Investigation of Developing Wave Energy Technology In the Gulf of Mexico

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ABSTRACT

This article presents an investigative study on developing wave energy technology in the Gulf of Mexico (GOM). The characteristics and conditions of GOM such as weather, wave climate, and activity of the oil industry were assessed first for possible development of wave energy. The linear wave theory was then reviewed to identify methods to estimate wave power. Using wave data recorded from several stations in the GOM, methods used to estimate the wave energy were verified. Based on the findings, the potential in the GOM for implementing wave energy technology was confirmed. It is expected that the wave energy captured from the GOM can provide a considerable portion of power required by operating the oil platforms in that area.

Keywords: wave energy technology; Gulf of Mexico, alternative energy, oil platform

INTRODUCTION

Alternative energy is gaining momentum worldwide because of the growing demand for electric power and petroleum products along with the limitation of petroleum resources as nonrenewable fuels. All energy is created from two main sources, heat and motion. People working with alternative energy are looking for natural, reproducible, low emission, and sustainable sources of both heat and motion. Several avenues of sustainable energy have been found such as solar, wind, geo-thermal, biofuels, and hydropower, which are all examples of renewable energy sources that are currently being developed.

Wave energy in the US was estimated by the Electric Power and Research Institute (EPRI) to average 2,100 terawatt-hours per year for a depth of 60 meters. If only 20% of this wave energy were utilized with a wave energy converter (WEC) capturing 50% of the wave power, it could provide for 7% of the US electrical consumption in 2005 [1]. So far, wave energy projects around the world are focused on providing power to a grid. There has also been a study that is developing better technology to power offshore platforms from land [2]. Both of these ideas involve great costs in the transmission of power to the shore, estimated at $5 million per mile for wave generation. Another concern is that a majority of wave energy development has been in the areas near shore on the inner continental shelf, and there has been little to no exploration and exploitation of the outer continental shelf [3]. Because the industry is not as developed as wind and solar power, there has been little to no emphasis on capturing mild energy wave climates.

Wave energy is a combination of solar, wind, and hydropower. As stated by Mcormick [4], gravity along with wind and the sun combine in seas and oceans to create and sustain waves. Like wind, waves are a naturally occurring force that has the potential for creating energy, which are also more predictable and continuous than other natural sources like wind and solar sources. There are many areas that get more overcast days than days of sunlight or areas that do not have heavy winds that could propel turbines. Solar and wind energy can capture and generate energy only 20% to 30% of the time, but wave energy can have power generation about 90% of the time [5].

Water is also considered as a more efficient fluid than air. Unlike air, water has a much higher density and is also considered to be an incompressible fluid; these characteristics mean that the movement of water is more powerful than that of air over the same volume. Thus, it requires much more air to move an object than to move the same object with water. Furthermore, since air is compressible, therefore, before the air can do any work, energy has to be consumed to compress air so as to acquire enough power and energy required for outputting power. On the contrary, as an incompressible fluid, water can immediately provide output work without spending energy to compress it. Comparing to solar energy, the average wave power intensity produced over a square meter is about ten times as the average solar energy intensity produced in the same area [5].

Most of the current projects that are being developed have the similar objective of connecting with an electric grid and transmitting power to land operations. One company, Ocean Power Technologies, has compared their technology, the Power Buoy, with solar, wind, biomass, and natural gas resources. When compared to wind and solar power, wave energy has a high power density. Ocean Power Tech. estimates that when producing 400 buoys per year from the wave power costs is around 15 cents per kilowatt-hour. Solar power is estimated at 9-19 cents, and wind power is from 5-24 cents [6]. It is noted that while wave power might be more expensive, the cost could be substantially reduced by reducing the distance between the wave-capture site and the power consumption site.

In spite of the listed advantages over other energies, wave energy is an under explored resource that has great potential. Because of its higher power intensity and reliability, wave energy should be an excellent candidate for further development and consideration as a prime alternative energy source.

Because of its rich potential in the wave energy, it is expected that a large amount of electricity can be converted from the wave energy in the Gulf of Mexico (GOM) to power the oil platforms in the outer continental shelf of GOM. In order to verify this idea an investigation study was performed and demonstrated, which includes (1) review of the physical characteristics of the GOM; (2) assessing the oil platform activities in the GOM; (3) finding or developing equations for waves and wave power; (4) estimating the wave energy potential in GOM and analyzing local trends and weather information. They are discussed in the following sections.

CHARACTERISTICS OF THE GULF OF MEXICO

Before fully launching the wave energy technology in GOM, the real conditions of that area have to be reviewed and analyzed so as to verify the potential of wave energy. The GOM is a circular body of water that borders the United States and Mexico. The GOM is approximately 1.5 million km2 and measures approximately 1,600 km from east to west and 900 km from north to south. The GOM has a continental shelf that is approximately 180 meters deep before the major drop-off, and this shelf comprises nearly 38% of the entire gulf area [7]. The Gulf Stream is created from water moving in through the Yucatan Strait, which causes the direction of waves to change in a circular manner around the GOM. There is also water that drains from the mouth of the Mississippi River into the GOM, which creates more water flow in the northeast corner. From observations made from wave forecasts of the GOM, it can be seen that landmasses cause reduced wave activity near the eastern tip of Louisiana, but there is much higher wave activity as the distance from shore increases [8].

Currently, there are over 4,125 active platforms drilling in the gulf with 2,380 qualified companies, and 161 active operators with 561 Gm2 (138,722,278 acres) of leased work sites [9]. Because of political and environmental concerns after the Deep Water Horizon oil spill, drilling in the GOM had a large period of low production and many platforms were closed, most of them temporarily. According to the Bureau of Safety and Environmental Enforcement's (BSEE) website [10], permits are being granted to more companies and platforms are slowly re-opening. Over the past ten years offshore work has been shifting to "deep-water" drilling, where the "deep-water" is considered to be stations located in depths of over 305 meters (1,000 ft.). For depths of less than 305 meters, there are two classifications based on the drilling depth. The first is called "shallow-water shallow" and is considered to be drilling depths of 4,572 meters (15,000 ft.). The second is "shallow-water deep" and includes stations, which drill below the 4,572 meters and are located in areas where the sea floor is less than 305 meters [11]. While these platforms, stations, and work areas are used to help obtain crude oil, natural gas, or other petroleum substances, they also consume a fair amount of energy during operation. A map of oil and gas platforms in the GOM with indications of deep water areas can be found in [12].

Currently, companies have to ship in diesel or other petroleum products to the work stations to power generators. Not only is there the direct cost of purchasing processed fuels, but there is the cost of shipping the fuel. In the oil and gas industry there are also high costs of doing business when it comes to carbon emissions. Wave energy, however, would be a source of low to no emissions and if wave energy technology becomes feasible, it could replace the current use of diesel which does much less harm to environment. This means that by using wave energy, not only could the operational costs potentially go down, but the fees that these companies pay for high carbon emissions could be reduced as well.

Government regulations, political pressure, and environmental concerns are driving companies to reduce their emissions through regulation and fees with bills like "Cap-and-Trade" [13]. The U.S. government is also trying to create incentives, such as tax credits, for companies who produce their own energy or for using alternative energy sources in their production process [14]. "Good press" is another incentive for these companies. Openly utilizing a new technology that is considered "green" would help the reputations of oil and gas companies and provide them with an avenue of diversity and expansion.

Overall, the GOM is a large body of salt water with varying level of wave activity that increases when moving away from the shoreline. The continental shelf provides an excellent base for mounting platforms and can serve in the same capacity for mounting wave energy converters (WECs). Understanding the physical characteristics of the GOM helps to set a baseline of the potential power area in the GOM. The GOM is highly populated by oil and gas platforms. There are a growing number of platforms that are moving further offshore and these platforms have higher energy requirements than those located closer to shore. With the growing industry demands it is becoming more and more expensive to operate these platforms in the GOM. Thus, application of wave energy is one way that those companies can offset their fuel operating costs and come into the forefront of developing low emission technology, which makes the GOM a great market site for wave energy.

LINEAR WAVE THEORY

Linear wave theory is a method that describes the motion and effects of water-surface waves. It has been established for use in naval and ocean science to help explaining the movement and forces of water waves and has been used for developing equations for estimating wave energy density and wave power [15]. Even there are several other theories that are used to determine wave equations, linear wave theory remains the most commonly-used theory and was applied for wave analysis in this study.

According to linear wave theory, the greatest amount of force activity is found on the surface of the wave. As stated by Drew et al. [5], "up to 95% of the energy in a wave is located between the water surface and one-quarter of a wavelength below it." The idea behind linear wave theory is that water waves can be physically represented as a sine (cosine) function and has position and time variables. Figure 1 shows an approximate model of a sine wave and the various components, which will be used to describe the wave.

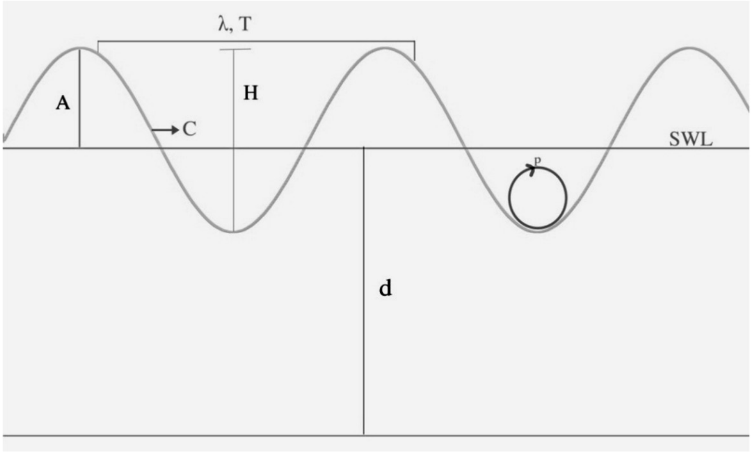

Figure 1. Wave Diagram

The parameters displayed in that figure are depicted as:

A: amplitude, the distance from standing water to the top of crest, half of the wave height (m)

H: significant wave height, measure from the top of the crest of a wave to the bottom of trough (m)

λ: wavelength, distance measured from crest to crest (m)

T: period, time to cycle through one full wavelength (s)

C: phase velocity (celerity), speed that a single wave is moving (m/s)

SWL: still water level, water level when no waves are present

d: water bin depth, measurement from seabed to the still water level (m)

p: particle motion, motion of a particle sitting on the surface of the wave

In most cases of data collection, not all of these parameters would be available for direct measurement but they can be calculated based on three basic primary parameters: SWL, T, and d. Different equations were developed for modeling and predicting wave motion at different levels of water depth, therefore can be categorized into three sets: equations for shallow water, for deep water, and for water with transitional depths. In order to avoid confusion due to different equation sets, the equations and parameters with the subscript "o" refer to the deep water calculations, the subscript "shallow" refer to the shallow water calculates, and the subscript "T" refer to the calculations for the transitional water depths. Equations without subscript, however, are applicable for all depths of water. In all calculations involved in this study, the density of the gulf water (ρ) is taken as 1,025 kg/m^3 and the gravitational acceleration (g) is 9.81 m/s^2.

Wave Motion

According to the Shore Protection Manual created by the Army Corps of Engineers [16], a regular wave moves with time t and along direction x can be modeled as a normal sine function, based on the wave height H, wave period T, and wavelength λ (Eqn. (1)).

$$\eta = \frac{H}{2}\sin\left(\frac{2\pi t}{T} + \frac{2\pi x}{\lambda}\right) \tag{1}$$

Wavelength Calculation

Wavelength (λ) is used to determine the water depth levels. Specifically, the water is considered as shallow if its depth d is less than twentieth of the wavelength ($d < \lambda/20$); transitional when the depth is between twentieth and half of the wavelength ($\lambda/20 < d < \lambda/2$); deep if the depth reaches half of the wavelength ($d \geq \lambda/2$). It is obvious that the wavelength cannot be directly measured from the gulf but can be calculated as [4]:

$$\lambda_o = \frac{T^2 g}{2\pi} \tag{2}$$

$$\lambda_{shallow} = \lambda_o \tanh\left(\frac{2\pi d}{\lambda_{shallow}}\right) \tag{3}$$

However, a more exact and general equation for determining the wavelength at any depth was presented in [16] as:

$$\lambda = T\sqrt{\frac{gd}{F}} \tag{4}$$

$$F = G + \frac{1}{1+0.6522G+0.4622G^2+0.0864G^4+0.0675G^5} \tag{5}$$

$$G = \left(\frac{2\pi}{T}\right)^2 \frac{d}{g} \tag{6}$$

Phase Velocity

Phase velocity, which is also known as celerity, is the velocity of a single wave and defined as $C = \lambda/T$. It is well known that the waves generated in the ocean can be considered as moving in groups and Eqn. (7) describes the relationship between the celerity (C) and the group velocity of waves (C_g).

$$C_g = \frac{C}{2}\left[1 + \frac{4\pi d}{\lambda \sinh(\frac{4\pi d}{\lambda})}\right] = \frac{\lambda}{2T}\left[1 + \frac{4\pi d}{\lambda \sinh(\frac{4\pi d}{\lambda})}\right] \tag{7}$$

For shallow water, the group velocity equals the phase velocity ($C_g = C$) and for deep water group velocity can be approximated as half of the phase velocity ($C_o = C/2$).

Energy Density

The energy density (E), a wave's specific energy, measures the amount of energy over the surface area of the wave. According to linear wave theory, the energy density is directly proportional to the square of the significant wave height and is measured as the summation of potential and kinetic energy of the wave unit wave surface area (Eqn. (8)) [4, 15].

$$E = E_P + E_K = \frac{\rho g H^2}{16} + \frac{\rho g H^2}{16} = \frac{\rho g H^2}{8} \tag{8}$$

Underwater Loss

Eqn. (8) determines the wave energy density at the surface of the water; however, an underwater loss needs to be considered when measuring the energy density at certain depth below the water surface. The energy underwater decays exponentially, as depicted in Eqn. (9), where z is the depth below the still water level [17].

$$E(z) = E \times e^{-\frac{2\pi}{\lambda}z} \tag{9}$$

Wave Power

Wave power (P), also known as the energy flux, is the power of a wave over the length of the wave crest. According to Mcormick [4], the wave power is a function of the square of the wave height and the group velocity, which is also a function of wavelength and period (Eqn. (10)). It is apparent that the overall power potential of wave over certain area can be estimated as the product of the wave power and that area.

$$P = E * C_g = \frac{\rho g H^2 \lambda}{16T}\left[1 + \frac{4\pi d}{\lambda \sinh(\frac{4\pi d}{\lambda})}\right] \tag{10}$$

In the next section, wave height, period, and water depth collected from the GOM will be substituted into above equations to estimate the wave energy potential in that area.

WAVE DATA ANALYSIS

There are a number of stations were established in the GOM to record data of wave and climate. In this study, data collected from three stations (station #6, #9, and #15) were used for estimation of the wave energy potential. Those stations, which are located off the coast of Louisiana, are run by the Coastal Studies Institute (CSI) of the Louisiana State University (LSU) and provide the most complete data about the waves in GOM [8].

The updated wave data measured from above CSI stations can be found from the official website of LSU's Wave-Current-Surge Information System (WAVCIS). Important wave data that were used for calculation in this study include the wave height, the period, and the water bin depth, which are collected every hour from October 2010 to March 2012.

It is noted that a tropical storm, Lee, occurred in early September of 2011 and lingered in that area for a few days while moving westward. It is apparent that during that time, most wave energy devices would not be able to perform properly due to the extremely high waves. The peak wave height caused by the tropical storm Lee can be easily identified. Consequently, the wave power calculated based on the wave height and other parameters exhibit a peak value during that storm.

Based on the data collected from the three stations, the physical characteristics of wave in the GOM can be calculated using the equations presented in the previous section. For example, the wavelength was calculated using Eqns. (2-4); the phase velocity and group velocity was calculated using Eqn. (7); the wave energy density Eqns. (8) and (9); and the wave power Eqn. (10). Each of the calculated characteristic parameters was averaged and results are listed in Table 1. The "event data points," which are the data related to the tropical storm Lee, were then removed and the average values were recalculated and listed in Table 2. The percentage differences between the average values calculated with and without those "even data points" were calculated and displayed in Table 3.

From Tables 1, 2, and 3, it can be found that for stations #9 and #15, the wave energy density and wave power estimated without those events data points are considerably lower than those with the events data points. It is also found that for other wave parameters of those stations, the effects of the events data points were much lower, and for the station #6, the events data points did not apparently affect the wave parameter values. The discussion above suggests that all the events data points can be considered in estimating the wave power. This is because that (1) it is hard and time consuming to identify the events data points from a huge number of measured data points and completely remove them; and (2) the operational range of a wave energy device could possibly cover some of those events data points. Thus, if further study, the events data points will be included in estimation but their effects on the results will be indicated separately.

For wave power estimation, it is commonly to calculate annual averages and monthly averages to reveal the trends of wave power potential in warm or cold weather. The average values for each station are displayed in Tables 4 to 6.

From that data it can be found that the potential wave power which may be extracted from station #6 is higher than that from other two stations. For all the stations, the highest monthly wave power appears in September because of the tropical storm Lee, which brought very high

Table 1. Average parameter values for each station, all data points

Station	Height (m)	Period (s)	Depth (m)	Wavelength (m)	Phase velocity (m/s)	Group velocity (m/s)	Energy density (J/m^2)	Wave power (W/m)
#15	0.61	4.96	17.05	38.55	7.60	4.06	681.56	3341.86
#9	0.60	3.78	17.30	23.60	5.86	3.01	622.20	2614.81
#6	1.02	4.51	21.26	32.89	7.01	3.57	1519.85	5837.06
Average	0.74	4.42	18.53	31.68	6.82	3.55	941.20	3931.24

Table 2. Average parameter values for each station, without events data points

Station	Height (m)	Period (s)	Depth (m)	Wavelength (m)	Phase velocity (m/s)	Group velocity (m/s)	Energy density (J/m^2)	Wave power (W/m)
#15	0.59	4.94	17.05	38.23	7.58	4.04	602.19	2793.95
#9	0.57	3.73	17.30	22.93	5.80	2.96	504.34	1824.95
#6	1.02	4.51	21.26	32.89	7.01	3.57	1519.85	5837.06
Average	0.73	4.39	18.53	31.35	6.79	3.52	875.46	3485.32

Table 3. Percent difference between values with and without the events data points.

Station	Height (m)	Period (s)	Depth (m)	Wavelength (m)	Phase velocity (m/s)	Group velocity (m/s)	Energy density (J/m^2)	Wave power (W/m)
#15	3.27%	0.40%	0%	0.83%	2.63%	0.49%	11.65%	16.40%
#9	5%	1.32%	0%	2.84%	1.02%	1.66%	18.94%	30.21%
#6	0%	0%	0%	0%	0%	0%	0%	0%
Average	1.35%	4.39	0%	1.04%	4.4%	0.85%	6.98%	11.34%

Table 4. Average values calculated for station #6

Date	Wave height (m)	Wave period (s)	Water bin depth (m)	Wavelength (m)	Phase velocity (m/s)	Group velocity (m/s)	Energy density (J/m^2)	Water power (W/m)
Oct-11	0.75	4.42	20.98	31.52	6.84	3.53	979.36	4193.32
Nov-11	1.10	4.54	21.16	32.68	7.07	3.58	1668.68	6253.30
Dec-11	1.08	4.52	21.28	32.92	7.02	3.60	1659.94	6525.56
Jan-12	0.96	4.53	21.29	32.52	7.05	3.57	1355.88	5086.08
Feb-12	1.11	4.51	21.42	32.72	7.00	3.58	1742.23	6584.98
Mar-12	1.01	4.44	21.46	31.31	6.92	3.49	1520.79	5658.06

Table 5. Average values calculated for station #9

Date	Wave height (m)	Wave period (s)	Water bin depth (m)	Wavelength (m)	Phase velocity (m/s)	Group velocity (m/s)	Energy density (J/m^2)	Water power (W/m)
May-11	0.57	3.77	17.23	23.04	5.88	2.97	458.65	1499.05
Jun-11	0.57	3.90	17.25	24.39	6.08	3.07	472.81	1601.43
Jul-11	0.45	3.28	17.30	17.56	5.11	2.58	320.73	1022.24
Aug-11	0.36	2.92	17.26	13.55	4.56	2.28	172.23	405.90
Sep-11	0.71	3.77	17.33	24.44	5.75	3.07	1455.07	8821.34
Oct-11	0.58	3.70	17.35	22.93	5.72	2.95	548.56	2094.57
Nov-11	0.72	4.10	17.41	27.06	6.38	3.26	722.82	2594.86
Dec-11	0.71	4.19	17.37	28.77	6.46	3.38	747.84	3064.99
Jan-12	0.65	4.00	17.25	26.00	6.21	3.18	622.85	2327.89
Feb-12	0.68	4.12	17.26	27.60	6.38	3.30	679.42	2621.14
Mar-12	0.69	4.14	17.22	27.85	6.41	3.32	717.15	2885.73

Table 6. Average values calculated for station #15

Date	Wave height (m)	Wave period (s)	Water bin depth (m)	Wavelength (m)	Phase velocity (m/s)	Group velocity (m/s)	Energy density (J/m^2)	Water power (W/m)
Dec-10	0.67	4.82	16.92	36.57	7.41	3.93	788.37	3678.14
Jan-11	0.61	4.81	16.90	36.43	7.37	3.93	664.13	3245.18
Feb-11	0.56	4.89	16.91	37.37	7.56	3.97	487.48	1965.93
Mar-11	0.64	5.24	16.95	42.63	7.98	4.35	645.66	3316.90
Apr-11	0.76	5.20	16.90	42.03	7.90	4.31	935.89	4396.40
May-11	0.58	5.08	16.90	40.16	7.63	4.11	506.78	2139.70
Jun-11	0.48	5.00	16.95	39.00	7.69	4.09	351.80	1512.52
Jul-11	0.30	4.73	16.90	35.06	7.69	3.81	124.13	497.89
Aug-11	0.29	4.61	17.13	33.26	7.31	3.68	122.86	446.76
Sep-11	0.56	5.21	17.18	42.43	7.16	4.34	954.16	5995.12
Oct-11	0.65	4.98	17.23	39.02	7.89	4.09	794.97	3957.94

wave heights. Also, slights decrease in the estimated wave power were observed during the warmer months (May ~ August).

Locations of the stations also affected the readings. Station #9 locates at the mouth of a gulf embankment, where the wave activities are affected by wave reflection and deflection. Thus, the estimated potential wave power is less than the wave power estimations of the other two stations. Stations #6 and #15 are close to each other and locate far from the land; therefore their wave power estimations are higher because of less interference of the land on the wave activities.

In summary, the average wave power for all of the data points collected from all the stations is 3.54 kilowatts per meter of wave crest, based on which the wave power potential in the GOM can be estimated. The total area of the drilling platforms and surrounding areas (green) in the GOM is approximately 252,829.85 km^2. Assuming that a wave energy device can work 8,760 hours per year, the total wave power provided in the area around the platform will be 3.54 kW/m × 252,829.85 km^2 × 8760 hours/year ≈ 7.8 TWh/yr, which equals about 10% power required by operating the oil and gas platforms in that area. It is confirmed that the wave energy/power in the GOM has the potential of providing 10% of power needed by the oil and gas platforms in that area. The wave energy technology thus deserves further development and investment.

CONCLUSIONS

This article reports an investigational study on the potential and prospect of developing wave energy technology in the GOM. Based on a review of physical conditions in the GOM and a series of estimation by using the linear wave theory, it was concluded that the wave energy in that area is worth pursuing. Important research results and contributions are summarized as follows.

(1) It is confirmed that as a green and renewable energy, despite its high utility cost, wave energy is a more productive, reliable, and continuous energy resource when compared to solar and wind energy.

(2) The GOM is a large body of water with two main sources of water inlet, which create flow, currents, and waves. The shelf area is a

good site for developing and testing wave energy devices because the water depth is sufficient for deep-water activity.

(3) The GOM is a thriving and active area that boasts over 4,100 platforms, and is continuing to grow, which demands growing requirements of power and costs for new and bigger platforms. It is therefore urgent to develop and utilize new energy source to power the growing industrial activities in that area. Wave energy, as stated above, is an ideal option.

(4) Linear wave theory was employed to estimate the wave power potential in the GOM and the results showed that it was possible to produce 3.54 kW/m of wave crest out from the waves in the GOM. The total wave power that can be produced in the GOM is about 7.8 TWh per year, which can power 10% of the electricity needed by operating the platforms in that area.

(5) From the monthly estimation, it was found that the wave power produced in summer months is notably lower than that produced during the rest months. This phenomenon should be considered in operating wave energy converters (WEC), for example, it may be suggested that the WECs are repaired and maintained during summer.

Overall, the potential of wave energy in the GOM was confirmed and the UL Lafayette wave energy team is setting their goals to design and develop a WEC with a small scale and low transmission cost, which could power oil and gas platforms. In the future, more research effort is required for the development of the WEC; the future research should focus on following two areas: wave energy device design and economic analysis to prove the feasibility of the WEC.

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