Study review of the electrical power generation: Wave energy converting device system from the swell

J V Taboada1*, V D Casás1, X Yu2, G M Gemilang3 and P Sampaio4

1Integrated Group for Engineering Research, CITIC, University of A Coruña (UDC) – Campus do Mar, C/ Mendizabal, 15403, Ferrol, A Coruña, Spain
2FEMOTECH Ltd (University of La Coruña), 43 Berkeley Square, London, United Kingdom, W1J 5AP.
3Faculty of Infrastructure Planning, Department of Civil Engineering, Universitas Pertamina, Terusan Simprug, Jakarta, 12220, Indonesia.
4Department of Quality and Organizational Excellence, University of Minho.

* Corresponding author: jose.taboada1@udc.es

Abstract. This paper presents the design of an innovative wave energy converter, namely, Electrical Power Generation - WEC Device System from the Swell, abbreviated as WECFS. This WEC device has been registered for a patent in the Spanish Office of the Patents and Brands (OEPM) with the registration number of the innovative utility model-Patent Model: 202131440(5). The study reported in this paper endeavours to demonstrate the technical feasibility, functional mechanical-kinematic behaviour, and the performance of the proof-of-concept WEC device system, in order to determine their energy extraction capacities and functionalities. The overall energy extracted with eight electrical generators A/C is 0.185 MWatts calculated analytically. The levelized cost of energy is a very important metric in determining whether to move forward with the project, where the cost of energy target has been as cheap as $0.07kWh; this value of LCOE could be improved with optimisations on the practical design parameters. This preliminary study investigates the factors influencing standardized and industrialized for the new WEC device system and can be used to guide the optimization of this type of device technology.

Keywords: Wave energy converter, Renewable energy, Energy of ocean waves, Mechanical engineering, Proof of concept (POC), Life cycle.

1. Introduction

The exploitation of ocean renewable energy resources is an incipient alternative to the continual consumption of polluting fossil fuels resources, helping at the same time to the energy freedom of marine coastal countries. The sea, as it is known, holds a potential source of the six major renewable energy resources, i.e. waves, tides, ocean currents, thermal, salinity gradients and biomass. The 1973 oil crisis caused a significant shift in the renewable energy landscape, sparking interest in large-scale wave energy generation; ocean waves have a higher energy density than wind and solar panels depending on their characteristics [1]. The theoretical energy reserves of the ocean are compared in Table 1, where wave energy has the benefits of huge potential energy reserves, meaning high density yet in a range of power production depending on the efficiency of the devices [1], [2]. Thus, as renewable energy with great
development potential, wave energy has gradually attracted the attention of various coastal countries. In addition, wave energy is more stable and more predictable, making them easier to optimize the power output and production forecast. Normally, technical decisions are made based on the levelized cost of electricity (LCOE) for those Wave Energy Converter (WEC) device systems.

The huge amount of wave power available at the ocean waves has encouraged many researchers and engineers to develop devices and machines to capture this oceanic power. In addition, wave energy is a non-polluting renewable source of energy. Thus, many developments are happening around the world, and researchers around the world are making efforts to advance the technologies and bring the green energy from the sea. The pursuit of wave energy dates much earlier back in 1799 when Girard and his sons filed a patent to utilize wave energy in Paris [3]. Later, the navigation buoys powered by wave energy, invented by Yoshio Masuda in the 1940s, was regarded as the father of modern wave energy technology.

Table 1. Theoretical reserves of global ocean energy [1], [2].

| Source          | Capacity (GW) | Annual generation (TWh) |
|-----------------|---------------|-------------------------|
| Tide            | 90            | 800                     |
| Wave            | 1000–9000     | 8000–80000              |
| Marine currents | 5000          | 50000                   |
| Osmotic         | 20            | 2000                    |
| Ocean thermal   | 1000          | 10000                   |

In this study, a novel wave energy converter is proposed, which features triangular beams combined with transmission gear to provide an amplified rotational speed to the generator. This paper is mainly concerned with technological aspects of a wave energy converter, namely, the Electrical Power Generation - WEC Device System from the Swell, abbreviated as WECFS. This technology has been registered for a patent in the Spanish Office of the Patents and Brands (OEPM) with the registration number of the innovative utility model-Patent Model: 202131440(5). This article is organized as follows. Section 2 outlines the global introduction of the exploitation of the ocean renewable energy resources, where the trajectory and a brief history of the development of research and development (R&D) of WEC devices are discussed. Section 3 introduces the concept of WECFS, followed by Section 4 explaining the functional analysis of the WECFS. Section 5 provides the summary and conclusion of this paper that the concept of WECFS can efficiently generate renewable energy reliable to harvest.

2. Background

2.1 Wave theory

Wave theories are approximations to actual waves which can be used to forecast wave energy in mathematical expression under given conditions that satisfy the assumptions made in relevant derivations. Waves that occur on the sea surface are generally generated by wind frictions, the force of gravity and surface tension, reacting to cause wave propagation. As the wind blows across the sea surface, it transfers the energy to the waves, through moving air particles transferring their energy to the water molecules that they touch, forming a loop like motion that progress along the sea surface until reaching a shoreline with varying orbital motion as illustrated in Figure 1.

The evaluation of the wave energy resource is a fundamental requirement for strategic planning of its usage and the design of wave energy devices. Every single wave in the wave train contains an amount of energy, $E$, per unit horizontal sea surface area depending on the gravity acceleration, $g$, and seawater density, $\rho$ as written in (1),

$$E = \frac{1}{8} \rho g H^2.$$ (1)
These energies are characterised based on the wavelength, \( L \), which is the horizontal distance between two peaks or two troughs, the wave height, \( H \), which is the vertical distance between the wave crests and troughs, the wave period, \( T \), which is the time taken to reach one wave trajectory, the depth, \( h \), which is the water depth.

Waves generated by wind can be classified based on their origination into the local wave and swell wave. The two types may coexist on the ocean surface. The local waves are driven by prevailing local wind field in irregular form from the superposition of many regular waves of different frequencies, different heights, and different propagation directions. The swell is fully developed waves that have propagated out of the area of the local wind field, which is no longer generated by the local wind and could even propagate for hundreds of miles even to areas where no wind prevails. Individual swell wave can be regarded as a regular wave with constantly long periods (short frequencies) and amplitudes [5].

Because swells may travel such long distances, the wave field is usually the product of contributions from local wind waves with varying characteristics and swell waves representing distinct sources with relatively uniform characteristics. Swell waves have a consistent influence on the overall turbulence structure of the boundary layer since it reduces the wind shear in the marine atmospheric boundary layer and consequently producing forward thrust on the mechanical production of turbulence [6]. Thus, the relatively constant frequency of swell waves can be matched with the natural frequency of a wave energy converter to make resonant effects for optimising wave energy extraction. This concept was one of the backgrounds for developing the WEC device system from the Swell. At many offshore locations, such as West Africa or Sarawak, Malaysia, the wave field is dominated by swell energy located at and around the spectral peak frequency, with a comparatively small local wave component at higher frequency [7], [8]. The specified wave spectra dominated by the swell waves are often expressed in terms of the Pierson Moskowitz (PM) or Ochi Hubble, which describe the frequency spectrum of fully developed and the sum of two separate component spectra, respectively.

2.2 Assessment of available wave energy

Ocean has energy resources that are classified as types of renewable energy resources and are quite environmentally friendly, clean, and easy to convert to electricity energy. In this section, the subject matter of the energy is generated from ocean waves. Wave energy is characterised by metocean conditions, i.e. wind, wave, current to achieve targets of power production viability potential for WEC.
devices. Wave power is the capture of energy from wind waves to do useful functional work, i.e. electricity generation, pumping water. Commercial technology is not intensively employed for wave-power generation, in comparison to other well established renewable energy sources such as solar power and wind power. The world wave atlas is the collective name for a series of comprehensive high-resolution interactive wave atlases capable of providing accurate wave climate statistics for any country or region worldwide. Figure 2 provides access to average annual wave power (KW/m) data. In the global wave energy map, all global wave model grid points indicated the intensity value of the average annual wave power in KW/m. It can be seen that coast lines along big continents such as Australia, South America, North Scotland and South Africa have great potential for wave energy that can be installed WEC device for wave energy extraction.

![Average Annual Wave Power (kW/m)](image)

Figure 2. Example screen picture from World Wave Atlas showing the average annual wave power (KW/m) [9].

The available wave energy flux (also named as wave energy potential per unit crest, in W m⁻¹) is considered as the amount of energy contained at a given specific location, being defined as the integral of the wave energy spectrum shown in (2).

\[
P = \frac{\rho g^2}{64\pi} H_{m0}^2 T_e \approx \left(0.5 \frac{kW}{m^3 \cdot s}\right) H_{m0}^2 T_e
\]

With \(P\) as the wave energy flux per unit of wave-crest length, \(H_{m0}\) as the significant wave height, \(T_e\) as the wave period, \(\rho\) as the water density and \(g\) the acceleration by gravity. This formula stated that the wave power is proportional to the wave energy period and to the square of the wave height.

2.3 Existing wave energy converters

Different types of existing WECs may be grouped in various ways with respect to their form, shape, horizontal orientation and size. There are three fundamentals used in converting wave power into electric power as illustrated in Figure 3, and these are:

- Wave Profile Devices (Point of Absorber & Linear Absorber): these are wave energy devices that turn the oscillating height of the ocean surface into mechanical energy. Wave profile devices are a type of wave energy device that floats on or near the sea surface and moves in
reaction to the form of the incident wave or, in the case of submersible devices, moves up and down due to differences in underwater pressure when a wave passes by.

- Oscillating Water Columns: these are wave energy devices that convert the energy of the waves into air pressure. The Oscillating Wave Column (OWC) is a shoreline wave energy device usually positioned onto or near rocks or cliffs which are next to a deep-sea bottom.
- Wave Capture Devices: these are wave energy devices that convert the energy of the waves into potential energy [10]. Wave Capture Device, also known as an Overtopping Wave Power Device, is a wave energy device along shoreline to nearshore that captures the movements of the tides and waves and converts them into potential energy. A more detailed explanation can be found in the literature [10].

![Wave Energy Devices](image)

**Figure 3.** Wave energy devices: (a) Point and linear absorber oscillating, (b) Wave column (OWC) and (c) Capture wave energy devices [10].

As seen above, some of the wave energy devices are currently used to extract electrical energy from wave energy. However, there are many technical challenges to be solved with the main barrier preventing wave energy extraction, with the usual efficiency of a wave energy device now being around 30%. For example, wave energy devices are subjected to harsh weather conditions, with some devices previously destroyed by the forces of tides and violent storms, along with expensive maintenance, accessibility, and repair. However, wave energy devices have numerous benefits over other kinds of renewable extraction device if the maintenance and efficiency can be improved. One of its primary benefits is that wave energy is often regarded as a clean form of renewable energy with much less land use issue for large scale implementation of wave power technologies for capturing high density of energy in large water areas.

3. Concept of the electrical power generation – WEC device system from the swell (WECFS)

3.1 WEC device system

The WEC device introduced in this paper is a new system for generating electricity from ocean waves, featuring an 8 x 2 m floater. The WEC device emerges a new solution that develops compact and high efficiency WEC. The electricity outputs form this device can be generated by relative motion between two elongated inner body floating structures where the movement is controlled by relative velocity up and down along each gear track line and gear box technology. The two elongated inner body absorbs
the incoming energy from wave and transmits to a relative motion up and down along gear track lines into generator A/C. The generator A/C delivers energy through a simple and reliable system that ensures energy from any rotational movement by gears, converting linear movement into a rotational one. This energy is transformed by the rotation of each single gear axle directly connected to each generator A/C, offering high efficiency. The complete system is fully adjustable in size to different environmental conditions, and the floating structures of this WEC are designed in such a way to have a matching natural frequency as close as possible to the frequency of the swell waves in order to maximize energy output. As mentioned previously, swell waves have a relatively constant frequency in an open water area, meaning that the natural frequency of the WEC floating structure can be matched with the frequency of swell waves for the resonant effect to take place to maximise the efficiency of wave energy extraction.

Thus, the WEC device delivers outstanding performances, with high efficiency and optimizes use of construction materials. The WEC device, produce energy at a low cost, making it competitive with the global energy supply. The key to the technology is the design of a floating system acting as a self-buoyant, which transform wave energy into relative motion (up & down) generating electrical energy. This WEC device technology is efficient enough to exploit the enormous resources in wave energy this has been probed by recently R&D, coupled with their low cost. It will be an important contribution to tomorrow’s growing need for energy. The Electrical Power Generation - WEC device system could be a significant game-changer for how we perceive the future of wave power, especially, by Ocean farm system that comprises a network combination linked to mechanical or electrical aspects. This WEC device concept design is simple and sophisticated, allowing to harvest wave energy at a thoroughgoing efficiency.

The electrical power generation - WEC device system is scalable and adaptable to waves conditions. However, the biggest challenge is to design WEC devices that are strong enough to survive varying wave storms and at the same time produce enough energy to pay back the operating cost. The existing WEC is still today too large and expensive, which is preventing commercial harvesting activities. In addition, the utilization of existing WECs encounters challenges and difficulties in a broad technical and non-technical perspective. The proposed WEC device (The Electrical Power Generation – WEC device system from the swell) as emerging technology could help to raise the penetration and commercialization entrance of the WEC systems in the offshore renewable energy market. In order to be fairly competitive with other renewable energy technologies such as wind or/and solar, the CAPEX and OPEX shall be reduced to enable this WEC device system to be competitive enough, as well as the LCOE shall be as lower as possible. Since this WEC device still has not yet done an extensive testing in order to prove the unique control method works reliable, so the prototype needs to be tested in the most severe storm conditions that can occur in the sea in order to probe good survivability and to validate the efficiency. Based on the background and extensive design of the utility model, it aspires that this WEC with elongated buoys can deliver more energy per tonne of the device, even more installing wave farms can be combined for mass production at a lower cost.

The concept of this WEC device is characterised by its main principals. Here below the core characteristics:

- Partial submerged WEC, formed by two main parts:
  - Floating Body 1: Floating steel structure formed by 4 Buoys/Floaters, 4 mooring lines (wire cables/chains), 8 Electrical Generators A/C, Pinions-Gears and Control and Regulation electronics.
  - Floating Body 2: Floating steel structure formed by various pyramid hulls (acting as floaters), stop points, Gear track lines with teeth, Pressure Spillway, Electrical Generator A/C and Turbine.

- Electrical Power extraction and conversion:
  - Fully Offshore.
Location: around Shallow water depth (d < 50 m) and transitional water depth (100 m > d > 50 m), where steeper waves are available.

3.2 Input data

The dimensions (8 x 2 meters approx.) of this type of point absorber has a small width in comparison with the wavelength of the incoming waves, see Figure 4. As we can observe from Figure 4, there exists a relationship between all the components, that are having an inter-functionality. Please, refer to Table 2 for the list of components named and listed by order. As we can see from Figure 4 and Table 2, the schematic figure and the nomenclature list are representing and describing all the parts/components that belong to the Electrical Power Generation - WEC device system from the swell (WECFS).

![Figure 4. The schematic figure of Electrical Power Generation - WECFS.](image)

Most of the materials being structural steels for the main structure (20) and mooring lines (3), while the buoyance/floaters (21&50) are made from polymers. Although, the total compendium of materials makes an equilibrium of the overall floating/buoyancy for the first and second Floating Bodies. The aim is to make the device remaining intact against the incoming waves and currents that are making a continuous impact.

| No. | Description                                           |
|-----|-------------------------------------------------------|
| 1   | Electrical Power Generation - WEC device system from the swell |
| 2   | First Floating Body                                   |
| 3   | Mooring Lines                                         |
| 4   | Sea-Bottom                                            |
| 5   | Second Floating Body                                  |
| 6   | Gear track line with teeth / Set of Racks             |
| 7   | Pinions-Gears                                         |
| 8   | First Electrical Generator A/C                        |
| 9   | Conduct Pressure Spillway / Pressure Spillway         |
| 10  | Electrical Distribution Line                          |
| 11  | Cover/Roof                                           |
| 12  | Control and regulation electronics                     |
| 20  | Structure                                             |
4. Functional analysis of the WEC device system

4.1 Design shape

The fundamental mechanism used in the design of this WEC device is to absorb an acceptable amount of wave power for higher and steeper seas, which means near shore areas and shallow waters where shoaling takes effect. In response to incoming waves, the fundamental requirements demand the WEC device motion results in the power take off extraction, by the relative movement and potential energy of the waves. The device mechanism consists of four main parts: Floating Body 1, Floating Body 2, tension legs, and anchor seabed. Being the principal part of the complete system, the Floating Body 2 contains a gear track driveline connected with generator A/C in the Floating Body 2. The input energy generated into the generators is driven from the relative movement up and down between Floating Body 1 and Floating Body 2 by the entire mechanism. Figure 5 shows schematic global overviews of the WEC system.

The functionality itself rests on relative motion (up & down) of Floating Body 2 along the gear track lines induced by the incoming waves; so then, as much stronger and steeper waves as much movement up & down of the Floating Body 2 is going to produce. Although, the main functionalities are the generated electrical energy through input from gear track driver lines, are the ones that give an output in order to make rotate the generators A/C. In summary, the input energy transmitted into the generators is driven from the linear and relative movement up and down by the entire Floating Body 2 where it is essential that Floating Body 1 rest as much rigid and firm as possible, in order to ensure the maximum functional vertically position for the Floating Body 2. Also, the design-shape adopted and the location (near shore and shallow waters) of the WEC device should achieve the demands for maximum efficiency and power absorption behaviour.
4.2 Dimensioning process for the machinery units

The WEC device requires a specified mechanical design and dimensions, due to the linear relative movement described along 2 m of stroke length established along each Gear Rack Line on the Floating Body 2. The mechanical dimensioning adopted is according to the functional parameter’s requirements. As was described before, the main input movement described by Floating Body 2 comes from the wave height which allows the mass of the Floating Body 2 to move up and down along the Gear Rack Lines providing input directly to helicoidal gear racks. The whole relative movement up and down holds a mass of 14219 Kg, as well as the total range of Buoyance of 16000 Kg for the Floating Body 1. The corresponding lineal speed and time for FALL (going down) are 2.50 m/s and 0.796 sec, respectively; while the corresponding lineal speed and time for UP (going up) are 0.85 m/sec and 2.35 sec, respectively. Although, if we share the total mass of the Floating Body 1 (13050 kg) between the eight lines rack the corresponding lineal forces, the force on each one will be 17436.23 N.

It must be taken into account that the power transmitted goes from outside to the inside of the mechanism. So then, the machinery unit dimensioning shall carry out from outside to inside. The order of mechanical elements is integrated as:

1. Gear Rack Lines.
2. Shaft Drivers.
3. Torque Limiters.
4. Generators A/C.

Following this last order, the entire calculation transmission system is based upon commercial catalogue data. We decided to choose the gear rack line from “Stober” as shown in Figure 6. From catalogues data, functional limitations of any gear selected are:

- Linear Force (max. mass in a movement supported, Fmax = 25 kN)
- Max. Output Torque.
- Nominal diameter of drivers gear racks.
- Output revolutions (475 rpm)

Taking into account these cited limitations from above, we have emitted the analytical calculations, see Table 3.

Table 3. Main parameters of movement fall and up of the Floating Body 2.

| Helicoidal_Stober g.rack ZTRS | FALL →  + : |
|------------------------------|------------|
| Nºlines rack | Force each rack (N) | Pot linear mov. (kW) | M (Nm) | Pot (kW) rotation | r (m) | V1fall (m/s) | V1fall (m/min) | θ (rad) | ω (rad/s) | f (Hz) | n(rpm) |
| 8 | 17436,23 | 43,764 | 417,65 | 417,89 | 0,027 | 2,509 | 150,59 | 92,79 | 886,088 | 141,02 | 8461,52 |

| Nºlines rack | Force each rack (N) | Pot linear mov. (kW) | M (Nm) | Pot (kW) rotation | r (m) | V1up (m/s) | V1up (m/min) | θ (rad) | ω (rad/s) | f (Hz) | n(rpm) |
| 8 | 17436,23 | 14,822 | 471,65 | 141,531 | 0,027 | 0,850 | 51,005 | 31,42 | 300,099 | 47,762 | 2865,74 |

As we can see from Table 3, the limitation by the output revolutions (475 rpm) is not an issue because the model will demand a torque limiter on each shaft driver, just for safety measures, in order to keep a constant output to each gear box. More details about the analytical calculation can be found in Jose [11]. Also, we have calculated the range of output revolutions up and down along the gear rack lines which are 8461,52 rpm and 2865,74 rpm, respectively. With these dimensional inputs, the whole output revolutions will be set at 475 rpm, and the shafts driver need to have a “torque limiter” to reduce these
high output speeds, maintaining constant output revolutions, along the movement described by the Floating Body 2.

![Figure 6. Gear Rack model, adopted from Stober [12].](image)

With all stated above, the dimensioning mechanical process, as well as the theoretical calculations are showed in Table 4 below.

**Table 4.** Results of dimensioning model of the “Electrical power generation - WECFS.

| Design Parameters (Unit)                  | Value   |
|------------------------------------------|---------|
| Power Output Generator (KW)              | 24,8691 |
| n input (rpm)                            | 1900    |
| n output (rpm)                           | 475     |
| i (ratio)                                | 4       |
| n°stages                                 | 2       |
| Gear-Model X-series                      | 0,01004 |
| T1 input Generator (Nm)                  | 125     |
| T2 output Driver "a"&"b" (Nm)             | 500     |
| Efficiency, η(%)                         | 0,93    |
| T1 input (Nm)                            | 116,25  |
| Power Input (KW)                         | 23,128  |
| losses↓ (%)                              | 0,07    |

As we can see from Table 4, it has been listed the main parameters and variables that correspond to the mechanical dimensioning of the Gear Box (i.e. X-Series), which is assembled to the Generator. The Gear Box acts as a functional mechanical link that transforms rotational forces from “Stober” Gear Racks, into electrical energy through the outer Generator A/C. Therefore, according to the previous calculations, with a total number of eight generators A/C from Sicei [13], the total amount of electrical energy obtained offshore will be approximately 0.185026 MW.
4.3 Levelized cost of energy

The levelized cost of energy (LCOE), also referred to as the levelized cost of electricity or the levelized energy cost (LEC), is a measurement used to assess and compare alternative methods of energy production. The LCOE of energy is formulated as follows:

\[
\text{LCOE} = \frac{\text{NPV of Total Costs Over Lifetime}}{\text{NPV of Electrical Energy Produced Over Lifetime}}
\]

For instance, the example calculated for this hypothetical WECFS device takes one year to build and costs $1 million. The O&M costs (for 30 days) are $100,000 per year, with an associated growth rate of 2% annually. There are no associated fuel costs. The WEC’s lifespan is 10 years, and it is estimated to produce 1,487,609.04 kWh each year. Finally, the discount rate for the project is 8%. The calculation of the LCOE for this project is $0.07/kWh.

5. Summary and conclusion

The paper presented a study review for the case study model from the Electrical Power Generation – WEC device system from the swell (WECFS), demonstrating the efficiency available by this WEC device. Section 2 outlines the global introduction of exploitation of the ocean renewable energy resources, where the trajectory and a brief history of the development of research and development (R&D) of WEC devices are discussed along with the assessment of available worldwide wave energy data, giving a comprehensive resolution of interactive wave atlases capable to provide access to the average of annual wave power (KW/m) data. Section 3 provides an understanding of the Electrical Power Generation from the WECFS device system, which is scalable and adaptable to wave conditions. Section 4 outlines the concept and main characteristics of the WECFS device, which is characterized by input data (Schematic + Nomenclature List) along with the materials. All of them gives a definition description of the Electrical Power Generation – WEC device system from the swell. Section 4 outlines the methodology calculations adopted, which are addressed from theoretical calculations analytically by a mechanical dimensioning process adopting from commercial catalogues, which have been the aim to get practical approximations of energy extraction. According to the functional requirements demands of the Electrical Power Generation – WEC device system from the swell, the overall energy obtained with eight electrical generators A/C is 0.185 MW calculated analytically. The levelized cost of energy is a very important metric in determining whether to move forward with the project, where the cost of energy target has been as cheap as $0.07/kWh; this value of LCOE determines that the project is profitable.

The model could be configured as “WEC arrays” to ensure efficient wave energy extraction balancing the cost and production. The arrays could be located between transitional and shallow waters, where the steeper waves are available. In terms of efficiency, the energy extraction of the WEC device system will be efficient when their frequency response function from heave motion closely matches the natural frequency spectrum of the incoming waves to cause resonance. Therefore, the natural frequency of the WEC device needs to be calculated by knowing the water cross sectional area and pretension of the moorings. We need to tune the functional parameters (Water Cross section, Mooring-pretension, weight material, buoyancy force, damping force, inertia force and stiffness force), in order to make a matching between the natural frequency of the WEC device with the frequency of Sea-Swell. Such consistent frequency from the swell will ensure efficient energy input to the WEC device. Since this WEC device still has not yet done an extensive testing in order to probe the unique control method works reliable, so the prototype needs to be tested in the most severe storm conditions that can occur in the sea in order to probe good survivability and to validate the efficiency.
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