TECHNICAL ANALYSIS OF HYDROGEN PRODUCTION FROM WAVE ENERGY: A CASE STUDY FOR NORTH CAROLINA

by

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ABSTRACT

GAGEE RAUT. Technical Analysis of Hydrogen Production from Wave Energy: A Case Study for North Carolina (Under the direction of DR. NAVID GOUDARZI)

The energy requirements of the world are increasing at alarming rate. The available fossil fuels and other conventional resources are not sufficient to keep up the pace with ever-increasing energy demand. Also, the use of fossil fuels causes the negative impact on the environment. The solution for all these issues is the development and adaption of the renewable energy resources. The mainstream renewable energy resources such as solar energy and wind energy have sufficient potential to fulfill the world energy demand. However, they are marked down due to their uncertain and intermittent nature. An extremely abundant, promising, and comparatively new source of renewable energy is the marine and hydrokinetic resource. It includes wave energy, tidal energy, ocean and river currents, and ocean thermal energy. Among these, ocean wave energy is being increasingly regarded with the predictable resource characteristics and high energy density value for the significant energy extraction. A framework has been developed in this study to estimate the ocean wave energy potential of the North Carolina based on the National Oceanic and Atmospheric Administration's (NOAA) five stations and it is estimated as 567 GWh based on the wave data available for the period of 2013-2017. The wave energy production is estimated using the Department of Energy's (DOE) benchmark models of the wave energy converter. As this is a naïve technology the cost of energy generation is relatively high with an average value of $11.04/kWh. The hydrogen production from the ocean wave energy using the method of water electrolysis can be implicated for storing an excess amount of the energy. The produced hydrogen is used in the various applications and it may help to reduce the integrated system cost. The sensitivity analysis has been performed

to analyze the impact of a feed factor to an electrolysis system on the hydrogen potential and cost of the integrated system.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

1.1: BACKGROUND

Since the beginning of the industrial era, fossil fuels play an important role. The International Energy Outlook (IEO) 2017, claims that total world energy consumption is expected to increase from 575 quadrillions British Thermal Units (Btu) in 2015 to 736 quadrillions Btu in 2040, an increase of 28% [1]. This increased demand is expected to meet about 77% with the help of fossil fuels in 2040 [1].The historical and the projected world energy consumption for various energy sources showcased in Figure 1. The reckless use of the fossil fuels to meet increasing energy demand exhausted the finite reservoir of the fossil fuels.

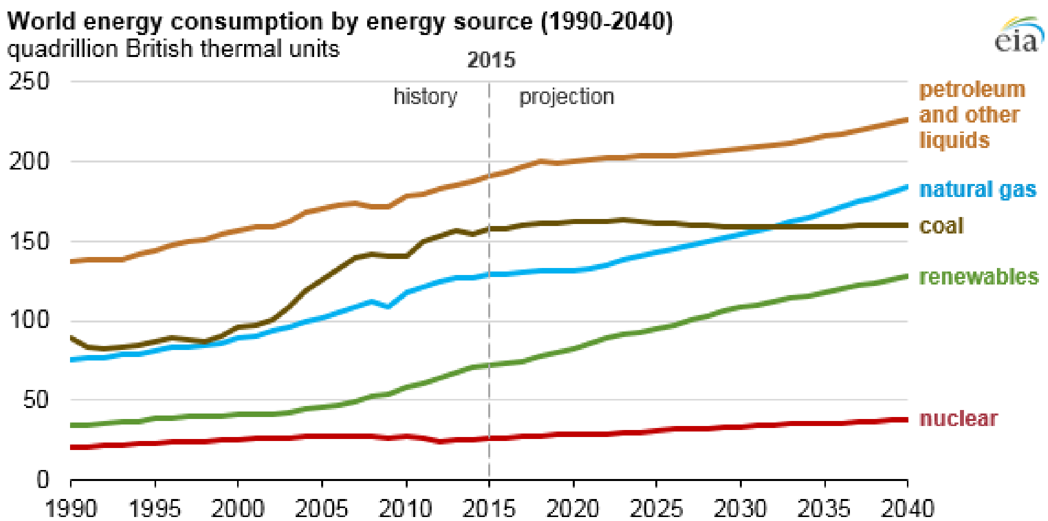

FIGURE 1: The Net World Energy Consumption for Various Energy Resources in quadrillion Btu for the period of 1990-2040 [2].

Shafiee and Topal proposed the modified analytical model, the modified version of the Klass model for calculating the depletion time for fossil fuels. It demonstrated the significant relation between finite fossil fuel reserves, consumption and price. They concluded that with the decreasing oil and gas reservoirs their consumption will also decrease as result of high price. The coal price is expected to reduce with depleting coal reservoir which will increase the coal consumption. The available fossil fuel reservoirs 17.67 %, 64.99% and 17.34% are contributed by the oil, coal, and gas respectively. Middle East countries are the main source of oil and gas, whereas Russia has the largest reservoir for coal. This proposed model states that around 35, 107 and 37 years for oil, coal, and gas respectively will require for complete depletion and after 2042, coal is the main and only conventional energy source [3]. Mohr el at estimated the fossil fuel production for four main energy markers (China, USA, Canada and Australia) for the three different scenarios.

The estimation is based on the Geological Resources Supply-Demand Model (GeRS-DeMo) which requires only energy supply and energy demand. The fossil fuel price is not the important parameter for the model. The result of this model concluded that the fossil fuel production is most likely to reduce after 2025 [4]. The rapid growth in industrialization and urbanization is the main contributor to an increased level of greenhouse gases (GHG). As per the Environmental Protection Agency's (EPA) report, the level of GHG has increased by 35 % from 1990 to 2010, globally [5]. The carbon dioxide (CO_2) has the maximum share about 75 % among all GHG. The heat trapped by carbon dioxide and other GHG increased the surface temperature by 0.8 °C over the last century. The consequences of these emissions are resulting in the increased ocean acidity, a sudden change in the climate, and heavy global precipitation. As per the Paris climate agreement to maintain the emission level as low as 450-550 parts per million (ppm) and it is necessary to reduce current emission level by 50-80% [5]. This is achievable by increasing the share of renewable energy resources (RES) in the current energy mix.

1.2: DEVELOPMENT OF RENEWABLE ENERGY RESOURCES

The first known energy crises of 1970 accelerated the development of RES, mainly mainstream resources (solar and wind energy). The solar energy is well established and frequently used RES throughout the world as the sun is the primary and main energy source. Annually around four million exajoule (EJ) of solar energy reaches to the earth surface. However, only five EJ of the solar energy is extractable with currently available technologies. Kabir el at. analyzed the current country wise development in the field of solar energy. According to their results, in 2015 the world installed capacity of solar energy reached to 256 GW and China has excelled with the contribution of about 46 GW. The social awareness, increased efficiency of solar power, and favorable government policies helped to reduce the total cost of a PV model by 60% [6]. Desideri et al., performed and compared the life cycle assessment of two different solar energy harvesting methods such as concentrating solar power (CSP) and photovoltaic technology (PV). They concluded that the electricity production from PV system is greater than CSP system. Moreover, the PV system requires almost 23% less land space as compared to CSP system. The environmental impact of both the system is mainly due to assembly phase and decommissioning phase. But the PV system produces more GHG than CSP system. Both of these systems produce more energy than the cumulative energy demand of their life cycle. The energy payback time for CSP system is 2 years whereas; 5.5 years payback period is required for PV systems [7].

The second most important and developed mainstream renewable energy resource is the wind energy. The worldwide total cumulative installed electricity generation capacity from the wind energy is accounted for 487 GW, with an annually increased factor of 12.5%. Bonou et al. assessed the environmental impact of the onshore and offshore wind power plant. The EPBT is less than a year for both power plants. The GHG emission for onshore is 7 g CO_2-eq/kWh and 11 g CO_2-eq/kWh for offshore plants as they required more materials such as floating platform, mooring cables, and more fuel is required for water transportation [8]. Though solar and wind energy is a sustainable, clean source of energy and high potential for achieving the increased energy demand. They faced some technical and economic challenges. Integration of the mainstream RES in the electric grid is associated with many difficulties. The mainstream RES experienced the high intermittency and uncertainty. The fluctuation in the energy supply due to the variation in the time, location, and climatic conditions disrupt not only the hourly load planning but also the second to second energy balance. In past, many strategies implemented to overcome the variability such as the integration of various RES in the electric grid. This gave a positive result as the whole system than the individual unit.

Though the integrated energy mix can guarantee the continuous energy supply it will increase the complexity of energy system. The advancement in technologies helped to reduce the energy generation cost from these mainstream RES. However, the energy generation cost for RES is not able to compete for the energy generation cost for the traditional energy resource due to the high initial investment required for RES. The high potential sites are usually located far from load centers, which require the need of the transmission lines. Wind turbines can cause noise and aesthetic pollution. The wind blades are responsible for wildlife damage as the birds have high chances of getting hurt by the blades [9].

In comparison to the mainstream RES, the ocean wave energy is more reliable, predictable and highly dense source of the energy. As per the world energy council, the theoretical world energy potential is approximately 11400 TWh/year and Figure 2 illustrates the average annual wave power potential across the globe.

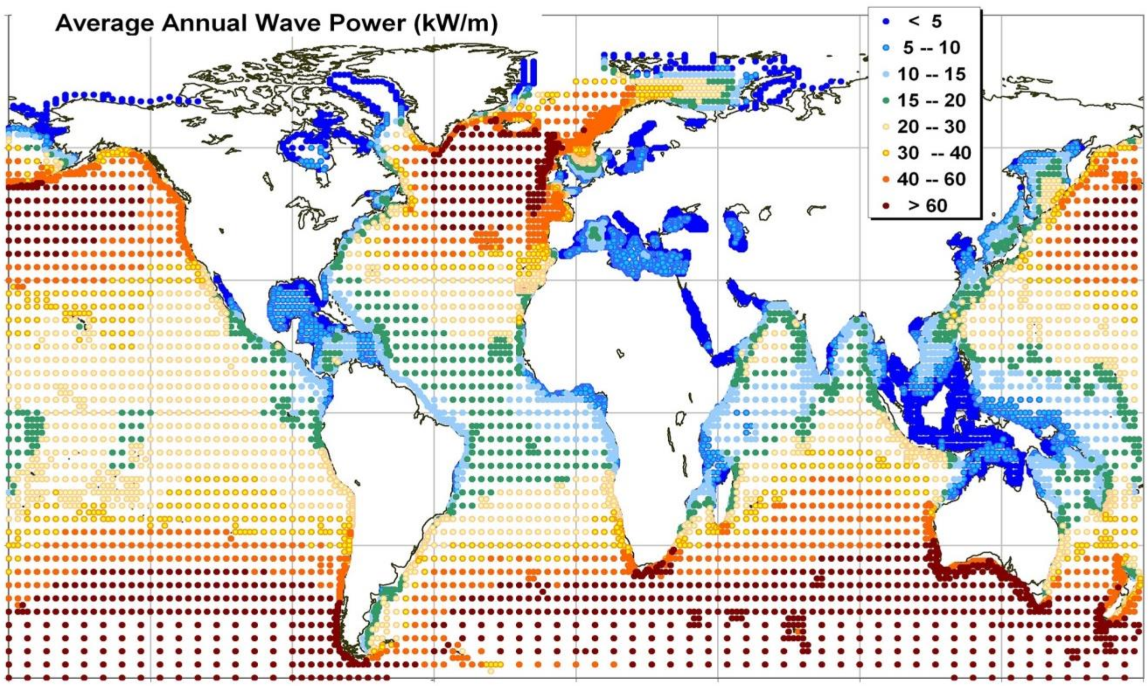

FIGURE 2: The Average Annual Wave Power Potential across the globe in kW/m [10].

The Department of Energy’s (DOE) water program estimated the United States’ (U.S.) wave energy potential equivalent to the 2640 TWh/year and Figure3 highlights the potential regions of the U.S for the wave energy [11]. Even after having such a high potential, the commercially grid-connected ocean wave energy farms are not yet in function in the U.S. In U.S. many wave energy farms are under research phase and major installations are planned to contribute to the energy mix. The ocean waves generate the energy due to blowing wind across the ocean and it is expected to vary with changing season and locations.

Due to this, it is very important to analyze wave parameters of selected high potential location for harvesting wave energy more efficiently and economically.

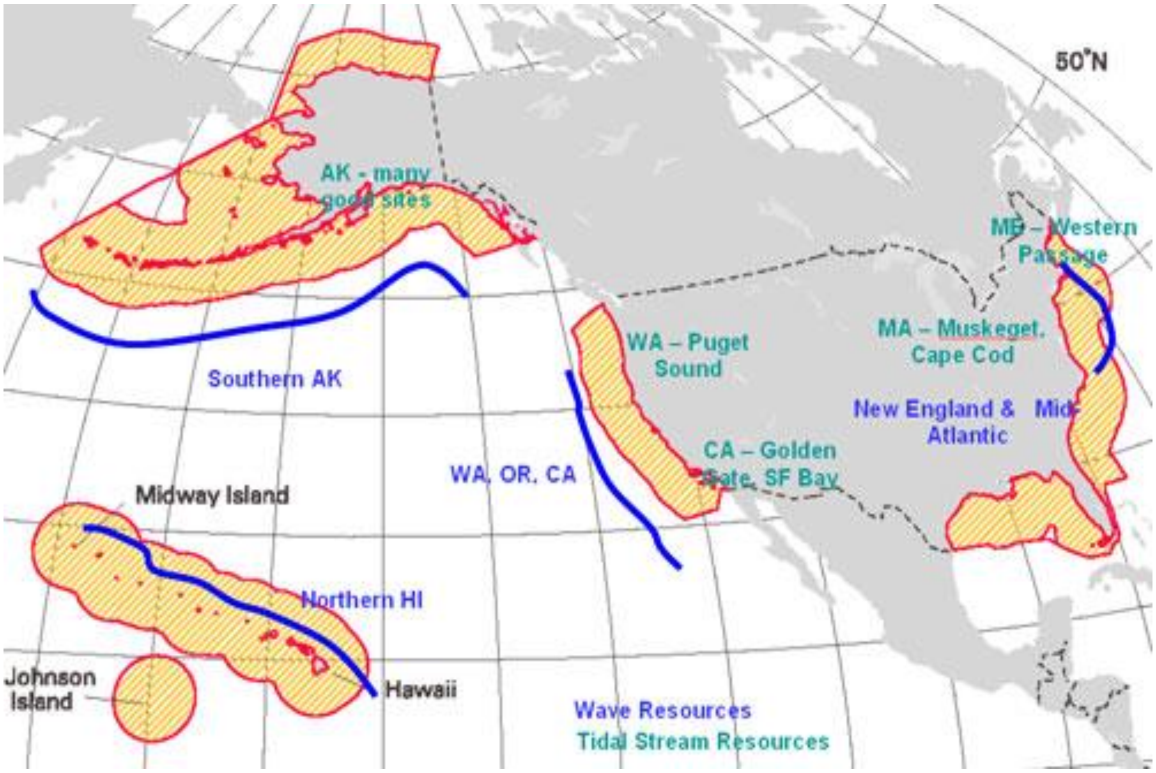

FIGURE 3: The Potential Regions for the Wave Energy Extraction in the U.S. [11].

The variety of the location across the globe has been analyzed in many kinds of literature for selecting a suitable site for the deployment of wave energy converters (WEC) based on their theoretical and technical assessment. Alamian et al. collected the 15-years wave parameters data for 17 different locations along the Caspian sea near northern Iran for selecting a most suitable site for wave energy extraction. The annual and seasonal analysis suggested that the wave energy potential is comparatively high in the fall period. The south-east part of Caspian Sea is not proper to place for installation WEC cause of low depth. The average range for significant wave height is 0.5-1.0 m and the time period is in the range of 4- 6 sec.[12]. Lisboa and Fortes estimated the wave energy potential for the southern coast of Brazil considering both offshore and nearshore cases, using 10-year data. The MIKE 21 SW spectral model is used to carry out the numerical evaluation of this data. There is the noticeable potential difference for offshore (22.3 kW/m) and nearshore (6.7 kW/m) cases. But for deployment of WEC in the near future nearshore location is more preferred due to the low cost of deployment, operation, and maintenance. They also evaluated that the wave energy potential increases with higher latitudes [13]. Sundar and Sannasiraj estimated the wave energy potential for various coastal regions of India using 10-years of the wave data. The results stated that the maximum power is equivalent to the 25.08 kW/ m assuming a 1 km effective stretch of coastline is utilized [14]. Lehman el at. reviewed and documented the current development and ongoing research on the academic and industry level and government policies in the field of wave energy. Theoretical potential of U.S. west coast (590 TWh/year) is more than twice the wave energy potential of the east coast (240 TWh/year). These results are excluding the wave energy potential of Alaska (1570 TWh/year) and Hawai (130 TWh/year). As briefly documented in [10], various U.S. government agencies which include DOE, National Laboratories, National Science Foundation (NSF) are financially and technically supporting the development of the wave energy. The DOE's water power technology office invested more than $116 million to reduce current (LCOE) value to 0.84 $/ kWh for wave power by 2030. The NREL has significantly contributed to designing the WECSim, an open source Wave Energy Converter Simulation tool. It has the ability to model WEC individually or as the whole system consisting rigid bodies, power-take-off system and mooring systems to give results in terms of the reaction forces. Sandia National Laboratories in collaboration with DOE and other National Laboratories developed the Reference Models (RM) for harnessing the energy from wave, tidal, ocean and river currents. This RM are used as benchmarks at all levels (laboratories, industries, and universities) for validating theoretical and numerical proposed models. Pacific Northwest National Laboratory (PNNL) conducted the research to address the adverse effect of WEC on the aquatic ecosystems.

The U.S. Department of the Navy has the aim to meet their maximum energy requirement from renewable energy resources by 2020. They developed the Wave Energy Test Sites (WETS) in collaboration with the University of Hawaii which provides an actual sea state atmosphere to test WEC, mainly point absorbers and oscillating water column. The Bureau of Ocean Energy Management (BOEM) examines the energy exploration and exploration activities in U.S. water bodies. BOEM's saltwater wave basin in NJ is used for testing of various WEC. Northwest National Marine Renewable Energy Center (NNMREC) is equipped with the two potential test sites, North Energy and Sound Energy test site. The North Energy Test Site is equipped for full-scale WEC up to 100 kW power rating. The South Energy Test Site is in the permitting phase and planned to be operational at end of 2018. They are facilitated with testing and demonstration capabilities for deepwater technologies. The site is designed for grid connectivity, four testing berths that can accommodate arrays of devices and four independent power cables that will accommodate a total of 20 MW of installed capacity. This financial and technological support from the government agencies, universities and private sector will potentially lead to advancement that could help to achieve the targeted LCOE for wave power in the near future.

1.3: THE WAVE ENERGY AS A RESOURCE

The ocean waves are a result of the combination of a variety of the different disturbing and restoring forces. They can be differentiated on the basis of the size and period such as tides are considered as a very long period wave, on the other hand, small capillary waves have the period of less than a second. The waves generated by the wind blowing across the ocean surface are typically used by WEC for harnessing wave energy. A huge amount of energy is transferred from the wind to the ocean in the form of capillary waves, wind waves and swell wave. All these waves always start as small ripple and with the more energy transfer from the wind they tend to increase in their size till they reach to the point where they are not able to grow due to the energy losses in the form of the white-capping and the wave breaking. They are considered as fully developed and depends on the wind speed and fetch length. The distance over which wind has been blowing on the ocean surface as known as fetch length. Wind waves have the capacity to travel a long distance without any energy losses even after the wind stops blowing over the ocean surface. These waves are also called as swell waves as the wind is not responsible for their propagation. Though the ocean waves are differentiated as wind waves and swell waves for describing the wave climate of a specific location, there is no significant difference in the hydrodynamic behavior of the wind and swell waves[15] [16].

The behavior of waves in shallow water where, there is an interaction between shore, the ocean floor, and water is more complex as compared to the behavior of waves in deep waters. Due to this reason deep water is considered for the WEC deployment. In the case of deep water there is no interaction in between the ocean surface and ocean floor, makes the behavior simple for defining an equation for the wave motion. The assumptions are made for the purpose of getting uniform wave energy equation such as wave train is monochromatic, having uniform wave height and wavelength. In later section wave spectrums are been considered for balancing irregularities of the real ocean [16, 17].

A basic wave is considered as a sinusoidal variation of the ocean surface due to the wind. The wave is mainly defined by the following parameters as shown in Figure 4.

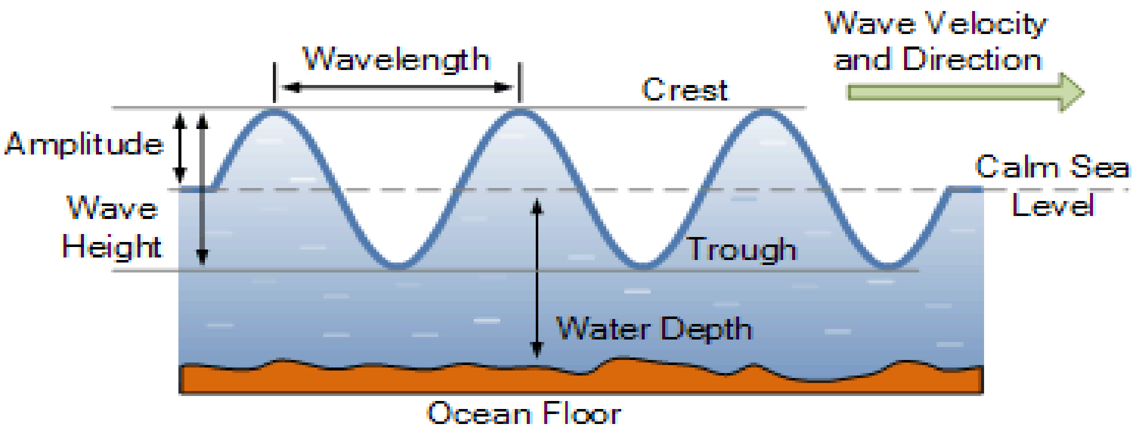

FIGURE 4: The Various Parameters of the Sinusoidal Ocean Wave.

1. Wave height – The vertical distance between the trough and crest of the wave.
2. Time period – The measure of the time required to complete one wave cycle, which has one trough and one crest.
3. Wavelength – The distance between two similar points of the wave.
4. Wave amplitude – The elevation from the mean water level to either trough or crest.
5. Wave number – The reciprocal of the wavelength which measures the number of wave cycles per meter.

1.4: WAVE ENERGY CONVERTERS

The WEC is developed to extract an ocean wave energy from the shoreline out to the deep water offshore. The first known and modern WEC model is developed by Yoshio Masuda in 1940s in Japan. It is navigational buoy powered by ocean wave energy and equipped with an air turbine which is known as the floating oscillating water column after development. After that thousands of WEC has been developed and patented mainly in Japan, North America, and Europe. But only a few concepts have progressed to sea testing. The various types of the WEC are used based on the requirements, location, and magnitude of the project. The shoreline or onshore, nearshore and offshore WEC are three different types of WEC based on the location. The WEC installed in the offshore conditions requires high installation and operation cost as they experience harsh and tough conditions.

The principal operations of the WECs are mainly classified into the following areas [18-20].

1. Oscillating Water Column – This device consists of a large chamber for capturing ocean waves, air turbines and an air chamber, wing walls. The approaching ocean waves enter in the partially submerged chamber and forcing the air upwards through the air turbine. This pressure forces the turbine to rotate. As the waves retreat, air enters back into the air chamber from the other side of the turbine.

2. Overtopping Devices – This WEC is mainly deployed in the shoreline to nearshore locations. The working principle for this type of WEC and hydropower dam is similar. Seawater is captured and stored at a height above the sea level creating a low head and then it is drained out through a reaction turbine such as Kaplan turbine for generating electricity.

3. Wave Activated Bodies – These devices usually equipped with moving parts which can oscillate with wave motion. The wave energy is then extracted by converting the kinetic energy of these moving parts into the electric current. They are suitable for deep water as they are usually very compact and light. However, they require high investment cost compared to the other WEC as they required to convert the irregular oscillatory flux into the electricity.

4. Point absorbers and Attenuators- Point absorber are buoy type WEC which extracts wave energy from all the directions. They can be placed offshore or nearshore locations. The attenuator type WEC has a number of floaters on movable arms. This kinetic energy stored in the moving arms by means of hydraulic line and gets converted into the electricity. These types of WEC provides minimal contact with water, placing delicate machinery and electrics safe from corrosion or physical forcing of the waves.

The WEC is composed of the multiple sub-systems such as a hydrodynamic subsystem, power take-off (PTO) system, reaction subsystem and control and instrumentation subsystem.

1. Hydrodynamic subsystem - It is the primary wave absorption system that extracts the ocean wave power. They are in the contact with both the reaction and the PTO subsystem, which will help to transfer the forces and motions. The different WEC work on the various principal as explained above.

2. Power take-off subsystem - The PTO subsystem converts the extracted ocean wave energy into the electric energy. The hydraulic PTO, direct drive mechanical PTO, linear generators, air turbines and low head water turbines are different types of PTO.

3. Reaction subsystem - The WEC are required to anchor to the seabed for maintaining their positions and withstanding the harsh environmental conditions. The typical WEC mooring system composed of three parts: the mooring line, the connectors and the anchors. Chain, wire rope and synthetic fiber rope are three different types of mooring lines that can be used for mooring system of the offshore WEC. Chains are the frequently used due to high stiffness and abrasion resistant. The buoyancy property of the synthetic ropes helps to reduce the mooring weight due to which they are a suitable option for the deep-water applications.

4. Control and instrumentation subsystem – It mainly consists of the processors for the automation and electromechanical processes, the sensors for data acquisition, data transfer and human interface and communication. They are responsible for controlling the WEC and its measurements.

The results of this study are based on the DOE's RM3 [21], RM5 [22], and RM6 [23]. The following sections give brief information of these three WEC.

1.4.1: WAVE POINT ABSORBER (RM3)

The RM3 is a floating type of the wave point absorber. As shown in Figure 5 and Figure 6, the model of RM3 consists of a surface float that oscillates up and down with the wave motion relative to a vertical column spar buoy. This vertical column is intermediate connecting link between the surface float and reaction plate. The float is designed to oscillate up and down the vertical column up to 4 m. The 3 mooring line system maintains its position. It is equipped with the hydraulic PTO system, placed inside the vertical column. When the oscillating element of the RM3 is in-phase with the hydrodynamic wave excitation force, the system extracts the optimum energy. Table 1 describes the detail description of the RM3.

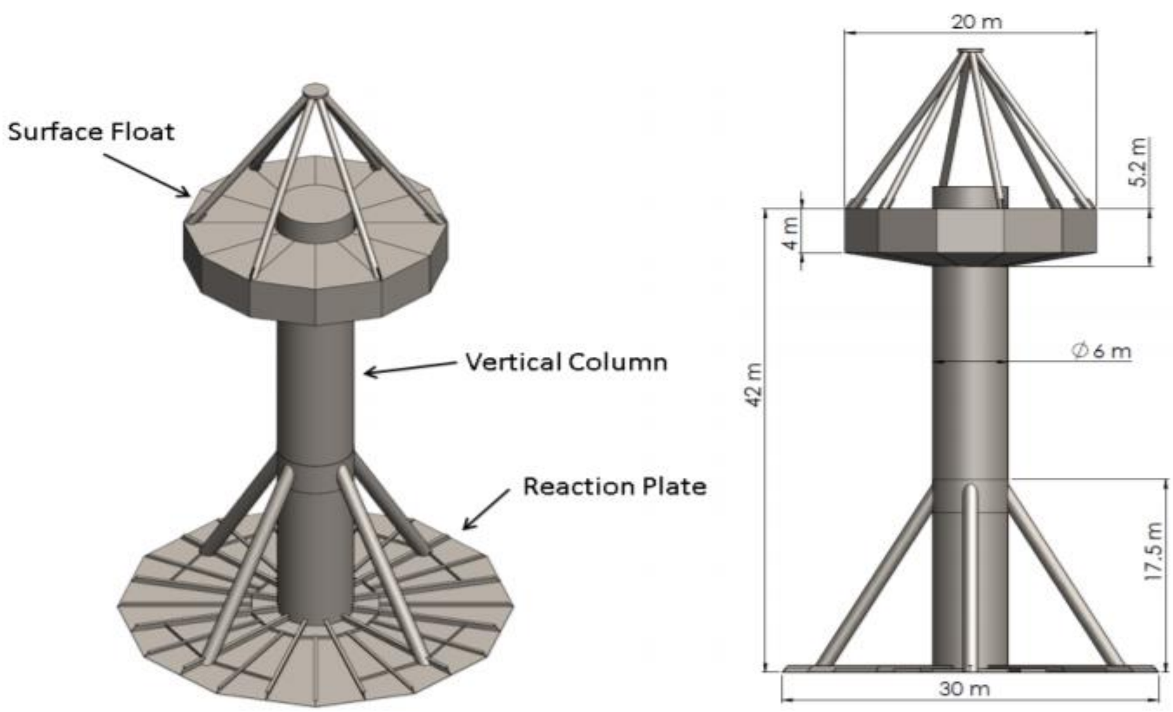

FIGURE 5: RM3 Device Design with dimensions [21].

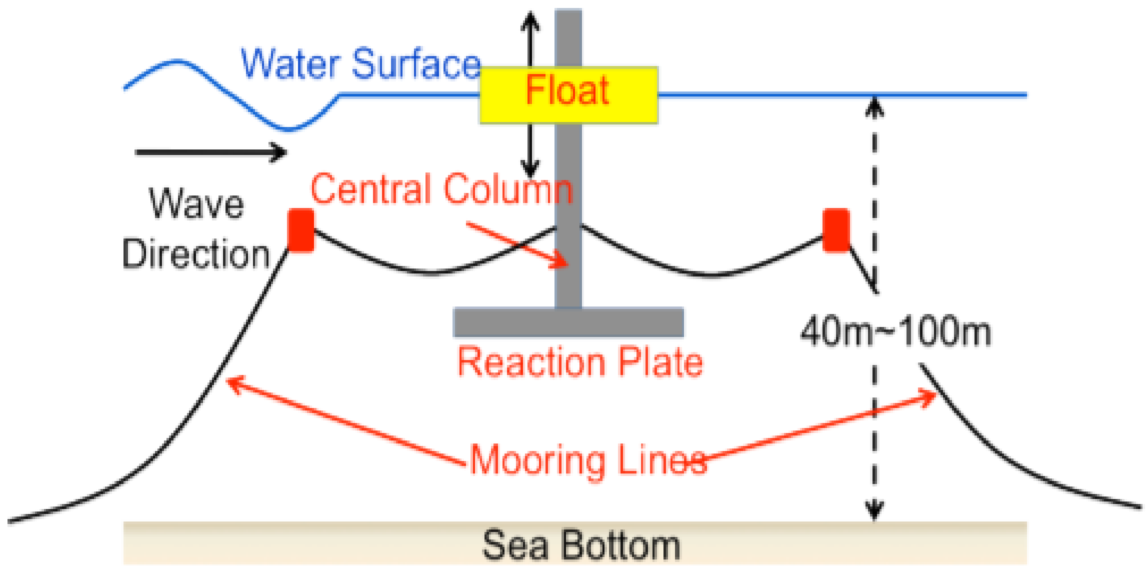

FIGURE 6: RM3 Device Design and Working from the Side View [21]

TABLE 1: RM3 Design Specification

Description	**Specification**
Type	Wave point absorber
Mooring system	3-mooring line design
Rated Power	300 kW
Operational sea state	H_s – 0.75 m to 6 m, T_e – 5 sec to 18 sec
Material	Steel (A36)
Total Weight	695000 kg
Array Configuration	600 m distance between two RM 3

1.4.2 OSCILLATING SURGE WAVE ENERGY CONVERTER (RM5)

The RM5 is a floating and oscillating surge wave energy converter. It generates the electricity from the surge motion of the ocean waves. Unlike the typical oscillating surge wave energy converter, RM5 is designed to function in the deep-water and it maintains the position with the taut mooring system. Figure 7 and Figure 8 shows the detailed configuration of the RM5 model which consists of the supporting frame and flap. The flap is designed to rotate against the supporting frame to convert wave energy into the electric power from the relative rotational motion induced by incoming ocean waves. Table 2 describes the detail description of the RM5.

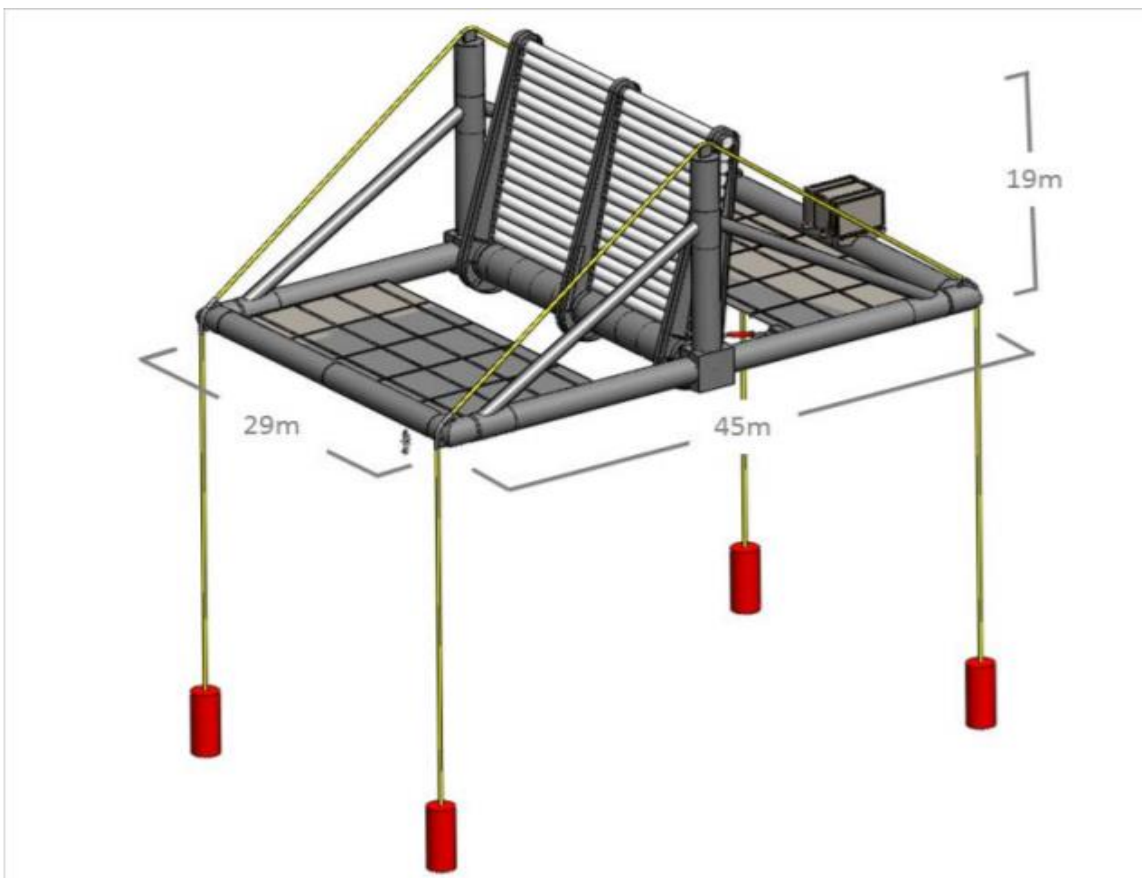

FIGURE 7: RM5 Device Design with dimentions[22].

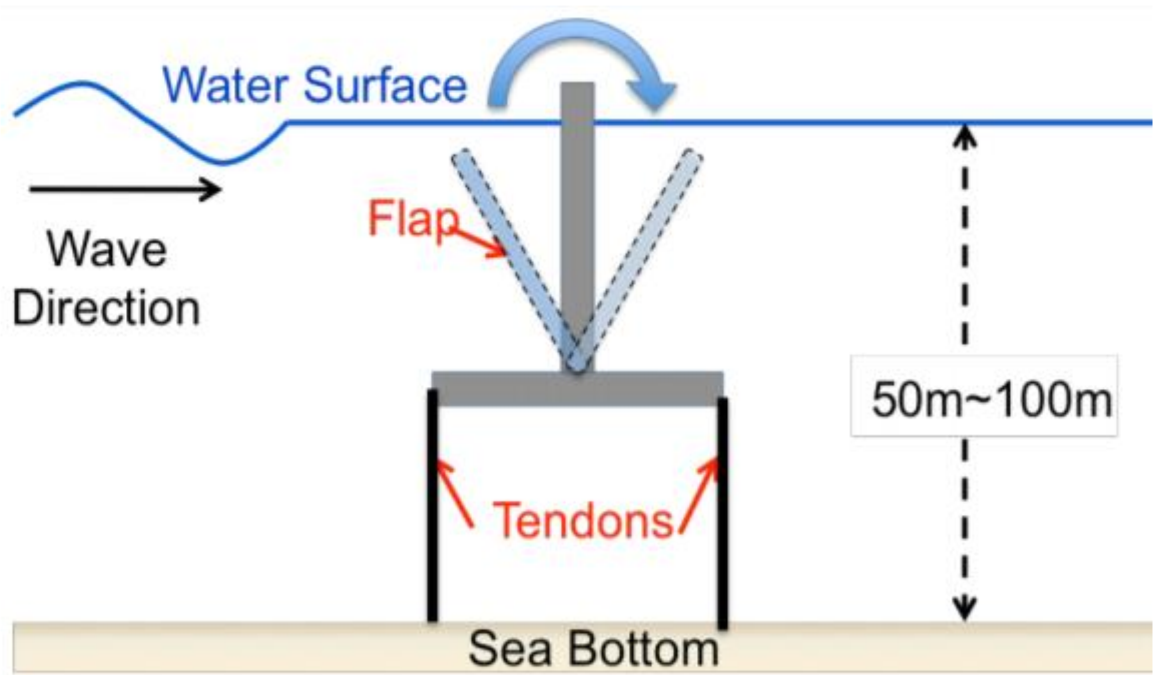

FIGURE 8: RM5 Device Design and Working from the Side View [22].

TABLE 2. RM5 Design Specification.

Description	Specification
Type	Terminator
Mooring system	Taut mooring (four legs & two line per leg)
Rated Power	360 kW
Operational sea state	H_s – 0.75 m to 6 m, T_e – 5 sec to 18 sec
Structure	Fiberglass & Steel (A36)
Total Weight	725000 kg
Array Configuration	600 m distance between two RM 5

1.4.3: OSCILLATING WATER COLUMN (RM6)

The RM6 is a Backward Bent Duct Buoy. It is a type of oscillating water column wave energy converter and detailed model with the dimensions can be seen in Figure 9. The model consists of an air chamber, L shaped duct, bow and stern buoyancy modules, Wells air turbine and generator. The L shaped chamber is open to the ocean downstream in the direction of the wave propagation. Due to this the ambient pressure of the air chamber vary and forces the air to flow through Wells turbine. The rotation of the Wells turbine produces the electric power. This floating and oscillating WEC extracts the wave energy from the motion of the structure and the motion of the free surface, this increases the wave generation frequency and thus gives high primary conversion efficiency compared to other WEC. Table 3 describes the detail description of the RM6.

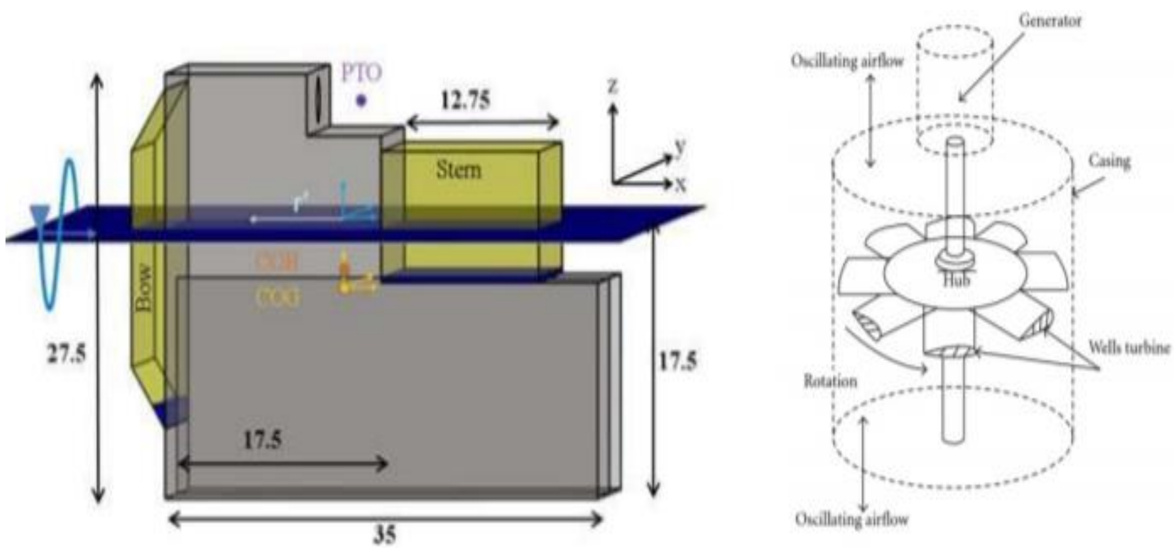

FIGURE 9: RM6 Device Design with dimensions [23].

TABLE 3: RM6 Design Specification.

Description	**Specification**
Type	Oscillating water column
Mooring system	3- mooring slack line design
Rated Power	298 kW
Operational sea state	H_s – 0.75 m to 6 m, T_e – 5 sec to 18 sec
Structure	Fiberglass & Steel (A36)
Total Weight	1810000 kg
Array Configuration	600 m distance between two RM 6

1.5: ENERGY STORAGE

All the RES are intermittent and unpredictable in nature. The fluctuation can limit the share of RES in the energy mix. Hence, it is important to develop the technology to store the electric energy so it will be available to meet demand whenever needed. The electric storage methods manage the amount of power required to supply customers at times when the need is more, at a peak time. They can maintain the smooth functioning microgrids by balancing generation and load. Storage devices can regulate the voltage and control the frequency regulation to maintain the balance between the network and power generated load. There are various technologies available for storing the excess amount of energy and releasing it when generation rate is low and demand rate is high[24, 25]. Some different forms in which energy can be stored include heat, mechanical, chemical or electrochemical. These include,

1. hydrogen
2. batteries
3. Flow batteries
4. flywheel
5. pumped hydro
6. supercapacitors
7. compressed air
8. superconducting magnets

1.5.1: FLOW BATTERIES

The flow battery is a chemical storage of the electrical energy. The working principle for the flow batteries is similar to the fuel cell. The ion selective membrane separates oxidation and reduction reaction. Unlike the fuel cell, the electrolyte is stored outside the cell on each side and fed into the cell at the time of electricity generation. The amount of electricity generation depends on the size of the storage tanks. The vanadium redox battery is one of the commonly used flow battery. The flow battery has more tolerance for deep discharge as compared to the conventional lead batteries.

1.5.2: PUMPED HYDRO

The pumped hydro method uses the potential energy of the stored water for electricity generation. At the time of high demand, water flows from the high reservoir to the lower reservoir through the turbine and produces electricity. The pump-back method is used for water shifting between two reservoirs. At present, pump hydro accounts around 99% of the bulk storage capacity worldwide.

1.5.3: BATTERIES

Many renewable energy projects use electromechanical storage in the form of batteries such as lead batteries due to wide availability in size and capacities. They are mainly used on the small scale, off-grid application. The major disadvantage for batteries is that the efficiency decreases with the lifetime particularly in the case of deep discharging.

1.5.4: HYDROGEN SYSTEM

Hydrogen can be produced from the various resources using multiple technologies. It can be stored in the form of solid, gas or liquid. If the hydrogen is stored in the form of gas it requires the high-pressure tanks whereas liquid hydrogen requires cryogenic temperature as the boiling point of hydrogen at one-atmosphere pressure is -252.8 °C. Hydrogen can also be stored on the surfaces of solids (by adsorption) or within solids (by absorption). The stored energy in the hydrogen can be utilized with the help of fuel cell.

Ideal requirements for energy storage would be rapid access to the energy stored and the ability to supply it in the different energy forms.This study has considered hydrogen as storage media.

1.6: HYDROGEN AS AN ENERGY CARRIER

Hydrogen is considered as a promising energy carrier for storing excess of energy produced from RES for the smooth and continuous supply of energy. Energy carrier can store and transfer energy from one source to another source. The suitable properties of hydrogen listed as below makes its efficient energy carrier for sustainable energy system[26-28].

1. The simplest, with atomic number as one and most abundant element, representing about 75 w % of all the matter.
2. The energy content per unit weight is high. The lower heating value (LHV) and high heating (HHV) value corresponding to 33.3 kWh kg^{-1} and 39.4 kWh kg^{-1} respectively.
3. The combustion of hydrogen results in water or water vapor, hence considered as non-polluting fuel.
4. Hydrogen can be produced from both conventional and renewable energy sources by using various processes.
5. It can be stored as liquid, gas or solid as a metal hydride.
6. Hydrogen can be used in multiple applications such as transportation, energy generation, and heat production.

1.6.1: HYDROGEN PRODUCTION FROM FOSSIL FUELS

Hydrogen production from natural gas requires a thermal process such as steam gas reformation and partial oxidation. Currently, the majority of the hydrogen is produced from the natural gas as it cost less in comparison to RES.The natural gas contains methane (CH_4) which decomposes into hydrogen and carbon dioxide and carbon monoxide.

In steam reforming reaction, firstly the natural gas reacts with high-temperature steam (700°C–1,000°C) in the presence of metal (nickel) based catalyst to produce hydrogen and other byproducts such as carbon dioxide and carbon monoxide. In the next reaction of water–gas shift reaction, the carbon monoxide reacts with steam to produce more hydrogen and carbon dioxide. This carbon dioxide along with other impurities is removed in a final step called as pressure-swing adsorption.

Steam-methane reforming reaction

$CH_4 + H_2O + \text{heat} \rightarrow CO + 3H_2$

Water-gas shift reaction

$CO + H_2O \rightarrow CO_2 + H_2 + \text{small amount of heat}$

In partial oxidation, methane and other hydrocarbons react with the limited source of oxygen or air to produce hydrogen. The limited amount of oxygen is not sufficient for complete combustion of hydrocarbons and this result into the production of hydrogen, carbon dioxide, carbon monoxide and nitrogen. More hydrogen is produced from carbon monoxide in the water-gas shift reaction.

Partial oxidation of methane reaction

$CH_4 + \frac{1}{2}O_2 \rightarrow CO + 2H_2 + \text{heat}$

Water-gas shift reaction

$CO + H_2O \rightarrow CO_2 + H_2$ + small amount of heat

Steam reforming is an endothermic process whereas; partial oxidation is an exothermic process. Partial oxidation is a fast process and requires less space. But, the partial reaction produces less quantity of hydrogen as compared to the steam reforming reaction for the same amount of fuel [29, 30].

Coal is the complex and versatile chemical substance and it can produce a variety of substances. Coal uses gasification process for hydrogen production. In this process, coal reacts with the high temperature and high-pressure steam to form carbon monoxide and hydrogen. Then water- gas shift reaction takes place to produce more hydrogen from the carbon monoxide. Then hydrogen is removed by separation system.

Coal gasification reaction (unbalanced)

$CH_{0.8} + O_2 + H_2O \rightarrow CO + CO_2 + H_2$ + other species

The hydrogen production from the fossil fuel is an economic and developed method but it increases the GHG emission and other pollutants. The development carbon capture technology can efficiently help to reduce these emissions [30, 31].

1.6.2: HYDROGEN PRODUCTION FROM RENEWABLE ENERGY RESOURCES

1. Solar Energy – Hydrogen can be produced from the solar energy by implementing variety of the processes such as photovoltaic process, photo-electrolysis process, and photo-biological process[32, 33]. In the photovoltaic process, solar energy is converted into the electric energy by using photovoltaic (PV) cells. This electric energy is then passing through electrolyzer produces hydrogen. The efficiency of this process is low, 16%. Photo-electrolysis is slightly different than the photovoltaic process as it uses direct sunlight to decompose water into the hydrogen and oxygen. This reaction takes place in a photoelectrochemical cell which has photo-cathode and photo-anode made of semiconductor material. The system has limitations due to low conversion efficiencies of the semiconductor materials. The photobiological process involves the decomposition of water in the presence of solar energy carries out by microorganisms under anaerobic conditions. Currently, this process is in the early stage of development. One report had investigated that with the help of photobiological hydrogen generation process, 100 m^3 algae culture gave an average of 240 W powers for 100 h with maximum efficiency of 0.64% [34].

2. Wind Energy – The contribution of wind energy in today's energy mix can be increased efficiently with the help of energy storage facilities [35-37]. The electrolysis of water can be used for hydrogen production from wind energy. The electric energy produced from the wind is passed through central or distributed electrolysis plant. This stored energy can be utilized at the time of low availability to ensure the continuous energy supply.

3. Wave Energy – The energy production from the ocean waves is relatively new and developing technology. Hence, the cost of the electricity production from the ocean wave

energy is more as compared to the mainstream solar and wind energy. The electrolysis of water is utilized for the hydrogen production [38]. The working model for hydrogen production from the ocean waves as seen in Figure 10.

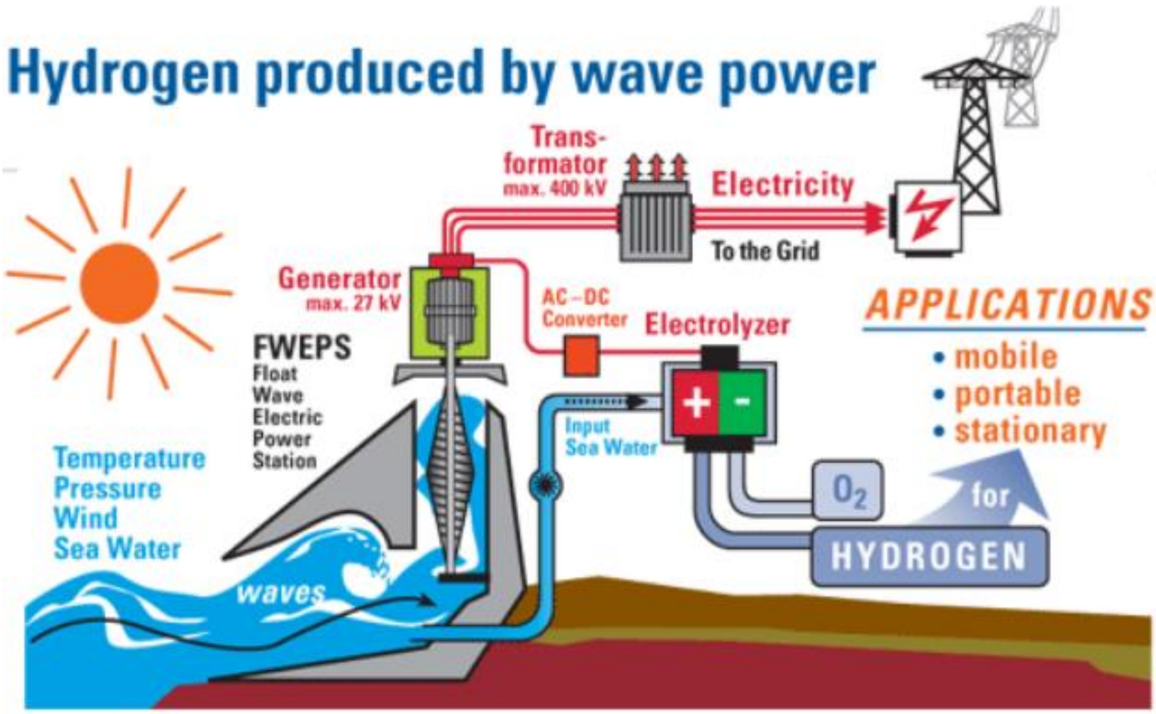

FIGURE 10: The Schematic for Hydrogen Production from the Ocean Waves [39].

1.7: HYDROGEN PRODUCTION: ELECTROLYSIS OF WATER

In the process of electrolysis of water, an electric current is passed through the electrolyzer to split the water molecule into the hydrogen and oxygen. The electrolyzer model as shown in Figure 11 consists of an anode, cathode, and electrolyte which separate them.

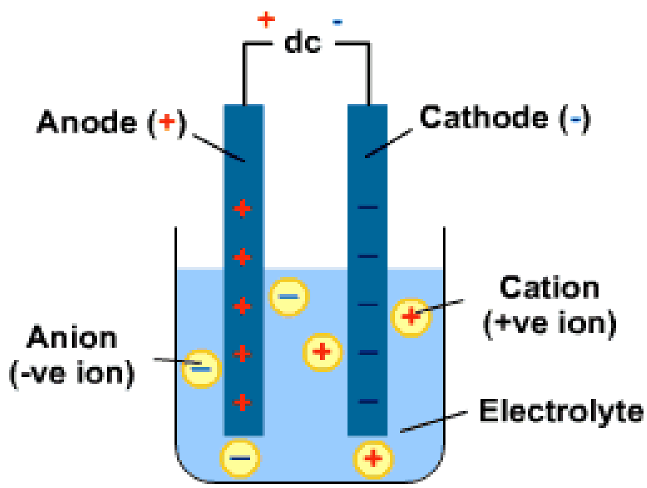

FIGURE 11: The Electrolyzer Model for Hydrogen Production

The electrolysis of water is a versatile process; it can produce hydrogen with electricity produced from various conventional and RES. The hydrogen produced from RES results into low GHG emission. It results into the pure hydrogen as it uses only water. Electrolyzers vary in the sizes and depending on the size they can produce from some cm^3/min to thousands m^3/h. The efficiencies of electrolyzer depend on many parameters such as electrolyte material, applied current, available voltage, the source of electric current. The electrolyzers can be classified as an alkaline electrolyzer, polymer electrolyte membrane (PEM) electrolyzer, and solid oxide electrolyzer as shown in Figure 12 [40, 41] and Table 4 on the basis of electrolyte material used in the electrolyzers.

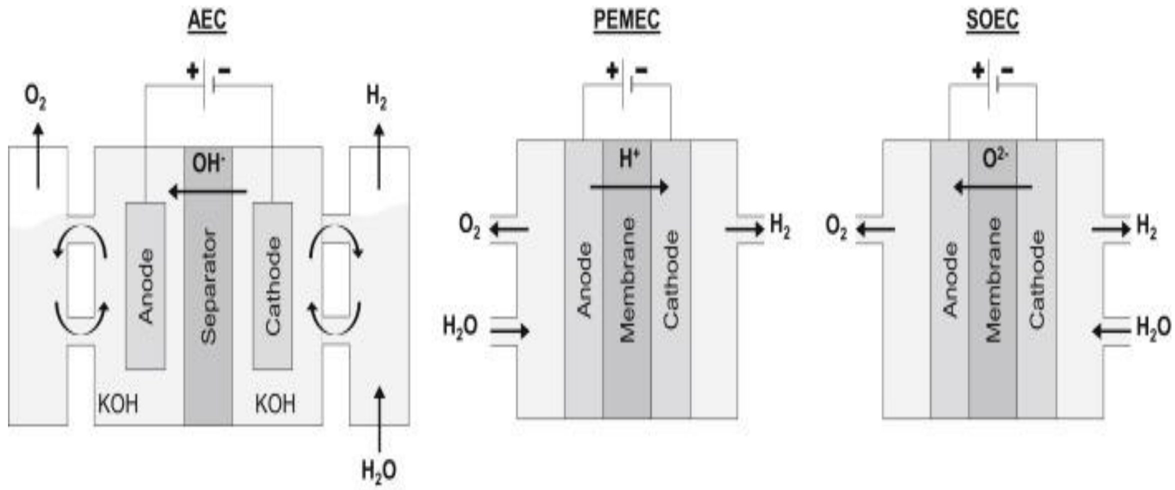

FIGURE 12: The Electrolyzer Models for Alkaline Electrolyzer, PEM Electrolyzer, and Solid Oxide Electrolyzer.

TABLE 4: The Comparison between Electrolyzer Models.

	Alkaline Electrolyzer	PEM Electrolyzer	Solid Oxide Electrolyzer
Electrolyte	Potassium hydroxide solution	Proton Exchange Membrane	Oxide ion conducting ceramic
Electrical Efficiency	60 -70%	65 -80%	60-65%
Purity of Hydrogen	> 99.8 %	99.9999 %	99.8 %
Energy Output	300W- 5kW	1kW	100kW
Technology Maturity	State of the art	Demonstration	Research and Development

1.7.1: PEM ELECTROLYZER

PEM electrolyzer contains solid polymer electrolyte instead of traditional liquid electrolyte for conduction of protons, gas separation and electric insulation for the electrodes and prevention of spontaneous recombination into the water [41]. The thickness of the solid polymer electrolyte is very less (0.2 mm). The Nafion (sulfonated tetrafluoroethylene based fluoropolymer-copolymer) is commonly used electrolyte in PEM electrolyzers. Both sides of the membrane are coated with the porous catalytic layer which provides a connection to an external DC power source. After passing the electric current, water reacts at the anode and produces oxygen and protons (positively charged hydrogen ions). Subsequently, electrons flow through an external circuit and protons move across the polymer membrane and at cathode they both get combine to produce hydrogen gas [42]. These two chemical reactions are expressed as follow,

Anode Reaction: $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$

Cathode Reaction: $4H^+ + 4e^- \rightarrow 2H_2$

1.7.2: ALKALINE ELECTROLYZER

An alkaline electrolyzer uses a variety of different chemical substances for electrodes and electrolytes such as simple iron or nickel steel electrodes are used to produce hydrogen and nickel electrode is used to produce oxygen production. These electrodes are immersed in a highly concentrated alkaline solution of sodium or potassium hydroxide. The diaphragm, a porous solid material separates anode and cathode and avoids mix-ups of gases. It also allows smooth transfer of hydroxyl ions (OH^-) between the electrodes. The reaction requires the supply of electrical energy through a potential difference between the two electrodes. The cell voltage lies in the range of 1.0-2.0 V. When the required amount of potential difference is applied between the electrodes, oxidation of water at anode and reduction of water at cathode take place simultaneously [41]. As seen in the reactions, at anode OH^- ions of the electrolyte are oxidized into oxygen gas. The electrons coming from the external electrical circuit are used to reduce the water into the hydrogen gas. The amount of gas produced is directly proportional to the current flowing through the electric circuit [43].

Anode Reaction : $4OH^- \rightarrow O_2 + 2H_2O + 4e^-$

Cathode Reaction : $4H_2O + 4e^- \rightarrow 2H_2 + 4OH^-$

1.7.3: SOLID OXIDE ELECTROLYZER

Solid oxide electrolyzer uses the solid ceramic material as an electrolyte that produces the hydrogen at elevated temperatures. When a potential difference is applied between the electrodes, water combines with electrons from an external supply to form hydrogen gas and negatively charged oxygen ions at the cathode. Then this negatively charged oxygen ion is passed through the solid ceramic membrane and forms oxygen gas and electrons at the anode. Solid oxide electrolyzer requires high operating temperature. This high heat is also used for hydrogen generation hence it reduces the need for electric energy [41].

Anode Reaction: $O_2^{-} \rightarrow 1/2O_2 + 2e^{-}$

Cathode Reaction : $H_2O + 2e^{-} \rightarrow H_2 + O_2^{-}$

The capital cost of the electrolyzer is very high and it creates the obstacle for integration of hydrogen system with RES. The produced hydrogen needs to be stored at high pressure. The integrated compression-electrolyzer unit can help to achieve this and reduces the cost of compression [41, 44, 45].

1.8: HYDROGEN APPLICATION

Hydrogen creates only water or water vapor with low or zero emission. The internal combustion engine can efficiently use hydrogen to increase their overall efficiency by 20% [41]. It also can be used in turbines and jet engines, with the same emissions. It is readily used in fuel cell technology, the electrochemical generation of electricity. In a fuel cell, hydrogen combines with an oxygen to produce pure water and electricity. Depending on the electrolyte used, the fuel cells (FC) can be categorized as Alkaline fuel cells, polymer electrolyte membrane or proton exchange membrane fuel cells (PEM), phosphoric acid fuel cells, molten carbonate fuel cells or solid oxide fuel cells. A fuel cell is comparatively efficient and produces low pollutants but the material used in the fuel cells are expensive, which makes them costly in comparison to the internal combustion engine.

1.9: NORTH CAROLINA CASE

North Carolina (NC) is located in the southeastern part of U.S., between 35°46 ’ N and 79° 01’W. It is surrounded by South Carolina and Georgia to the south, Tennessee to the west, Virginia to the north, and Atlantic ocean to east with the coastal length of 485 km. It is 9th most populous state of the U.S. with a total population of 10,146,788 in the year of 2016. It is third largest banking hub in the U.S. and leading industrial area in the southeastern region. The nuclear energy is the main source of energy for NC, it holds 32.5% share of electricity generation. The share of natural gas, coal and renewable energy resources in the current energy mix is 30%, 28.6%, and 8% respectively. The fossil fuel is mainly imported as NC does not have any fossil-based power plant. From the last 5 years, the renewable energy share is increasing in the energy mix. In 2016, NC rank third for producing energy from solar photovoltaic cells. The largest wind farm in southeast region with 208 MW capacity has been developed in NC. The vast coastal length of NC has high offshore wind and wave energy potential. The tidal energy potential at nearshore is also estimated earlier[46].

This study estimates the ocean wave energy potential of NC based on the five selected sites such as Masonboro Inlet, Oregon Inlet, Wilmington Harbor, Duck FRF 17-m and Duck harbor 26-m along the NC’s coastline as shown in Figure 13. Table 5. Provides the detail information of each station.

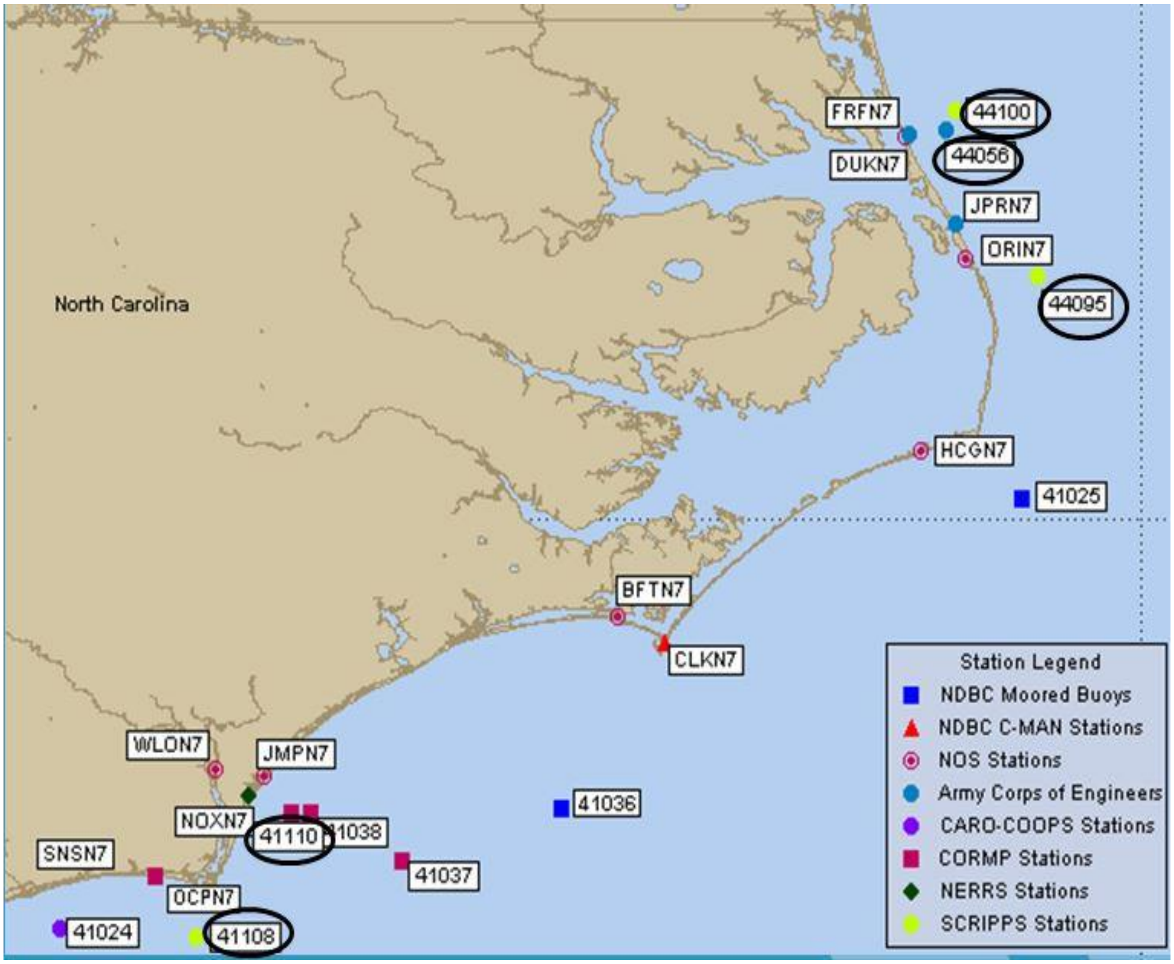

FIGURE 13: The Map of NC with the Five Selected Stations.

TABLE 5: The Detail Information of Five Stations along the NC Shore.

Station Number	Buoy Number	Location	Depth (M)	Distance (Km)
US 150	41110	Mansonboro inlet	17	12
US 192	44095	Oregon inlet	18.3	35.2
US 200	41108	Wilmington	12.8	14.4
US 430	44100	Duck frf, 26 m	25.91	17.6
US 433	44056	Duck frf, 17 m	17.4	4.2

CHAPTER 2: METHODOLOGY

2.1: PROPOSED MODEL

The proposed model can be divided into two components: the wave farm and the electrolysis system as shown in Figure 14. The wave farm, consisting number of WEC collects the energy from the ocean wave and converts into the electric power. The produced electricity could be AC or DC. When the wave farm is integrated with an electrolysis system the desired output should be in the DC form as electrolyzers run with DC current. The electricity produced from the WEC must be conditioned before submitting to electrolysis system. Also, the power must be smoothed before providing to the electrolyzer as variation in power tend to increase the internal wear, impurities in the produced hydrogen, and reducing the efficiency of the electrolyzer. The conductivity of water used for electrolysis must be very low to avoid impurities in the produced hydrogen. The electrolysis system also needs to be equipped with desalination of seawater facility. The output of the electrolyzer system is hydrogen and oxygen at a pressure that depends on the type of electrolyzer used. This study has considered the PEM electrolyzer for hydrogen production from the electrolysis of water. The produced gas needs to be store under required pressure for that plant should include storage system with the compressor unit. Also, an auxiliary power supply system based on the hydrogen energy is needed to include in the plant for providing power to compressors, pumps, lighting, and control system. The following section explains the working theory for the wave farm and electrolysis system.

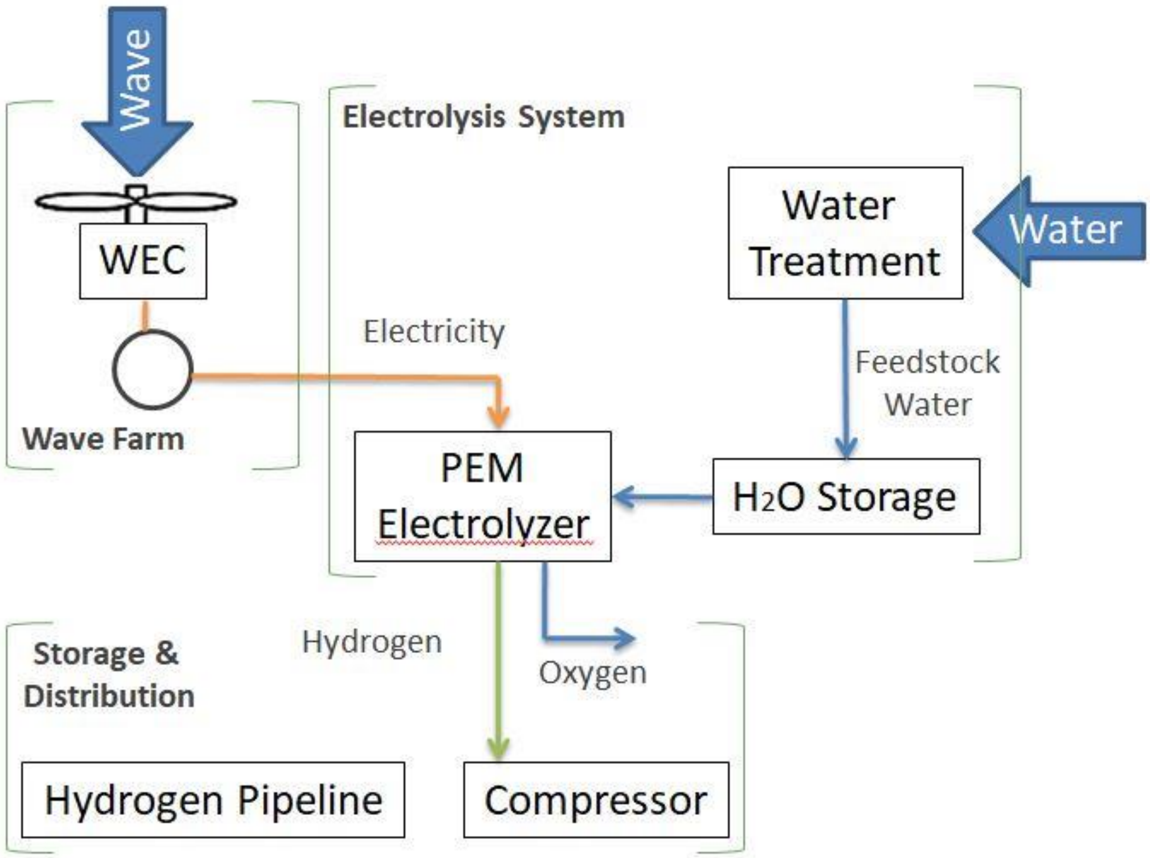

FIGURE 14: The proposed integrated model of wave farm and Electrolysis System.

2.2: THE POTENTIAL OF OCEAN WAVES

The amount of power stored in the ocean waves can be estimated from the change in potential energy of the water and it can be derived from the following equations based on [47]. The water is continuously changing its position from crest to through, above the sea level under the influence of the wind.

The mass of water above the sea level during the crest (M_{crest}) can be written as,

$$M_{crest} = W\rho\left(\frac{\lambda}{2}\right)\left(\frac{H_C}{2\sqrt{2}}\right) \tag{1}$$

Where W is the width of the wavefront (m), $\rho$is the density of the sea water(1029 kg/m$^{3)}$, g is the acceleration due to gravity (9.81 m/sec^2), λ is the wavelength (m), and H_c is the crest height(m).

The height of the center of the gravity (H_{cg}) above the sea level can be written as,

$$H_{cg} = \frac{H_C}{2\sqrt{2}} \tag{2}$$

The change in the potential energy of water following the standard equation of the potential energy ($PE = mgh$) can be written as,

$$\rho g W\left(\frac{\lambda}{2}\right)\left(\frac{H_C}{2\sqrt{2}}\right)^2 = \frac{\rho g \lambda W H_C^2}{16} \tag{3}$$

The frequency (f) of the gravity waves in the deep water is given as,

$$f = \lambda = \sqrt{\frac{g\lambda}{2\pi}} \tag{4}$$

Therefore, the wave power can be written as,

$$P = \frac{\rho g W H_C^2 \sqrt{g\lambda}}{16\sqrt{2\pi}} \tag{5}$$

The significant wave height (H_s) and time period (T_p) of the wave are commonly used and available parameters. The H_s is defined as the average height of highest one-third of the waves. The crest height can be converted into significant wave height using root mean square displacement (D_{rms}) method.

$$\frac{H_C}{2\sqrt{2}} = D_{rms} \tag{6}$$

$$H_s = D_{rms} \tag{7}$$

Hence,

$$H_s^2 = 2H_C^2 \tag{8}$$

The wavelength can be converted to the time period as follow,

$$\lambda = \frac{T_P{}^2 g}{2\pi} \tag{9}$$

The theoretical wave power can be expressed as the function of H_s and T_p as follow,

$$P = \frac{W\rho g^2 T_P H_s^2}{64\pi} \tag{10}$$

For the real sea-state, in the deep water, the wave power is estimated considering significant wave height and energy period (T_e). It is calculated as,

$$T_e = \alpha T_p \tag{11}$$

Where α is the wave period ratio for the wave spectrum The value for α depends on the selection of the wave spectrum [48].

The wave power for the real sea state is estimated by using following equation,

$$P = \frac{W\rho g^2 T_e H_s^2}{64\pi} \tag{12}$$

2.2.1: WAVE SPECTRUM

The sea surface is composed of not only the simple sinusoidal waves but also the random waves of various lengths and periods [49]. The linear superposition of random waves of different lengths and period is characterized in the frequency domain by a wave spectrum. The wave spectrum can be characterized by different parameters such as significant wave height, peak period, wind speed, fetch length. The general form of the wave spectrum is given as follow [50],

$$s(f) = Af^{-5}\exp\left[-Bf^{-4}\right] \tag{13}$$

Where *f* is the frequency, *A* and *B* are constants, and *s(f)* is the long-crested wave spectral density ordinates. The spectrum moments (m_k)for wave spectrum for k= 1,2,3,4,…

$$m_k = \int_0^{\infty} f^k s(f)df \tag{14}$$

The Pierson-Moskowitz spectrum, JONSWAP (Joint North Sea Wave Project) spectrum are commonly used spectrums in the marine applications.

2.2.1.1: PIERSON-MOSKOWITZ SPECTRUM

The Pierson Moskowitz wave spectrum is the simplest wave spectrum. This is for fully develop sea-state where the wave period is about 10,000 and wavelength of roughly 5,000. The H_s cannot represent this wave spectrum. However, the JONSWAP wave spectrum can be modified on the basis of H_s and T_p.The results of this work are based on the JONSWAP spectrum and it is explained briefly in the following section. The commonly used value of α is 0.81 and can be written as,

$$S_{\tau_0}(f) = \alpha g^2 (2\pi)^{-4} f^{-5} \exp[-\frac{5}{4}(\frac{f}{f_0})^{-4}] \tag{15}$$

Where f_0 is the peak frequency of the wave spectrum.

2.2.1.2: JONSWAP SPECTRUM

The JONSWAP spectrum is developed by the Hasselmann in 1967, to measure the wave growth under the limited fetch conditions and to analyze the attenuation of waves propagating into the shallow water. The JONSWAP spectrum is the fetch based version of the Pierson-Moskowitz spectrum. Unlike the other spectrum, JONSWAP spectrum is never completely developed and tends to develop with distance or time as a result of non-linear wave-wave interaction for the prolonged time period. Hence an additional factor is added to the Pierson-Moskowitz spectrum to improve the fit of the curve. The fetch length dependent JONSWAP spectrum can be written as [50],

$$S_{\tau_0}(f) = \alpha g^2 (2\pi)^{-4} f^{-5} \exp[-\frac{5}{4}(\frac{f}{f_0})^{-4}]\gamma^{\exp[\frac{(f-f_0)^2}{2\sigma^2 f_0^2}]} \quad (16)$$

Where f_0 is the peak frequency of the wave spectrum, σ is the width of the spectral peak, and Υ is the shape parameter of the spectrum. The value of σ is different for shallow water (0.07) and deep water (0.09). The values α and f_p are dependent on the fetch length and wind speed. The relation between them written as,

$$\alpha = 0.076 X_{ref}^{-0.22} \quad (17)$$

$$f_p = 3.5 X_{ref}^{-0.33} \quad (18)$$

$$X_{ref} = \frac{gX}{U^2}$$

(19)

Where U is the wind speed, X is the fetch length, and X_{ref} is the reference fetch length calculated at reference wind speed at 10 m above the sea state.

The fetch dependent JONSWAP can be modified to be based on H_s and T_p. The modified JONSWAP spectrum [51],

$$S_{\tau_0}(f) = \frac{16.942(H_s)_{1/3}^{1.375}}{g^{1.375}T_p^{2.75}} g^2 (2\pi)^{-4} f^{-5} \exp[-\frac{5}{4}(\frac{f}{f_p})^{-4}]\gamma^{\exp[\frac{(f-f_p)^2}{2\sigma^2 f_p^2}]} \quad (20)$$

The empirical relation between Υ and α for the JONSWAP spectrum is written as follow, and Table 6 represents the different combinations of them [48].

$$\alpha = \frac{4.2+\gamma}{5+\gamma}\left(\frac{11+\gamma}{5+\gamma}\right)^{\frac{1}{2}} \quad (21)$$

TABLE 6: The value of α corresponding to the given Υ.

Peak Shape Factor (γ)	Wave Period Ratio (α)
1	1.22
2	1.20
3.3	1.18
5	1.16
7	1.14
10	1.12

The most frequently used JONSWAP form (γ =3.3) is used to convert T_p to T_e for estimating the wave power. Though, the value of α is generally higher than the theoretical relationships for the real sea-state, depending on the geographical location [48]. This study estimated T_e using JONSWAP spectrum with α = 1.18. As JONSWAP spectrum gives more realistic results (narrow distrubution for same frequency) compared to the Pierson-Moskowitz spectrum.

2.2.2: WAVE ENERGY FARM

In the wave energy farm, the number of WEC are linked together to form an array to increase the output power.The annual energy production *(AEP)* of the wave energy farm is calculated by adding the contribution of each WEC and the potential of the site.

$$AEP = \eta * 8760 * RP * \sum P_S \tag{22}$$

Where η is the overall efficiency, *RP* is the rated power of WEC, P_s is the annual average wave power potential of the selected site, and 8760 are the hours in the Julian year.

The rated power of the wave energy farm is a summation of the rated power of each WEC. The energy produced by an array of WEC and energy produced by single WEC in the same position multiplied by the number of WEC in the array can differ due to array losses. For avoiding array losses and increasing the array efficiency, WEC needs to be spaced evenly, along with the incoming wave direction. The design of a wave energy farm should be able to cover a full wavelength along the predominant wave direction. An angle of 45◦ to the incoming wave direction is considered as an optimal for efficient power extraction. The WEC in the wave energy farm should be placed closing so they can share a common mooring system and it also helps to simplify the electrical connections between WEC as the cable can run along them. The *RP* of WEC is considered as same for scale-down models to meet the available water depth.

2.3: ELECTROLYSIS SYSTEM

The hydrogen production is estimated by an integrated system of WEC and electrolysis system on the basis of *AEP*, and energy consumption of an electrolyzer. The electrolyzer energy consumption is the amount of energy required to produce a certain amount of hydrogen. The hydrogen production is also dependent on the efficiency of the electrolyzer. The efficiency of an electrolyzer is defined as following [52],

$$\eta_{el} = \frac{M_{H_2} HHV_{H_2}}{E_W} \tag{23}$$

Where η_{el} is the efficiency of an electrolyzer, M_{H2} is the amount of the hydrogen produced, *HHV* is the higher heating value of the hydrogen (39.4 KWh/kg), and E_W is the wave energy provided to an electrolyzer.

The electrolyzer system can be designed using the following steps[53],

The size of an electrolyzer system (ESS) depends upon the maximum energy available (MEA) to the electrolyzer.

$$EES = \left(\frac{MEA}{24 \frac{h}{day}} \right) \tag{24}$$

$$MEA = (f_1 f_2 f_3)(24 \frac{h}{day}) \tag{25}$$

Where f_1 is the installed capacity of a wave energy farm (MW), the summation of the rated power of WEC, f_2 is the maximum feed factor that is the maximum percentage amount of the wave energy supplied to the electrolyzer unit. It can vary with the time. f_3 is the average energy produced by a wave energy farm.

The energy required by an electrolyzer (EER) depends on the electrolyzer efficiency, parasitic power consumption (PP), equipment efficiency (EE), and product losses (PL).

$$EER = MEA - MEA(1-\eta_{el}) - \left[PP + EE + PL\right] \tag{26}$$

The hydrogen produced per hour(P_{H_2}) is given as,

$$P_{H_2} = \frac{EER(1000)}{(24)(ER)} \tag{27}$$

ER is the electric energy input required for an electrolyzer, the current commercial PEM electrolyzers require 55-70 kWh/kg of hydrogen.

2.4: LIFE CYCLE ASSESSMENT

LCA is the methodology developed to measure and compares the environmental impacts of the product or the service over their entire life cycle. It is also known as ‘cradle to grave’ analysis which considered all the energy and emissions associated with everything from the extraction of raw materials to disposal at the end of a product’s serviceable life everything from the extraction of raw materials to disposal at the end of a product’s life. LCA can be applied to the fossil fuel energy system as well as RES. The LCA study mainly considers four stages of operation such as manufacturing, assembly and installation, operation and maintenance, and decommissioning and disposal. The required data for each stage is then collected and if not available justifiable assumptions can be made. This method gives a comprehensive result for each component, used materials and stages of the LCA for energy use and environmental impact [54]. There are few limitations associated with the LCA based on the assumptions made for the system boundaries and data source. This study presents an analysis of the life cycle energy use and GHG emission associated with the proposed model of wave energy extraction considering various WEC. The current study estimates these results by considering all energy input and GHG emission from the extraction of the raw materials used for manufacture from their natural state to the complete disposal of the product at end of its life. The life cycle energy use and GHG emission from the mooring system and submerged transmission system are not included in this result.

2.4.1: GREENHOUSE GAS EMISSION

RES rely on the natural sources (wind, sun, water) for energy production, due to which they are considered as a clean, and pollutant free source of energy. However, they tend to produce some amount of GHG due to indirect use of fossil fuel. The indirect use of fossil fuel in RES includes material manufacturing process, transportation required for initial setup, and dismantling process. The GHG emission from RES is very low in comparison to the fossil fuel based energy system. Although there are other environmental emissions such as NO_x and SO_2, this study has the main focus on the emission from the GHG. CO_{2eq}, or carbon dioxide equivalent (CO_{2eq}), is a standard unit for measuring greenhouse gas emissions. This unit expresses the impact of various GHG in terms of CO_2 that would create the same amount of warming. GHG emissions ($gCO_{2eq}\ kWh_e^{-1}$) is generally estimated as, [55]

$$GHG\ emission = \frac{Total\ CO2\ emissions\ throughout\ life\ cycle\ (g\ CO2\ eq)}{Annual\ power\ generation\ \left(\frac{kWh}{year}\right) * lifetime(year)} \tag{28}$$

This equation is useful for the life cycle assessment (LCA) of each renewable energy source from the manufacturing of the plant to full operation and dismantling of the system (i.e., cradle to grave). Amponsah el at reviewed 79 articles related to the LCA of various (onshore and offshore winds, hydropower, marine technologies (wave power and tidal energy), geothermal, photovoltaic (PV), solar thermal, biomass, waste, and heat pumps) RES for electricity and heat generation. This review indicated that the variation in the existing LCA studies for calculation of the GHG emissions from RES for electricity and heat generation. The GHG emissions from the offshore wind energy farm are lowest, in the range of 5.3-13 gCO_{2eq}/kWh. The GHG emission from the wave energy is not that accurate as the information is limited. The mean value ranges from 22.5 to 35.5 gCO_{2eq}/kWh. This study concluded that the LCA can be a useful tool for assessment and comparison of environmental impacts from RES [55]. Nugent and Sovacool reviewed 153

LCA studies for the wind and solar photovoltaic electricity generation technologies. The wind and solar energy technology caused the GHG emissions with the mean value of 34.11 gCO_{2eq}/kWh and 49.91 gCO_{2eq}/kWh respectively. The manufacturing and dismantle process caused the majority of the GHG emissions. The review also suggested that the electricity storage medium such as battery and fuel cell have a negative implication for emission intensity of wind energy systems [56]. R. Parker el at is among the few who had done the investigation for GHG emission for the wave energy technologies. They estimated the energy use and CO_2 emission from the first generation of Pelamis converters.

The study shows that the GHG emission from these WEC is 22.8 gCO_2/kWh. The material used in manufacturing is the main contributor to the GHG emission. After that, the transportation accounted for 42% GHG emissions. The energy payback period is approximately 20 months and the CO_2 payback is around 13 months. They concluded that the use of alternative materials for steel in the manufacturing and use of electric vehicles can increase the performance and reduce the environmental impact [57]. The energy use and emission factor associated with materials and post-processing operations are listed in Table 7.

TABLE 7: Energy Use and GHG Emission Factor for the Material Used [57].

Material	Energy Use (MJ/kg)	GHG Emission Factor (kg CO_2/kg)
Aluminum	167.5	9.21
Copper	55	4.38
Nylon 6	120.5	5.5
Paint	80	6.1
Polyurethane	72.1	3
PVC Pipe	67.5	2.5
Sand	0.1	0.005
Stainless Steel	51.5	6.15
Steel	45.4	3.19

2.5: ECONOMIC ANALYSIS

2.5.1: COST OF ENERGY

The ocean wave energy is an emerging field of RES, which faces several technical, economic, social and political challenges. Among all these limitations the high cost of energy generation is the most prominent issue. The aim of this section is to determine the cost of energy generation from the ocean wave energy in the terms of levelised cost of electricity (LCOE). The LCOE method is a well-established calculation and standard practice mainly used in energy generation field for comparing most of the RES projects. In order to calculate LCOE for any RES, the total project cost including capital expenditure (CAPEX), operational expenditure (OPEX), and AEP over its lifetime are the mainly required values. The LCOE is defined as the sum of the total of the capital expenditure, operational expenditure, and decommissioning costs, discounted to present day value divided by the annual energy produced by the wave farm in its lifetime [58-60].

$$LCOE = \frac{(CAPEX * FCR) + OPEX}{AEP} \tag{29}$$

The *CAPEX* includes costs required for manufacturing the components of subsystems, assembly and installation of the model. These costs are associated with the project development from selecting the suitable location for the energy extraction to analyzing the scale down model in the wave tank, and material, labor, and transportation cost required for the various subsystem of the model (WEC, electrolysis system, interconnecting cable, mooring system, transmission system) and insurance cost during the construction phase. The height of the wave and the time it lasts for which are the major factor affecting the wave energy potential increase along with the depth of the ocean.

However, it increases the installation costs. The WEC with high rating power can extract more energy in an efficient manner but such high precision machinery will need more investment. The change in global and national policies, natural disasters, can significantly affect the CAPEX. The OPEX comprises ongoing costs which are required to operate and maintain the smooth functioning of the model. OPEX usually consists of fixed cost and variable cost. The fixed cost needs to pay regardless the performance of the model which includes rent of the facilities, other back office activities, and an interest rate on the invested amount which do not depend on the model uptime. The variable cost can increase or decrease with the time depending on the performance of the model. This includes schedule inspection of the model for preventative and corrective maintenance of the repair or replacement components of the proposed model.

2.5.2: COST OF HYDROGEN

The hydrogen production cost is depended on the cost of electricity used for the electrolysis system, the energy requirement of an electrolyzer and initial cost of design and development of an electrolyzer system. The CAPEX accounts for electricity cost and design and development cost which is considered as $ 488/kW. The OPEX is calculated as 10% of the CAPEX and it considers the maintenance cost and replacement cost of the components of an electrolyzer system. The annual hydrogen production is estimated from the Eqn. 27.

CHAPTER 3: RESULT

3.1: LOAD PROFILE FOR NC

The electricity consumption varies with the season, the day of the week, and the time of day. The load variation is considered as the important factor for the modeling of the wave farm. In this section, the changes in load are analyzed so that the input for the proposed model can be representative of the real sea conditions.The main aim of this study is to balance the electricity load of NC with the help of wave energy extracted from the proposed model.The proposed model of the wave energy extraction explained in this thesis is able to calculate the hourly results and it requires the hourly load data for electricity consumption. Since the hourly load data is not available, the monthly electricity consumption data is considered and it is compared with the monthly wave energy potential of NC. The U.S. Energy Information Administration (EIA) has collected the electricity consumption data for each state and for various sectors such as residential, commercial and industrial. The figure shows the average electricity consumption of NC in a period of 2013-2017 with the separate traces for the residential, commercial, industrial, and total loads. As shown in the Figure 15, the energy consumption has significantly decreased in the year of 2016 and it has again increased in the year 2017 but it is relatively lower than energy consumption of period 2013-2015.

The Figure 16 shows the monthly variation in the electricity consumption for the NC state. The energy consumption for the summer season is relatively higher than the winter season. The seasonal energy consumption for NC in descending order is summer, winter, fall, and spring and it is in the similar order for the residential, the commercial, and the industrial sector.The shape of total electricity used by all the sector is similar to the shape of energy consumed by the residential sector. The industrial sector utilizes the least energy and its trace is similar to the commercial sector.

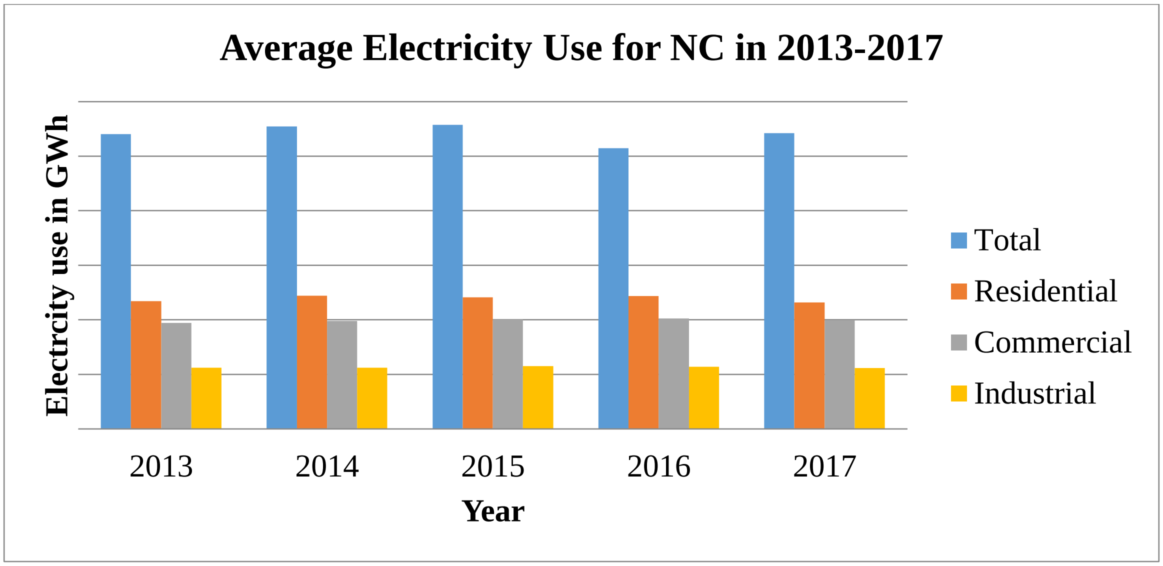

FIGURE 15: The Average Electricity Use of NC in the period of 2013-2017.

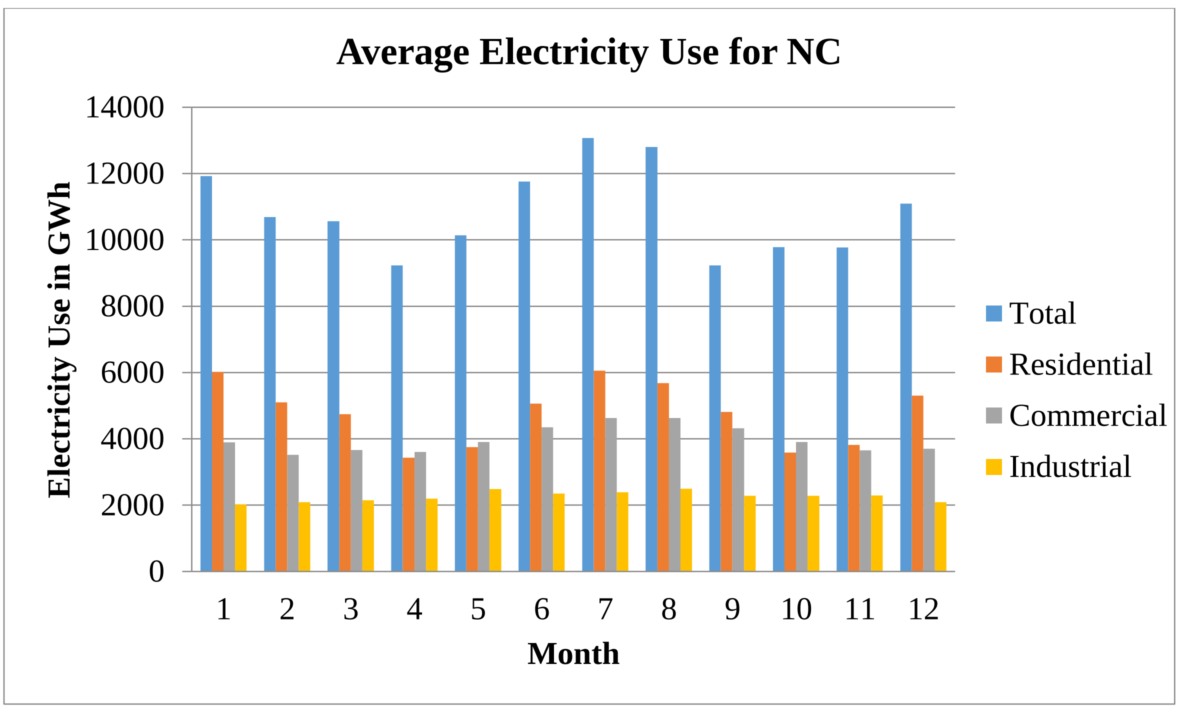

FIGURE 16: The Monthly Average Electricity Use of NC in the period of 2013-2017.

3.2: WAVE ENERGY POTENTIAL OF NC

This section estimates the wave energy potential of NC based on the equations explained in the section 2.1.1 and the wave data collected from the NOAA for the time period of 2013-2017. The wave data includes H_s, T_p, seawater temperature and wave direction available for every 30 minutes of the time interval. However, the results of this study are based on the H_s and T_p considering the unidirectional motion of the waves. The wave energy is calculated for every half hour and the cumulative sum of the wave energy for each month is estimated. The estimated wave energy (GWh) based on the real wavedata is plotted for the five years. As seen in the Figure 17, the data is too obscured by missing data and sudden fluctuations. This is not useful for any interpretations. Hence, the interpolated average wave energy data for each month is considered as seen in the same figure. Moreover, the energy consumption data of NC is also available in the monthly format. Table 6 represents the total wave energy potential of NC which is the sum of wave energy potential of all the five sites considering the interpolated average data. The minor grid lines and the major grid lines on the X-axis represent each month on the year and year from 2013 to 2017 respectively. The raw data and processed data represents the actual wave energy and average interpolated wave energy respectively.

The wave energy potential is highest for the fall season and it is lowest for the summer season compared to the other seasons. As per Table 8, a month of October is the most potential month for the wave energy extraction with an average potential of 567 GWh. The following section explains the wave energy potential for each site.

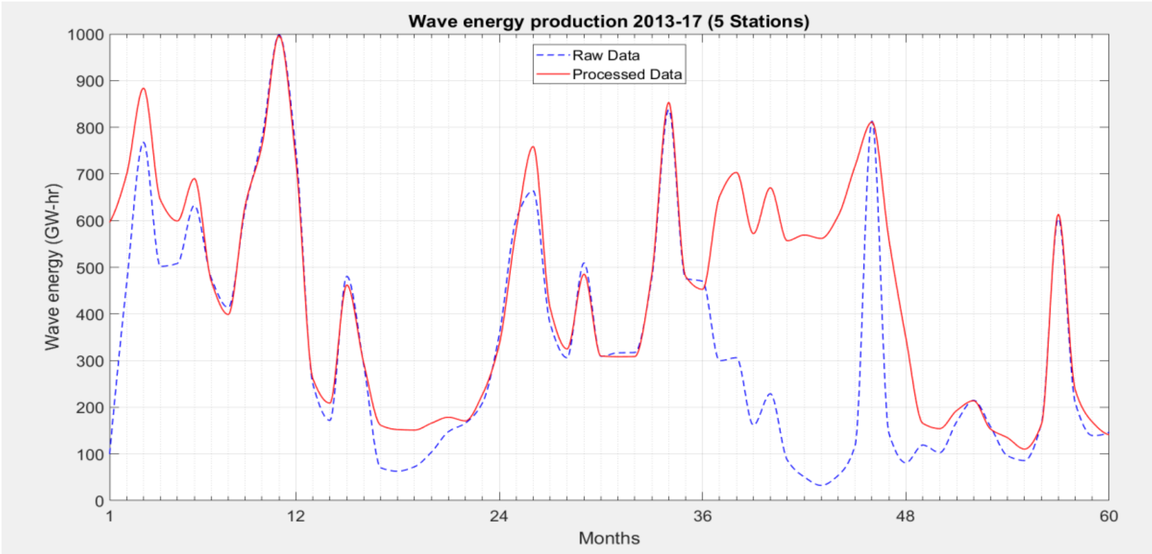

FIGURE 17: The Actual and Interpolated Average Wave Energy Potential of the NC.

TABLE 8: The total wave Energy production for NC in the period of 2013-2017.

	2013	2014	2015	2016	2017
January	596.14	260.89	581.76	651.76	165.49
February	698.71	208.81	758.86	703.22	154.19
March	83.61	461.95	412.72	572.04	192.97
April	644.8	294.65	324.92	670.27	213.81
May	599.15	161.40	484.97	556.81	153.11
June	689.84	152.14	309.71	568.97	134.49
July	470.11	151.06	308.44	561.77	110.38
August	398.84	165.92	308.69	609.85	163.35
September	631.61	178.54	483.95	716.73	613.12
October	762.50	170.82	852.91	811.13	236.96
November	996.62	224.85	480.32	559.45	165.66
December	762.50	335.17	452.70	348.52	141.02

3.2.1: MASONBORO INLET (US150)

The average wave energy potential for US150 for each month in the period of 2013 to 2017 represented in Figure 18 and Table 9. The trend indicates that the wave energy potential is comparatively higher in the fall season and lower in the summer season. The average wave energy potential for this site approximately equals to 25 GWh.

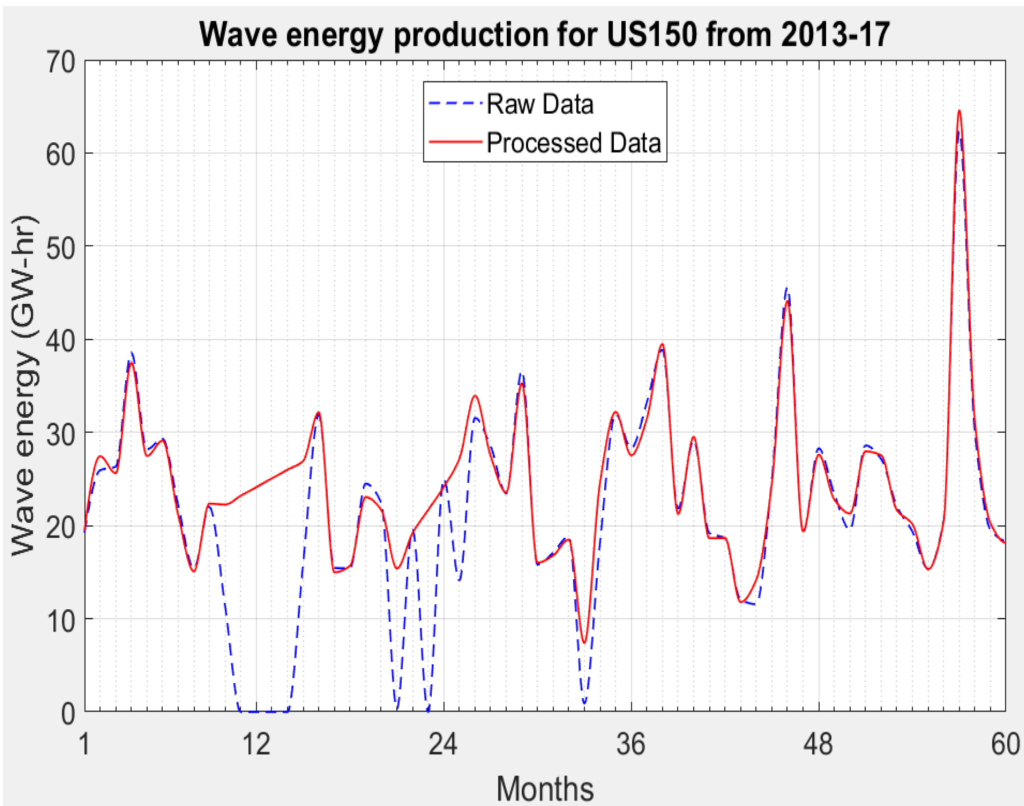

FIGURE 18: The Actual and Interpolated Average Wave Energy Potential for the US150.

TABLE 9: The Net Average Wave Energy Potential for the US150 Station in the Period of 2013-2017.

	2013	2014	2015	2016	2017
January	19.46	25.06	27.18	31.45	22.79
February	27.44	26.00	33.95	39.49	21.29
March	25.62	26.94	27.46	21.25	27.97
April	37.47	32.15	23.56	29.51	27.53
May	27.47	14.98	35.27	18.65	21.67
June	29.10	15.68	16.02	18.66	20.14
July	21.13	23.05	16.78	11.78	15.30
August	15.08	21.67	18.49	14.15	20.46
September	22.35	15.40	7.40	24.47	64.58
October	22.25	19.18	24.58	44.09	31.19
November	23.19	21.67	32.19	19.38	20.25
December	24.13	24.15	27.54	27.61	18.14

3.2.2: OREGON INLET (US192)

The average wave energy potential for US192 for each month in the period of 2013 to 2017 represented in Figure 19 and Table 10. The trend indicates that the wave energy potential is comparatively higher in the fall season and lower in the summer season. The average wave energy potential for this site approximately equals to 70 GWh.

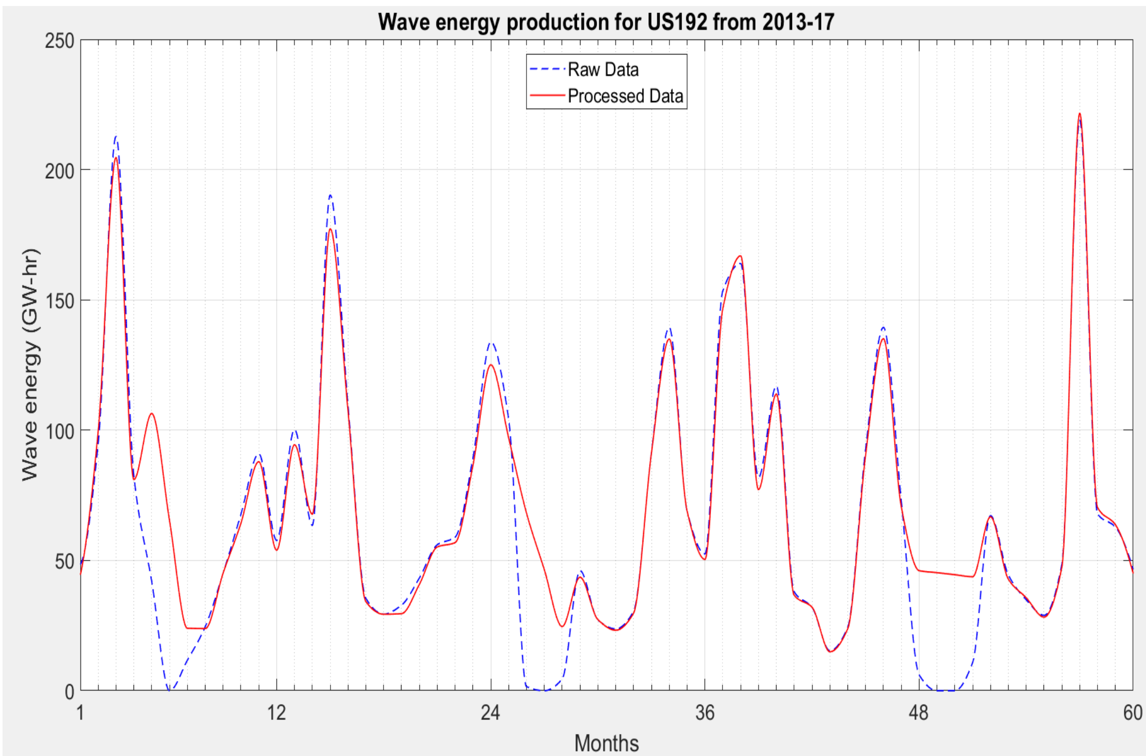

FIGURE 19: The Actual and Interpolated Average Wave Energy Potential for the US192.

TABLE 10: The Net Average Wave Energy Potential for the US192 Station in the Period of 2013-2017.

	2013	2014	2015	2016	2017
January	44.47	94.38	97.04	146.64	45.30
February	99.62	67.78	68.20	166.89	44.52
March	204.63	177.25	46.41	77.22	43.74
April	81.05	107.32	24.63	113.79	66.72
May	106.38	34.18	43.56	36.63	42.83
June	65.17	29.33	27.28	32.03	35.66
July	23.97	29.58	23.22	14.95	28.25
August	23.84	40.83	29.76	23.75	47.45
September	45.10	55.15	91.09	90.32	221.63
October	64.28	56.85	134.96	135.09	70.32
November	87.89	86.51	68.96	70.67	63.69
December	53.93	125.06	50.39	46.08	44.95

3.2.3: WILMINGTON HARBOR (US 200)

The average wave energy potential for US200 for each month in the period of 2013 to 2017 represented in Figure 20 and Table 11. The trend indicates that the wave energy potential is comparatively higher in the fall season and lower in the summer season. The average wave energy potential for this site approximately equals to 207 GWh.

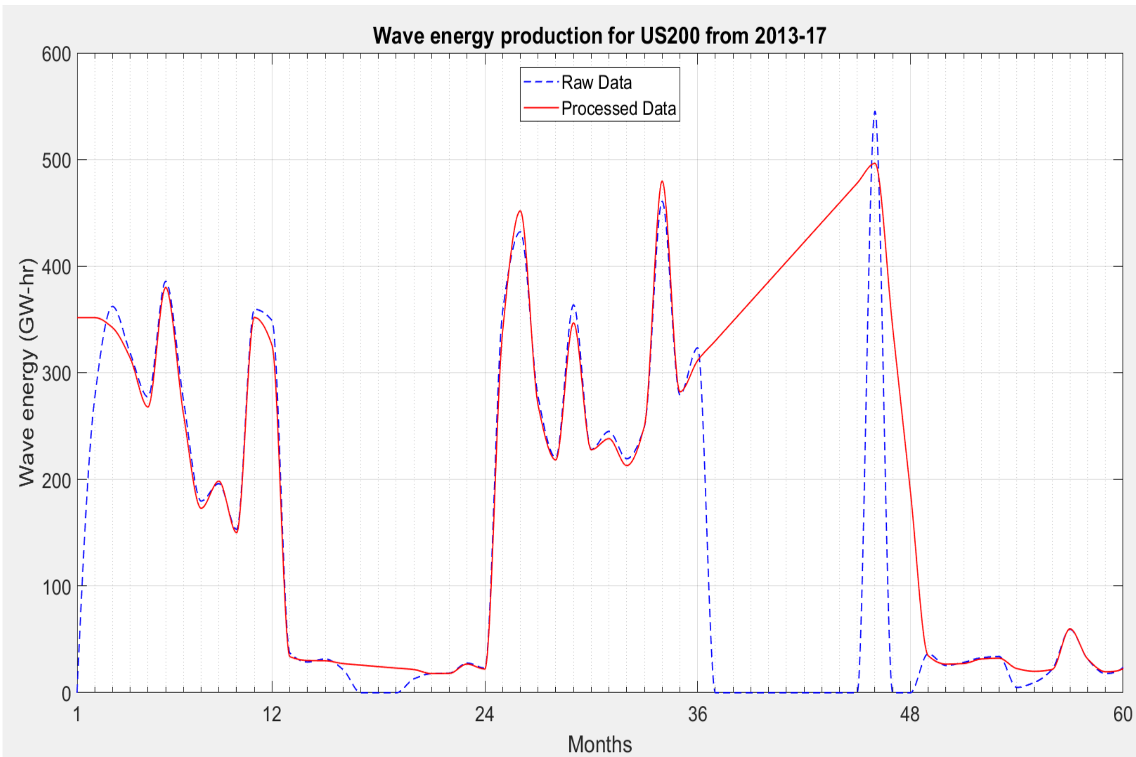

FIGURE 20: The Actual and Interpolated Average Wave Energy Potential for the US200.

TABLE 11: The Net Average Wave Energy Potential for the US200 Station in the Period of 2013-2017.

	2013	2014	2015	2016	2017
January	351.73	33.84	338.37	329.95	34.79
February	351.73	30.21	451.75	348.44	26.80
March	342.33	30.00	269.82	366.92	27.34
April	313.70	27.29	218.33	385.41	31.60
May	267.96	25.88	346.78	403.89	32.30
June	379.92	24.48	227.82	422.38	22.62
July	261.48	23.08	238.13	440.86	20.08
August	172.89	21.67	212.97	459.35	21.80
September	198.31	17.91	250.22	477.83	59.90
October	150.08	18.10	479.67	496.32	31.58
November	351.85	26.83	282.13	342.48	19.73
December	325.61	22.21	311.47	188.64	22.61

3.2.4: DUCK FRF-26M (US 430)

The average wave energy potential for US430 for each month in the period of 2013 to 2017 represented in Figure 21 and Table 12. The trend indicates that the wave energy potential is approximately same for the spring and winter season The average wave energy potential for this site approximately equals to 54 GWh.

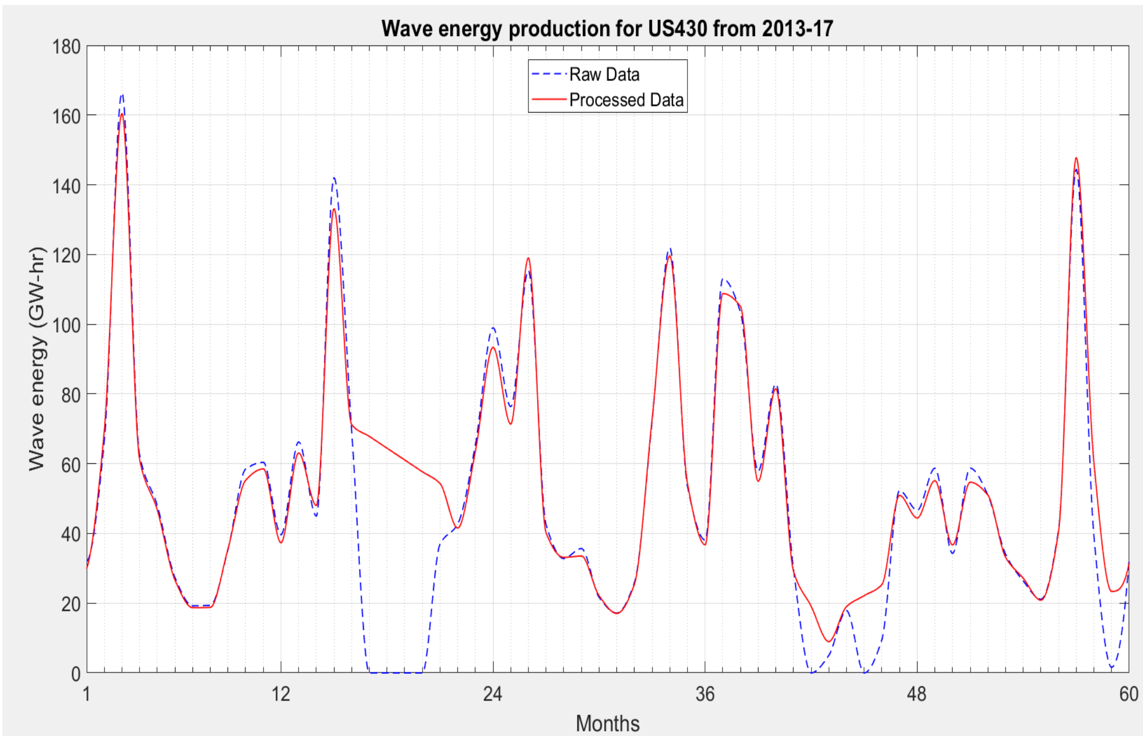

FIGURE 21: The Actual and Interpolated Average Wave Energy Potential for the US430.

TABLE 12: The Net Average Wave Energy Potential for the US430 Station in the Period of 2013-2017.

	2013	2014	2015	2016	2017
January	29.87	63.07	71.36	108.79	55.12
February	69.31	48.02	119.00	105.10	36.71
March	160.41	133.12	40.20	54.97	54.68
April	61.24	71.21	33.12	81.49	50.98
May	46.73	67.83	33.50	29.19	33.17
June	26.66	64.45	22.13	19.09	27.14
July	18.71	61.07	17.04	8.98	20.86
August	18.78	57.68	25.42	19.01	40.63
September	35.56	54.30	72.82	22.16	147.73
October	55.23	41.54	119.57	25.30	60.29
November	58.49	63.54	54.42	50.90	23.38
December	37.34	93.36	36.75	44.42	31.57

3.2.5: DUCK FRF-17M (US433)

The average wave energy potential for US433 for each month in the period of 2013 to 2017 represented in Figure 22 and Table 13. The trend indicates that the wave energy potential is approximately same for the spring and summer season. The wave energy potential for the fall season is the highest. The average wave energy potential for this site approximately equals to 85 GWh.

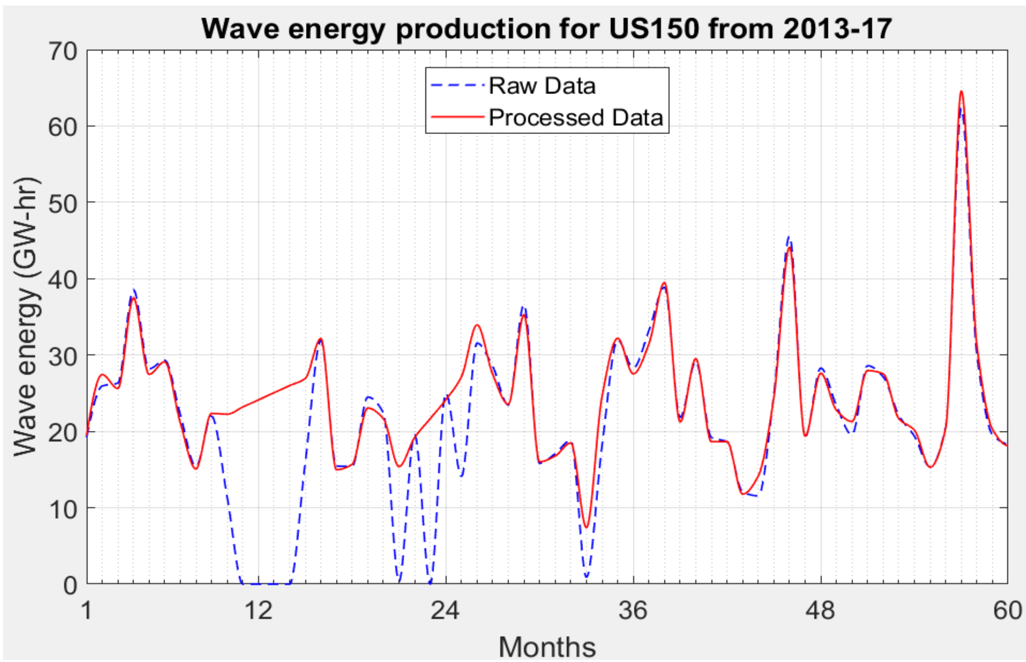

FIGURE 22: The Actual and Interpolated Average Wave Energy Potential for the US433.

The wave energy potential for US150 is the lowest among all sites and US200 has the highest wave energy potential based on the interpolated data. However, US200 site has the maximum missing real-time wave data. The US192 with the average potential of 70 GWh has the lowest missing real-time wave data. Whereas, US433 is the second most potential site with the wave energy potential of 85 GWh and comparatively uniform real-time wave data.

TABLE 13: The Net Average Wave Energy Potential for the US433 Station in the Period of 2013-2017.

	2013	2014	2015	2016	2017
January	150.61	44.54	47.82	34.93	7.48
February	150.61	36.81	85.66	43.31	24.86
March	150.61	94.64	28.82	51.68	39.25
April	150.61	56.68	25.28	60.06	36.98
May	150.61	18.53	25.86	68.44	23.14
June	188.98	18.20	16.47	76.82	28.93
July	144.82	14.30	13.27	85.20	25.89
August	168.26	24.06	22.05	93.58	32.95
September	330.29	35.78	62.41	101.96	119.28
October	470.66	35.15	94.13	110.33	43.58
November	475.20	28.31	42.63	76.05	41.62
December	285.84	70.39	26.55	41.76	23.75

3.3: ANNUAL ENERGY PRODUCTION

The annual energy production (AEP) is estimated based on the Eqn. 21considering the rated power is same for the scaled down model of the considered WEC as NC has shallow water with water depth in the range of 12-26 m. As the AEP is based on the wave power potential of the site and the rated power of WEC, 15 different combinations of the site (5 sites) and WEC (3 WEC) are analyzed and listed in Table 14.The estimated results for AEP in Table 12 are based on the 2017 wave data. The AEP increases with increasing number of WEC. However, the wave farm of 50 and 100 is not feasiable in the near future. The most suitable is wave farm of 10 WEC among the considered cases.

TABLE 14: The AEP for five sites in the combination of RM3, RM5, and RM6.

AEP (MWh)				
US150				
Unit	1	10	50	100
RM3	580	5800	29000	58000
RM5	717.25	7172.5	35863	71725
RM6	504	5040	25200	50400
US192				
Unit	1	10	50	100
RM3	1406	14060	70300	140600
RM5	1740	17400	87000	174000
RM6	1222	12220	61100	122200

US200				
Unit	1	10	50	100
RM3	654	6540	32700	65400
RM5	809	8090	40450	80900
RM6	568	5680	28400	56800
US430				
Unit	1	10	50	100
RM3	1084	10840	54200	108400
RM5	1342	13420	67100	134200
RM6	942	9420	47100	94200
US433				
Unit	1	10	50	100
RM3	833	8330	41650	83300
RM5	1031	10310	51550	103100
RM6	725	7250	36250	72500

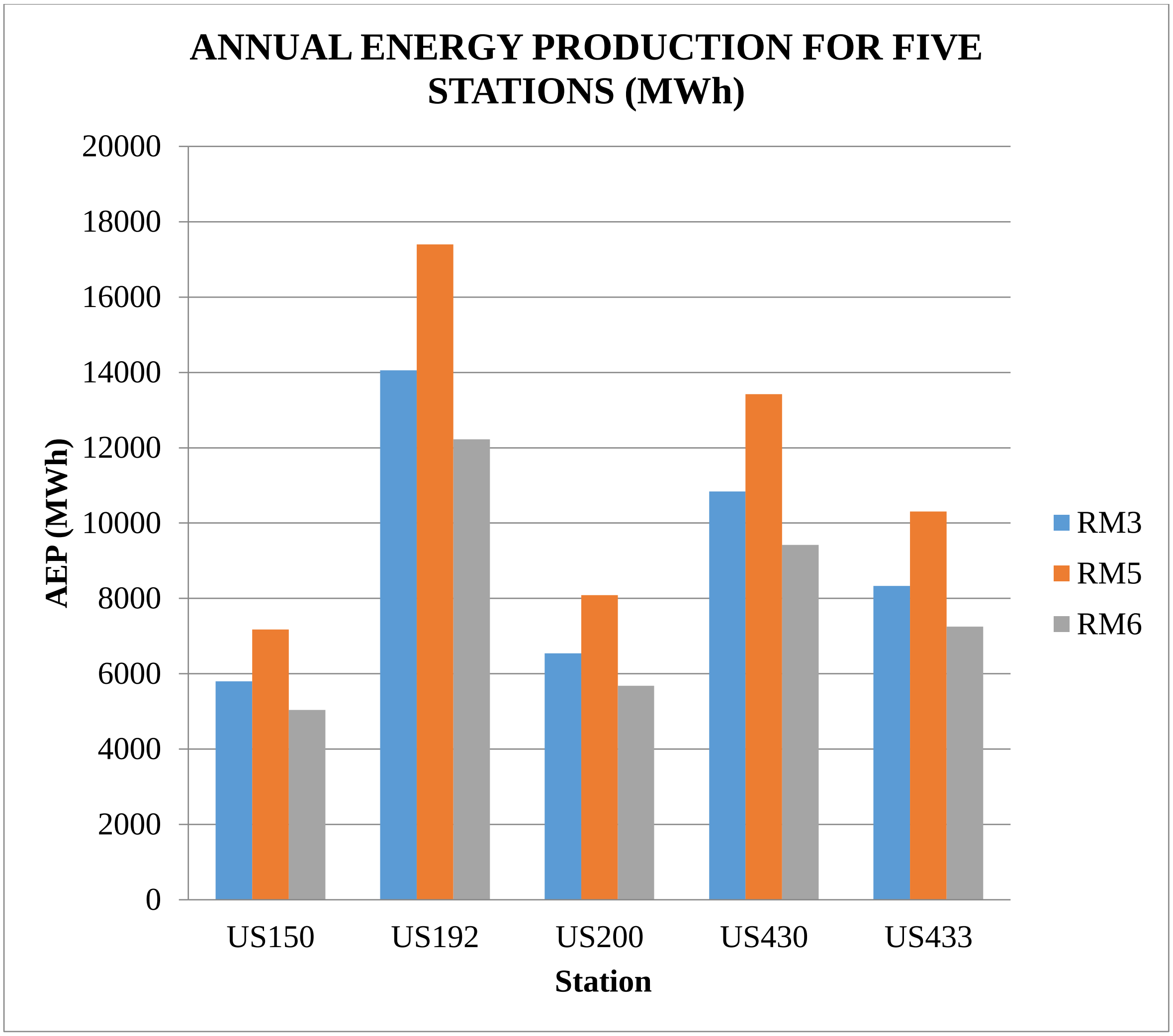

FIGURE 23: The AEP for five stations considering 10 units.

The AEP for each site with RM5 has more potential compared to the other WEC, due to high (82.5%) mechanical to electrical efficiency of the RM5. It linearly increases with the increasing number of WEC for every combination. US192 with RM5 has the highest AEP among all. The AEP for all sites considering RM6 has the lowest potential. Figure 623 represents the AEP for all sites for RM3, RM5, and RM6 considering 10 units.

3.4: ELECTROLYSIS SYSTEM

The hydrogen production depends on the rated power of a WEC, electrolyzer energy requirement, and maximum feed factor. The electrolyzer energy requirement is considered as 70 kWh/kg. The efficiency of an electrolyzer is considered as 70%. The maximum feed factor varies with the load requirement. It is observed from Figure 24, the hydrogen production potential reduced with the decreasing feed factor. It is considered as the average wave energy is available for 80% of the time. Table 15. represents the daily hydrogen production potential for one and ten units of RM3, RM5, and RM6.

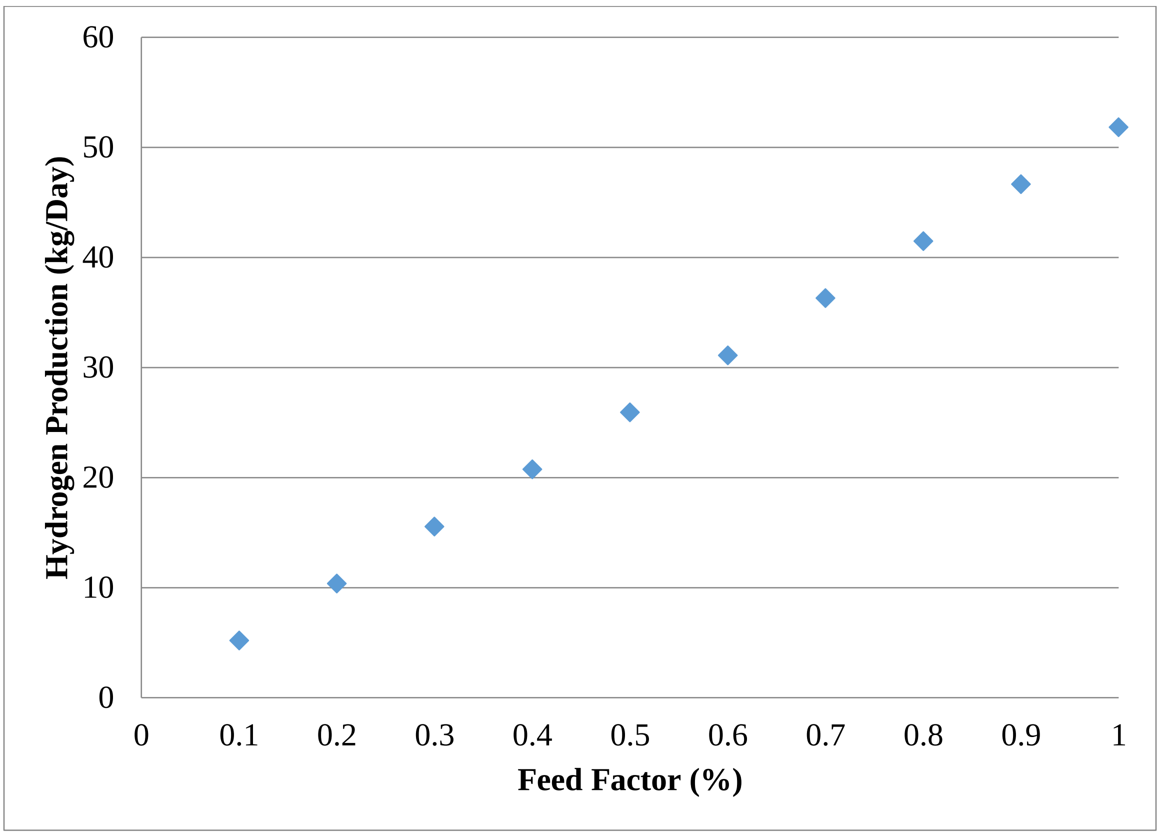

FIGURE 24: The Hydrogen Production for Different Feed Factors.

TABLE 15: The Hydrogen Production Potential of integrated system with RM3, RM5, and RM6 considering one and 10 units of WEC.

Hydrogen Production Potential (kg/ day)		
Unit	1	10
RM3	52	520
RM5	62	624
RM6	51	510

The integration of the RM5 with an electrolysis system produced more hydrogen compared to the RM3 and RM6. The nearly same amount of hydrogen is produced from the integrated system of RM3 and RM6.

3.5: GREENHOUSE GAS EMISSION

The GHG emission of the system is dependent on the material used for the manufacturing, AEP of each site and it is estimated from the Sec. 2.4 The estimated GHG accounts only for the manufacturing and installment of the WEC. The considered WEC in this study are mainly made of the steel (A-36 type) material. Hence, the considered emission factor for the steel is 3.19 kgCO_{2eq}/ kWh. As the GHG for 15 different combinations of the site (5 sites) and WEC (3 WEC) are analyzed and listed in Table 16.

TABLE 16: The GHG emission for five sites considering RM3, RM5, and RM6.

GHG (kgCO_{2eq}/kWh)				
US150				
Unit	1	10	50	100
RM3	0.1529	0.0153	0.0030	0.0015
RM5	0.1289	0.0129	0.0091	0.0046
RM6	0.4582	0.0458	0.0092	0.0045
US192				
Unit	1	10	50	100
RM3	0.0630	0.0063	0.0012	0.0006
RM5	0.0532	0.0053	0.0010	0.0005
RM6	0.1890	0.0189	0.0038	0.0019

US200				
Unit	1	10	50	100
RM3	0.1355	0.01356	0.0027	0.0013
RM5	0.1143	0.01143	0.0022	0.0011
RM6	0.40661	0.0406	0.0081	0.0040
US430				
Unit	1	10	50	100
RM3	0.0818	0.0081	0.0016	0.0008
RM5	0.0689	0.0069	0.0014	0.0006
RM6	0.2451	0.0245	0.0049	0.0024
US433				
Unit	1	10	50	100
RM3	0.1064	0.0106	0.0021	0.0010
RM5	0.0897	0.0089	0.0018	0.0009
RM6	0.3185	0.0318	0.0064	0.0031

As the AEP increased with the increasing units of WEC, the GHG emission is reduced with AEP and the increasing units of WEC. The GHG emission for each site with RM5 has the the lowest value compared to the other WEC. Whereas, GHG emission for each site with RM6 has the the highest value compared to the other WEC due to high weight (1810 Mg). US192 with RM5 has the lowest GHG emission among all. Figure 25 represents the GHG emission for five sites for RM3, RM5, and RM6 considering 10 units.

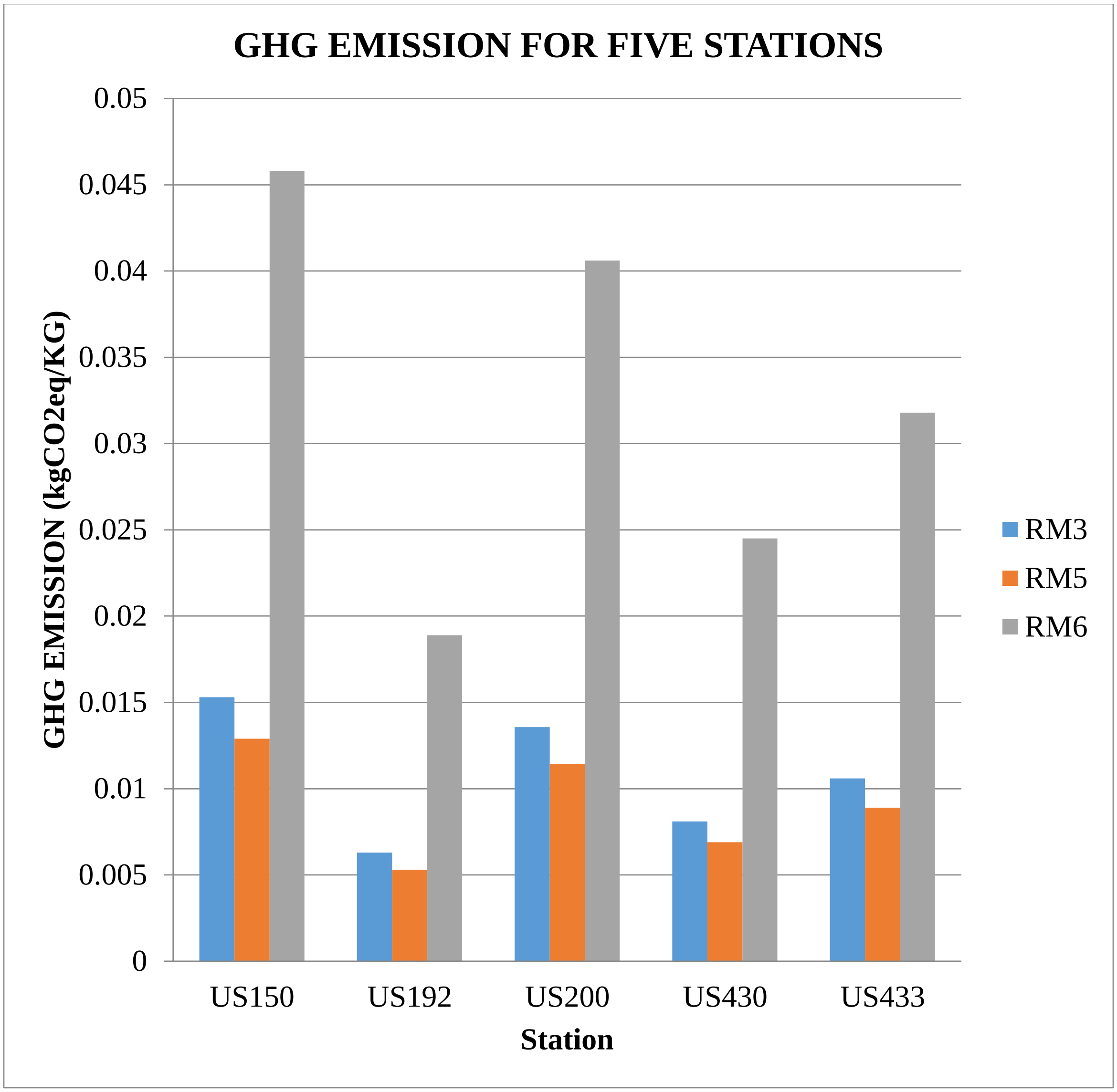

FIGURE 25: The GHG Emission for Five Stations considering 10 Units.

3.6: COST OF ENERGY

The cost of energy production (LCOE) is based on the CAPEX, OPEX, and AEP values. It is estimated based on the Eqn. 25.The CAPEX and OPEX values of RM3, RM5, and RM6 are considered same as DOE report [21],[22],[23]. However, these cost may be diiferent for NC state. The estimated result of LCOE is based on the AEP calculated in Section 3.3. The installation of system, design, and development of the system has the maximum share in the CAPEX value as seen in Figure 26. It represents the cost breakdown (CAPEX) of RM5. The insurance cost and shoreside operation which mainly includes the back office activities have the highest share in OPEX value.Whereas, the marine operations (maintenance of WEC) and replacement cost accounts less than 20% share in the OPEX value.

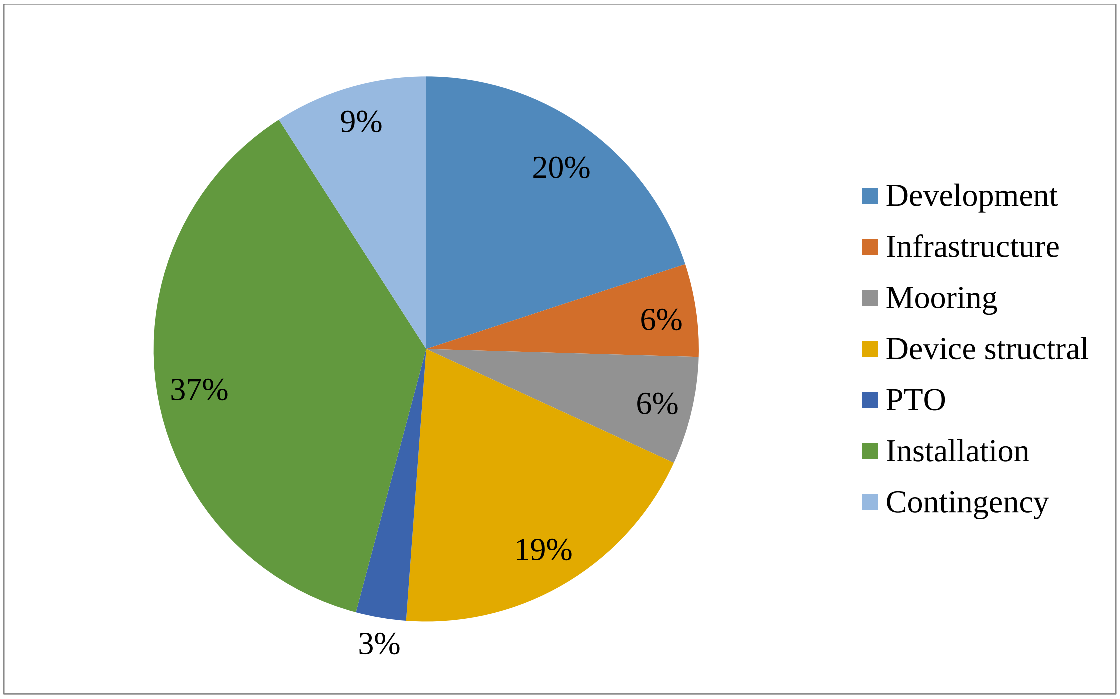

FIGURE 26: The Cost Breakdown (CAPEX) for RM5.

The LCOE for each site with RM3 has the lowest value compared to the other WEC.Whereas, RM6 has the highest LCOE cost for all sites The LCOE of single unit of WEC cost an average of $11.68/kWh and $4.877/kWh for WEC array of 10 units. The LCOE decreased with increasing units of WEC as mass production reduces the manufacturing cost. However, the wave energy farm with 50 or 100 units is not feasible for the near future. It cost same for RM3 and RM5 considering 10 and 50 units of each. US192 with RM3 has the lowest LCOE among the considered combinations and RM6 has the highest LCOE. The lowest value of LCOE is found as $1.94/kWh for US192 station considering RM3.

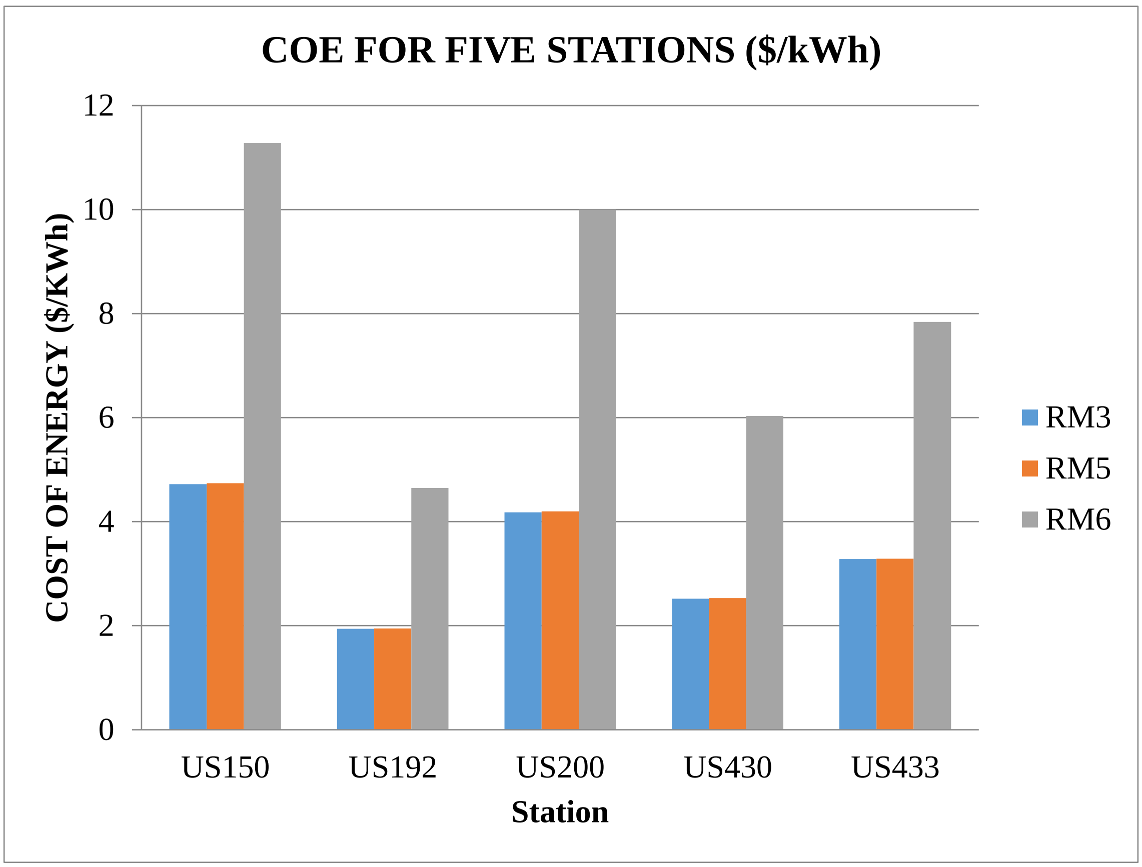

FIGURE 27: The Cost of Energy (LCOE) for Five Stations considering 10 Units.

3.7: COST OF HYDROGEN

The cost of hydrogen is based on the cost of electricity, energy used for an electrolyzer system and annual hydrogen production. The central type of an electrolyzer system is considered for the hydrogen production. The electricity produced by an ocean wave energy is used for hydrogen generation. The hydrogen production capacity of the combined system of an electrolyzer and each WEC is estimated in Sec. 3.4. The hydrogen production integrated the system with 50 or 100 units of WEC is not feasible in near future. Hence, only one and 10 units of each WEC is considered for hydrogen production. It is assumed as the net wave energy is only used for hydrogen production. The initial cost of an electrolyzer system is considered the same for an integrated system of one and 10 units. The cost of hydrogen generation for each site with RM3 has the lowest value compared to the other WEC.Whereas, RM6 has the highest hydrogen production cost for all the sites. It decreased with increasing units of WEC. US192 with RM3 has the lowest value of $ 7.58 /kg and $ 7.16/ kg for single and 10 units of WEC. The second highest potential site (US433) has a value of $ 8.14/ kg with one unit of RM3 and $ 7.44/ kg with 10 units of RM3 and RM5. Figure 28 represents the hydrogen production cost for a US192 site for RM3, RM5, and RM6.

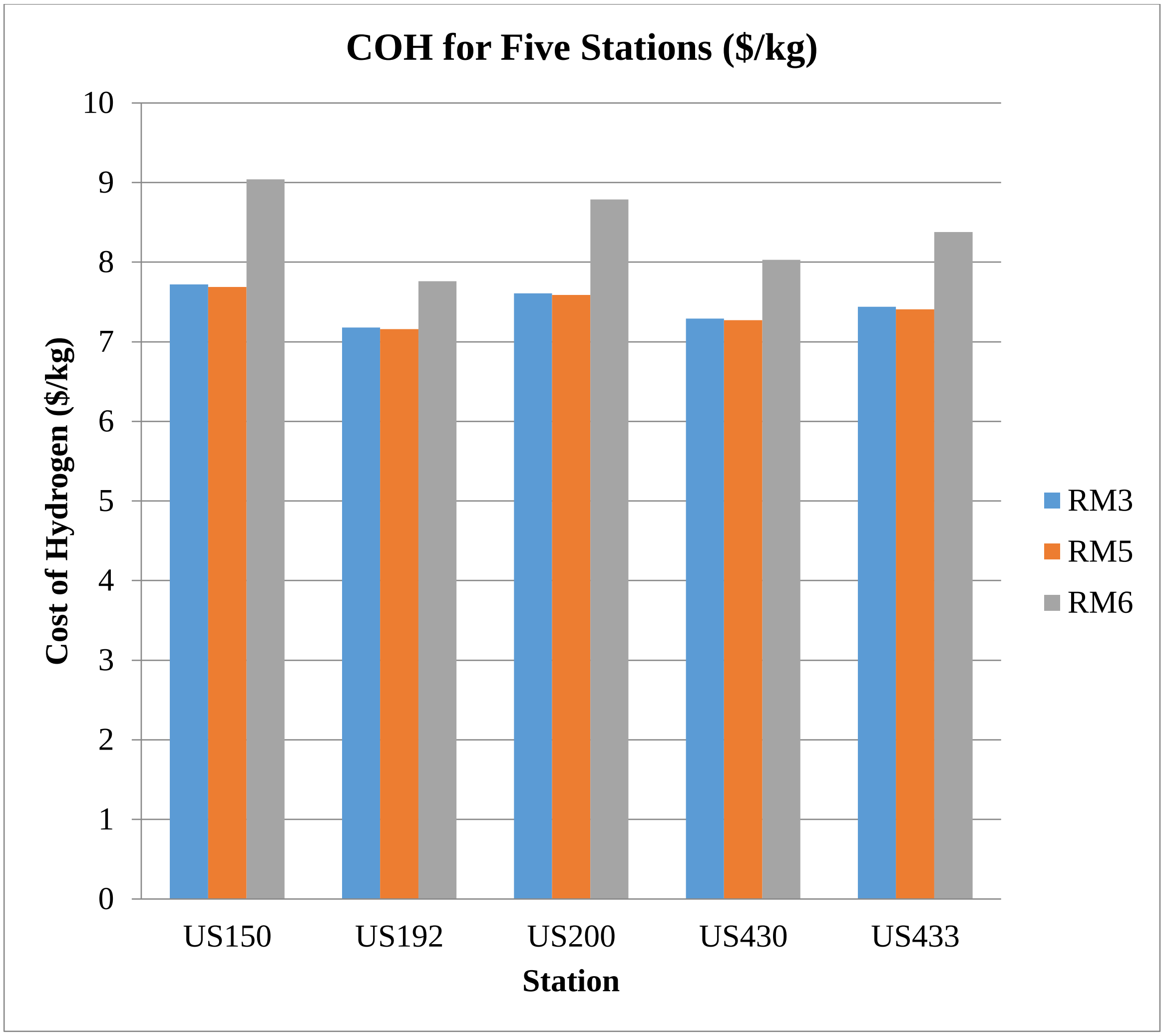

FIGURE 28: The Cost of Hydrogen for Five Stations considering 10 Units.

CHAPTER 4: CONCLUSION

The objective of this study was to determine how much wave power can be feasibly being converted for use in balancing the electricity load of NC and performance characteristics of the integrated system of wave energy and hydrogen production.

First of all, the wave energy potential of NC was determined based on the data provided by NOAA for five stations along the shore of NC and considering benchmark models of WEC designed and developed by DOE. The performance of these WEC is considered as same for all water depths. After that, it is compared with the NC net electricity load for the same time frame. It is found that the wave energy with available technologies can balance only 4-6 percent of the total energy consumption. However, the average wave energy is capable of balancing approximately 9%, 10% and 19% of total energy consumption from the residential, commercial and industrial sector respectively. The number is comparatively small, however, it can be improved with an advancement in WEC performance. The average wave energy potential for US150, US192,US200, US430, and US433 is 25 GWh, 70GWh ,207 GWh, 54 GWh and 85 GWh respectivily.The wave energy can be used in coastal part for reducing transmission cost. The average cost electricity produced from the wave energy is $11.08/kWh and it is not competitive with the current electricity price of NC which is $0.12/ kWh. The dominant structural design (wind turbines for wind energy extraction) for the wave energy extraction can increase the wave energy potential. The conventional fuels produced an average GHG of 162.74 kg CO_{2eq}/ kWh whereas; the wave energy produces only 0.024 kg CO_{2eq}/ kWh of GHG. On an average 550 kg of H_2/ day can be produced from the available wave energy using the electrolysis of water method considering the efficiency of a selected PEM electrolyzer is

70%. The average price of hydrogen produced with this technology is around \$7.50/ kg of H_2 and it is not competitive with the current price of hydrogen produced from the natural gas which is \$0.98/kg of H_2. From the economic point of view, considering the environmental cost of fossil fuels, the electricity produced in this way is still not competitive with conventional fuels but hydrogen production cost can be effectively competitive in the near future. The dominant structural design (wind turbines for wind energy extraction) for the wave energy extraction can increase the wave energy potential.

Finally, it can be concluded that while WEC technologies are nowhere near mature, a significant potential exists for the extraction of wave energy off the coast of NC. The integrated system of wave energy and hydrogen production requires more research and it is important to consider the energy storage method for the smooth functioning of large-scale wave energy projects.

4.1: RECOMMENDATIONS FOR FUTURE WORK

This work is the preliminary step in determining the ocean wave energy potential of NC. However, it requires much more study for the functioning of the wave energy projects.

Recommendation for Future Studies-

1. The available wave data is not uniform with 30 minutes of resolution. The uniform data with much lower resolution can estimate the exact wave energy potential of the region.
2. The performance of a considered WEC for scale-down size as the maximum considered depth is 26 m.
3. The design and development of the water treatment plant for electrolysis system.
4. The hydrogen storage is an important issue and requires determining economic and feasible solutions.
5. The calculation of the GHG emission should consider the electrolysis system, storage, and transmission system.

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6: APPENDIX

TABLE 17: The CAPEX and APEX breakdown for RM3 Model.

Total Capital Investment Cost (CAPEX) in $				
Units	1	10	50	100
Development	455389	8773812	11003159	10820060
Infrastructure	990000	4860000	7566000	17310000
Mooring	524775	4722975	23614875	47229750
Device structral	2939052	20674690	91548379	177933334
PTO	623464	4936833	21684569	41283900
Installation	5908522	9081973	21531225	37859591
Contingency	1144120.2	5305028.3	17694820.7	33243663.5
TOTAL CAPEX	12585322.2	58355311.3	194643028	365680298.5

Annual Operating Cost (OPEX) in $				
Units	1	10	50	100
Insurance	226841	936752	1772683	1717691
Marine O/P	26569	265690	562320	1124640
Shoreside O/P	141561	399936	454692	674634
Replacement cost	53808	491314	2305303	3920875
Consumables	8000	80000	400000	800000
Total OPEX	456779	2173692	5494998	8237840

TABLE 18: The CAPEX and APEX breakdown for RM5 Model.

Total Capital Investment Cost (CAPEX) in $				
Unit	1	10	50	100
Development	3945384	8190558	10160806	10798814
Infrastructure	1086800	7608000	14186000	33190000
Mooring	1263918	8330208	37594315	72749547
Device structral	3817046	26838142	118871463	230967106
PTO	588144	4723367	20733846	393823
Installation	7264070	10516854	23320215	40091216
Contingency	1796536	6620713	22486665	38819051
TOTAL CAPEX	19761898	72827842	247353310	427009557

Annual Operating Cost (OPEX) in $				
Unit	1	10	50	100
Insurance	262099	1194757	2268774	2205917
Marine O/P	75785	757850	617700	1235400
Shoreside O/P	261561	399936	454692	674634
Replacement cost	63866	48197	43453	41905
Consumables	13500	135000	675000	1350000
Total OPEX	676811	2535740	4059619	5507856

TABLE 19: The CAPEX and APEX breakdown for RM6 Model.

Total Capital Investment Cost (CAPEX) in $				
Unit	1	10	50	100
Development	5205030	22990070	31387065	30857431
Infrastructure	1111000	7850000	1618800	35610000
Mooring	835152	7441596	36178982	70299965
Device structral	7682482	54016526	239249925	464862307
PTO	1637246	9749373	34183640	58812564
Installation	7410975	11985904	30665465	54781716
Contingency	2388189	11403347	37328388	71522398
TOTAL CAPEX	26270074	1.25E+08	410612265	786746381

Annual Operating Cost (OPEX) in $				
Unit	1	10	50	100
Insurance	362128	1890321	3746751	3599060
Marine O/P	31357	313567	541967	1083933
Shoreside O/P	261561	399936	454692	674634
Replacement cost	46759	42695	40066	68307
Consumables	2000	20000	100000	200000
Total OPEX	703805	2666519	4883476	5625934