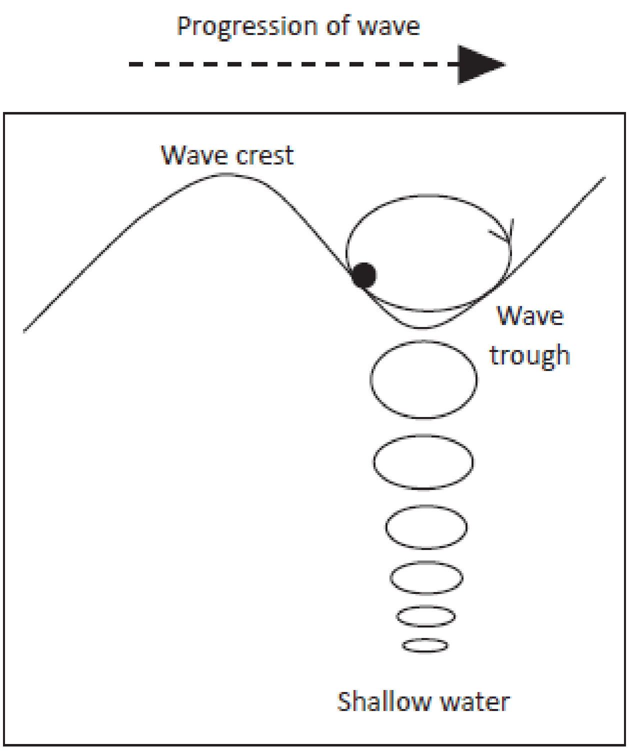

Figure (2.10): a particle motion in a wav at shallow water.

In shallow water, the wavelengths are larger than twenty times the water depth. The wave speed can be approximated by $\sqrt{gd}$ meaning that wave speed is only dependent on water depth and is no longer a function of wave period or wavelength. The waves are also characterized by group speeds. While in shallow water, the group and the phase speed are considered to be equal.

The wave group speed behaves differently for waves in deep or shallow water; therefore, the wave energy transport speed will be different accordingly. Wave power in shallow water is provided by equation (2.11):

$$P = \frac{\rho g^2 TH^2}{32\pi} \tag{2.11}$$

Where P is the wave power in (kW/unit length) of crest length, ρ is the sea water density in (kg/m^3), g is the acceleration due to gravity in (m/s^2), T is the period of the wave in (s), and H is the wave height from crest in (m), which is the highest point in a waveform, to trough, which is the lowest point in a waveform, in (m).

2.6 Wave energy absorption concept

The absorption in wave energy refers to the conversion of the incoming wave energy flux to mechanical power. Most wave energy converters are designed to have a relative motion between two or more bodies induced by the interaction with the waves. The relative motion or the wave-induced mechanical power is what drives the power train, usually referred to as the Power-Take-Off (PTO) to maximize absorption force compared to incident wave force [17], as will be discussed later.

CHAPTER THREE
WAVE ENERGY CONVERSION

3.1 Introduction

In the previous chapter, we discussed the potential energy in sea waves. Thinking began to be exploited in various fields for more than a century, some of them succeeded but the electric power generation is currently under significant research and development to join later to a series of renewable energy sources as an environment friendly source.

When a certain energy to be discovered such as wind, solar and wave. Wonderful in that you see hundreds of minds thinking about how to make it as a generator for electricity.

A machine able to exploit wave power is generally known as a wave energy converter (WEC) [14]. The first patent of a wave energy device was registered in France by the Girards father and son at the end of 18th century and since then more than one thousand patents have been filed in various countries.

It can be said that research on wave energy conversion based on adequate scientific background started in the 1970s when the oil crises provoked the exploitation of a range of renewable energy sources, including waves [18].

However, wave power generation is different from other renewable energy sources in that it is not currently a widely employed commercial technology and the majority of projects are still at an early stage.

Only a small range of devices having been tested at large scale, deployed in the oceans. The LIMPET shoreline oscillating water column (OWC), installed at Islay, Scotland, in 2000 represents one system that is currently producing power for the National Grid [19]. In September 2008, another commercial wave power system started operating in Northern Portugal. It makes use of the Pelamis power generating device [20].

The large number of wave energy converter can be due to the attention of many countries have already focused their energy strategy towards achieving maximum greenhouse gas reductions from power generation plants.

3.2 Wave power generation evaluation

In general, there are advantages and disadvantages for wave power generation, but it varies from one to another device, so we will discuss in general then comparison in terms of WEC's according to their distance from the beach.

Advantages:

- ✓ **In general:**
  - Wave power is a renewable energy source.
  - There is potential to produce large amounts of energy.
  - Waves can travel large distances with little energy loss [20].
  - Limited negative environmental impact, where it's not pollution or produces greenhouse gases.
  - Compared with other forms of offshore, such as photovoltaic, wind, or ocean current, wave energy is more continuous but highly variable, although wave levels at a given location can be confidently predicted several days in advance [16].

- ✓ **Shoreline Devices:**
  - It is near to the beach, easier to connect with the power grid.
  - Easier maintenance, repair and installation.
  - High power availability [21].
  - Have less impact on marine navigation.

- ✓ **Offshore devices:**
  - There are more places suitable to put devices with vast areas.
  - The available power offshore is higher than in shoreline installation [21].
  - Easier calculation of real energy performance in offshore devices [21].

Disadvantages:

- ☒ **In general:**
  - Nowadays, the cost of the produced sea energy cannot compete with other renewable energies or with the traditional ones [21].
  - Usually, the installation points are in a remote areas, making it difficult to transfer energy and maintenance.

- **Shoreline Devices:**
  - There is difficulty in choosing the installation point, the options are limited.
  - Low available power is lower than offshore devices.
  - Difficult calculation and predict of real energy performance.

- **Offshore devices:**
  - Its presence in a far place difficult to link in the network, in addition to higher power losses and high costs because of the longer connection cables used.
  - Maintenance costs are more than those for shoreline devices and harder to repair and mooring.
  - Affect marine navigation, there is a possibility of collisions with ships and marine species.
  - More exposure to be destroyed by storms and marine turmoil's.

3.3 Challenges of wave power generation

The evaluation of any power generation sources according to several criteria, notably the cost and efficiency of the technology, is constantly improving. Generally, to achieve these criteria successfully should be overcome the challenges that may be faced.

Wave power generation has faced significant challenges, the most important of which are:

- Presence in nearby for easy link in the network, as well as the storage problem.
- As waves vary in height and period, their respective power levels vary accordingly [20].
- In offshore locations, wave direction is highly variable, and so wave devices have to align themselves accordingly on compliant moorings, or be symmetrical, in order to capture the energy of the wave [20].
- Irregularity in wave difficult to obtain maximum efficiency of a device.

3.4 Wave energy converters (WEC's)

3.4.1 Wave energy converters classification

The large number of wave energy converters makes it difficult to general classification, but can be classified according to many categories, as follows:

- **Classification according to location:**

  A. **The shore-line converters:** are located at the shore, devices can be placed on sea bottom in shallow water, integrated in breakwater-like structures or fixed to a rocky cliff [22].

  B. **The near-shore converters:** are installed in moderate water depth, usually they are fixed to the sea bottom in order to take the most of the energy when the waves possesses [22].

  C. **The offshore converters:** are floating or submerged devices in deep waters, moored to the sea floor [22].

- **Classification according to operating principle:**

  There are several operating principles upon which WEC's design, the most important concepts for WEC's can be classified as:

  A. **Attenuator:** is a long multi-segment floating structures placed in parallel with wave direction.

  B. **Point absorber:** is a floating or submerged under sea surface buoy absorbs energy from sea waves in all directions.

  C. **Terminator:** is an oscillating water column device extend perpendicular to the direction of wave travel and capture the power of the wave.

  D. **Overtopping:** is composed of reservoirs of water filled from incoming waves. The water is released from the reservoir which drives to hydro turbines.

- **Classification according to Power Take-off system:**

  There are three most used type of PTO systems, as follows:

  A. **Air turbines:** where the air pressure exploited to drive the turbine, as found in Oscillating Water Column devices.

  B. **Linear generators:** are produces energy directly from the linear movement between the fixed stator and the moving translator [22], as found in Lysekil wave energy device .

  C. **Hydraulic systems:** these systems are able to handle large forces at slow speeds [23]. The devices which use the hydraulic usually located offshore, as found in point absorber devices.

3.4.2 Famous wave energy converters

Wave energy converters are designed to operate in certain wave climates or sea-states, and most of the device developers today have machines designed for Atlantic conditions where the wave energy potential is the greatest. The wave conditions do not only set the size of the WEC, it also determines the characteristics of the PTO [17].

Now, the most important concepts for WEC's will be discussed through the famous WEC's tested in the world, taking into account that most of the devices have been developed are still in prototype demonstration stage. Therefore, early to predict which of these devices will be reliable in the future.

3.4.2.1 Point absorber

A point absorber is a buoy floating on the water surface that is referenced to a fixed system. The device motion is due to the heave displacement caused by a passing wave and the relative heave motion between the two bodies is used to extract power. Point absorber devices can be designed to work at near shore and off shore sites and at most sea states and can be designed for short or long wave periods [17].

These devices are basically offshore oscillating bodies because they exploit the more powerful wave available in deep water. Also, some of these devices designed with the submerged structure below the surface relying on pressure differential instead of floating. There are many devices that rely on the point absorber principle, as follows:

A. **Power Buoy Device:**

   Consists of a cylindrical structure with one component relatively fixed as the bottom, and a component with movement driven by wave motion as the top end floating buoy inside a fixed cylinder.

   The relative motion of the two components which is caused by the rising and falling of the waves is used to drive electromechanical generators or hydraulic energy converters. The electric power generated is transmitted to shore over a submerged transmission line [16] (Fig. 3.1).

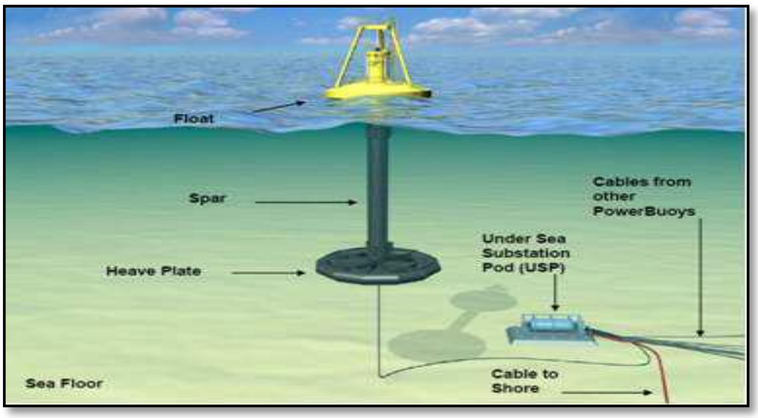

Figure (3.1): Principle of operation of Power Buoy wave technology.

B. Aqua Buoy Device:

Utilize the wave energy to pressurize a fluid that is then used to drive a turbine generator. The vertical movement of the top floating buoy drives a broad, neutrally buoyant disk acting as a water piston contained in a long tube beneath the buoy. The water piston motion in turn elongates and relaxes a hose containing seawater, and the change in hose volume acts as a pump to pressurize the seawater [16] (Fig. 3.2).

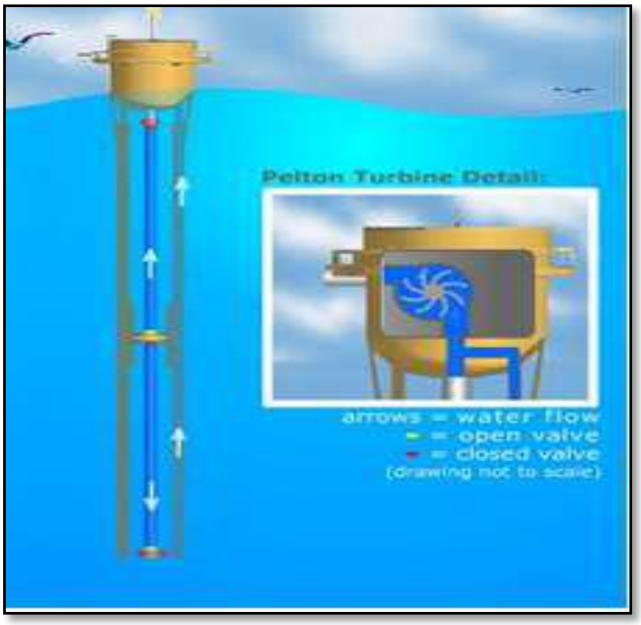

Figure (3.2): Principle of operation of Aqua Buoy wave energy technology.

C. Archimedes Wave Swing Device:

This device falls within submerged pressure converters, also called Direct Drive, are typically located near shore and attached to the seabed.

The motion of the waves causes the sea level to rise and fall above the device, inducing a pressure differential in the WEC. The alternating pressure can then pump fluid through a system to generate electricity [12].

The AWS consists of a hollow cylinder and a lid, called floater. The cylinder is filled with air, and is fixed on the sea bottom. The floater moves in the vertical direction. When the wave comes, the floater sinks because of increase of the weight of the water above, while the pressure of the air in the cylinder increases; when the wave trough is above the AWS, the weight of the water above decreases, and the floater moves up by the pressure of the air in the cylinder [24].

The AWS device went for several years through a program of theoretical and physical modeling. The AWS was the first converter using a linear electrical generator [16] (Fig. 3.3 a-b).

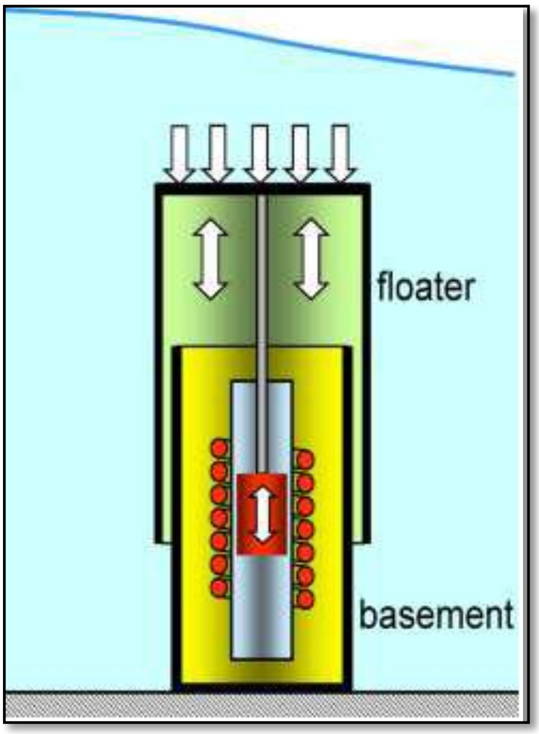

Figure (3.3a): Principle of operation of the Archimedes wave Swing.

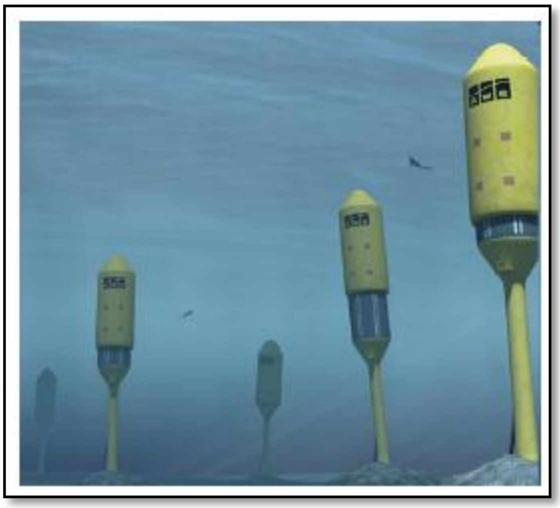

Figure (3.3b): Archimedes wave Swing devices.

D. CETO Device:

The device consists of piston pumps attached to the sea floor with a fully submerged float tethered to the piston. The oscillatory motion of the float due to water motion generates pressurized water from the pistons, which is piped to an onshore facility to drive hydraulic generators or run a reverse osmosis water desalination plant [16].

Instead of generating electricity offshore which then has to be transmitted at high voltage to the shore, the CETO system instead pumps large volumes of sea water directly to shore at high pressure. Some of this seawater is used to turn an electricity generating pelton-type hydro turbine while the rest can be desalinated and converted into drinkable freshwater [25] (Fig. 3.4).

Figure (3.4): Principle of operation of the CETO devices.

E. SDE Device:

The device is made of buoys which are placed on a breakwater, or on some other sea based structure, which create a vertical motion, according to the frequency of the sea wave. The buoys' movement presses on a hydraulic liquid [26].

In other words, this device utilizes the vertical motion of buoys to yield hydraulic pressure that produces electricity, by exploiting the full potential of wave speed, height, depth, rise and fall, and currents beneath the surface of the water (Fig. 3.5).

The SDE device operated and tested in Jaffa Port.

Figure (3.5): SDE device.

The following table shows the available point absorber wave energy devices:

Table (3.1) Indicates list of installed point absorber type wave energy devices (mid 2013) [16].

Device	Company	Type	Status	Unit power (kW)	Country installed
Archimedes Wave Swing	Teamwork Technology BV	Fixed near shore, fully submerged	Prototype/ Demonstration	2000	Portugal
CETO	Carnegie Wave Energy	Fixed near shore, fully submerged	Prototype/ Demonstration	400	Australia
AquaBuOY	Finavera Renewables	Offshore, floating non-fixed	Prototype/ Demonstration	250	USA
Swedish buoy (Lysekil)	Uppsala University	Fixed offshore	Prototype/ Demonstration	To reach 100	Sweden
PowerBuoy	Ocean Power Technologies	Ofshore, floating non-fixed	Prototype/ Demonstration	50	USA
SDE	SDE Energy	Fixed near shore	Prototype/ Demonstration	40	Israel

Through the previous table, it appears that all of these devices are still in the prototype status, and vary in amount of power produced, but this is not enough yet and need to develop and overcome the challenges they face to become reliable commercial technology to compete with other renewable energy technologies.

3.4.2.2 Terminator

Is oscillating water column device, this is the case of the LIMPET device. LIMPET (Land Installed Marine Powered Energy Transformer) is a shoreline WEC ideally placed to generate electricity in areas exposed to strong wave energy. It is placed on the island of Islay, off Scotland west coast (Fig. 3.6). The current LIMPET device (LIMPET 500 kW) was installed in 2000 and produces power for the UK grid [12].

Figure (3.6): The LIMPET project in Islay installation.

The device generate electricity from the wave-driven rise and fall of water in a chamber. The rising and falling water column drives air into and out of the top of the shaft to drive air turbine (Fig. 3.7).

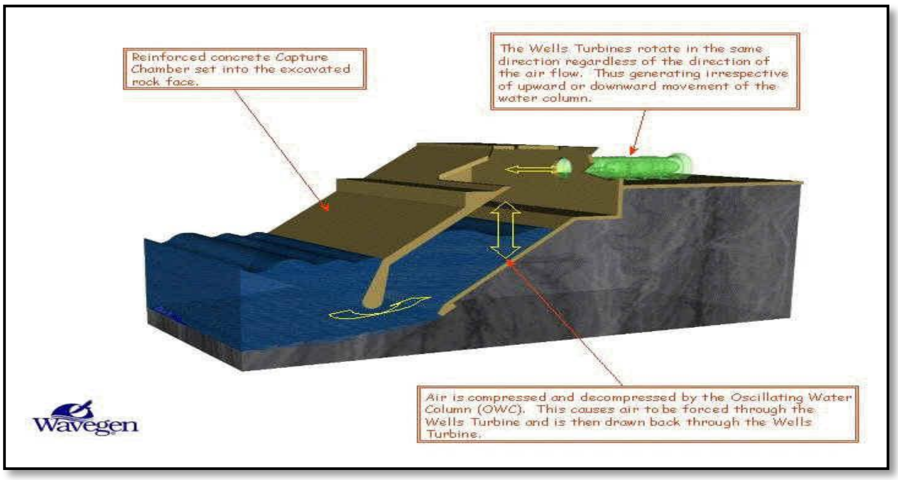

Figure (3.7): Schematic of the LIMPET device.

3.4.2.3 Attenuator

Is a long multi-segment floating structures placed in parallel with wave direction. An example of an attenuator WEC is the Pelamis device (Fig. 3.8).

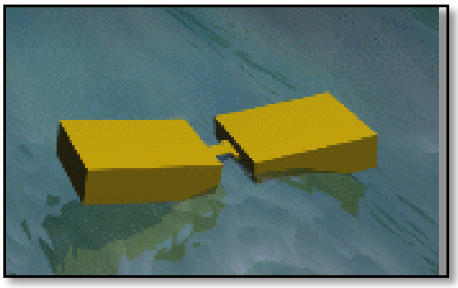

Figure (3.8): Principle of operation of the attenuator technique.

Pelamis is a wave power generator which has been successfully installed three miles off the northern coast of Portugal (Fig. 3.9). This is the first commercial scale wave power station in the world. The sea snake-like device is made up of a series of three semi-submerged cylinders linked by hinged joints. Each cylinder has a 3.5-m diameter and is made from 700-tones of carbon steel. The motion of each hinge is resisted by hydraulic rams driving generators which produce electricity.

Figure (3.9): Pelamis installation in northern coast of Portugal.

3.4.2.4 Overtopping devices

This type of WEC relies on physical capture of water from waves which is held in a reservoir above sea level, before being returned to the sea through conventional low-head turbines which generates power. An overtopping device may use collectors to concentrate the wave energy (Fig. 3.10) [27]. Overtopping devices can be designed for both onshore and floating offshore. An example of an Overtopping WEC is the wave dragon.

Wave dragon is an offshore floating overtopping WEC device. It consists of two parabolic reflecting arms, a double curved overtopping ramp, a storage basin and multiple low head turbines [12].

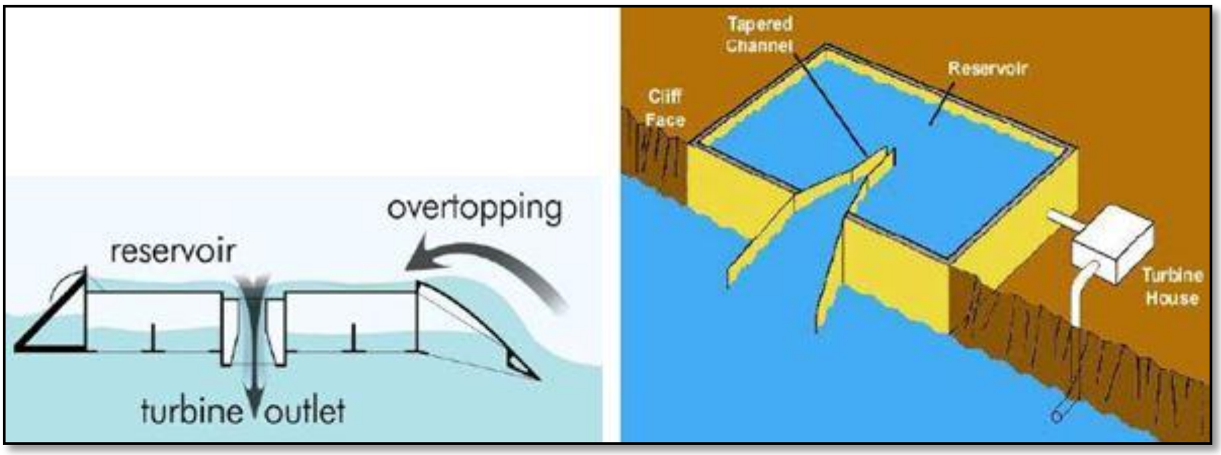

Figure (3.10): Principle of operation of Wave dragon device.

CHAPTER FOUR
DESIGN AND SIMULATION

4.1 Introduction

In previous chapter, we have seen many famous converters for wave energy. The conditions such as water depth and wave climate (i.e. wave height and period) will determine what is the best technology for a given site.

Most of the WEC's that have developed around the world were designed for oceans. Point absorber device more appropriate for the sea, where the waves height and period lower than those in the oceans.

In this thesis, a point absorber device was simulated in order to convert energy in the east coast of the Mediterranean Sea. The simulation results from Gaza Strip can certainly be applicable to all countries located on the eastern Mediterranean.

Figure (4.1) shows the geographical map of the eastern Mediterranean.

Figure (4.1): The geographical map of the eastern Mediterranean.

The Reference Model 3, (RM3) two-body point absorber, is designed through DOE's reference model project (RMP). This device was selected because it was modeled using WEC-Sim an open source tool. It also one of the best converters of the sea waves.

The WEC is free to move in all 6 DOF in response to wave motion. Power is captured in the relative heave direction, consisting of a float and a spar/plate, the full-scale dimensions and mass properties of which are shown in figure 4.2 and table 4.1 [28]. The geometry simulated by WEC-Sim tool and MATLAB codes to get experimental data.

Figure (4.2) shows the RM3 model two-body point absorber full-scale dimensions [28].

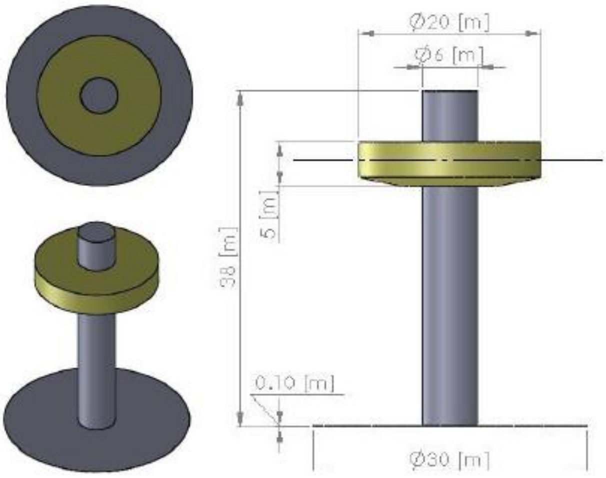

Figure (4.2): RM3 heaving two-body point absorber full-scale dimensions.

Table 4.1: RM3 heaving two-body point absorber full-scale mass properties.

Float Full Scale Properties				
CG [m]	Mass [tonne]	Moment of Inertia [kg-m²]		
0	727.01	20907301	0	0
0		0	21306090.7	4304.89323
-0.72105		0	4304.89323	37085481.1
Plate Full Scale Properties				
CG [m]	Mass [tonne]	Moment of Inertia [kg-m²]		
0	878.30	94419614.6	0	0
0		0	94407091.2	217592.785
-21.285		0	217592.785	28542224.8

4.2 WEC-Sim tool

4.2.1 Introduction [28]

WEC-Sim is a multilaboratory project sponsored by the U.S. Department of Energy's Wind and Water Power Technologies. WEC-Sim code development is a collaboration between the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (SNL). The first public version was released in June 30, 2014 as version 1.

WEC-Sim (Wave Energy Converter SIMulator) is an open source wave energy converter (WEC) simulation tool. The code is developed in MATLAB and Simulink using the multibody dynamics solver SimMechanics. WEC-Sim has the ability to model devices that are comprised of rigid bodies, power-take-off (PTO) systems, and mooring systems. Hydrodynamic forces are modeled using a radiation and diffraction method, and the system dynamics is performed in the time domain by solving the governing WEC equations of motion in 6 degrees of freedom (DOF).

4.2.2 Downloading and installing WEC-Sim

Download WEC-Sim from the Open website http://en.openei.org/wiki/WEC-Sim/.

WEC-Sim is implemented in MATLAB and running the code requires installing MATLAB R2014a Which contains the necessary toolboxes for WEC-Sim presented in Table 4.2.

Table (4.2): Required MATLAB toolboxes.

Matlab package	Required release
MATLAB Base	R2014a Version 8.3
Simulink	R2014a Version 8.3
SimMechanics	R2014a Version 4.4
Simscape	R2014a Version 3.11

To use the WEC-Sim in MATLAB, you must add the WEC-Sim Source Code to the MATLAB Search Path, also Add the WEC-Sim Blocks to the Simulink Library Browse, as shown in Fig. (4.3 a-b).

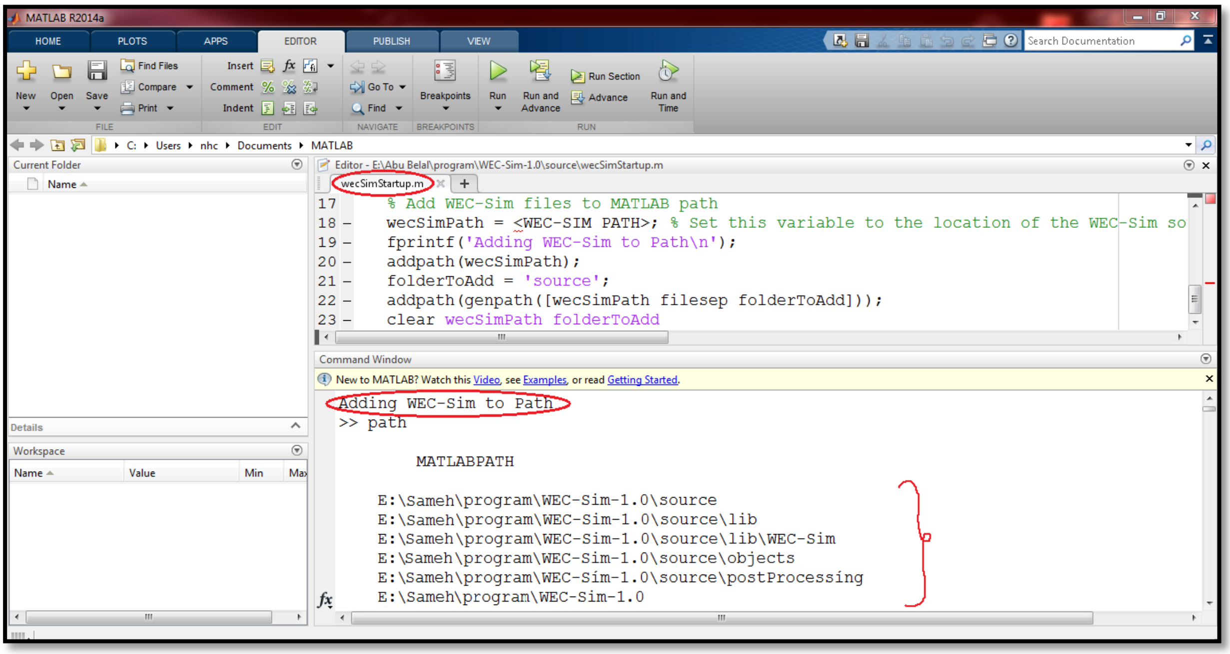

Figure (4.3 a): Add the WEC-Sim source code to the MATLAB search.

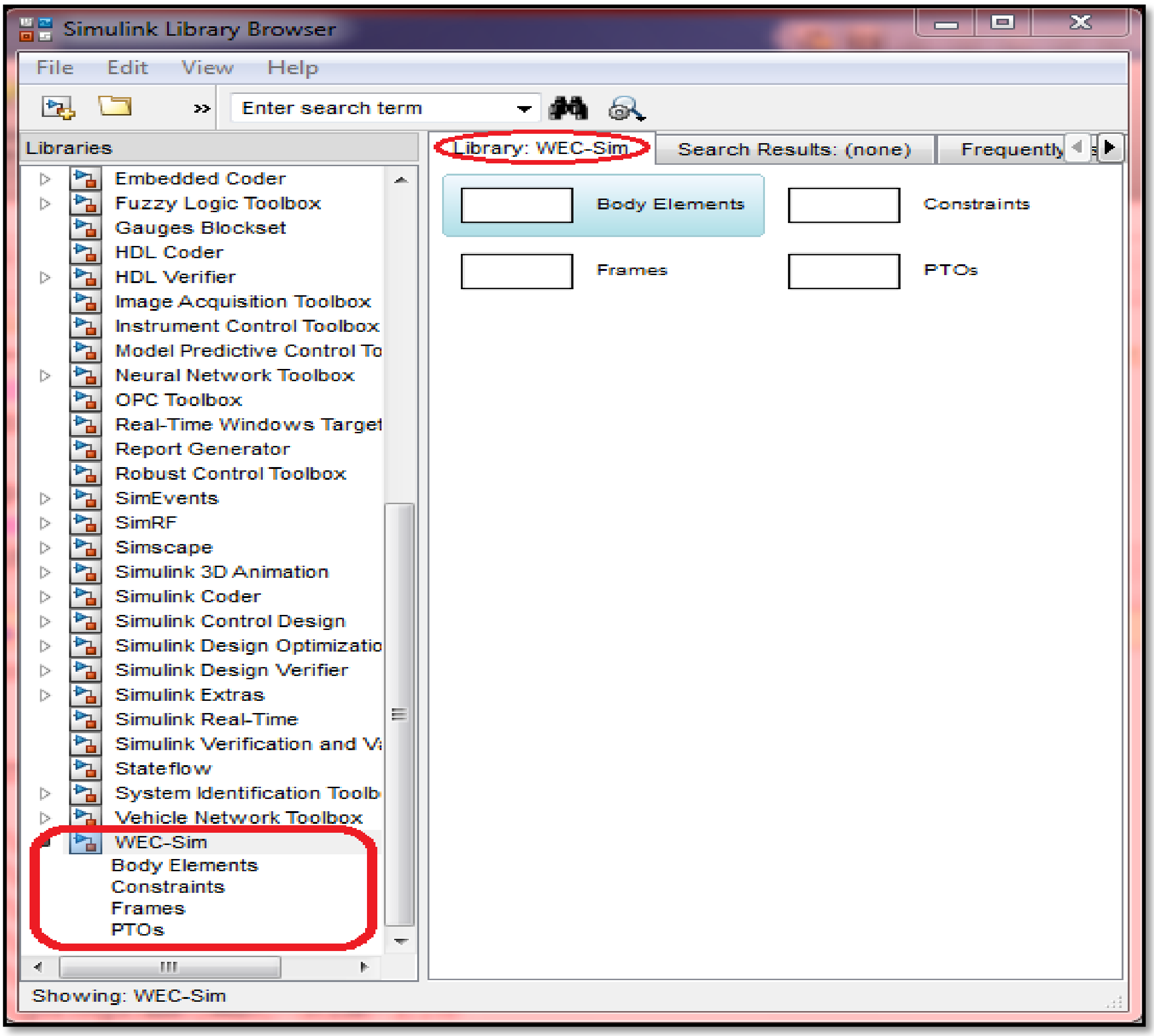

Figure (4.3 b): Add the WEC-Sim blocks to the Simulink Library Browse.

4.2.3 WEC-Sim contents [28]

In general, this tool contains two structures code and library, as following:

1. **Code structure:**

   All data that are needed for a WEC-Sim simulation are contained within simu, body, waves, pto and constraint variables that are instances of the simulationClass, bodyClass, wavesClass, and jointClass objects, respectively. These objects are created in MATLAB classes. The user can interact with these variables within the WEC-Sim input file, wecSimInputFile.m. Description of the classes mentioned above are as follows:

   - simulationClass: contains the simulation parameters and solver settings needed to execute WEC-Sim.

- bodyClass: contains the mass and hydrodynamic properties of each body that comprises the WEC device being simulated. Each body must have a bodyClass initiated in the input file.
- waveClass: contains all the information that defines the wave conditions.
- constraintClass : The constraint object is used to connect bodies to the Global Reference Frame.
- ptoClass: the pto object extracts power from body motion with respect to a fixed reference frame or another body. It can also constrain motion to certain degrees of freedom.

A WEC-Sim input file is required for each run. It MUST be placed inside the case directory for the run and MUST be named wecSimInputFile.m. The input file contains information needed to run WEC-Sim simulations. Specifically, it serves the following four primary functions:

- Specification of Simulation Parameters.
- Specification of Body Parameters.
- Specification of Wave Parameters.
- Specification of Power Take-Off and Constraint Parameters.

Note: All units within WEC-Sim are in the MKS (meters-kilograms-seconds system) and angular measurements are specified in radians unless otherwise specified.

2. Library structure:

The WEC-Sim library is divided into 4 sublibraries. The user should be able to model their WEC device using the available WEC-Sim blocks, and possibly some SimMechanics blocks. Table 4.3 lists the WEC-Sim blocks and their organization into sublibraries.

Table (4.3): WEC-Sim library structure.

Sublibrary	**Blocks**
Body Elements	Rigid Body
Frames	Global Reference Frame
Constraints	Heave Pitch Surge

	Fixed Floating
PTOs	Rotational PTO (Local RY) Translational PTO (Local X) Translational PTO (Local Z)

The general purpose for each sublibrary as following: the Body Elements sublibrary contains the Rigid Body block used to simulate the different bodies, the Frames sublibrary contains the Global Reference Frame block necessary for every simulation, the Constraints sublibrary contains blocks that are used to constrain the DOF of the bodies. Without including any additional forcing or resistance, the PTOs sublibrary contains blocks used to both simulate a PTO system and restrict the body motion. Both constraints and PTOs can be used to restrict the relative motion between multi-body systems.

4.3 Steps to run WEC-Sim

To simulate any device by using WEC-Sim tool needs necessary files presented in the table 4.4, located within a user defined folder for running the tool.

Table (4.4): Default files required for running the tool.

File description	File name
Input file	wecSimInputFile.m
WEC Model	WEC Model Name.slx
WAMIT	WAMIT File Name.out
Geometry	STL File Name.stl

Now, the steps to setting up and running a WEC-Sim simulations are pre-processing, build device simulink/simMechanics model, create WEC-Sim input file and execute WEC-Sim. The four steps overviewed in a work flow as shown in fig. (4.4) and described as follow:

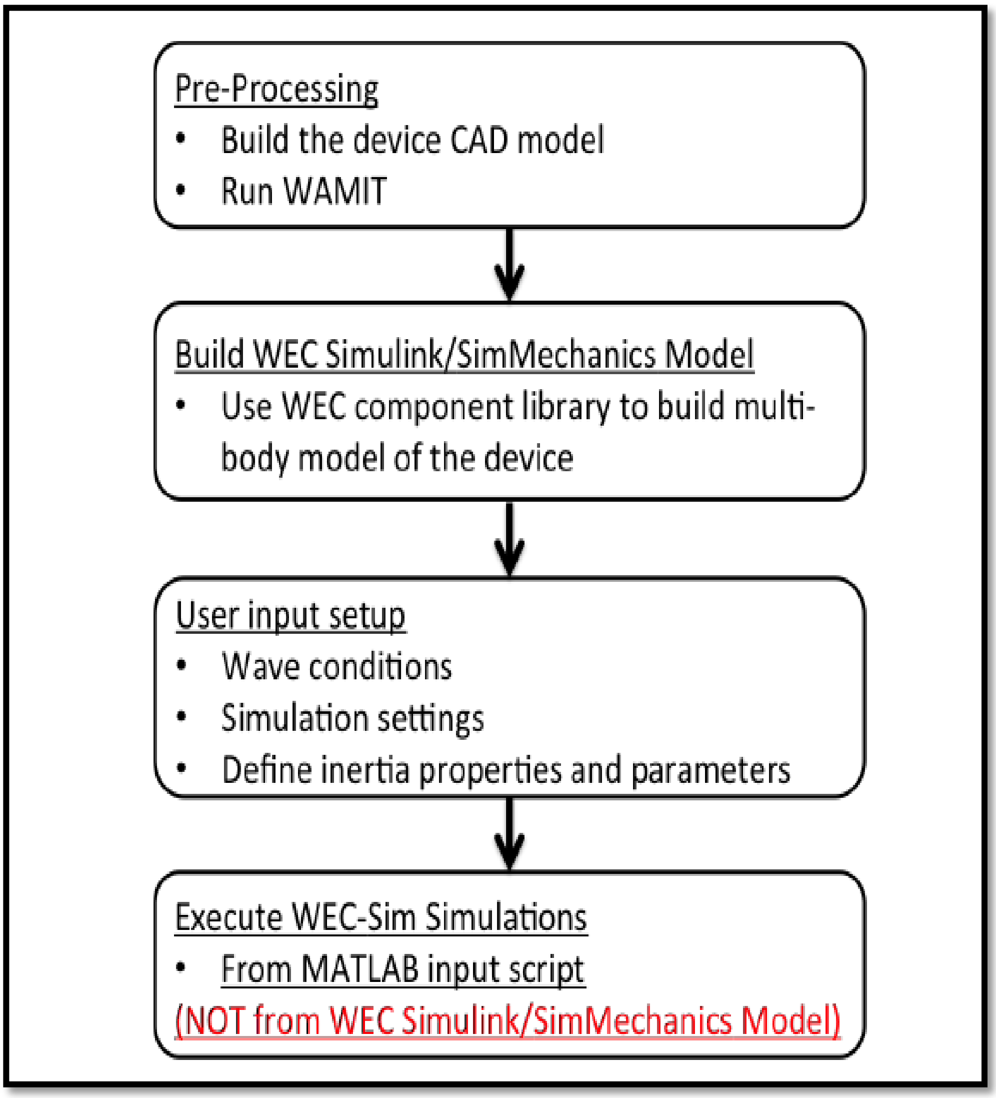

Figure (4.4): Work flow diagram for running WEC-Sim simulations.

Step 1: Pre-Processing

This step is achieved through two works: build the device CAD model and obtain the hydrodynamic coefficients for each body of the WEC device.

- **CAD model:** the user must create representations of the WEC bodies in the STL file format, there are many programs to work 3D-CAD Models of the most famous SolidWorks software.

  STL files are used to visualize the WEC bodies in the WEC-Sim/MATLAB graphical user interface.

Figure (4.5 a-b) shows the CAD model of a float and plate in RM3 point absorber respectively.

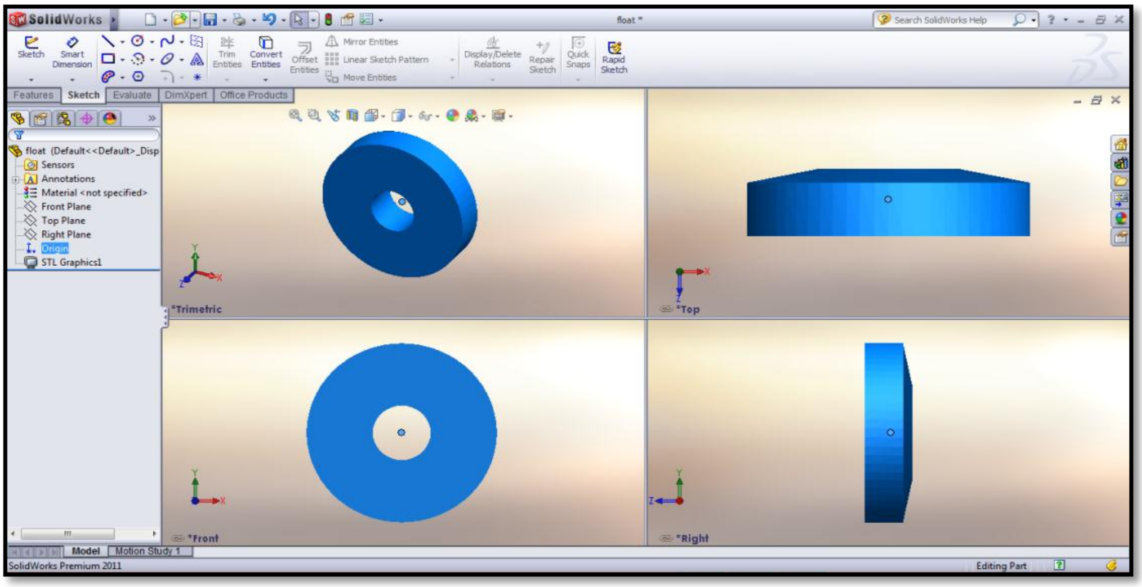

Figure (4.5 a): CAD model of a float in RM3 point absorber.

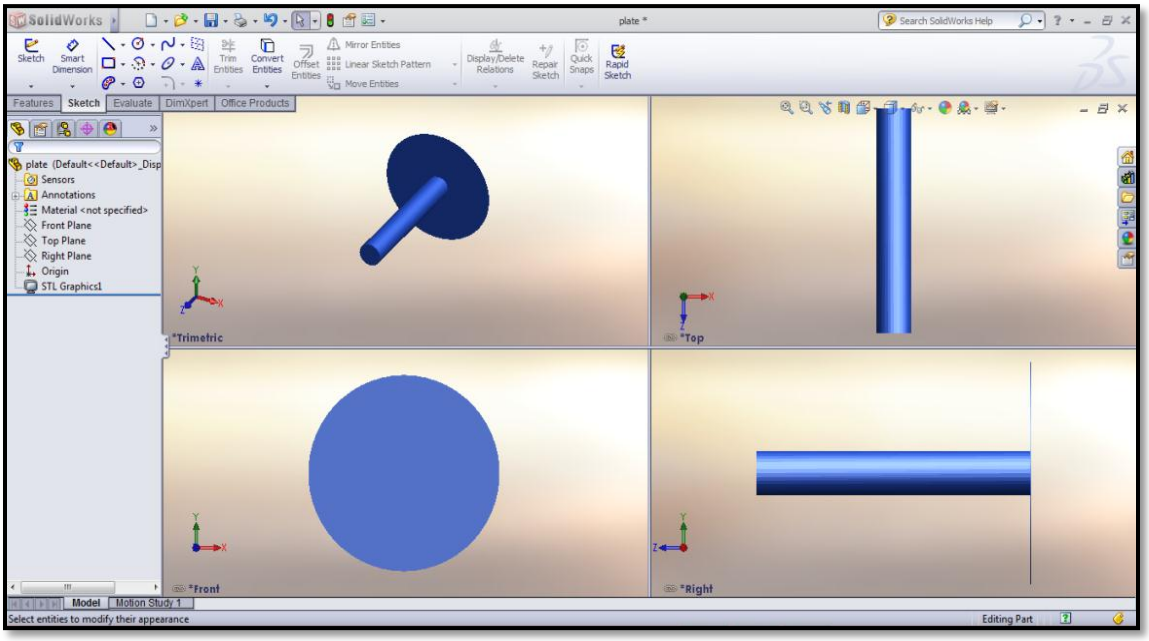

Figure (4.5 b): CAD model of a plate in RM3 point absorber.

- **Run WAMIT:**

  To generate the hydrodynamic coefficients for each body of the WEC device, we use the WAMIT program. WAMIT is a radiation/diffraction program developed for the analysis of the interaction of surface waves with offshore structures. WAMIT has gained widespread recognition for its ability to analyze complex structures with a high degree of accuracy and efficiency.

WEC-Sim will read the generated hydrodynamic coefficients from the WAMIT output file (<wamit file name>.out).

In this thesis, the WEC-Sim tool was used to measuring the efficiency of the Eastern Mediterranean Sea for production of electrical power from two- body point absorber WEC Device, so the CAD design and WAMIT file for the RM3 model used to ensure the accuracy of the results.

Note: if anyone wants to design another WEC device, he will need to add a program used in CAD design such as Rhinoceros 3D program.

Rhinoceros can be used as a secondary program because analyzing a model in WAMIT requires the input model to be converted to a mesh and saved in a compatible file format. SolidWorks can perform neither of those actions. The simplified model saved in SolidWorks as a .STEP file. This file is then opened in Rhino, and the resulting polygon mesh for the model saved as a .GDF file, compatible with wamit.

Figure (4.6 a-b) shows the CAD model of a float and plate for RM3 point absorber in Rhino 4.0 respectively.

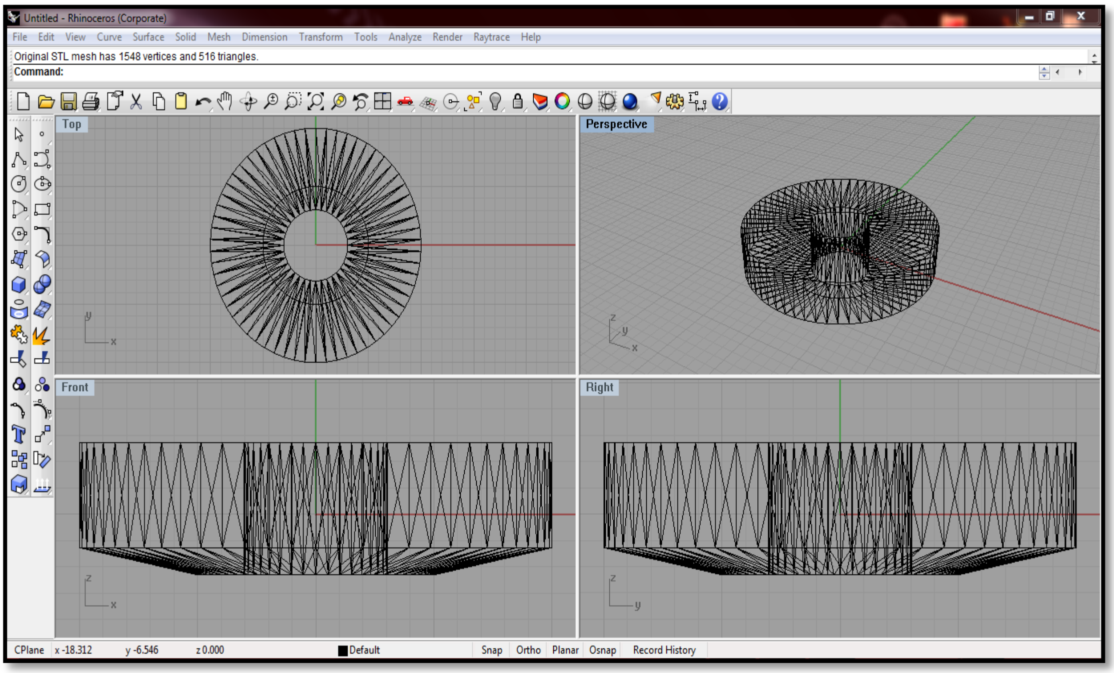

Figure (4.6 a): CAD model of a float for RM3 point absorber in Rhino 4.0.

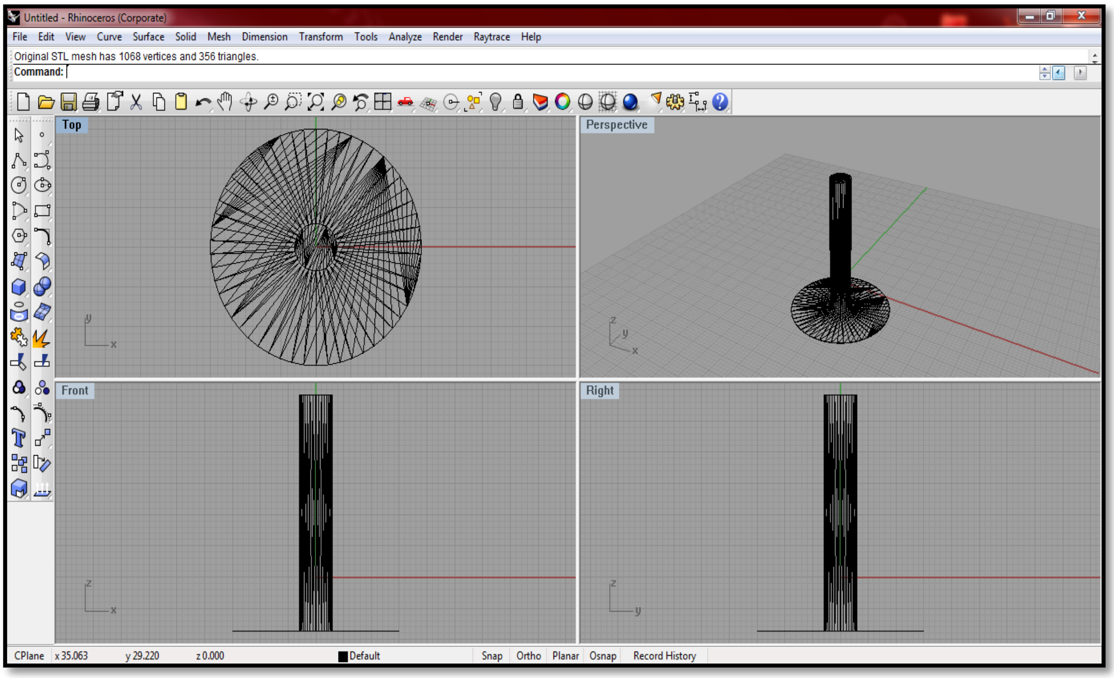

Figure (4.6 b): CAD model of a plate for RM3 point absorber in Rhino 4.0.

Step 2: Build Device Simulink/SimMechanics Model

The device model must be built using the Simulink/SimMechanics toolboxes and the WEC-Sim Library, as shown in fig. (4.7).

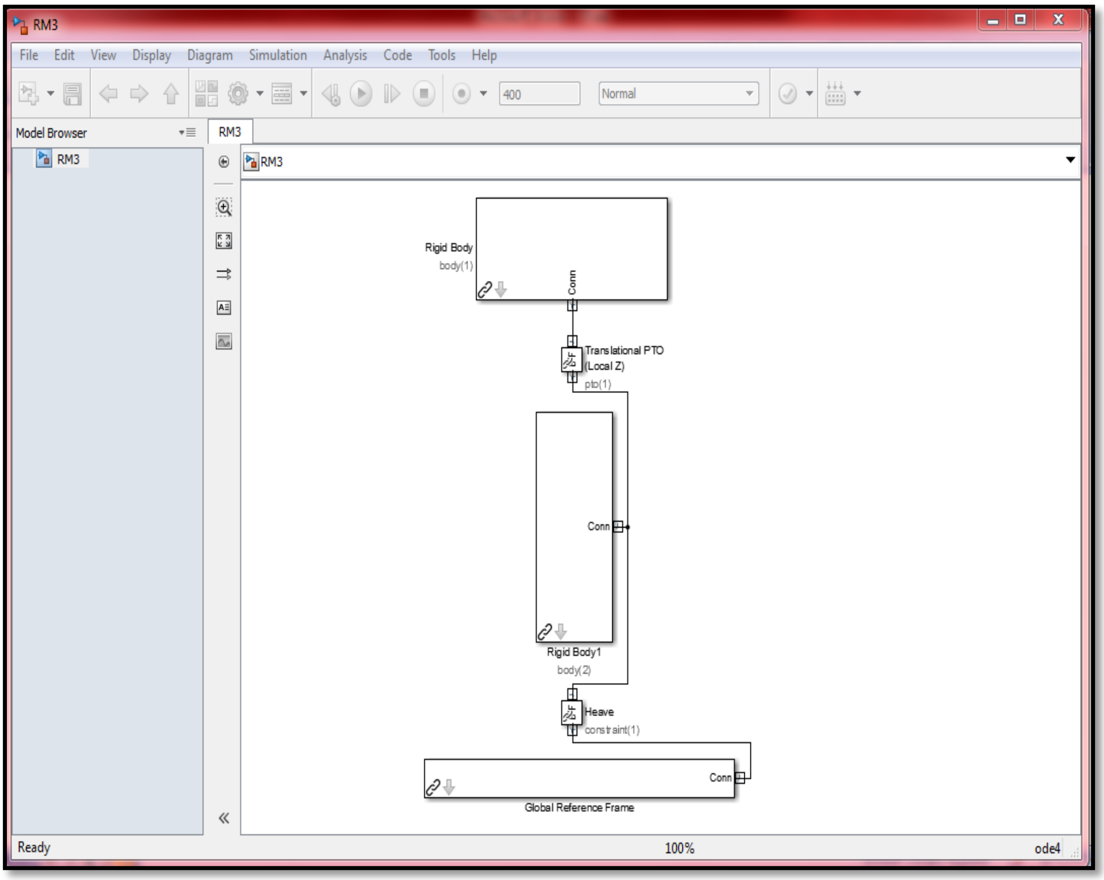

Figure (4.7): A two-body point absorber modeled in Simulink/SimMechanics.

Step 3: Create WEC-Sim Input File

A WEC-Sim input file needs to be created in the case directory, and it must be named wecSimInputFile.m. In the input file, the simulation settings, sea state, body mass properties, PTO, constraints and the Simulink/SimMechanics model file name which was designed in step2 are specified.

The specified input parameters used for RM3 point absorber are shown in table (4.5).

Table (4.5) Input parameters used for the RM3 point absorber in MATLAB.

Input Parameter	Value
End Time [s]	3600
Step_Time [s]	1
Wave Height [m]	Variable according to the data in table (4.3.).
Wave Period [s]	Variable according to the data in table (4.3.).
Type of Waves	Irregular
Wave Spectrum Type	BS
PTO Stiffness Coeff. K [N/m]	0
PTO Damping Coeff. c [KNs/m]	1200

Wave spectrum type (BS) is Bretschneider Spectrum, which is given in appendix (A). We can take the value readings for both mean wave Height and period of the areas east of the Mediterranean recorded by the weather forecast sites, the Israel Marine Data Center (ISRAMAR) [29] and National & Kapodistrian University of Athens [30]. Mean values of a year ago are presented by Tables 4.6.

Table (4.6): Mean values for Height and period.

Mean Wave Height (m)					
JAN	**FEB**	**MAR**	**APR**	**MAY**	**JUN**
0.57- 1.07	0.63- 1.13	0.5-1	0.5- 1	0.45- 0.95	0.43- 0.92
JUL	**AUG**	**SEB**	**OCT**	**NOV**	**DEC**
0.41- 0.91	0.43- 0.93	0.42- 0.92	0.44- 0.94	0.55- 1	0.54- 1
Mean Wave Period (s)					
JAN	**FEB**	**MAR**	**APR**	**MAY**	**JUN**
4.1- 5.7	4.2- 5.8	3.8- 5.4	3.7- 5.3	3.6- 5.2	3.5- 5.1
JUL	**AUG**	**SEB**	**OCT**	**NOV**	**DEC**
3.4- 5	3.5- 5.1	3.4- 5	3.5- 5.1	3.9- 5.5	3.9- 5.5

Step 4: Execute WEC-Sim

Finally, execute the simulation by running the wecSim command from the MATLAB Command Window (figure 4.8).

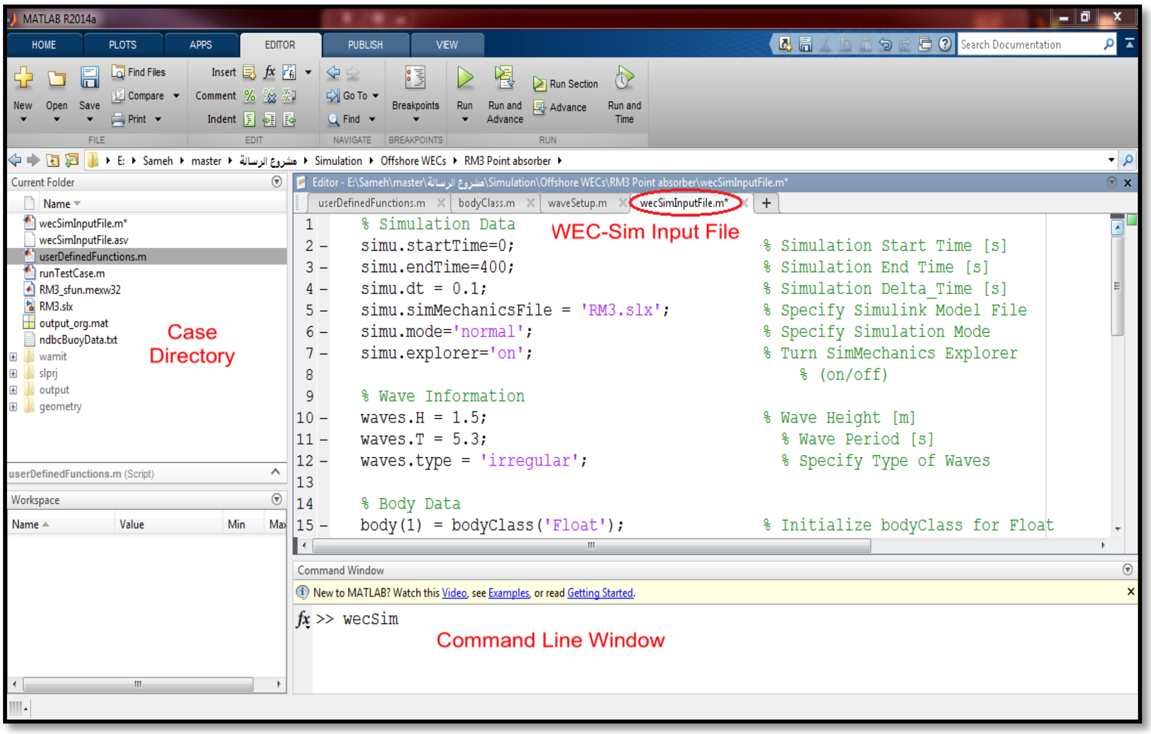

Figure (4.8): Running WEC-Sim.

4.4 Simulation outputs

All simulation outputs are saved in the output variable within the MATLAB workspace. Specifically, the output variable contains forces and motions of the WEC bodies, PTOs, and constraints. The output data file also contains time step information from the simulation.

At the completion of a simulation, WEC-Sim also saves all simulation data in the output directory within the WEC-Sim case file in three data files:

- <case name> simulationLog.txt : This text file contains all information displayed in the MATLAB command window during a simulation.
- <caseName> output.mat : This MATLAB data file contains forces and motions of the WEC bodies, PTOs, and constraints. The data file also contains time step information from the simulation.
- <caseName> matlabWorkspace : This MATLAB data file contains all workspace variables from the simulation. Note that this variable also contains the output.mat data in a variable named output.

Through the output data we get the power generated at each step Irregularly by the RM3 WEC device, we can take the average during a certain time. In addition, after making each simulation process of the different height and period values. Also RM3 modeled in WEC-Sim with the GUI MATLAB program.

Figure (4.9) Shows the output simulation in MATLAB program.

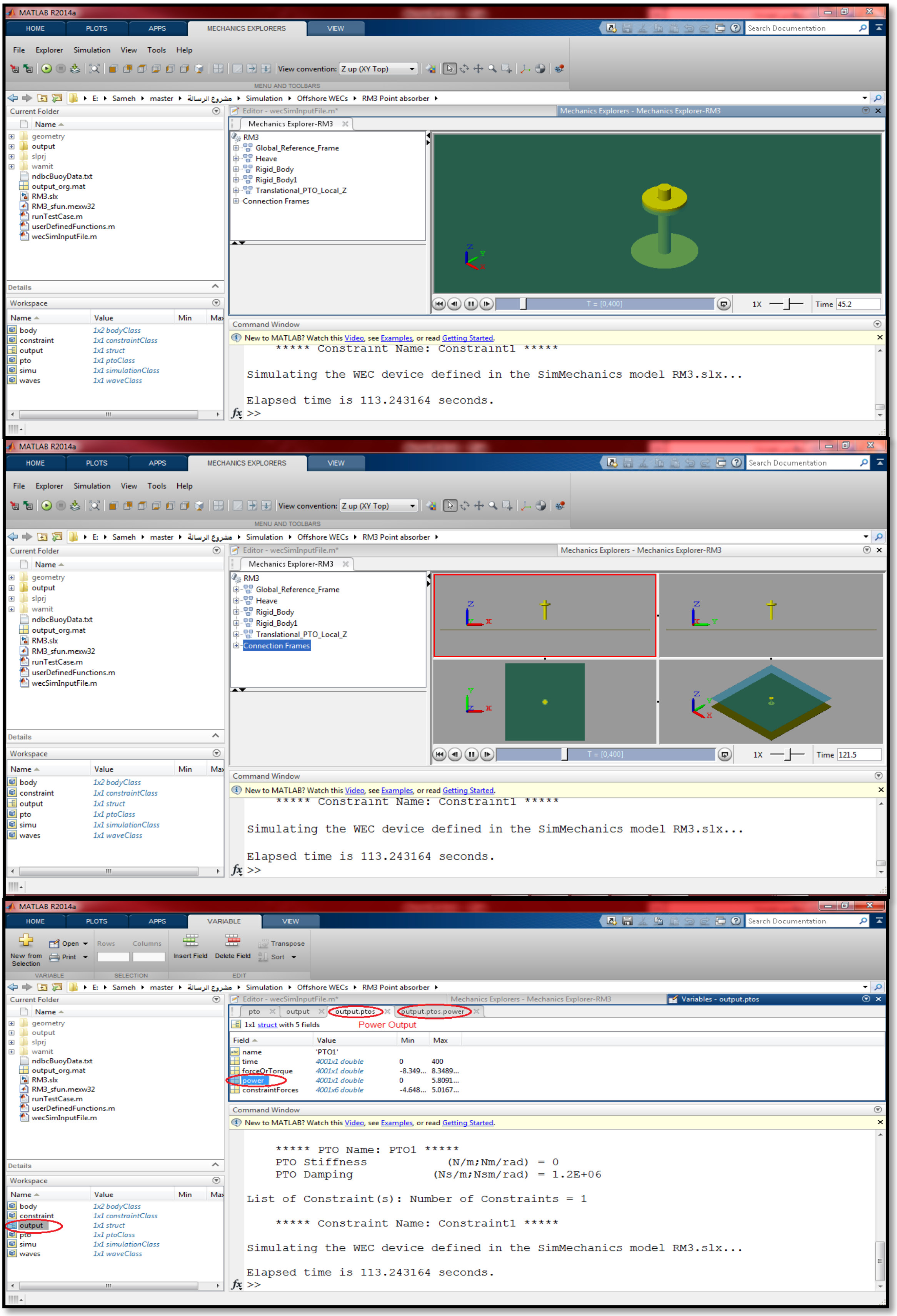

Figure (4.9): Output simulation in MATLAB program.

CHAPTER FIVE
RESULTS AND DISCUSSION

5.1 Introduction

In the previous chapter, the RM3 is modeled with specified input parameters values listed in tables (4.5-4.6). We run simulations using WECSim tool on Matlab platform, then analyze results.

The specified input parameters values listed in Table (4.5) are fixed in each simulation process, but each time the height and period of waves are changed according to the data listed in Table (4.6). Thus, each simulation contains wave data in a particular month of the year to measure the average power.

In this chapter, the power output of the device is calculated for each sea state to obtain the so-called power matrix, which is a bivariate matrix indicating the average power generated by the WEC as a function of significant wave height and wave period. The sketch shows the average electrical output power available for each month of a year, in addition to some of the graphics that illustrate the impact of the height and period of waves on the output power.

5.2 Simulation results

WEC-Sim Matlab tool is used in the simulations of project for (3600) seconds in each simulation and step time (1) s, PTO Stiffness Coeff. K equal zero N/m, PTO Damping Coeff. c (1200000) KNs/m in the irregular waves environment with (BS) wave spectrum type.

The results obtained from (output.mat) Matlab data file are shown in the power matrix Table (5.1). power matrix is a means of representing the output power values when there is two input variables as height and period.

Table (5.1): Power matrix (in watt).

T \ H	0.4	0.45	0.5	0.55	0.6	0.65	0.7	0.75	0.8	0.85	0.9	0.95	1	1.5
3.5	198	252	312	377	452	524	613	704	798	903	1009	1134	1252	2815
3.7	304	386	478	579	688	811	941	1071	1213	1372	1528	1706	1910	4300
3.9	442	566	690	839	995	1181	1362	1570	1776	2011	2248	2518	2780	6285
4.1	624	789	963	1161	1393	1626	1887	2174	2468	2786	3145	3504	3849	8802
4.3	826	1052	1300	1566	1854	2200	2549	2943	3303	3730	4219	4711	5182	11657
4.5	1074	1364	1673	2030	2427	2833	3298	3737	4265	4783	5383	6015	6704	15030
4.7	1351	1687	2093	2523	3047	3534	4087	4726	5363	6064	6823	7572	8370	18981
4.9	1644	2055	2526	3083	3649	4304	5004	5690	6506	7374	8255	9123	10281	22777
5.1	1941	2420	3011	3664	4345	5091	5943	6813	7819	8667	9770	10892	12021	27009
5.3	2244	2831	3478	4212	5069	5921	6795	7921	8951	10085	11185	12627	13929	31502

After numerical results are tabulated in the previous power matrix, Figure (5.1) demonstrates these results.

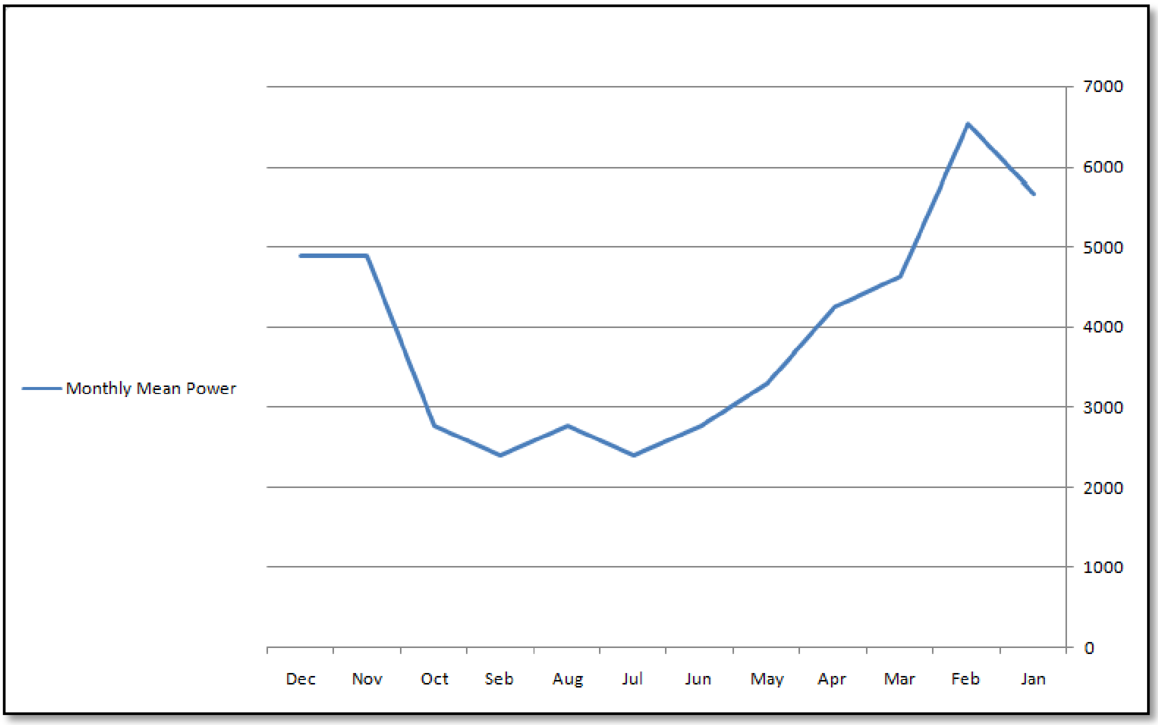

Figure (5.1): The average electrical output power available for each month of a year.

The previous figure shows the monthly mean power of the results in the power matrix according to the values of waves height and period in each month.

From the power matrix we note that the highest value that can be obtained from the device is 31.5 kW when T=5.3 s and H=1.5 m during January and February. At the same time, when the monthly average is taken, we find that it doesn't exceed the 6.5 kW which is capable of lighting about 5 homes. While in the lower average, we find that it doesn't exceed the 2.4 kW which is capable of lighting about 2 homes only.

These results mean that the output power produced from the device can be up to average 6.5 kW during the winter and 2.4 kW during the summer. In the autumn and spring, the output ranges between 2.4-6.5 kW; however, there are a vast difference.

Of course, this change in output power due to climate change. This is the disadvantage of renewable energies that they are not always available (e.g. in the summer weak waves reduce wave energy, droughts reduce water availability to produce hydroelectricity, cloudy days reduce solar energy, and calm days mean no wind blows to drive wind turbines…etc).

Since the wave height and period are the two main input variables on the output power. Figure (5.2) shows the the relationship between each of them and the output.

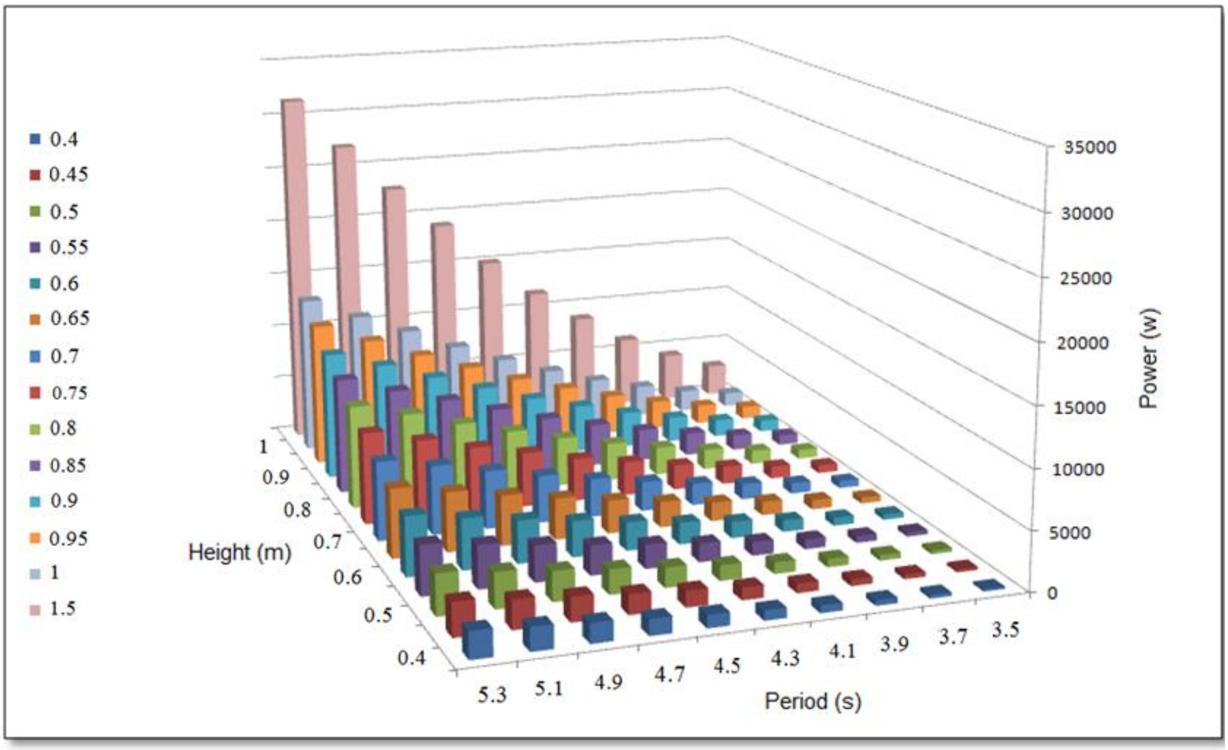

Figure (5.2): The impact of the height and period of waves on the power output.

From Figure (5.2), it is clear that the output power is proportional to the two input variables height and period for waves. However, it is noted that there is a difference in effect degree of each on the power output. When height is more than 1 meter rise there is a greater difference in the output increasing, while the output increases regularly with increasing period.

Figure (5.3 a-b) illustrates the effect of increasing height and period waves when taking higher values.

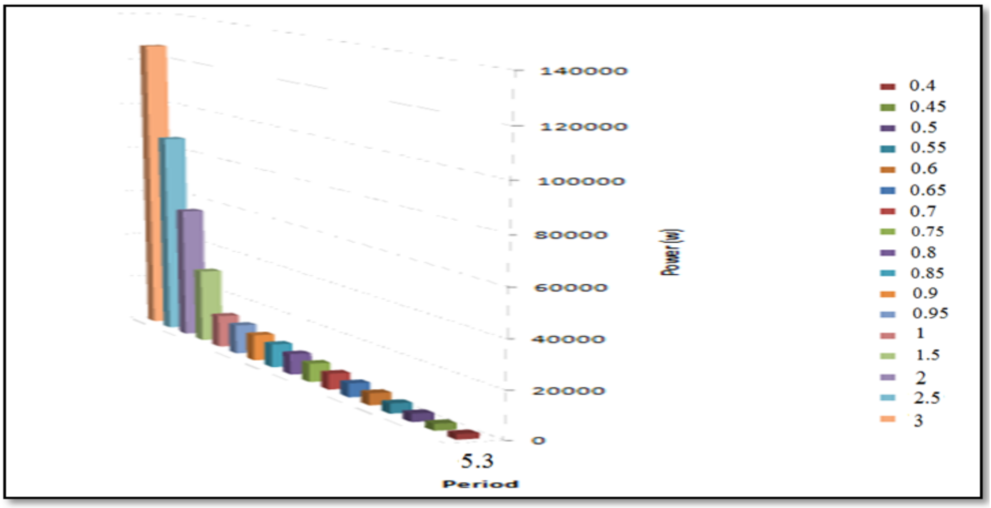

Figure (5.3 a): The period fixed at (5.3) s and height is varies.

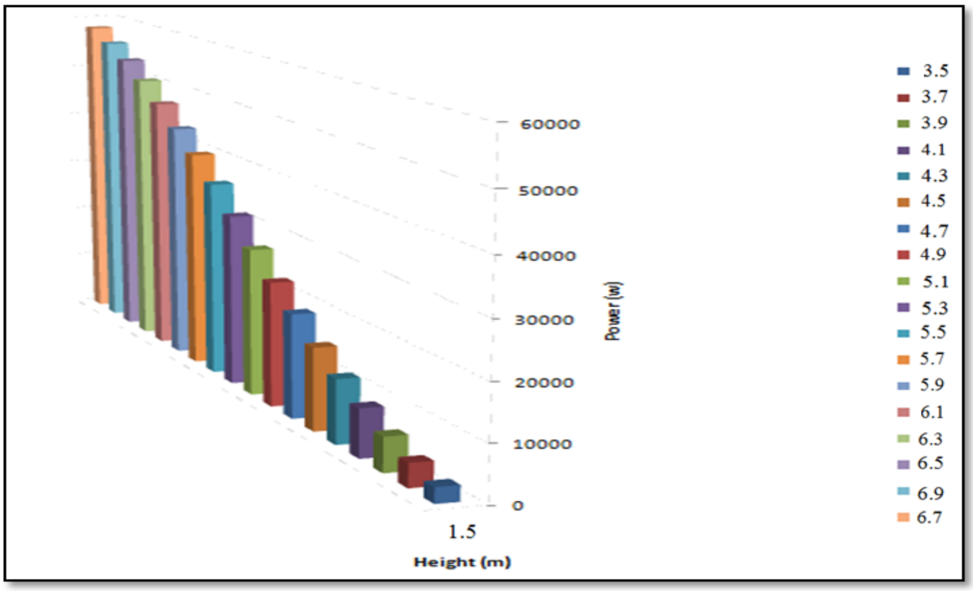

Figure (5.3 b): The height fixed at (1.5) m and period is varies.

5.3 Uncertainty effect results

In general, the most prominent disadvantages of renewable energy are their availability at all times. Wave power is affected by many factors due to climate change such as temperature, wind speed, water depth..etc. In our device, these factors directly affect the two variable input height and period of waves which the amount of energy produced depend upon it.

The results will be shown in Tables (5.3-5.5-5.7) show the effects of uncertain parameter variations on the system performance.

Wave heights is set to change up to 20% with the same period as in Table (5.1) are shown in Table (5.2).

Table (5.2): Mean values for height up to 20%.

Mean Wave Height (m)					
JAN	**FEB**	**MAR**	**APR**	**MAY**	**JUN**
0.684- 1.284	0.756- 1.356	0.6-1.2	0.6- 1.2	0.54- 1.14	0.516- 1.104
JUL	**AUG**	**SEB**	**OCT**	**NOV**	**DEC**
0.492- 1.092	0.516- 1.116	0.504- 1.104	0.528- 1.128	0.66- 1.2	0.648- 1.2

Table (5.3): Power matrix table when height increased up to 20%.

H / T	0.48	0.54	0.6	0.66	0.72	0.78	0.84	0.9	0.96	1.02	1.08	1.14	1.2	1.8
3.5	285	363	445	547	642	755	875	1022	1138	1302	1463	1624	1788	4020
3.7	438	557	687	829	987	1158	1347	1546	1743	1974	2239	2487	2730	6161
3.9	641	812	1002	1212	1443	1680	1966	2271	2558	2892	3237	3614	3998	8976
4.1	894	1131	1387	1686	2012	2343	2737	3113	3576	3996	4525	5045	5544	12556
4.3	1205	1521	1880	2269	2713	3151	3666	4197	4758	5386	6052	6716	7432	16696
4.5	1534	1955	2397	2920	3453	4050	4756	5448	6222	6926	7851	8642	9645	21948
4.7	1917	2458	3014	3646	4314	5084	5916	6797	7680	8735	9786	10761	11986	26867
4.9	2358	2946	3652	4468	5305	6209	7238	8234	9388	10575	11854	13232	14639	33201
5.1	2780	3515	4390	5306	6305	7350	8450	9825	11086	12500	14181	15624	17411	38855
5.3	3222	4045	5033	6077	7245	8445	9864	11362	13017	14488	16466	18195	20162	45665

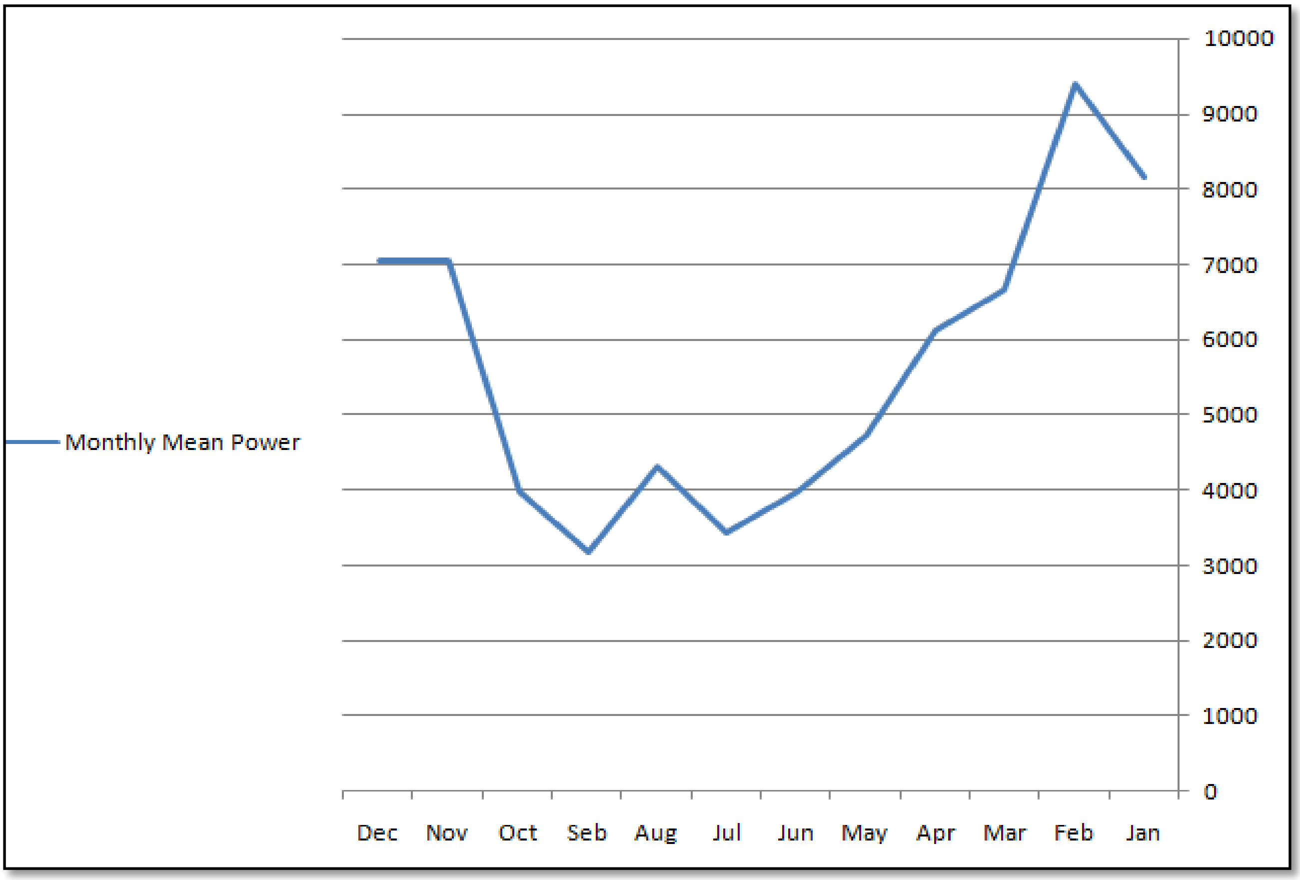

Figure (5.4): The average electrical output power available for each month of a year when height up to 20%.

The results shown in Table (5.3) and Figure (5.4) show the increase in wave height by 20% leads to an increase in power output by 40%.

When the change in wave heights down by 20% with the same period as in Table (5.1), the new values are shown in Table (5.4).

Table (5.4): Mean values for height down to 20%.

Mean Wave Height (m)					
JAN	**FEB**	**MAR**	**APR**	**MAY**	**JUN**
0.456- 0.856	0.504- 0.904	0.4-0.8	0.4- 0.8	0.36- 0.76	0.344- 0.736
JUL	**AUG**	**SEB**	**OCT**	**NOV**	**DEC**
0.328- 0.728	0.344- 0.744	0.336- 0.736	0.352- 0.752	0.44- 0.8	0.432- 0.8

Table (5.5): Power matrix table when height down to 20%.

T \ H	0.32	0.36	0.4	0.44	0.48	0.52	0.56	0.6	0.64	0.68	0.72	0.76	0.8	1.2
3.5	126	161	199	242	285	335	391	445	511	576	642	726	794	1788
3.7	195	248	305	367	438	515	595	687	784	885	987	1103	1228	2730
3.9	284	361	443	538	641	747	865	1002	1131	1275	1443	1603	1773	3998
4.1	396	500	617	743	894	1057	1206	1387	1587	1788	2012	2235	2478	5544
4.3	527	674	824	1001	1205	1395	1623	1880	2105	2391	2713	3020	3309	7432
4.5	684	872	1076	1286	1534	1805	2107	2397	2742	3092	3453	3877	4271	9645
4.7	852	1099	1352	1634	1917	2268	2624	3014	3429	3848	4314	4870	5333	11986
4.9	1046	1310	1634	1978	2358	2757	3185	3652	4212	4704	5305	5901	6540	14639
5.1	1228	1563	1911	2317	2780	3250	3783	4390	4959	5547	6305	7000	7776	17411
5.3	1439	1815	2260	2726	3222	4382	4340	5033	5751	6438	7245	8081	8965	20162

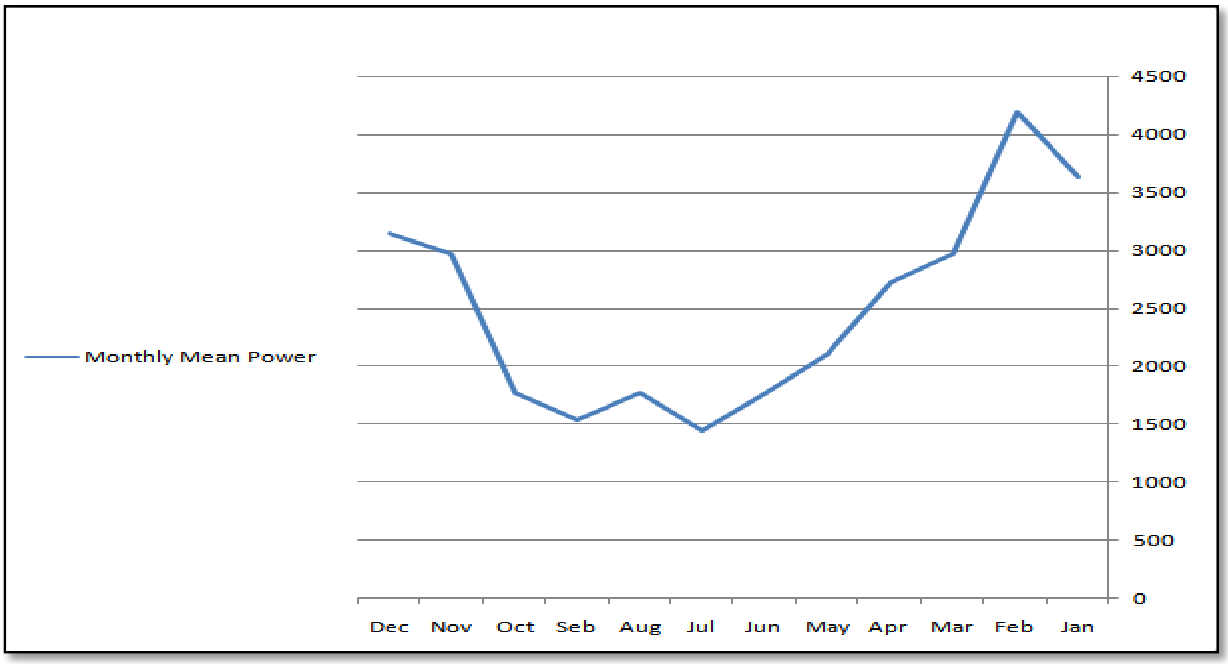

Figure (5.5): The average electrical output power available for each month of a year when height down to 20%.

The results shown in Table (5.5) and Figure (5.5) show the decrease in wave height by 20% leads to decrease the power output by 40%.

When the change in wave period is increased by 20% with the same height as in Table (5.1), the new values are shown in Table (5.6).

Table (5.6): Mean values for period up to 20%.

Mean Wave Period (s)					
JAN	**FEB**	**MAR**	**APR**	**MAY**	**JUN**
4.92- 6.84	5.04- 6.96	4.56- 6.48	4.44- 6.36	4.32- 6.24	4.2- 6.12
JUL	**AUG**	**SEB**	**OCT**	**NOV**	**DEC**
4.08- 6.2	4.2- 6.12	4.08- 6	4.2- 6.12	4.68- 6.6	4.68- 6.6

Table (5.7): Power matrix table when period up to 20%.

H / T	**0.4**	**0.45**	**0.5**	**0.55**	**0.6**	**0.65**	**0.7**	**0.75**	**0.8**	**0.85**	**0.9**	**0.95**	**1**	**1.5**
4.2	726	906	1117	1368	1614	1891	2215	2572	2887	3286	3625	4047	4490	10072
4.44	992	1254	1554	1875	2263	2620	3037	3508	3978	4474	5028	5583	6259	13940
4.68	1302	1672	2047	2481	2947	3455	3997	4593	5277	5876	6631	7410	8194	18474
4.92	1652	2082	2588	3167	3744	4374	5089	5773	6676	7526	8458	9384	10445	23407
5.16	2033	2573	3177	3844	4575	5362	6230	7064	8038	9074	10173	11335	12533	28392
5.4	2373	3004	3708	4487	5340	6313	7355	8435	9597	10834	12146	13533	14964	33656
5.64	2773	3510	4334	5244	6241	7273	8419	9719	11058	12484	13995	15594	17211	38319
5.88	3093	3915	4834	5849	6961	8107	9503	10831	12323	13912	15597	17378	19203	43435
6.12	3416	4324	5338	6460	7687	8968	10361	11931	13575	15324	17180	19142	21126	47535
6.36	3661	4634	5721	6922	8238	9651	11196	12867	14640	16527	18528	20644	23078	51737

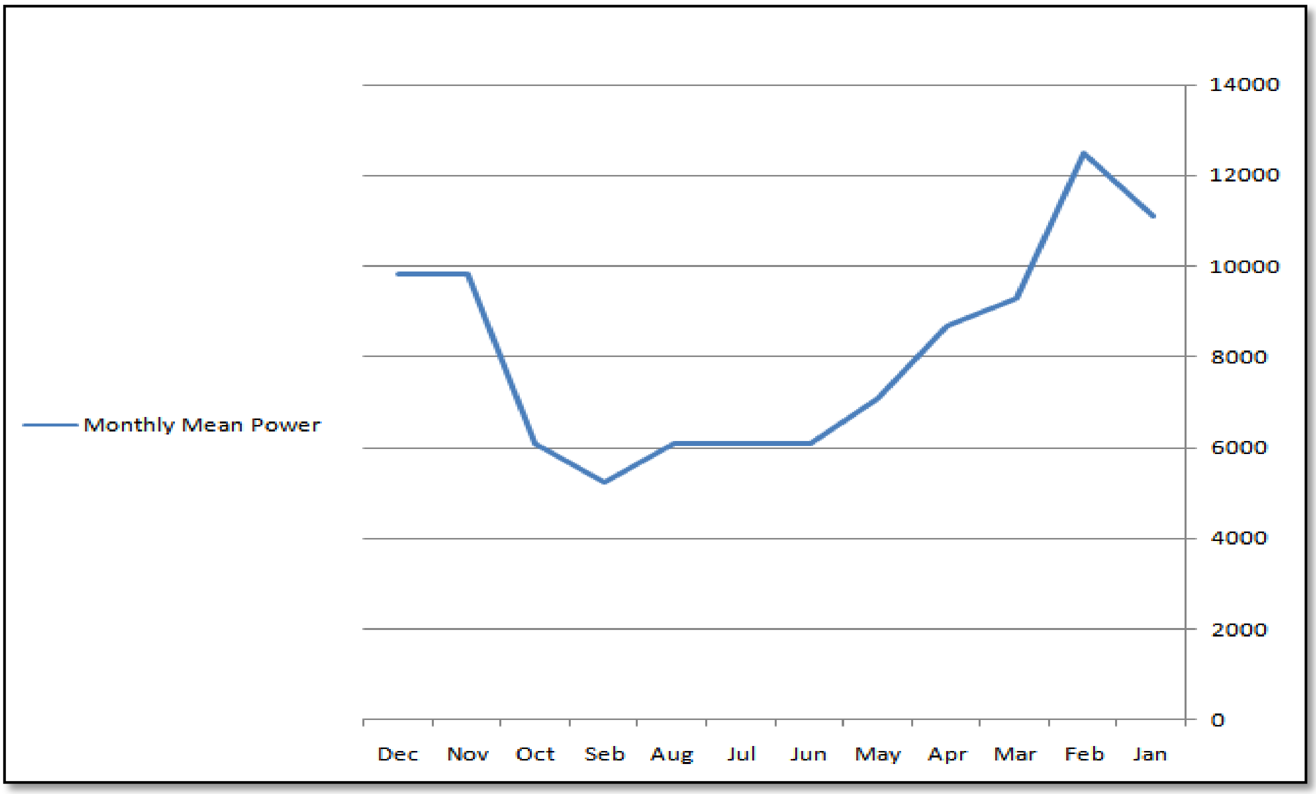

Figure (5.6): The average electrical output power available for each month of a year when period up to 20%.

The results shown in Table (5.5) and Figure (5.6) show that an increase in wave period by 20% leads to an increase in power output by 100%.

When the wave period is reduced down the values as in Table (5.1), the efficiency will be very few where these values inconsistent with the device design, because the wavelength for sea waves becomes less than the horizontal dimension of the device.

Any change in climate would lead to an increase in waves height or period certainly be in favor of the power output and vice versa, and be effective if the increase in wave heights exceed 1 meter.

5.4 Significant of results

The device that was installed on Gaza beach in spring of 2009 [3] produced 1.03 kW for DP=100 cm. The result was obtained after 9 hours testing/day. In comparison our system (RM3) can produce about 3.28 kW in May.

In comparison, high waves such as the Atlantic Ocean, produce a very large output power from the same device. For example, at Wave Height 2 (m) and Wave Period 8 (s) the average output power is about 115 kW.

The average electrical output power available for each month of a year compared with the results of study analyzed wave energy potential in the Eastern Mediterranean Levantine Basin an integrated 10-year study. It was supported by the E-WAVE project funded by the Research Promotion Foundation of the Republic of Cyprus and the European Regional Development Fund are shown in Figure (5.7) with the Mean monthly wave power potential (kW/m) for the period 2001-2010 over different areas of the Levantine.

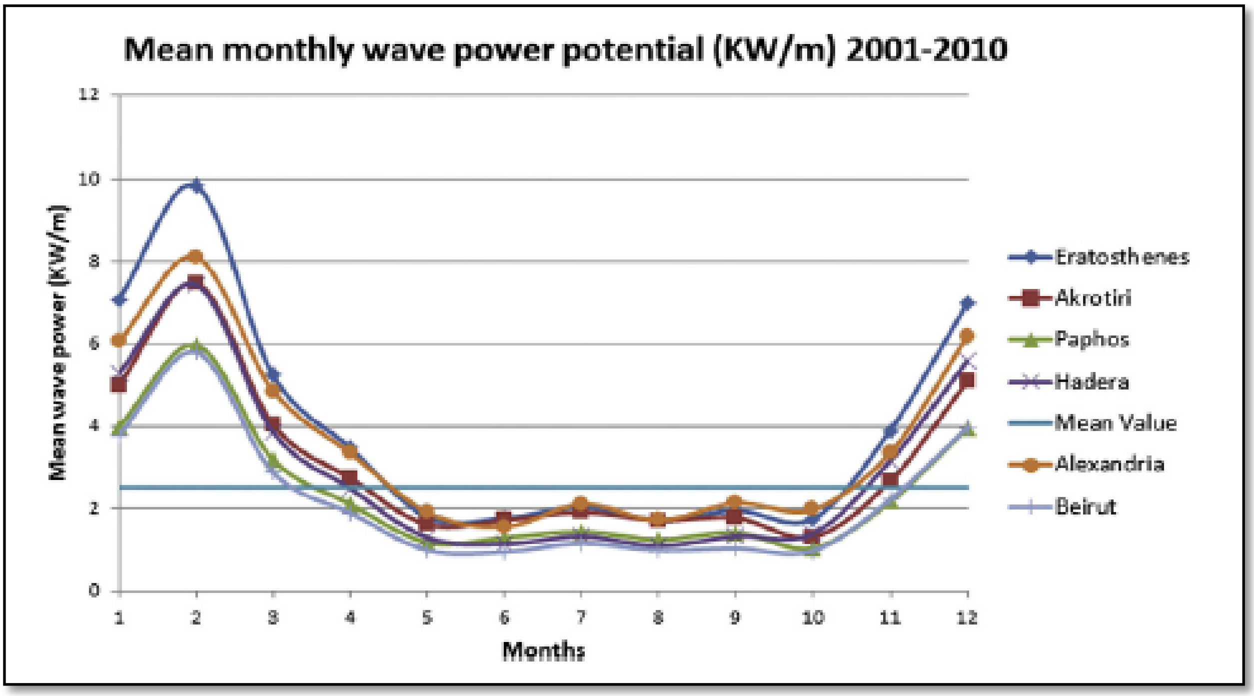

Figure (5.7): Mean monthly wave power potential (kW/m) for the period 2001-2010 over different areas of the Levantine.

Based on our results, we can say that the device is able to lighting two homes on the seashore throughout the year. When the device is linked to the network to be a source of energy, it needs to study the amount of power needs and the number of devices needed to be a power plant in the sea. The net output power from different devices can be transported to the shore through a single wire submerged in the water, and this help to ease the overall cost price, as well as the reduction of energy loss.

CHAPTER SIX
CONCLUSION AND FUTURE WORK

6.1 Conclusion

Wave energy is the primary target for countries and researchers interested in renewable energy because it is clean and available for many countries. However, the largest challenge is how to exploit this energy to become a reliable power source and be cost efficient.

Many of the technologies have been studied and tested to convert wave energy but each technology is still at an early stage of development to predict which technology or mix of technologies would be most prevalent in future commercialization. Almost all of the currently installed wave energy devices are still at a prototype demonstration stage and have not yet provided electricity production at a commercial level. Currently, only three wave energy projects can be classified as having achieved commercial status. These are the Pelamis, the Limpet and the Blue Wave projects.

At the same time these projects capital cost are huge. For example, the first Pelamis wave that was built in Portugal cost an 8 million euro and the Limpet in Scotland about 1.6 million DUS. This is higher than the capital cost of photovoltaic and wind systems.
In general, the capital cost estimation of wave energy devices is a complex procedure since it depends on many physical factors such as system design, wave energy power, water depth, distance from the shore and ocean floor characteristics.

In this thesis, the point absorber technology was chosen to investigate the feasibility of the eastern Mediterranean Sea for production of electrical power from the reference model 3 (RM3), using WEC-Sim, an open source numerical modeling tool for design and analysis of WEC devices. WEC-Sim allows users to simulate the device through building a device simulink model, importing the necessary files and create WEC-Sim input file with the specified input parameters of the study area.

A model was built based on a simple two-body point absorber, consisting of a float and a reaction plate. The RM3 WEC scaled 1:33 to full scale and tested in experimental tank at the Scripps Institute of Oceanography in San Diego- California State.

The results in this thesis showed that the output power produced from a two point absorber device in the eastern region of the Mediterranean Sea can produce up to average 6.5 kW during the winter and 2.4 kW during the summer, the autumn and spring ranges between them. A 20% increase or decrease in wave heights leads to 40% change in the produced power output. Also a 20% increase in wave period leads to 100% increase in power output.

Finally, there is no doubt that the device efficiency is not as high as other areas such as Atlantic ocean. However, we can say that the proposed device efficiency in the study area are acceptable and are good compared with other devices that can be used in the same area. However, deep feasibility studies are needed about the possibility to construct a plant that contains several devices to produce enough amount of energy to be linked in a network, and overcome the challenges, notably the cost.

6.2 Future work

The study makes the following recommendations:

- Conduct a comparison studies on the type of sea power generating technologies.
- Conduct feasibility studies on implementing the proposed technology.
- Conduct a feasibility study taking into a account the different hours during the day.
- Develop a prototype to test the output.

REFERENCES

[1] H. Thurman and A. Trujillo. *"Essentials of oceanography*", seventh edition, Chapter 8 p.236-264, USA, 2001.

[2] N. Kimoulakis and A. Kladas. *"Modeling and Control of a Coupled Electromechanical System Exploiting Heave Motion, for Energy Conversion from Sea Waves",* IEEE Conference (PESC), Nat. Tech. Univ. of Athens, 2008.

[3] Sh. El-Zaza. *Development of Wave Energy Conversion Device - Gaza Shoreline*, Master thesis, Faculty of Engineering at the Islamic University of Gaza, Gaza Strip, 2009.

[4] J. Foster, P. Garambois, R. Ghorbani. *"Development and testing of a point absorber wave energy conversion device*", IEEE Oceans Spain Conference, Spain, June 2011.

[5] J. Leclerc, P. Dumee, N. Kimoulakis, and A. Kladas. *"Advanced modeling and control of a wave energy conversion system",* IEEE Conference: Electrical Machines (ICEM), pp. 2041-2045, Marseille ,2012.

[6] S. Song, J. Kim, and J. Park. *"A new type of wave energy converter using under-water pressure oscillation*", IEEE Oceans Conference, Dept. of Electr. & Electron. Eng. at Yonsei Univ., South Korea, October 2012.

[7] S. Bozzi, A. Miquel, A. Antonini, G. Passoni, and R. Archetti. "*Modeling of a Point Absorber for Energy Conversion in Italian Seas*", Energies Article of Faculty of Engineering, ISSN 1996-1073, Italy, June 2013.

[8] M. Nazari, H. Ghassem, M. Ghiasi, and M. Sayehbani. *"Design of the Point Absorber Wave Energy Converter for Assaluyeh Port*", IJEE Journal of department of Ocean Engineering, ISSN 2079-2115, Amirkabir University of Technology, Tehran, Iran, , 2013.

[9] M. Faizal, M. Ahmed, and Y. Lee. *"A Design Outline for Floating Point Absorber Wave Energy Converters"*, Hindawi Review article of department of Mechanical Engineering, volume 2014, ID 846097, Korea.

[10] Waves, http://www.waterencyclopedia.com/Tw-Z/Waves.html/(last accessed Feb. 2015).

[11] waves, http://geography.about.com/od/physicalgeography/a/waves.htm//(last accessed Feb. 2015).

[12] M. Lagoun, A. Benalia, and M. Benbouzid. *"Ocean Wave Converters: State of the Art and Current Status*", IEEE Energy Conference, pp. 636– 641, Manama, 2010.

[13] Waves types, http://education-portal.com/academy/lesson/waves-types-features-effect-on-erosion.html/(last accessed Mar. 2015).

[14] Wave power, http://en.wikipedia.org/wiki/Wave_power/(last accessed Mar. 2015).

[15] Oceans in motion, http://ci.coastal.edu/~sgilman/770Oceansinmotion.htm/(last accessed Mar. 2015).

[16] A. Poullikkas. *"Technology Prospects of Wave Power Systems*", EJE&E journal, Vol. 2, No 1, ISSN: 0719-269X, United Arab Emirates, April 2014.

[17] P. Holmberg, M. Andersson, B. Bolund, K. Strandanger. *"Wave Power "Surveillance study of the development*", Research at Elforsk AB, SE-101 53, Stockholm, May 2011.

[18] M. Pontes, and A. Falcao. *"OCEAN ENERGY CONVERSION"*, Research at Instituto Superior Tecnico, Lisboa, Portugal.

[19] Wavegen. Available from http://www.wavegen.co.uk/what_we_offer_limpet.html/(last accessed Mar. 2015).

[20] B. Drew, A. Plummer, and M. Sahinkaya. *A review of wave energy converter technology*, Journal of department of Mechanical Engineering, University of Bath, Bath, UK, June 2009.

[21] G. Buigues, I. Zamora, A. Mazon, V. Valverde, and F. Perez. *"Sea Energy Conversion: Problems and Possibilities*", Journal of Electrical Engineering Department, Spain, 2013.

[22] B. Czech, P. Bauer, and H. Polinder. *"Review of Wave Energy Converters"*, IMechE Review paper, Vol. 223, pp. 887- 902, UK, 2009.

[23] R. Henderson. *"Design, simulation and testing of a novel hydraulic power takeoff system for the Pelamis wave energy converter"*, *Elsevier article*, Volume 31, Issue 2, Pages 271–283, Scotland, UK, 2006.

[24] F. Wu, X. Zhang, P. Ju, and M. Sterling. *"Modeling and control of AWS-based wave energy conversion system integrated into power grid*", IEEE Trans. Power Systems, vol. 23, Issue: 3 , pp. 1196-1204, UK, August 2008.

[25] CETO Wave Energy and Desalination, http://www.reuk.co.uk/CETO-Wave-Energy-and-Desalination.htm/(last accessed Mar. 2015).

[26] SDE WEC device, http://en.wikipedia.org/wiki/SDE_Sea_Waves_Power_Plant/(last accessed Mar. 2015).

[27] A. Muetzem, and J. Vining. "*Ocean wave energy conversion – A survey*", in Proceedings of the IEEE IAS’06, Tampa (USA), vol. 3, pp. 1410-1417, October 2006.

[28] K. Ruehl, M. Lawson, C. Michelen, and Y. Yu. *WEC-Sim user manual*, National Renewable Energy (NREL) and Sandia National Laboratories (SNL), Version 1.0, June 30-2014.

[29] Historical wave data, http://isramar.ocean.org.il/(last accessed Mar. 2015).

[30] Historical wave data, http://forecast.uoa.gr/(last accessed Mar. 2015).

APPENDIX A

Several theoretical representations of wave spectra have been developed using data collected by observation platforms and satellite data in various regions. These spectra such as (Pierson Moskowitz- JONSWAP- Bretschneider…etc).

Bretschneider Spectrum

the 15th International Towing Tank Conference (ITTC) in 1978 recommended using a form of the Bretschneider spectrum for average sea conditions when a more specific appropriate form of the wave spectrum is well defined. The general form of this spectrum is equation:

$$S^{+}(\omega) = \frac{A}{\omega^5} e^{-B/\omega^4}$$

The frequency peak is called the modal frequency. The area under the spectrum is the zeroth moment (M o).

The two parameters A and B are dependent on the modal frequency, ω_m, and the variance of the spectrum, $M_o = (rms)^2 = \sigma^2$.

$$\omega_m^4 = \frac{4}{5} B \;\; ; \;\; B = 5\,\omega_m^4/4$$

$$Variance = \sigma^2 = A/(4B) \;\; ; \;\; A = 4\sigma^2 B$$

If we normalize the frequency (w),

$$S(\omega) = 5\frac{\omega_m^4}{\omega^5} \sigma^2 \; e^{-\frac{5}{4}\left(\frac{\omega_m}{\omega}\right)^4}$$

For a narrow banded spectrum, $\varepsilon < 0.6$, the significant wave height, $\zeta = H^{1/3} = 4\sqrt{M_o}$, where M_o is the variance of the spectrum. For a wide banded spectrum, $\varepsilon = 1$, St. Denis (1980) showed that the significant wave height was approximately, $\zeta = 3\sqrt{M_o}$. This leaves us with the final form of the Bretschneider Spectrum.

$$S(\omega) = \frac{1.25}{4} \frac{\omega_m^4}{\omega^5} \zeta^2 \; e^{-125\left(\frac{\omega_m}{\omega}\right)^4}$$

In WEC-Sim tool. MATLAB code contains a function to define the spectrum, the Bretschneider spectrum as follows:

```
switch waves.spectrumType
    case 'BS'
        B = (1.057/Tp)^4;
        A = B*(Hs/2)^2;
        S_f = (A*freq.^(-5).*exp(-B*freq.^(-4)));
        Sf = S_f./(2*pi);
end
```