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Harnessing of Wave Energy as Renewable Energy: An Overview

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Abstract:- Wave energy is the most promising form of ocean energy which during extraction process does not emit carbon dioxide or produce any waste. It creates no noise pollution and is environmental friendly. Unlike other renewable energy sources, it is more predictable. Till date, only a small part of abundance energy stored in waves has been utilized. This large untapped source of energy could meet the global energy demand if technical and other barriers are overcome and its cost is thereby reduced. This paper presents an overview in respect of current status of research and development in harnessing of wave energy. The article focuses on available technology to extract power, its estimated potential and current exploitation level both globally as well as in India. Further, barriers and obstacles in its deployment and commercialization and perspective of the cost of generating power have also been discussed.

Keywords:- *Waves, Wave Energy, Wave Energy Converter, Wave Power.*

I. INTRODUCTION

Ocean waves as shown in Fig 1, represents a form of renewable energy generated by the winds blowing over the ocean. The potential of wave energy depends upon the strength of winds which is greatest between 30^0 and 60^0 latitudes in both hemispheres on the west coast because in these areas largest wind power and greatest fetch occur. In Europe, the stretch of coastline along the Atlantic Ocean is considered the most potential areas. North and Mediterranean Seas are also having future potential but it offers limited resources in comparison to Atlantic Sea. UK is considered the richest country in terms of wave energy. Other countries such as France, Ireland, Spain, Denmark, Italy, Norway, Portugal and Finland also have the potential.

Fig 1:- Wave Energy

Globally, wave energy is having 30 times more potential than the tidal energy but till date, it has not reached the level of technical maturity to ensure the penetration of energy markets. These largely untapped resources could play a very vital role in meeting the ever-increasing demand of electricity as it can produce power throughout the year.

II. PHYSICAL CONCEPT

Ocean waves are generated basically because of physical disturbances caused by blowing winds over long stretches of water known as fetch. Three main processes are involved in the development of wave:

- Wind blowing over the sea exerts a tangential stress on the water surface which results in the formation and growth of waves.
- Rapidly varying shear stresses and pressure fluctuations are produced due to the turbulent air flow close to the water surface. Because of which further wave development occurs when the oscillations are in phase with existing waves.
- Finally, additional growth of waves takes place because the wind can exert a stronger force on the upwind face of the wave when the waves have reached a certain size.

These have been shown in Fig 2 and 3.

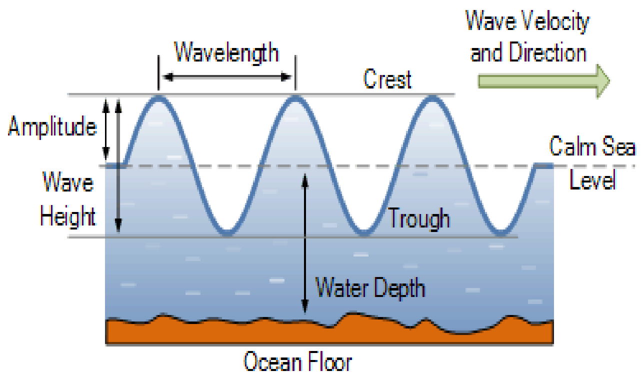

Fig 2:- wave Formation

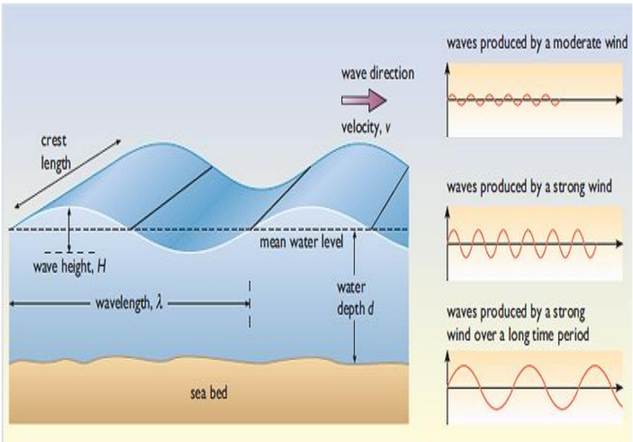

Fig 3:- Characteristics of Wave Formation

In many areas of the world, the wind blows with enough force and consistency to produce continuous waves along the shoreline. Landslides and tectonic movement of earth surfaces and gravitation attraction of earth-moon-sun also generate waves.

The wave height and steepness of the waves depend upon:

- The Wind Speed
- The duration for which wind is blowing
- The distance over which the wind energy is transferred into ocean to form waves i.e. the fetch
- The depth and topography of sea floor

When a steady wind blows for a sufficient time over a long fetch, the waves are referred to as constituting a fully developed sea as shown in Fig 4.

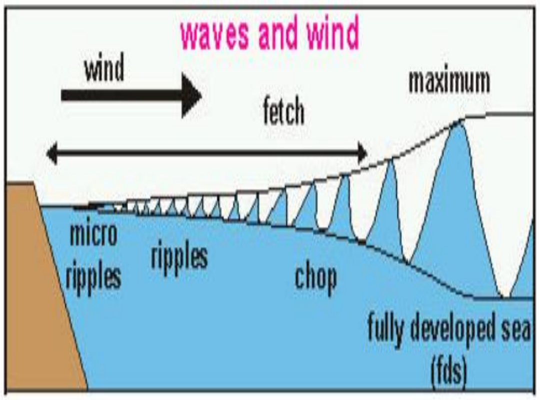

Fig 4:- Waves Constituting a Fully Developed Sea

Ocean waves carry huge amount of energy and as it propagates, its energy get transported. D′ Alembert had given the first linear wave equation theory for the study of the propagation of waves. Sir George Biddell Airy derived the first order description of waves which is popularly known as Airy Wave Theory. Further analysis was done by Sir George Stokes to adequately describe the waves with increased steepness ratio and Cnoidal wave energy was developed to accurately describe the waves in shallow water.

The wave energy power or flux per metre of crest length perpendicular to the direction of wave propagation is given as:

$P = E\ C_g$

Where, E = mean wave energy density which includes both kinetic and potential energy density per unit of horizontal area in which both contributing 50% towards the wave energy density and is given as: $E = \frac{\rho\, g\, A^2}{2}$ where A = Amplitude of wave which is half of wave height H, ρ = mass density of water, g = Acceleration due to gravity and C_g = Group Velocity which is the energy transport velocity and is given as $C_g = \frac{g}{2\omega}$ in deep water.

Hence, $P = \frac{\rho\, T}{32\pi}(g\, H)^2$

i.e. $P \propto H^2\, T$ where T = wave Period

Hence, wave power is proportional to square of wave height H and wave period T and is expressed as KW/m.

As the wave energy passes through the water, it causes the water particles to move into orbital motion as shown in Fig 5.

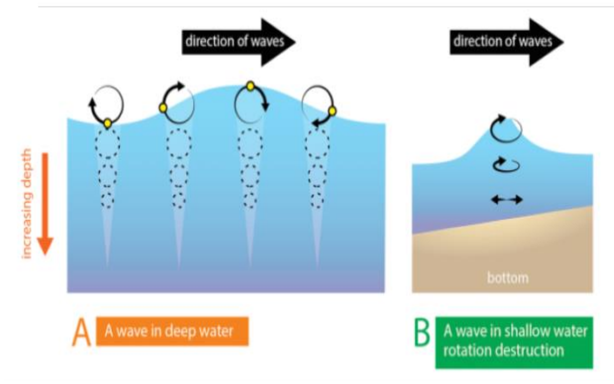

Fig 5:- Movement of Particles in Deep and Shallow Water

Near the surface, the particles move into circular orbits with diameter approximately equal to the wave height. Its orbital dia and the wave energy decreases deeper in water and below a depth half the wavelength, i.e. $d \geq \frac{1}{2}\lambda$, the particle is unaffected by the wave energy. 95% of the wave energy is contained in layers between the surface and a depth equal to quarter of wavelength as shown in Fig 6.

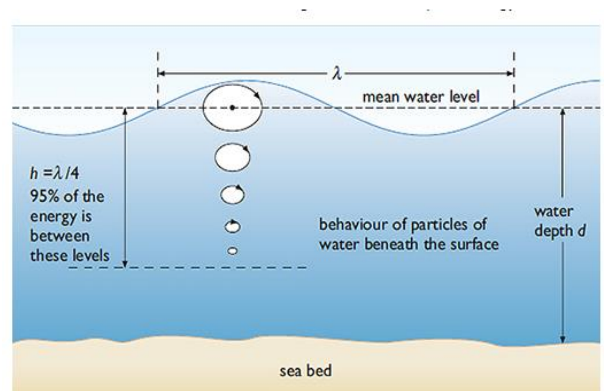

Fig 6:- Behavior of water particles beneath the water surface

As the deep water waves approach the shore and become the shallow water waves, its circular motion are distorted by the interaction with the bottom contours. Hence deep water waves gradually give up their energy as they move into shallow water. It has been estimated that a wave with power density 50 KW/m in deep water might contain only 20 KW/m as they approach close to shore in shallow water.

Swell or deep water waves are those waves which travel across a water body where the depth of water is greater than half the wavelength, i.e. $d > \frac{1}{2}\lambda$ as shown in Fig 7. These include all wind generated waves moving across the open sea. When these waves move into shallow water, they change into breaking waves which are turbulent in nature and energy dissipating. When the wave energy touches the floor of ocean, it drags the water particles along the bottom and makes their orbit flatten.

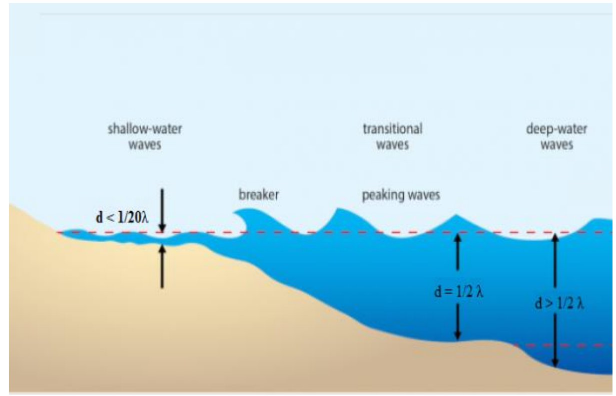

Fig 7:- Changes in Waves as they approach Shore

Transitional waves are those which travel in water where the depth of water is in between $\frac{1}{20}\lambda$ to $\frac{1}{2}\lambda$. These are often wind generated waves that move into shallow water. In this, the water particles move from swell to steeper waves called peaking waves. When this happens, the front surface of the waves gradually becomes steeper than the back surface.

Shallow water waves are those which travel in water where the depth of water is less than $\frac{1}{20}\lambda$. These waves include wind generated waves that move into shallow near shore areas, seismic waves generated due to the disturbances in ocean floor and tide waves generated by the gravitational attraction of sun and moon. In this case, top of waves travel very fast than the bottom one and because of this, the top of the wave begins to spill over and fall down the front surface. It is known as Breaking Waves as shown in Fig 8 which occur when one of the three things happens:

- The ratio of wave height H to wave length λ is in between 1 to 7.
- The wave's crest peak is steep having steepness less than 120^0.
- The wave height H is greater than $\frac{3}{4}$ of water depth d.

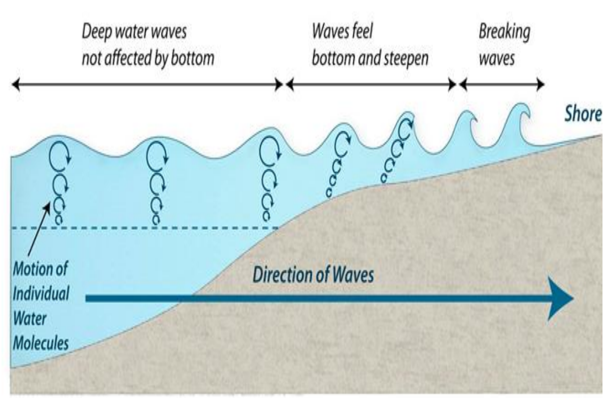

Fig 8:- Formation of Breaking Waves

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III. TECHNOLOGY

Wave Energy Convertor (WEC) is a device which captures the kinetic energy and potential energy of waves and converts it into electricity. A WEC consists of the following components:

- The structure and prime mover which captures the energy of wave.
- The foundation or mooring which keeps the structure and prime mover in place.
- The power take-off which converts mechanical energy into electrical energy.
- The control systems which safeguard and optimize the performance in different operating conditions.
- The installation which places the structure and device at its power generating location.
- The connection which connects the power output from the device to the electric grid.

Body in the sea subjected to waves can respond to six types of movement- sway, roll, yaw, pitch, heave and surge as shown in Fig 9.

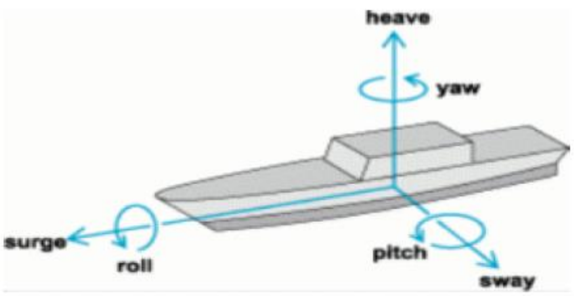

Fig. 9:- Motion of Body due to Incident Waves

The wave energy is absorbed using:

- A horizontal front or back motion known as surge that can be extracted with technologies using a roll rotation.
- A horizontal side to side motion known as sway that can be extracted with technologies using a pitch rotation.
- A vertical up and down motion known as heave that can be extracted with technologies using a yaw rotation or translation.

The pitch, heave and surge responses to an incident waves are shown in Fig 10.

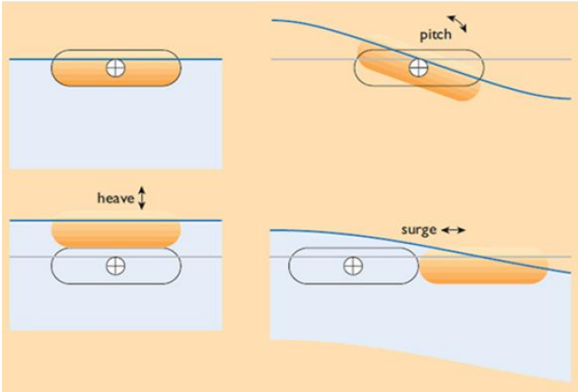

Fig 10:- Pitch, Heave and Surge Responses of an object to incident waves

Wave energy extraction history spans more than 200 years. Yoshio Masuda, a former Japanese Navy Officer, is regarded as the father of modern wave energy conversion technology. Since 1970 to till date, large numbers of concepts for wave energy conversion have been developed, offering a wide variety of designs, energy extraction systems and applications.

In general, wave energy extraction techniques can be categorized as:

A. Based on location with respect to the coastline

Based on location, wave energy devices can be divided into onshore, nearshore and offshore types. Nearshore wave energy devices are usually placed in shallow water within 10-15 Km from the coastline with water depth not exceeding 50 m. In case of onshore devices, it is located on the coastline over a cliff, usually taking advantage either of an existing or new structure to be built such as a breakwater while offshore devices are deployed in deep water having depth more than 50 m as shown in Fig11.

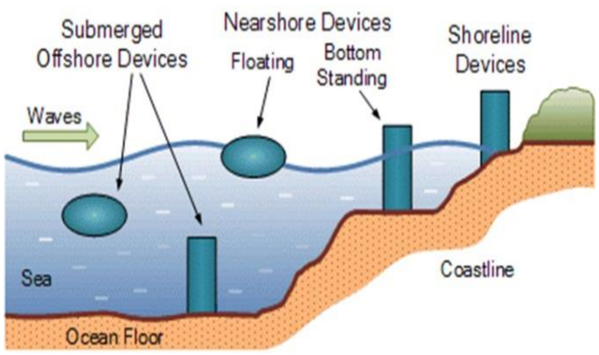

Fig 11:- Wave Energy Device based on Location

Onshore devices have the advantages of being close to the utility network. They have reduced chances of likely to be damaged and are easy to maintain. Like the onshore device, nearshore devices also harness less wave energy because of lesser energy content in shallow water. Offshore devices harvest more amount of energy as deep water waves contain more power but these devices are more difficult to construct, operate and maintain. Further, these devices must be designed to withstand the most extreme conditions. Currently, approximately 64% of Wave Energy Convertors (WEC) under deployment is designed as offshore devices as shown in Fig12.

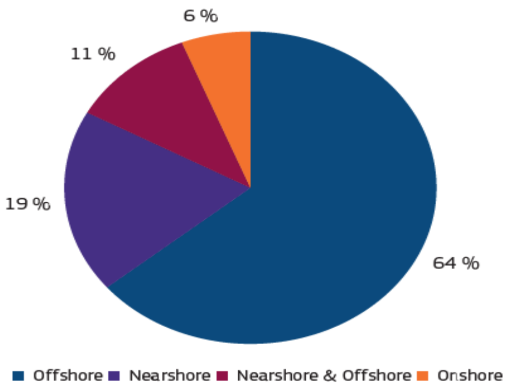

Fig 12:- WEC Designed based on Location

In spite of so much development of demonstration and testing facilities, till date no installation has taken place more than 5 Km away from the shore and in water depth of more than 75 m.

B. Based on Geometry and Directional Characteristics

WEC′s devices based on directional characteristics, i.e. the direction in which they exploit the waves, are as:

➢ *Attenuators*

An attenuator as shown in Fig 13 and 14 is a segmented device which operates parallel to the predominant wave direction and effectively rides the waves. The joints, separating the segments, generate power by compressing oil with the help of two pistons which drive a hydraulic motor and in turn run the generator. These devices try to utilize different translation of motion such as surge, sway and heave.

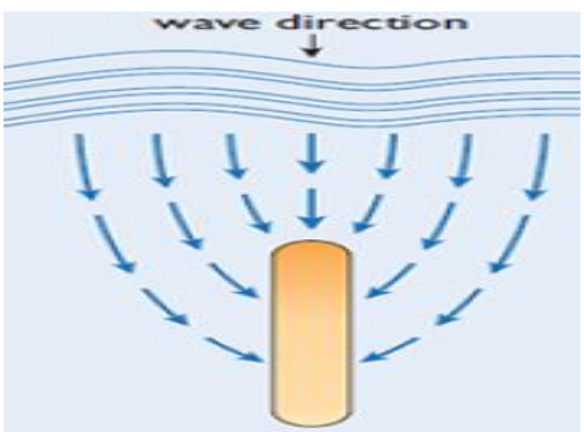

Fig 13:- Schematic Diagram of Attenuator

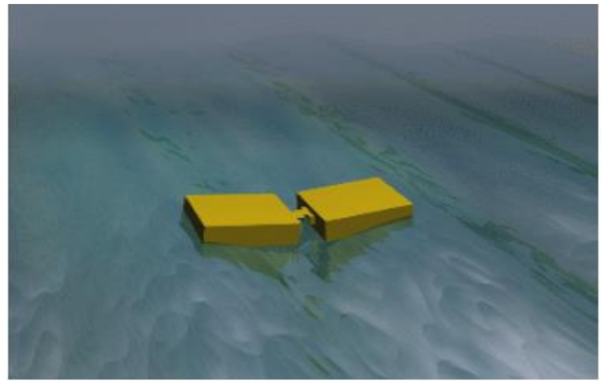

Fig 14:- Basic Concept of Attenuator Device

The most known attenuator WEC device is Pelamis manufactured by Scottish Company Pelamis Wave Power as shown in Fig 15. It is also known as GAINT SEA SNAKE as the name Pelamis is derived from Pelamis platurus, a yellow bellied sea snake found in tropical and sub- tropical shallow sea water. It is an attenuator type offshore device having a series of long cylindrical floating systems made of steel that are joined by hydraulic energy extracting hinges. Each hinge joint comprises four hydraulic rams, a reservoir, high pressure accumulator, motor and generator sets. One side of hinged joint will extract power from heavy motion while the opposite side will extract pitch energy.

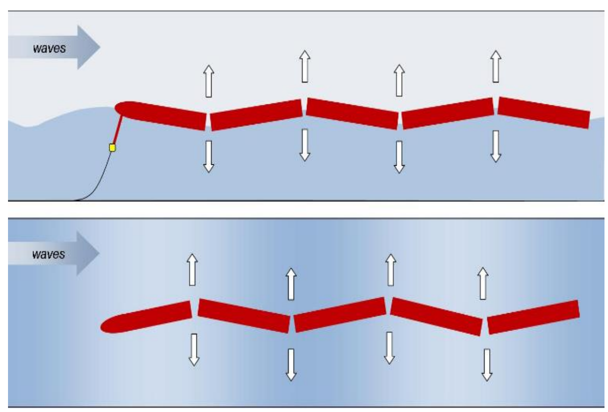

Fig 15:- Concept of Pelamis WEC

This type of device responds to the curvature of the waves, i.e. their shape rather than wave height. As the waves pass along the length of machine, the sections bend relative to one other. The movement of the section is converted into electricity through hydraulic power take off systems contained in each joint which is driven by hydraulic cylinders. These cylinders resist the wave induced motion and pump the high pressure fluid to an accumulator which drives the hydraulic motor as shown in Fig 16 and17. This in turn runs the electric generator to have a smooth and continuous production. Each of the power take off unit of the joints is identical and operates independently. Electricity from each of the unit is fed to a single umbilical cable to a junction on the

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seabed and finally, the power is transmitted to shore using subsea cables and equipment.

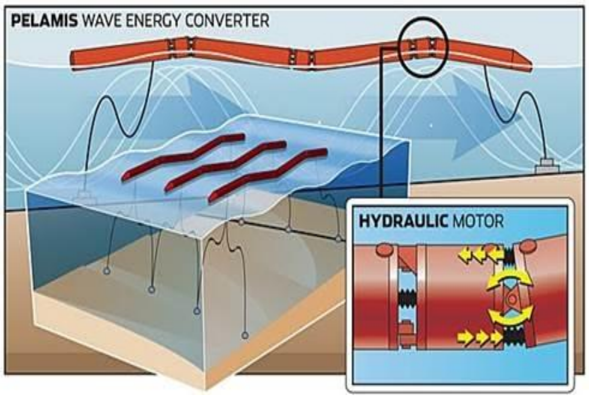

Fig 16:- Details of Pelamis Hinged Joint

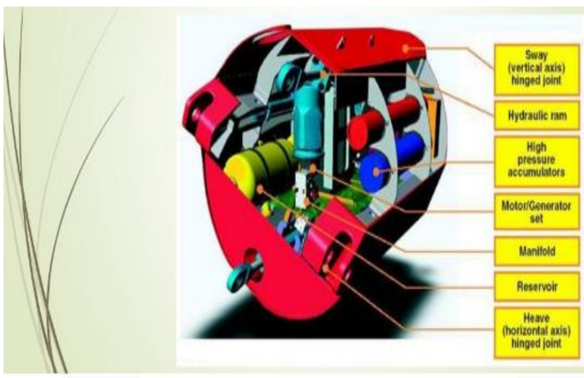

Fig 17:- Internal View of a Pelamis Power Conversion Module

The Pelamis device operates in water depth greater than 50 m and is installed 5 to 20 Km from the coast. The device is rated at 750 KW with mechanical to electrical efficiency as 70% to 80% and capacity factor 25% to 40% depending on the conditions of the chosen project site.

In 2004, Pelamis Wave Power demonstrated their first full scale prototype P1 in Orkney, Scotland which became the World′s first offshore WEC to generate electricity into UK national grid. This device comprised four tube sections, each of 120 m long and 3.5 m in diameter. After the success of P1, three first- generation P1 were tested on the coast of Portugal in 2009. Then two second- generation device Pelamis P2 were tested in Orkney, Scotland in between 2010 and 2014. P2 device comprised of five tube sections, each 180 m long and 4m in diameter and weighed approximately 1350 tonnes.

The world′s first wave farm using Pelamis technology was installed in Agucadura with a capacity of 2.25 MW, 5 Km from Portugal′s Northern Coast near Povoa de Varzim in 2008, using three Pelamis generators.

➢ *Point Absorber*

A point absorber as shown in Fig 18 and 19 is a device which is very small compared to the incident wavelength. It can be a floating structure which absorbs energy from all directions through its movement at or near the water surface. It can also be submerged below the surface relying on pressure differential. In these devices, the direction of wave is not important because of their small size. They derive energy due to the relative motion of the buoy, transferred to subsurface components. They have low rating power, a few hundred kilowatts, due to their small size. Hence, in large power plants, hundreds or thousands of such units are to be dispersed in a very long and narrow array along the coast. These devices take advantage of the heaving motion.

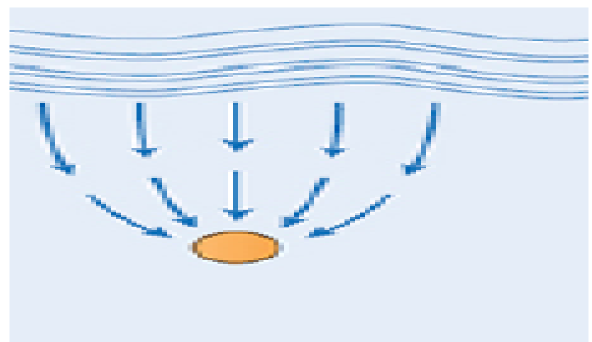
Fig 18:- Schematic Diagram of Point Absorber

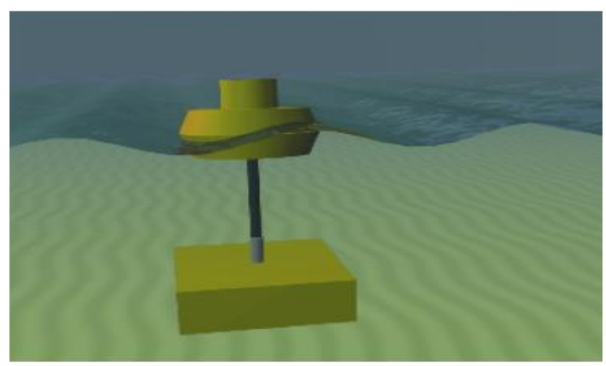
Fig 19:- Basic Concept of Point Absorber device

One of the point absorber devices functional in the world is Power Buoy developed by Ocean Power Technologies, an US based Company. The Power Buoy consists of a float, spar and heave plate as shown in Fig 20. The Float acts like a piston that move up and down as the waves pass. The heave plate keeps the spar in a relatively stationary position. The relative motion of float with respect to the spar drives the mechanical system contained in the spar. This linear motion of the float is converted into the rotary motion which in turn drives the generator to produce power. The entire power take off systems are sealed inside the device. The structure is loosely moored to the seabed, allowing it to move freely up and down. Finally, the electricity generated is fed to shore through a cable. Its power conversion and control system provide continuous power under the most challenging sea

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conditions. The spar also contains additional space for battery which if required, can provide power even under extended no wave conditions.

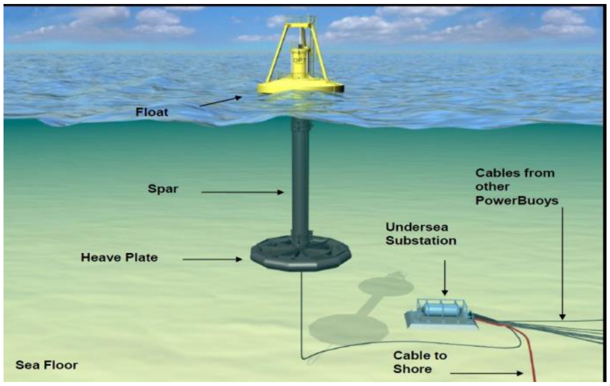

Fig 20:- Internal Details of Power Buoy

Ocean Power Technology (OPT) deployed its first commercial PB3 device as shown in Fig 21 off the coast of New Jersey, USA in July 2016.This PB3 device has a number of enhanced system than the earlier prototype, like a redesigned power take off, a battery pack, a higher voltage power management and distribution systems and a new auto ballasting system which facilitated faster and low cost deployment. Its dimensions are – height 14.3 m, spar dia 1.0 m, float dia 2.7 m and weigh 10280 Kg. it is moored at single point and produces 300 W of continuous power depending upon the ocean conditions and 7.2 KW at peak, 1 hour per day. It floats over ocean in depth between 20 m to 1000 m.

Fig 21:- PB3 Device Deployed off the Coast of New Jersey USA

With the success of PB3 device, OPT is planning to launch second and third generation PB3 device with more advanced system of capturing wave energy. They are also planning to develop PB15 Generation-1 device which could generate more than 15 KW payload power.

Currently, Power Buoy device is in use or in planning at 9 locations around the world like USA, UK, Australia, and Spain.

- *Terminator*

A terminator device is usually aligned parallel to the prevailing direction of wave crest. Sometimes it is also deployed at a slight angle to improve the performance as shown in Fig 22.

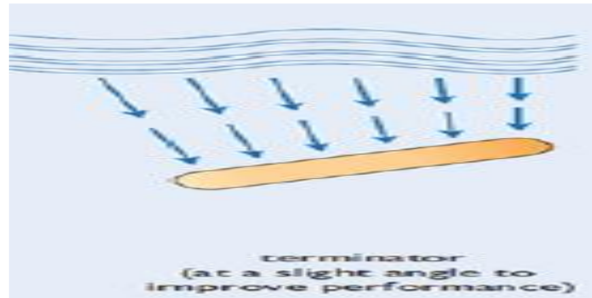

Fig 22:- Schematic Diagram of Terminator

Salter′s Duck Device developed at the University of Edinburgh UK, is one example of a terminator type device. This device was invented in 1973 by Stephen Salter, an Emeritus Professor at the University of Edinburgh. In this, the passing waves cause the Duck to rotate in a nodding action. This motion is used to pump hydraulic fluid or to compress air to drive a hydraulic motor or turbine which in turn drives the generator to produce power as shown in Fig 23 and 24.

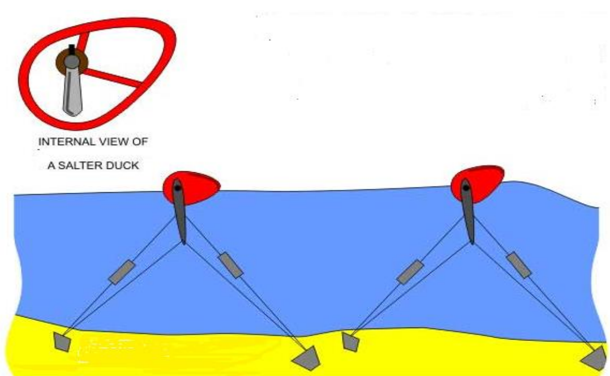

Fig 23:- schematic Diagram of Salter Duck Device

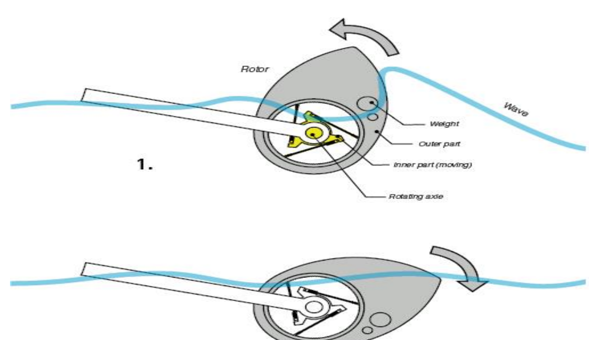

Fig 24:- Details of Functioning of Duck

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A prototype as shown in Fig 25 of this device was developed in 1976. Theoretically, this device has achieved 90% efficiency but in the laboratory testing, its efficiency dropped even up to 50%. In 1980, this programme was disbanded.

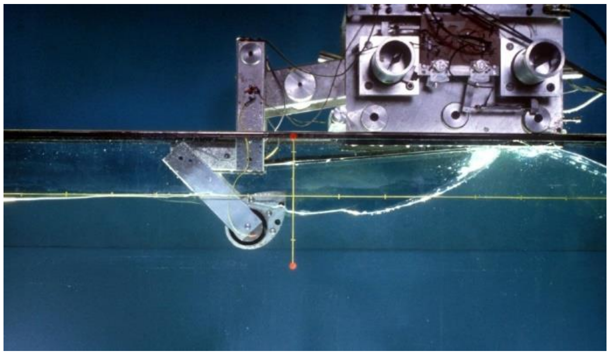
Fig 25:- Salter Duck Model in a Narrow Tank in Lab

C. Based on Operation

➢ *Oscillating Water Column (OWC)*

An OWC device consists of a rectangular chamber with its one end open to the seas and other end vented to an air turbine as shown in Fig 26. The lip or chamber wall allows the propagation of waves into the chamber. As the wave crest enters the chamber, the air column above the water is pushed upwards forcing it out through the turbine, thus driving the turbine which in turn produces power. Similarly, when the wave trough is present in the chamber, the air is sucked back through the turbine. Hence, there is an oscillation of air column above the water surface, the magnitude of which depends upon the incoming ocean waves and also on the amount of energy that can be captured by the system.

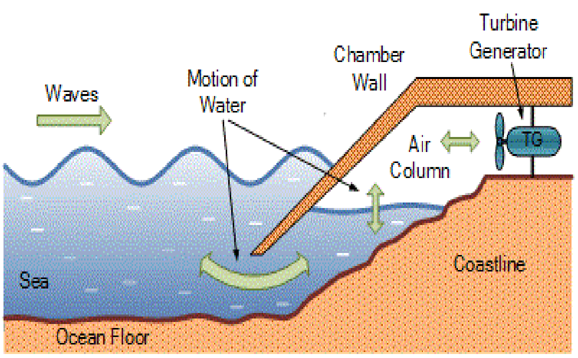

Fig 26:- Concept of OWC

In this application, a special turbine called Well turbine mounted on top of the device as shown in Fig 27 and 28 is designed which rotates in the same direction irrespective to the direction of flow on both cycles.

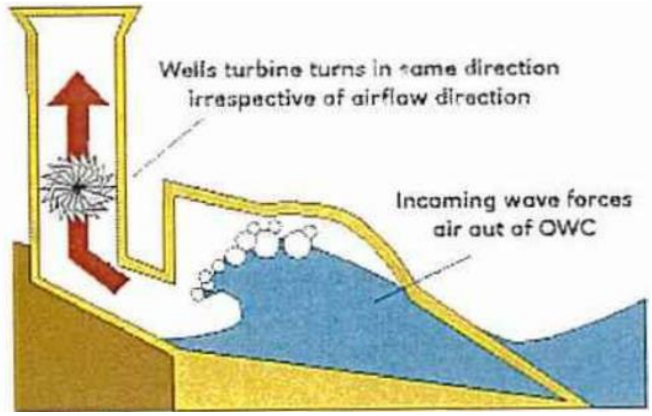

Fig 27:- Working of Well Turbine during Incoming Waves

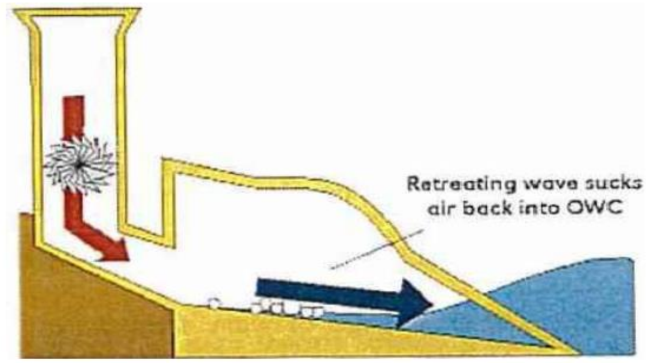

Fig 28:- Working of Well Turbine during Retreating Waves

Well turbine is basically an axial flow device as shown in Fig 29 that drives the generator and hence producing power. It has aerodynamic characteristics, particularly suitable for wave application.

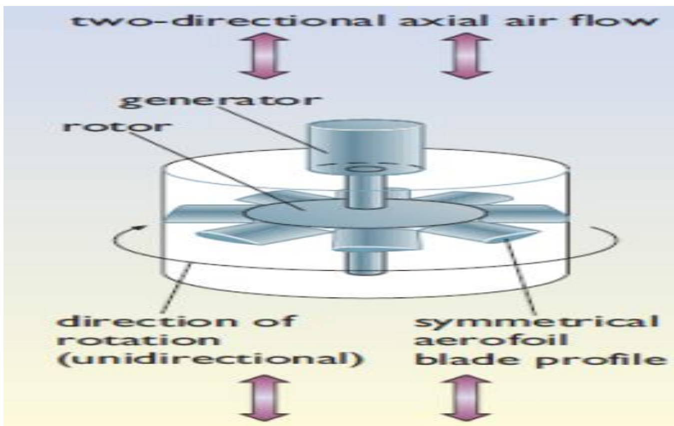

Fig 29:- Fundamental Concept of Well Turbine

The proper designing of air chamber is essential for the successful operation of OWC device. This must be designed based on wave height and wavelength characteristics available at the site. If it is not designed of proper size, wave could resonate within the air chamber and this may cause a net zero passage of air through the turbine. Hence the dimension of air chamber should be designed to capture maximum energy. Further the air chamber must also be conducive to air through the turbine. This can be best achieved by providing funnel shaped air chamber, narrowing from the water surface level to the turbine. This will increase the flow through the turbine.

The OWC devices are one of the first types of WEC developed and different devices are installed onshore in self-contained structures. Floating OWC devices have also been tested and are currently under development for offshore deployment. Wavegen Limpet installed on the Island of Islay, Western Scotland as shown in Fig 30 is an example of onshore mounted device. It produces power for the national grid.

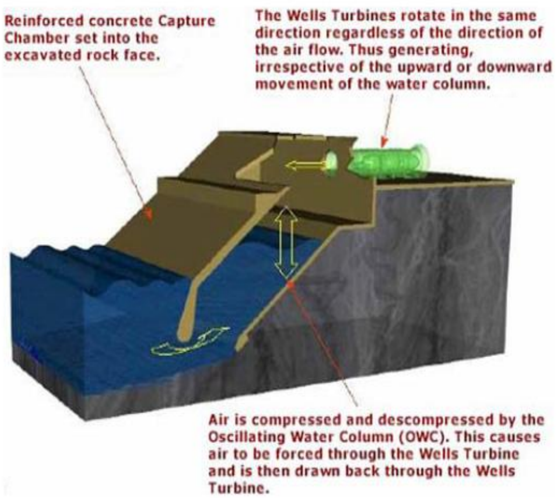

Fig 30:- Schematic Diagram of Wavegen Limpet

In June 2012, Australia′s Oceanlinx proposed to launch the world′s first 1MW nearshore OWC plant known as greenWAVE in Port MacDonnell, Adelaide South Australia as shown in Fig 31. It was made of simple flat packed prefabricated RCC that made the structure heavy enough to anchor itself to the seabed in approximately 10 to 15 m of water without the need of sea floor preparation and with no anchors, moorings or attachment to the seabed. It weighed 3000 tonnes and its dimensions were approximately 21 m wide and 24 m long. It had no moving parts under the water and was designed to withstand the most aggressive sea conditions. The construction of the device was completed in February 2014 and its transportation was started in March 2014. Complications were experienced during transportation and the device was damaged beyond repair. After that, the project was disbanded and its intellectual property and knowhow were sold in November 2014 to a new wave energy technology developer Wave Power Renewables Ltd. based in Hong Kong. The full scale of the more enhanced version of this technology will be launched by the company in 2018.The company is also developing plant in deep water known as blue WAVE.

Fig 31:- Oceanlinx 1MW Nearshore OWC Plant

The Following Table 1 gives the list of OWC devices installed:

Location	Type	Rated output in KW	Width in m	Depth of water in m	Operation Period
Sanze Japan	Coastal OWC	40	17	3	1983-84
Toftestallen, Norway	Coastline OWC	500	10	70	1985-88
Niigata, Japan	Breakwater OWC	40	13	6.5	1986-88
Kujukuri, Japan	OWC with pressure	30	10 × 2	2	Since 1987
Isle of Islay Scotland	Coastal OWC (Islay1)	75	17	3	1988-99
Dwanshan, China	Coastal OWC	3	4	10	Since 1990
Islay UK	Coastal OWC	500		15	Since 2000
Pico Portugal	Coastal OWC	1 MWh			Since 2005

Table 1:- List of OWC Devices Installed

➢ *Oscillating Wave Surge Convertor (OWSC)*

An OWSC device consists of a hinged deflector paddle aligned perpendicular to the wave direction which rotates around a fixed seabed mounting, moving back and forth exploiting the horizontal particle velocity of wave as shown in Fig 32.

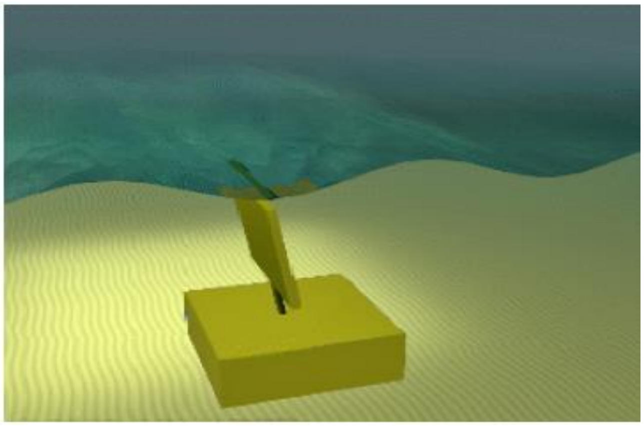

Fig 32:- Schematic Diagram of OWSC

The rotation of paddle due to the surge motion of wave compresses water which in turn drive the onshore turbine, similar to that of hydraulic turbine. These devices use the surge motion of the waves.

The most commercially available OWSC is the Oyster Wave Surge Device developed by Aquamarine Power UK as shown in Fig 33. It is a nearshore device in which the top of the deflector paddle is above the water surface and is hinged from the seabed. It is typically deployed in a water depth of 10 to 15 m.

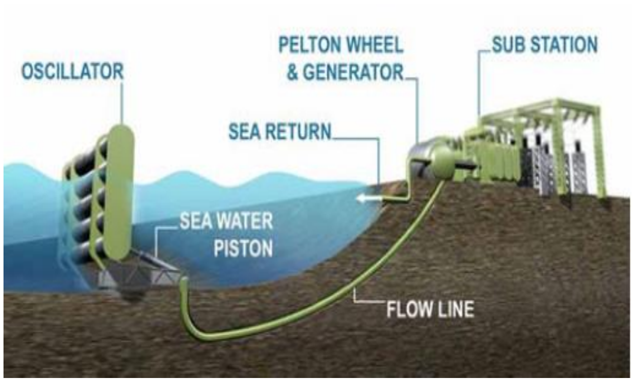

Fig 33:- Oyster OWSC

Oyster1 was the first full scale 315 KW grid connected device installed at the European Marine Energy Centre (EMEC) on Orkney UK in November 2009. The success of Oyster1 led to the testing of second generation 800 KW Oyster800 in 2012 which was 250% more powerful than Oyster1 and it supplied power to the grid. But Aquamarine Power could not get buyer by November 2015 and hence they have ceased trading.

➢ *Submerged Pressure Differential Device (SPD)*

The SPD devices are fully submerged which work on the basis of pressure differential induced due to the movement of waves as shown in Fig 34. It consists of an air filled cylindrical chamber with a moveable upper cylinder. As the wave crest passes over the device, the pressure of water above the device compresses the air within the cylinder, moving the upper cylinder down. Similarly as the wave trough passes over, the water pressure on the device is reduced and the upper cylinder rises. These alternating pressure pumps fluid through a system to generate power. As the devices are fixed with seabed, these are located nearshore.

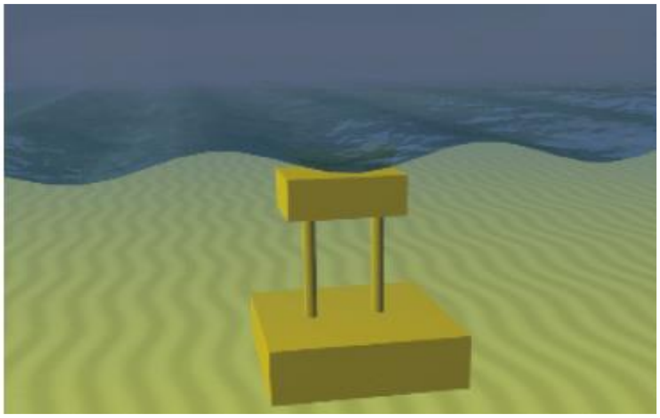

Fig 34:- Schematic Diagram of SPD Device

Archimedes Wave Swing developed by AWS Ocean Energy as shown in Fig 35 is a SPD device. The technology was tested offshore Portugal in 2004. It narrowly missed as the world′s first offshore wave power device connected to national electricity grid by Pelamis device approximately by six weeks. This technology is suitable for deployment in water depth exceeding 25 m and can be configured for ratings between 25 KW and 250 KW.

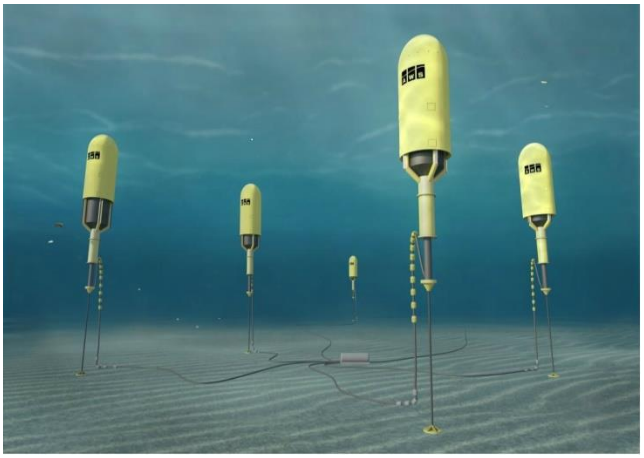

Fig 35:- Archimedes Wave Swing SPD Device

➢ *Overtopping Device*

Overtopping wave power device as shown in Fig 36 is an onshore to nearshore device that capture the movement of waves and convert it into potential energy by lifting the water on to a higher level in a reservoir above the sea level.

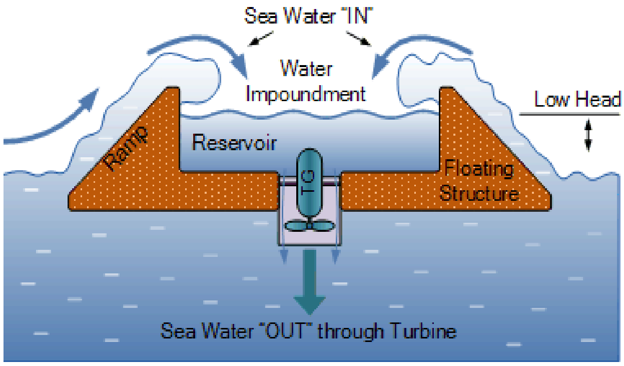

Fig 36:- Schematic Diagram of Overtopping Device

The impounded structure can be either fixed or a floating one tethered to the sea bed. As the waves hit the structure, they flow through a ramp into a raised impounded reservoir to fill it. This creates a low head which is then drained out by gravity through a low head Kaplan turbine provided at the bottom of device to generate power. It has a relatively low power output due to their low head and are only suitable in deep water shoreline.

Wave Dragon as shown in Fig 37 is an example of overtopping type device. It is a large floating structure which consists of two wave reflector arms and a reservoir. The reflector arms direct the waves towards a ramp into an elevated reservoir which collects and temporarily stores the water. The water leaves the reservoir through a battery of low head Kaplan turbines. It is one of the heaviest structures that are used to generate power from wave energy.

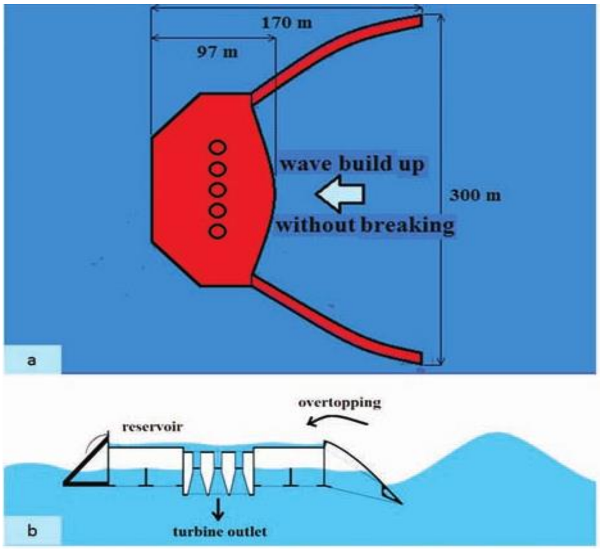

Fig 37:- Schematic Diagram of Wave Dragon Device

A 237 tonnes large scale prototype of this type was launched in 2003 at the Danish Wave Energy Test Centre in Nissum Bredning, Denmark. It was the world's first offshore grid connected device which supplied more than 20000 hours. Long term testing is still underway to determine the system performance under different sea conditions. Currently, a 7 MW demonstration plant is being applied in Wales and preparations are underway for a 50 MW array in Portugal.

➢ *Bulge Wave*

Bulge Wave technology as shown in Fig 38 consists of a rubber tube filled with water which is aligned parallel to the wave direction and moored to the seabed. As the wave front passes, it causes pressure variation along the length of the tube, creating a bulge. As the bulge travels through a flexible tube, it grows in size and gains kinetic energy which can be used to drive a low head turbine located at the end of tube and the power so produced is fed to shore through the cable.

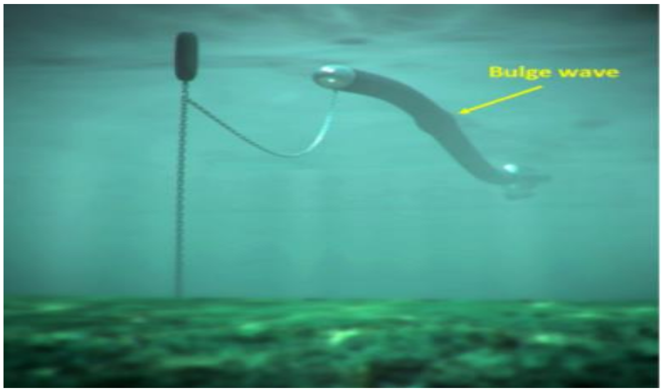

Fig 38:- Bulge Wave Technology Device

The Anaconda Wave device as shown in Fig 39 is an example of Bulge Wave Technology. This technology was invented in 2005 by Professor R.C.T. Rainey and F.J.M. Farley and it was manufactured by CheckMate SeaEnergy Ltd. UK. The company proposed to launch a full prototype in water by 2014 but it could not be materialized. Still a full scale version of the Anaconda has not been installed anywhere in the world. The full version is projected to be 7 m in diameter and 150 m long. This system is expected to produce an average power of 1MW and maximum 3 MW.


Fig 39:- Anaconda Wave Energy Device

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(i) Rotating Mass Convertor Device

Rotating Mass Wave Energy Convertors are generally surface riders in which internal weight rotating about a fixed point drive a rotational alternator as shown in Fig 40. These devices exploit the relative motion of waves to induce pitching and rolling in the device which force the rotation of an eccentric mass to drive an electrical generator.

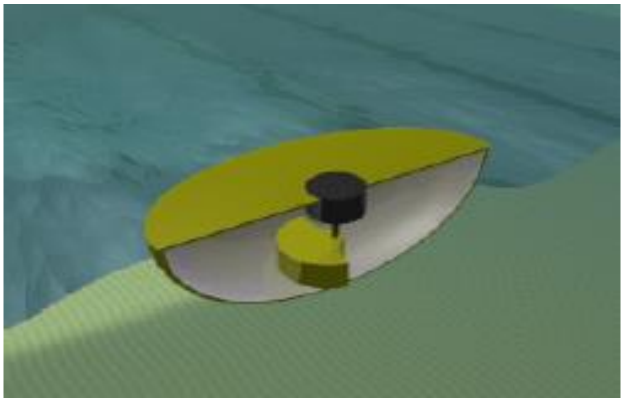

Fig 40:- Schematic Diagram of Rolling Mass WEC

Penguin device as shown in Fig 41, developed by Wello UK is an example of Rolling Mass WEC. The device weighs 1600 tonnes and is 30 m long, 9 m in height and has a draft of 7 m. During 2011-14, Wello conducted full scale demonstration of its device at Billia Croo in Orkney. The device nominal capacity was 500 KW and during operation, it fed electricity into a local grid. In March 2017, this device was reinstalled at Billia Croo as part of the Clean Energy From Ocean Waves (CEFOW) Research Project funded under the EU′ Horizon 2020 Programme, coordinated by Fortum and aims to test arrays of devices in more challenging sea conditions over a period of several years.

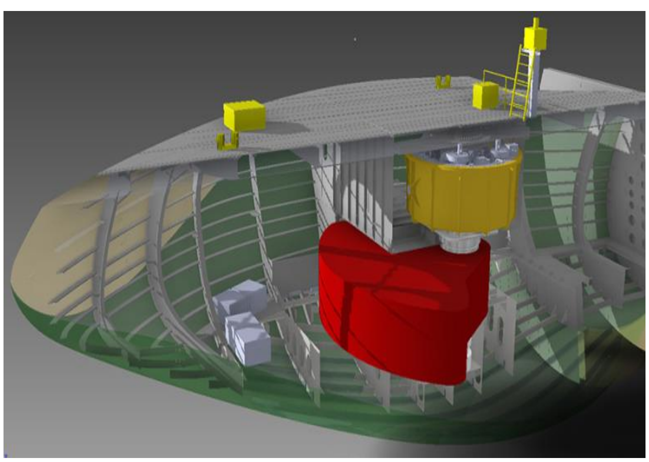

Fig 41:- Penguin Device

On the basis of above classification, the entire WEC can be summarized in Table 2.

Location	WEC Devices
Onshore	Oscillating Water Column Device Overtopping Device Terminator Device
Nearshore	Oscillating Wave Surge Device Point Absorber Device Submerged Pressure Differential Device
Offshore	Attenuator Device Bulge Wave Device Rotating Mass Convertor Device

Table 2:- Summary of WEC Devices

Currently, there is no leading category of WEC device in terms of research effort. Fig 42 represents the distribution of Research and Development Effort in developing various type of devices which indicate that majority of the research revolves around Point Absorbers, Attenuators and oscillating Wave Surge Devices.

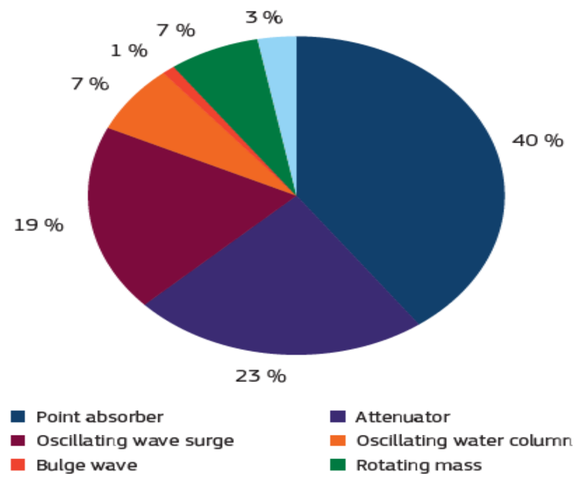

Fig 42:- Distribution of Various type of WEC Devices

IV. WAVE POWER POTENTIAL

The total theoretical wave energy potential is roughly estimated by Mork as of 32000 TWh. The regional distribution of the annual wave energy incidents on the coast of respective regions where the theoretical wave power P ≥ 5 KW/m and latitudes ≤ ± 66.5^0 is given in Table 3. The total annual wave energy comes out to be 29500 TWh which is 8% decrease from the theoretical wave energy potential.

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S. No.	Regions	Wave Energy in TWh
1.	Western and Northern Europe	2800
2.	Mediterranean Sea and Atlantic Archipelagos (Azores, Cape Verde, Canaries)	1300
3.	North America and Greenland	4000
4.	Central America	1500
5.	South America	4600
6.	Africa	3500
7.	Asia	6200
8.	Australia, New Zealand and Polynesia	5600
Total		**29500**

Table 3:- Theoretical Regional Potential of Wave Power

The global distribution of annual mean wave power is depicted in Fig 43.

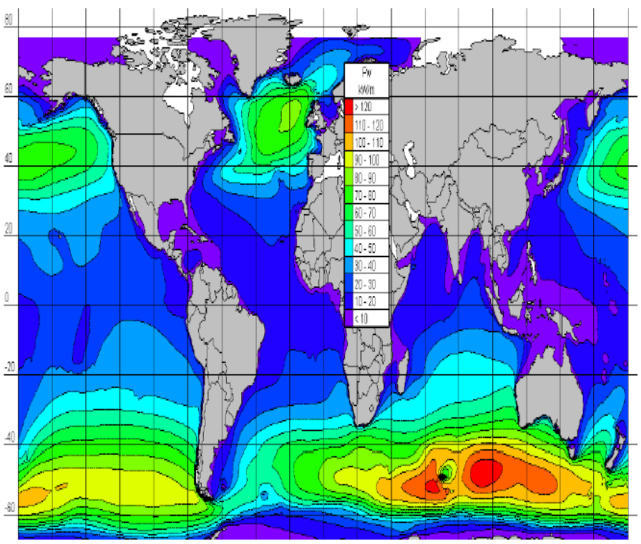

Fig 43:- Global Annual Mean Wave Energy Level

The annual mean wave power is highest in higher latitudes of southern hemispheres between 40^0S and 60^0S. The maximum annual mean wave power in the southern hemisphere is found approximately 125 KW/m in southwest of Australia near 48^0S, 94^0E. In the northern hemisphere, it exceeds 80 KW/m in south of Iceland around 56^0N, 19^0W while in North Pacific, the maximum value is found to be approximately 75 KW/m near 41^0N, 174^0W. These wave estimates give the energy flux due to wave propagation and only a fraction of available energy flux at any site can be harnessed into useful forms of energy due to geographical, technical and economic constraints.

➢ *Indian Scenario*

In India, there is a huge potential of harnessing wave energy as it has a long coastline of about 7500 Km. and about 336 islands in the Bay of Bengal and Arabian Sea. In order to explore the wave energy potential along the Indian coast, 10 years simulation wave data from 1993 to 2002 had been used and wave energy map of India had been developed as shown in Fig 44 below:

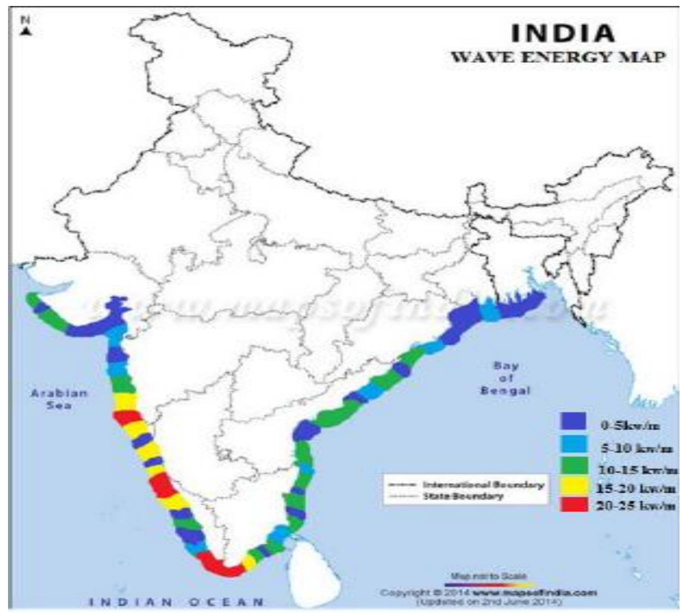

Fig 44:- Wave Energy Map of India

From the above map, it is observed that 10-15 KW/m wave contour is available along the both western and eastern coast. The wave contour of 15-20 KW/m is observed along the western coast – Maharashtra, Goa, Karnataka and Kerala. This high wave power is probably due the strong waves during the South-West Mansoon. The southern tip of the Indian Peninsula – Kanyakumari, Nagercoil and Koodankulam, has the maximum wave power which may be due to the effect of refraction and presence of strong winds prevailing in these regions.

Current estimate shows that the total power available along the coastline is about 50 GW. However, if wave power above 10 KW/m is efficiently harvested, the total available wave power would be 41 GW. Further 41 GW may not be harvested due to many physical and site constraints. Hence a realistic estimate for each site should be done based on detail survey and also considering other parameters such as near shore slope, statistics of daily wave, land availability, demand, grid connectivity etc. Based on above parameters, five potential sites have been proposed as shown in Fig 45.

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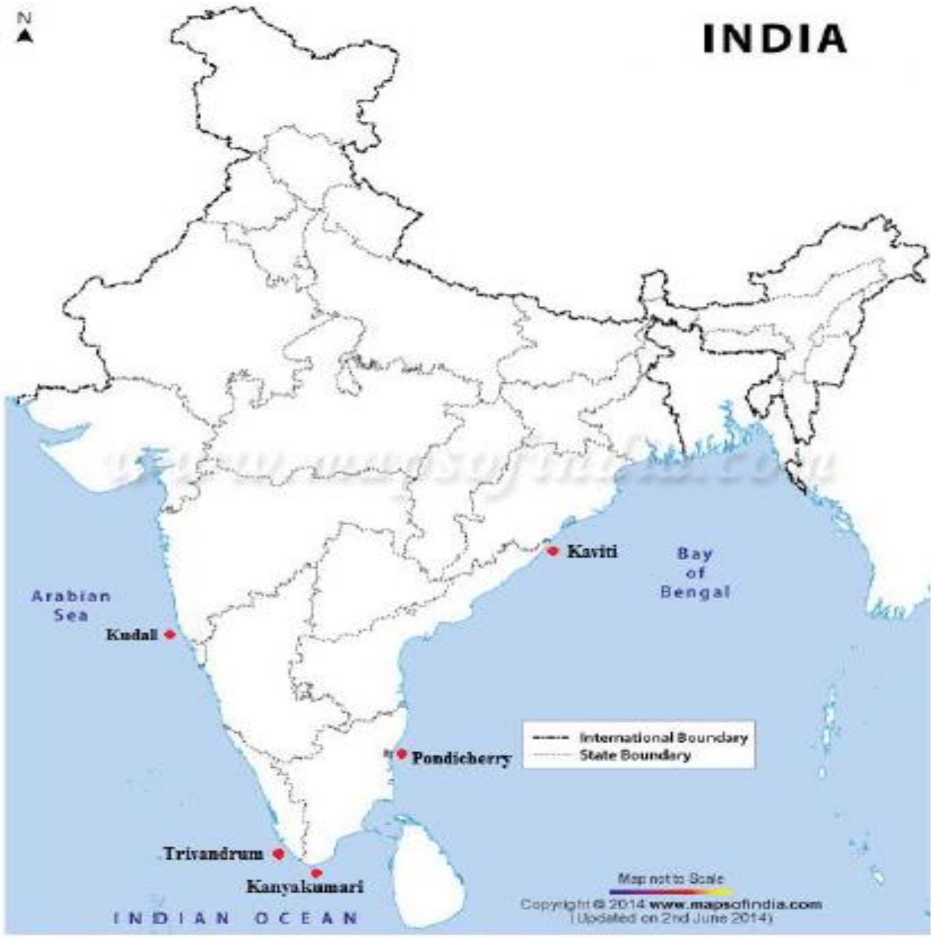

Fig 45:- Location of Proposed Site

The detail descriptions have been given below in Table 4.

S. No.	State	Place	Water Depth (m)	Wave Height (m)	Annual Energy Potential (GWh)
1	Maharashtra	Kudal	11-12	2.37	25.0
2	Kerala	Trivandrum	15-20	2.4	28.6
3.	Tamil Nadu	Kanyakumari	12-13	2.4	26.6
4.	Tamil Nadu	Puducherry	5-8	1.67	12.1
5.	Andhra Pradesh	Kaviti	10-14	1.97	17.0

Table 4:- Proposed Sites for Wave Energy Harvesting

The estimate of the annual energy potential for each site has been done by considering the utilization of 1 Km of effective stretch of coastal line at each site.

In India, power generation from wave energy was considered as an efficient source to meet the energy demand and Vizhinjam (Kerala) was chosen as the first site in the world to put an Oscillating Water Column Wave Energy Converter. The plant was built in 1991 by investing Rs. 99 Lakhs. The plant was supposed to generate 150 KW on continual basis and that had to be transferred to grid. But the amount of power generated varied considerably. During April to November, it generated only 75 KW and even lesser to 25 KW during December to March. The plant had worked at its maximum level only during Mansoon period. The plant was remained out of use for a longer period and in 2004, National Institute of Ocean Technology (NIOT) had taken the plant to desalinate ocean water. Initially, it was proposed that 10,000 Liters per day would be treated by the plant but it could not become successful. Finally, this plant was permanently decommissioned in 2011 and handed over to the Harbor Department. This study remained a pilot study any significant breakthrough in terms of structural optimization and PTO arrangements and the efforts have not continued since then.

V. BARRIER IN THE DEVELOPMENT OF WEC

A. Technological Barrier

Technological barriers represent the most important issues that need to be addressed in the short and medium term. The lack of design consensus related to converter technology and its components constitute as the main hurdles that this sector should overcome. Further, another factor is related to the survivability of the devices, particularly in extreme conditions. A number of WEC devices have been designed to operate in high resource environment, i.e. wave power greater than 50 KW/m but most of the deployments have done in the mild resource environment. It is, therefore, utmost necessary to employ innovation in designs and materials to ensure long term survivability of the devices. In case of onshore devices such as OWC, reinforced sulfate-resistant concrete for structural work and corrosion-resistant steel for turbine blades should be used. In case of offshore devices, reinforced rubber membrane should be used for Clams and Heaving Buoys and inert polymers with high strength anti-corrosion steel material should be used for rigid structure such as Pelamis. Mooring, PTO, power electronics gear box etc. also play a significant role in ensuring the overall reliability of the devices.

Despite of the large research and studies, wave energy harnessing technologies have not achieved its maturity level and most of the technology developed is still largely unproven and require further research, innovation and prototype testing and demonstration to reach the level of commercial stage.

B. Investment Issue

The market of harnessing wave energy is still dominant by some start-up companies and various research Institutes, particularly UK Universities. They are focusing on developing new technologies at pre-commercial stage or assisting in creating new demonstration site in open sea. The development of large scale wave farms requires different type of investment policy. Government grant and policy support are the key to attract investors for large scale deployment. In between 2006 to 2011, UK Government has funded EUR 20 million on annual basis for developing technologies and commercial deployment. Further policy measures may include large capital grants, project equity loan, tax exemption etc. to attract investors or feed-in-tariffs, power purchase agreements to attract end-users.

C. Environmental Issues

Wave energy is usually considered as non-polluting renewable source of energy as WEC devices produce no harmful emission of CO_2, NO_2 etc. during their normal operation. As majority of WEC devices are still in the early stage of development and deployment, little is known regarding the adverse impact on environment. However based on research and studies, following impacts are observed:

In case of Onshore Devices-

- The construction of devices and the road access causes some localized damage during construction phase, piling and transport of materials to the site. It also causes vibration.
- Some of the WEC devices produce noise at low frequency as in case of OWC in Islay which can be heard on long distances and make it harder to bear.
- In some cases, it has been observed that large array of onshore units affects the endangered species but it is not found to be very serious problem as the species tend to be adoptive.
- A WEC device has visual intrusion in the local landscape, the impact of which depends upon the type of device and extent of mitigating landscaping.
- Alteration of current and waves of ocean may have an impact on coastal erosion which is most common during the construction phase. Once constructed, the device will slow down the rate of erosion.

In case of Offshore Device –

- Archaeological site as shipwreck in some cases could be a problem for deployment as in case of West Coast of Europe. These shipwrecks are protected by different laws. Hence, studies should be done regarding the Archaeological sites before the deploying the device.
- Mooring of the devices lie on the seabed using pilings, concrete blocks, anchors, chains etc. These may cause local damage to the seabed which depends upon the number of devices installed and the mooring systems employed.
- Leakage of oil may take place from the devices which may pollute to the sea water and its quality may be affected. Biodegradable oil is encouraged as it is more environment friendly. Uses of anti-corrosion coating and painting also have impact on marine life.
- Wave devices have beneficial effect on fish. Anchor lines, tethers and power cables restrict the use of fish nets while floating devices provide the new shelter conditions for some marine species and habitats. However, the fishing activity may increase outside the boundary of installation.
- Marine mammals may be vulnerable to the floating structure as it acts as a barrier to the marine movement and migration of flora and fauna to the seabed. Further, the mooring lines may pose a threat of entanglement for some animals such as for large whales.
- Large offshore devices may cause serious obstacles to navigation of ships. However, ships use radar and navigation lights.
- The large offshore devices may have serious consequences on wave patterns and sedimentation rate. Changes in water velocities may cause deposition of coarse sediments such as pebbles or rocks.

Hence, very comprehensive and in depth analysis are required right from the development stage to the installation stages in order to develop the new range of technologies, devices and subsystem to design the mitigation measures.

D. Infrastructure Issues

For successful harnessing of wave energy, appropriate infrastructure such as grid and array connection and port facilities are essential. Further, deep water offshore devices require special substation design to connect arrays and long distance connections.

Majority of the site lack grid infrastructure except of European countries where high voltage transmission lines are available closer to shore. Thus, it requires either grid upgrades or new-built capacity which implies high additional costs. Further, grid codes for transmission and distribution networks such as frequency stability, voltage, power factor and harmonics has to be met in order to guarantee the safe operation of grid. Hence, adequate control systems for WEC and arrays have to be developed and further research is needed in the area of control strategies as it offers a great reduction in cost due to increased absorbed energy. Integration of wind energy network and WEC should also be explored.

For large scale deployment, port facilities are also important requirements. The operation and maintenance of devices are expensive as these are to be performed under severe difficult marine conditions. One of the alternatives of this problem is to unplug the device from their offshore place and to perform all the maintenance activities at a dedicated, safe and more accessible port. Such planning can be made more efficient by combining this to other functions such as offshore wind parking servicing, maintenance etc.

E. Regulatory and Legal Issues

Regulatory and legal issues are considered as the most important non-technical barrier for the development of the ocean energy sector. Ocean energy is usually developed by Government Agencies as a renewable source of energy to achieve the target of climate change and energy demand. Often much attention is not given regarding the regulations and legal barriers.

According to UN Convention on the law of the sea, territorial sea comprises the coastal water up to 12 Nautical Miles (22.224 Km) from a base line which is usually the mean water mark. Territorial sea is the sovereign territory of State and the State has full authority and rights over water, seabed and subsoil. The territorial State has the right to set laws and regulate the use of ocean. Majority of the countries yet do not have specific legal and regulatory framework and this uncertainty is one of the major bottleneck in the development. In USA, more than 23 Federal and State Regulatory Bodies are involved in the development of ocean energy projects. Hence, approval processes are very complex.

Maritime Spatial Planning is considered as one of the solution to overcome these problems. By doing so, over-regulation and administrative complexity can be reduced. It will help to avoid user conflicts and improve the integrated management of marine resource use. In 2013, European Commission proposed a directive on Marine Spatial Planning but yet it has not been fully introduced in all EU Members. Hence, still more research and studies are required regarding the regulation and legal framework.

VI. COST OF HARNESSING OF WAVE ENERGY

As per SI Ocean 2013 estimate, the levelised cost of electricity (LCOE) of wave energy farms of 10 MW comes out to be EUR 330 to 630/MWh. Due to limited commercial experience, these costs are considerably higher than other forms of renewable energies like wind energy and tidal energy. However, because of concerted research, studies and prototype testing, by 2030 its LCOE may be expected to reduce to EUR 150 to 180/MWh, provided that deployment level of more than 5 GW is achieved.

As per SI Ocean 2013 Report, the latest estimates for European wave energy projects suggest following distribution of the total lifetime project cost:

PTO System	22%
Installation	18%
Operation and Maintenance	17%
Foundation and Mooring	06%
Grid Connection	05%
Structure, Decommissioning and Others	32%

The reduction in the cost can be achieved with scale and volume, experience and through innovation. Increasing scale bring down cost by upscaling of devices, installing more number of devices and increasing the scale of production through better and higher utilization of equipment, standardization of processes and buying larger batches of components.

As more research, studies, prototype testing etc. will be done, more experiences are gained regarding the optimum routes for production, installation methodologies and operation and maintenance techniques. This know-how will help in cost reduction.

Innovation is the key factor in reducing the cost which involves changes in design concept, processes and materials to be used in the whole devices and in subsystems. It also includes the concept of capturing wave energy. All improvements in the device design are basically aimed to reduce capital cost and to improve reliability. Data obtained from field and prototype testing give ideas regarding the less and alternative materials that can be used for main structure and sub components. Alternative materials reduce the cost significantly by allowing changes in shapes and optimization of weight. Further, there is a requirement to optimize the configuration of PTO and structure of wave devices to increase yield. Other type of PTO also offers opportunities of improvement such as in case of OWC, improving the efficiency of turbines. Development of control system and software are crucial so that it can respond to the changing wave characteristics and adjust the device to give optimum energy output under each condition which involves minimal increase in capital cost. Hence, there is a tremendous scope for reducing the cost by optimization of the device and control system.

Currently apart from UK, a number of countries such as USA, Canada, Australia, China, South Korea and Japan are also taking a lot of interest in these sectors. Hence, there is a significant increase in the promotion of technologies and also in the research and development activities and programme. As a result, large multi-disciplinary engineering firms and industries are showing interest in this emerging sector and are expected to promote synergies which will install large wave energy farms. This will create conditions for the cost reduction.

VII. CONCLUSIONS

A comprehensive study of harnessing wave energy was made in this paper. Currently, there is no leading category of WEC device. Most of the research effort revolves around Point Absorbers (40%), Attenuators (23%) and oscillating Wave Surge Devices (19%). At present, about 64% WEC under deployment is designed as offshore devices. Even of so much development of demonstration and testing facilities, till date no installation has taken place more than 5 Km away from the shore and in water depth of more than 75 m.

The total annual global wave energy estimate comes out to be 29500 TWh which is 8% decrease from the theoretical wave energy potential of 32000 TWh as estimated by Mork. These wave estimates give the energy flux due to wave propagation and only a fraction of available energy flux at any site can be harnessed into useful forms of energy due to geographical, technical and economic constraints. In India, there is a huge potential of harnessing wave energy as it has a long coastline of about 7500 Km and about 336 islands in the Bay of Bengal and Arabian Sea. Current estimate shows that the total power available along the coastline is about 50 GW. However, if wave power above 10 KW/m is efficiently harvested, the total available wave power would be 41 GW. Further 41 GW may not be harvested due to many physical and site constraints. Based on survey and studies, five potential sites have been identified, having Annual Energy Potential as: Kudal (Maharashtra) – 25 GWh, Trivandrum (Kerala) – 28.6 GWh, Kanyakumari (Tamil Nadu) - 26.6 GWh, Puducherry (Tamil Nadu) - 12.1 GWh and Kaviti (Andhra Pradesh) - 17.0 GWh. In spite of huge potentials, available technology is still in the early stage of development and its commercialization has not progressed as expected. These technologies face a number of bottlenecks – technology development, finance and markets, environmental, infrastructure, regulatory and legal issues. Overcoming these issues require concerted efforts by industry, academia and policy makers.

Further, as per SI Ocean 2013 estimate, the levelised cost of electricity (LCOE) of wave energy farms of 10 MW comes out to be EUR 330 to 630/MWh which is considerably higher than other forms of renewable energies like wind energy and tidal energy. However, because of concerted research, studies and prototype testing, by 2030 its LCOE may be expected to reduce to EUR 150 to 180/MWh, provided that deployment level of more than 5 GW is achieved. Currently, large multi-disciplinary engineering firms and industries are showing interest in this emerging sector and are expected to promote synergies which will install large wave energy farms. This will create conditions for the cost reduction.

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