# Energy production from oceans

Adamantia Pagana

SID: 12345678

SCHOOL OF SCIENCE & TECHNOLOGY

A thesis submitted for the degree of

Master of Science (MSc) in Energy Systems

SEPTEMBER 2011

THESSALONIKI – GREECE

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# DISCLAIMER

This dissertation is submitted in part candidacy for the degree of Master of Science in Energy Systems, from the School of Science and Technology of the International Hellenic University, Thessaloniki, Greece. The views expressed in the dissertation are those of the author entirely and no endorsement of these views is implied by the said University or its staff.

This work has not been submitted either in whole or in part, for any other degree at this or any other university.

Adamantia Pagana

21/10/2011

# Abstract

The main purpose of this work is to present methods which can be used for energy production from ocean power and to provide information about the development status and the trends in the technology of ocean energy systems. This thesis is based on a detailed literature review.

The first introductory chapter includes a brief presentation of the ways by which the oceans' energy can efficiently contribute in a sustainable manner to meet the increasing global energy demand. In chapters two, three, four and five, the most developed ocean energy sources (tidal energy, wave energy, the Ocean Thermal Energy Conversion -OTEC and the offshore wind power energy) are described in detail and technical information is provided for each one of them. Chapter six analyses the economic charges and benefits related to the development of the ocean energy industry by providing both economic and environmental impacts of the above mentioned technologies. The conclusions are included in the final chapter.

I would like to thank Dr. D. Missirlis for his guidance and support throughout the production of this research and thesis. I would also like to thank the Committee Members for their helpful and meaningful comments.

Adamantia Pagana

21/10/2011

# Contents

# 1 Introduction

After the oil crisis in the 1970s, it was necessary to find out other energy sources in order to meet the increasing global energy demand. Nowadays, the fact that many developed countries have faced financial crisis has led them to intensify the search for new forms of energy. Moreover, the extensive environmental disaster, that followed the accident on the nuclear plant Fukushima in Japan last year, has led to a nuclear energy crisis, given that countries-users of nuclear energy have decided to switch to other more reliable and cost-effective energy sources.

Oceans could efficiently supply energy needed to power humans' activities. Up to now, only very few ocean energy power plants operate, most of which are of small capacity. In that context, finding cost competitive ways to get energy from oceans, so as to allow the development of broad commercial projects, is more than a challenge.

In this work the four basic ways to reclaim energy from the ocean are presented and analyzed. These are briefly the following:

- Ocean's high and low tides,
- Ocean's waves,
- Temperature differences in the water.
- Marine Wind

# 2 TIDAL ENERGY

## 2.1 General

The first ocean energy technology that has reached the level of maturity is tidal energy, due to its similarities with the conventional hydropower. However, tidal power plants are economically viable and cost competitive only in relatively few locations where there is a strong tidal energy concentration. The two main advantages which make such locations appropriate for the development of tidal energy plants are the large reservoir and the short and shallow dam closure [1].

The Earth's oceanic tides provide tidal power. More specifically, the periodic variations in the gravity exerted by celestial bodies produce tidal forces, which subsequently create respective motions or currents in the oceans. The positions of the Moon and Sun in relation to the Earth, the Earth's rotation as well as the geographic formation of the sea bottom and coasts affect the above mentioned motion and in particular its magnitude.

The flows from tidal can be converted into electricity with the use of a tidal generator. Areas where tidal variation and currents' velocity are high are more possible to be locations where tidal electricity plants can be developed.

Taking into consideration the origins of tidal energy and its direct links with the perpetual gravity interactions in our solar system, it could be said that tidal power is inexhaustible and represents a renewable energy source. In the above described Earth-Moon system there is a loss, as tides moves, due to the pumping of water through natural restrictions around coasts and subsequent viscous dissipation at the seabed and in turbulence. Because of this loss of mechanical energy, the Earth's rotation has been decelerated during the 4.5 billion years since its formation, resulting in an extension of the period of rotation from 21.9 hours to 24 hours. The Earth's rotational energy has diminished about 17% during this period. Despite of the fact that tidal power may take more energy from the system, this portion is insignificant and could only be observed over millions of years [2].

## 2.2 Technology

There are many similarities between a tidal power plant and a conventional hydro plant with large axial-flow turbines with low speed (50-100 rpm). The necessary structure of the plant includes a dam constructed across an estuary with a series of gated sluices and a bank of low head axial flow turbines (Starting from 1.5m.). The dam should be made of concrete or steel prefabricated, which are manufactured at construction yards and afterwards transferred to the barrage site and sunk on stable foundations. Turbo-generators consist of separate modules.

Alternatively, the dam can be constructed behind a coffer dam which is not permanent as later it can be removed. This is the case of the La Rance estuary, in France, in the 1960's. This method, called the "caisson" (or the waterproof box) entails fewer risks and is not much expensive. The most convenient and appropriate machinery for tidal energy projects is generally considered to be the Horizontal-axis water turbines of axial-flow (Kaplan or Axial). The main characteristic of the turbines which are used for tidal energy is that they are slow-turning (50-100rpm). Large units have runner diameter of up to 9 metres. The structure of sluice gates should permit large flow and this is succeeded by using a vertical lift gate with a motor operated lift [1].

## 2.3 Use of the tides

Tidal energy can be exploited in two different ways. The first one is carried out by taking advantage of the cyclic rise and fall of the level of the sea, whereas the second one entails the use of local tidal currents, such as the wind power. The latter is known as the “marine current turbine”.

### 2.3.1 Tidal barrage methods

Tidal power plant structure has its origins in the hydroelectric industry which appeared about forty years ago. The “traditional” power plants from tidal energy, which are developed in four countries (France, Russia, Canada and China), operate using a “barrage” which has many similarities with an onshore dam, but it also needs a tidal inlet or estuary. As the tide enters, it creates a difference in the height of the water which leads the water to go through the gates and come in the turbines [3].

Tidal stream power is presented in the following structures [4]:

- the tidal fence (underwater turnstiles spanning a channel or narrow strait) and
- the tidal turbine

As regards the current level of development of projects related to tidal energy plants, it should be mentioned that up to now there is a number of locations worldwide where electricity is produced from tides. The largest tidal barrage power plant generated 240MW and was constructed in La Rance, France, in 1966. Operational barrage sites are also located in Nova Scotia (20MW), near Murmansk, Russia (0.4MW) and in the Eastern seaboard of China (3.2MW).

The following figure illustrates the areas worldwide which are most favourable for extracting energy from tides. As mentioned earlier, in general, areas where the difference between high and low tide are greater are considered to be more suitable. Looking on a smaller scale, the creation of tidal currents and in particular their strength is largely attributed to the seabed contours [5].

Figure 1: World-wide locations where ocean tidal currents are viable energy sources

Principle of operation

The basic principal of is the same in all cases and is described as following:

First, a suitable location should be found, where there is an estuary or bay with a large natural tidal range. Afterwards, this location should be restricted with an artificial barrier. A road or rail crossing of the gap is also essential so as to have the maximum benefits from an economic view.

Electricity is produced as water flows from one side of the barrage, through low-head turbines.

The ways of operation vary. The suggested modes can be categorised in single and multi-basin schemes, from which the single-basin one is the simplest. The two modes are presented below in more detail.

Single basin barrage

A single barrage along the estuary is necessary in these schemes (Figure 2). Electricity can be generated with a single basin in three different ways, all of which include a combination of sluices and gated turbines. The sluices, when open, allow the flow of water freely through the barrage. The gates of the turbines can remain open in order the water to flow through the turbines and in that way electricity is generated.

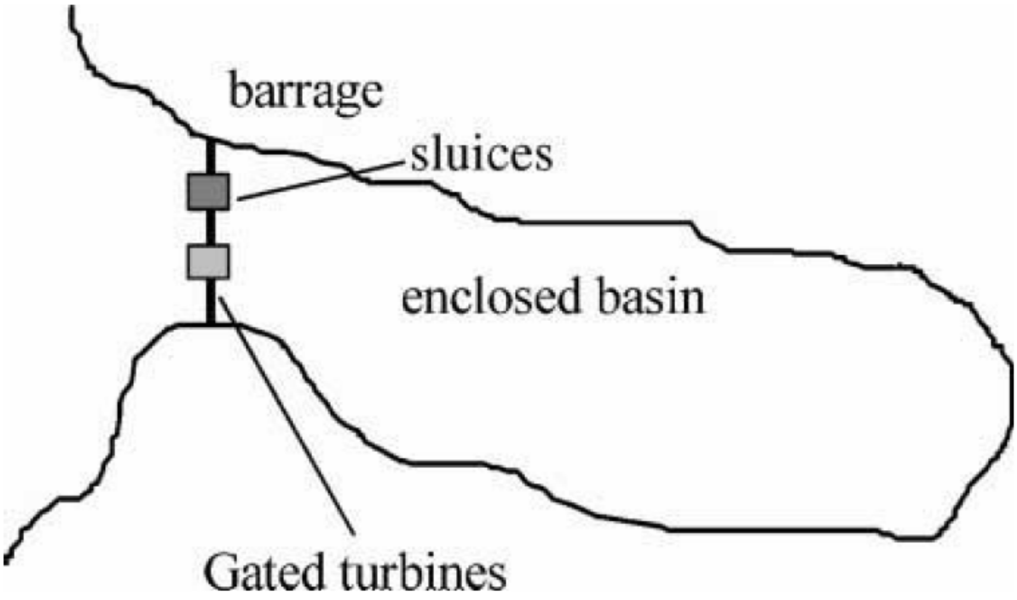


Figure 2: Single basin barrage [1]

Ebb generation mode

The way the ebb generation mode works is presented in this subsection. At the period of the flood, the water flows without resistance through the sluices into the barrage.

When the tide is high, sluices close and the water remains behind the dam. Once the level of the water outside the dam falls enough to create a head between the basin and the open water, the basin water flows out through low-head turbines and electricity is generated. This system consists of a series of stages. Only when the head is about half the tidal range, the water is permitted to flow freely through the turbines, resulting to electricity generation for about 40% of the tidal range [1]. The operation is carried out in a cycle form which includes the following four stages (Figure 3):

(1) The water flows through the sluices during the flood tide and fills the basin.

(2) Afterwards, the gates close until the tide which recedes, creates a head between the basin and open water.

(3) The water flows freely from the basin through the turbines on the ebb tide, until the head is decreased to a minimum operating point, as a result of the rising tide and the reducing water in the basin.

(4) The gates are closed until the tide increases enough to restart the first stage.

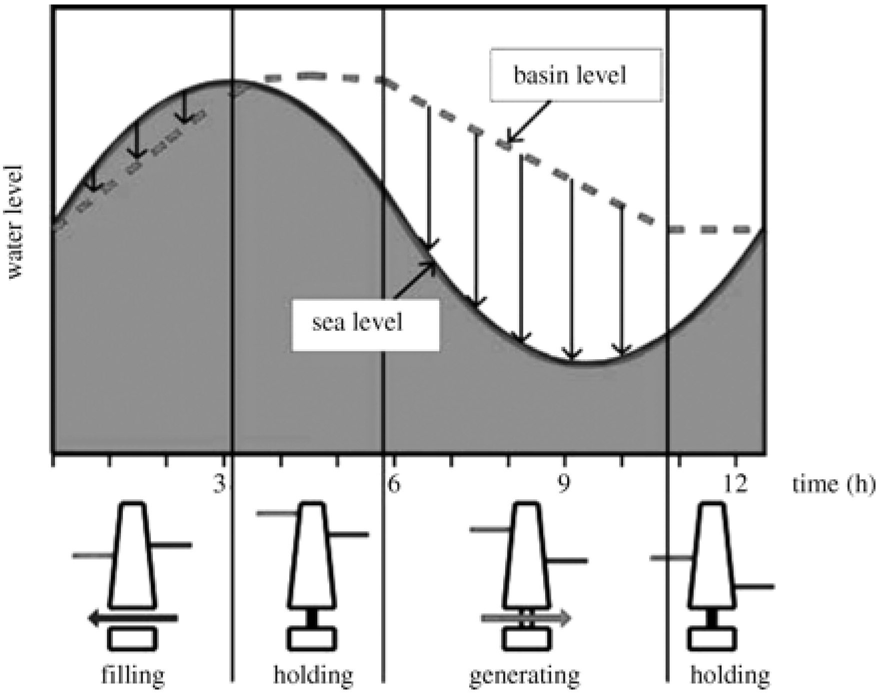


Figure 3: Variation of sea level, basin level and power output for one-way ebb generation [6]

### Double basin systems

The restriction of all single basin systems is that the electricity generated is delivered only during a part of the tidal range and consequently they are not able to meet consumers' demand which is continuous. This drawback is overcome when double basin systems are used, as they are designed to store and to grant control of time over power output levels.

The behaviour of the main basin is similar to the one of an ebb generation single basin system. During the ebb phase a portion of the electricity which is generated would be used for pumping water to and from the second basin, in a way that provides an electricity generation capability always, with no intervals.

Multiple-basin systems have little possibilities to gain the market, given that it is likely the low-head turbines to be inefficient for a cost-effective storage of energy. In most cases, the total efficiency of low-head storage of energy is not expected to be more than 30%. Alternatively, the conventional pumped-storage systems can be used, given that these represent an already proven technology which is more cost-effective, with a total efficiency of more than 70%.

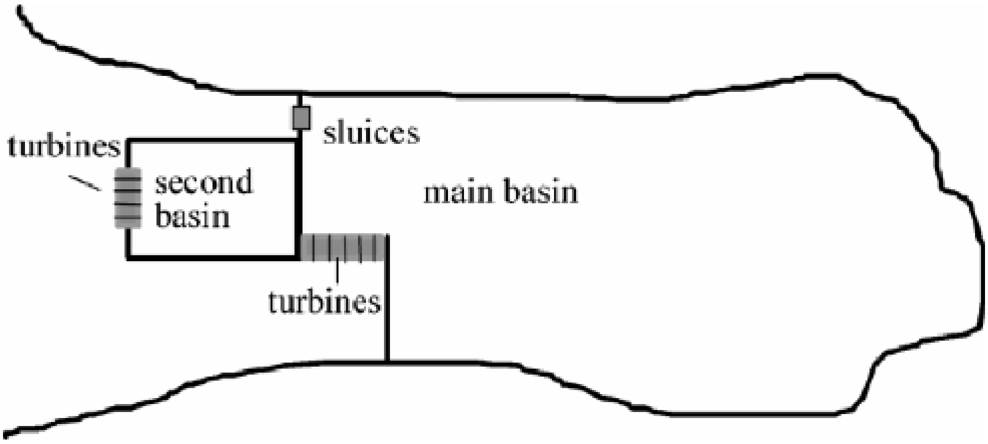


Figure 4: Double basin systems [1]

### Two-Way Generation

There is also available the two-way generation, which has a double effect cycle on both the ebb and the flood. Despite the fact that this system is more complex in terms of machinery used (reversible turbines), it does not generate more energy. However, the generation over a longer period of the day becomes feasible when using the two-way generation system. This would have advantages if the plant output is to be integrated into a week grid.

The two-way generation was first used in the La Rance tidal plant, but in present this plant operates only for ebb generation.

### Pumping

Pumping the water against the water head between the basin and the sea, increases the amount of the energy produced and for that reason it is applied in all modes of operation, under the condition that there is a turbine with an appropriate structure (double regulation). In the case of ebb generation, pumping can increase the level of the basin water at the outset, resulting in the generation of a greater amount of energy. It should also be mentioned that pumping at a low water head needs less energy compared to the amount of energy generated, as the same amount of water flows back through the turbine at a greater head. Consequently, pumping results in a net gain of energy of 5-15%. The La Rance tidal plant has applied pumping [1].

The energy is generated from tidal at different times, given that the tidal phase changes about an hour per day, depending on the cyclic variation of the moon's position in relation to the Earth, a cycle which lasts 24 hours and 50 minutes. As a result, there are many difficulties for the generation of energy to be synchronized with the electricity demand, and therefore it is almost impossible to meet the demand when it is on its peak. The capacity of tidal plants is considered to be low. More specifically, their load factors are between 22% and 35%, since only one or two pulses of energy are delivered per tide. Such an production can usually be used into the electric distribution grid provided that the non-firm capacity is a small percentage (say less than 30%) of the total system capacity [1].

### 2.3.2 Marine current turbine

There are many similarities between the process by which the electricity is produced from tidal stream generators and the one which is applied in wind turbines. Because of the fact that the water, in comparison with the air, is characterized by higher density (almost 832 times higher), a greater amount of power can be generated even at low tidal flow velocities, using a single generator. Consequently, it is expected that the same amount of power can be produced from similar magnitude of turbine, when using water with speed almost 1/10 of the wind velocity. This happens as the generation of power depends on the density of the medium and the speed (its cube). For that reason, areas where the velocity of the tide is more than 2 Knots (1 m/s) are favourable even close areas where tide's range reaches the minimum.

The main Ocean current resource is situated in the area between Florida and the Bahamas. This source of energy to produce electricity was first used in the seventies and the modelling based on estimations. The estimations and modelling that was carried out in the seventies showed that a combination of turbines of total capacity of 10.000 MW would affect the current's velocity, resulting in a decrease of its speed, similar to the one caused by to natural variation [7, 8]. In order to identify the level of technically available resource, more investigation should be carried out.

A number of designs for this technology are still in an experimental stage and their commercialisation is not very broad, while some of them have a great potential for being used in large scale projects. In most cases, prototypes have been applied in companies for relatively short periods, which are not adequate in order to estimate their performance and their return on capital invested.

There are two ways in order to install such systems in deep water. The fixed system is more suitable for shallow waters, whereas moored systems are appropriate for deep water sites.

According to the European Marine Energy Centre, these technologies can be classified in three categories.

- Horizontal axis turbine

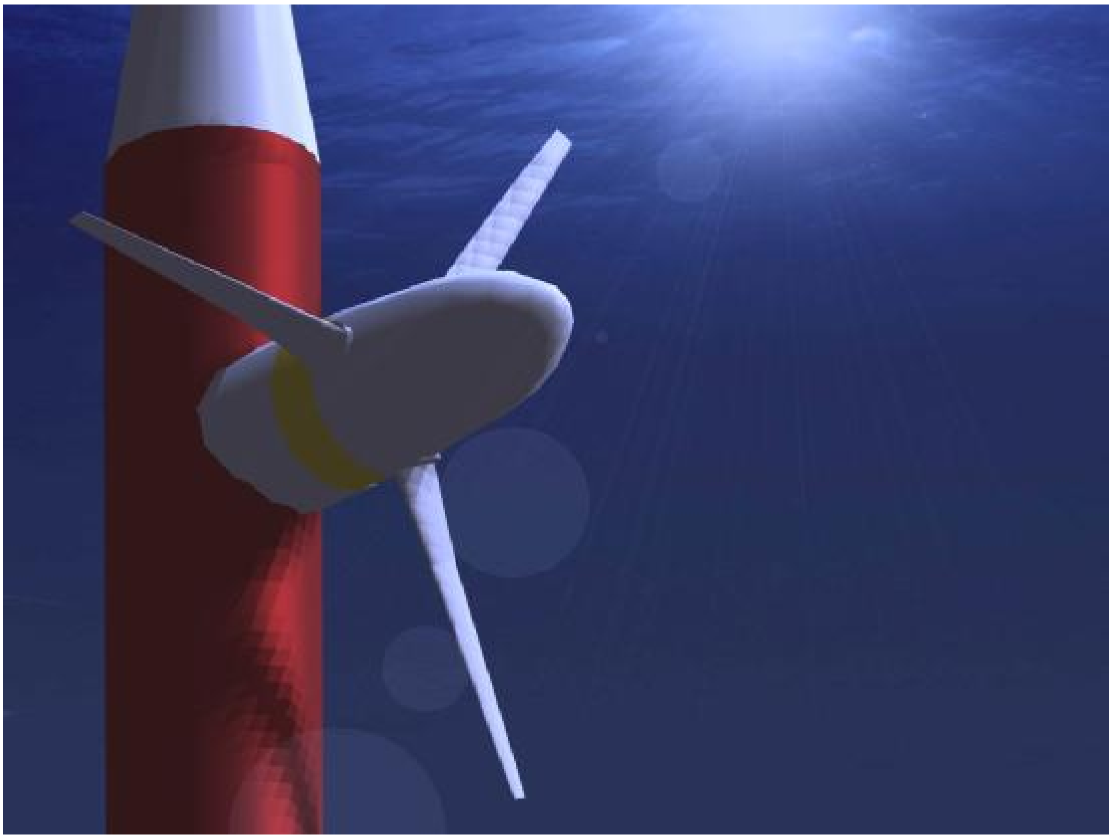


Figure 5: Horizontal axis turbine [9]

The basics of this turbine are similar with the function of the widely-used horizontal axis wind turbine. In particular, even the small fins which turn more slowly in the tidal stream, deliver a much greater amount of energy, primarily due to the high density which characterises the water in comparison to the wind.

Axial rotors of flow serve in order the generator is driven via a gearbox similar to a hydro-electric or wind turbine. The power units of each system are mounted on hydrofoils either side of the tubular steel monopile. Concentrators can also be used around the fins in order the flow to be driven and concentrated towards the rotors [9].

Indicative cases where this kind of technology has been used are:

- Kvalsund, south of Hammerfest, Norway. In 2003, a turbine of a capacity of 300 kW was connected to the grid, even though it was yet a prototype.
- In 2003 in Devon (England), a 300 kW period flow marine current propeller type turbine (the "Seaflow") was installed off the coast of Lynmouth by "Marine Current Turbines". The turbine generator, of a diameter of more than 10 meters, was placed in a pile of steel, which led to the bottom of the sea. Because it was a prototype, it wasn't linked to the network, but instead it was connected to a dump load.
- In 2007 in New York City, Verdant Power established a prototype project. That project was the first major tidal-power plant in the U.S. which also entailed a very challenging design, because of the strong currents in the East River between Queens and Roosevelt Island. In particular, the blades of the prototypes were broken and new improved turbines were put in placed in 2008.
- In 2008 "Marine Current Turbines" developed a full-size prototype, called SeaGen, in Northern Ireland. The turbine started full power generation of 1.2 MW and fed 150 kW into the network for the first time on July 17, 2008. Considering the above mentioned amounts, it is one of the most commercially viable devices which are installed worldwide.
- An Irish company which is called "Open Hydro" has been exploiting the Open-Centre Turbine and testing a prototype at the European Marine Energy Centre (EMEC), in Orkney, Scotland.
- Another prototype has been developed by "Ocean Flow Energy Ltd", a company with headquarters in UK. This prototype is a semi-submerged floating tethered tidal turbine ("Evopod") and it has been tested since 2008 in Strangford Lough, Northern Ireland at a scale of 1/10.

Figure 6: Systems used in shallow water [9]

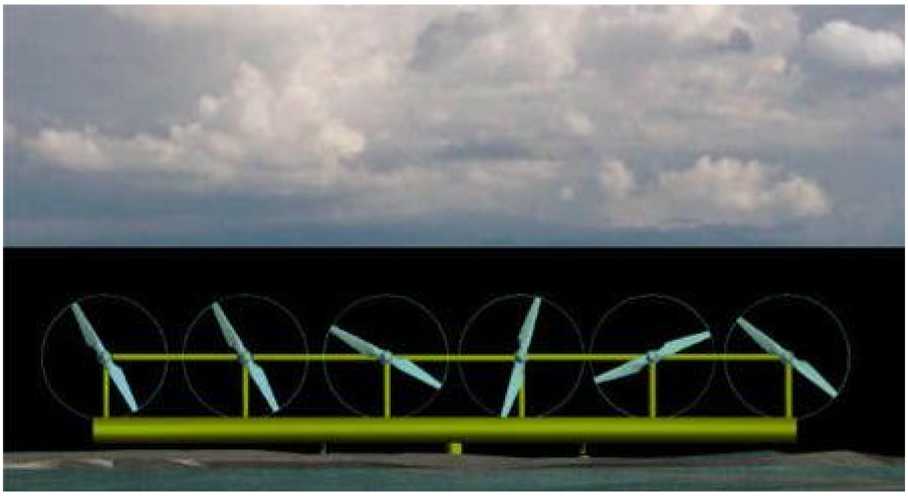


Figure 7: System used in deep water [9]

- Vertical axis turbine

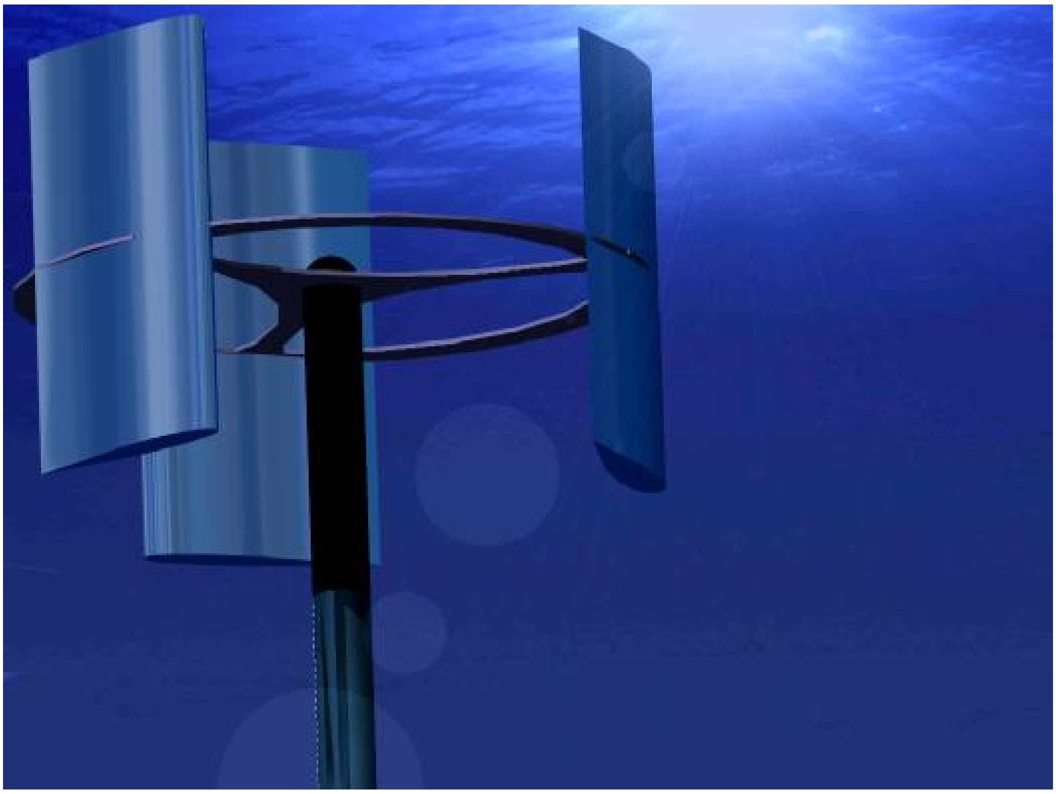


Figure 8: Vertical axis turbine [9]

The basics of the vertical axis turbine's operation in marine currents are similar to the ones applied in the land based Darrieus machineries. The name of these machines is attributed to their French designer, Georges Darrieus, who launched this technology in

1931. The main features of a standard darrieus machine are its troposkein (eggbeater) shaped blades, which are installed usually in wind darrieus devices in order to relieve the centrifugal forces encountered at high speeds. The underwater rotational velocities are possibly lower and therefore it is a straight bladed H type darrieus (Figure8) [9].

Representative examples of vertical axis turbines are:

- The "Gorlov" turbine represents an alternate of a helical structure and is commercially developed in a pilot scale in South Korea.
- Proteus is created by "Neptune Renewable Energy". It is used primarily in estuaries, as it is equipped with a barrage of vertical axis cross-flow turbines.
- Another turbine-generator unit (TGU) has been tested successfully by its originator, named "Ocean Renewable Power Company (ORPC)", at Cobscook Bay and Western Passage tidal locations close to the Eastport, in Maine. This prototype is uses cross-flow turbines of high technology, which leads a permanent magnet generator situated between the turbines and assembled on the same axis.  These TGU are developed and designed in order to be used for generating energy from rivers, tidal and ocean currents in deep waters.

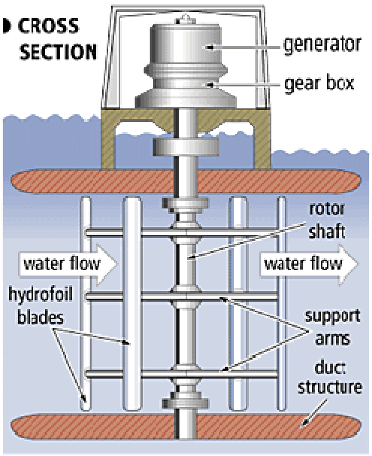


Figure 9: Schematic diagram of vertical axis turbine [9]

Figure 10: Vertical axis turbine in commissioning [9]

- Oscillating Hydrofoil

Figure 11: Oscillating Hydrofoil [9]

A hydrofoil, which has many characteristics in common with an aeroplane’s wing, is used in a Stingray in order to concentrate the energy from the tide (Figure 11). Stingray is a machine seabed located which is appropriate to be used in water up to 100m depth. Hydrofoils are structured in a way that their angle to the water stream changes. The arm oscillates because of forces lift and drag, resulting in the extension of the hydraulic cylinder which is attached to the main arm and the retraction of the pumping high pressure oil to a generator. Then, the oil goes into a turbine of hydraulic design which drives a generator and electricity is produced [9].

- Venturi effect designs

The Venturi effect uses a shroud in order the flow rate through the turbine to be higher. They are placed either vertically or horizontally.

- In 2002 “Tidal Energy Pty Ltd” successfully completed commercial tests of highly efficient shrouded tidal turbines on the Gold Coast. Tidal Energy has started a rollout of their shrouded turbine for a remote community in northern Australia, where the water flows have of the highest speed (11 m/s, 21 knots) – two small turbines give 3.5 MW.
- In 2008, in Brisbane (Australia), another larger turbine of 5 meter diameter, with a capacity of 800 kW in 4 m/s of flow, was developed as a desalination showcase which was powered from tidal.
- In in San Francisco Bay, another device, the Hydro Venturi, was under trials.
- In 2001, tests of the Kobold concept have also commenced in the Strait of Messina (Italy).

### 2.3.3 Commercial plans

The tidal stream generator SeaGen in Strangford Lough was the first worldwide which functions in a large commercial scale.

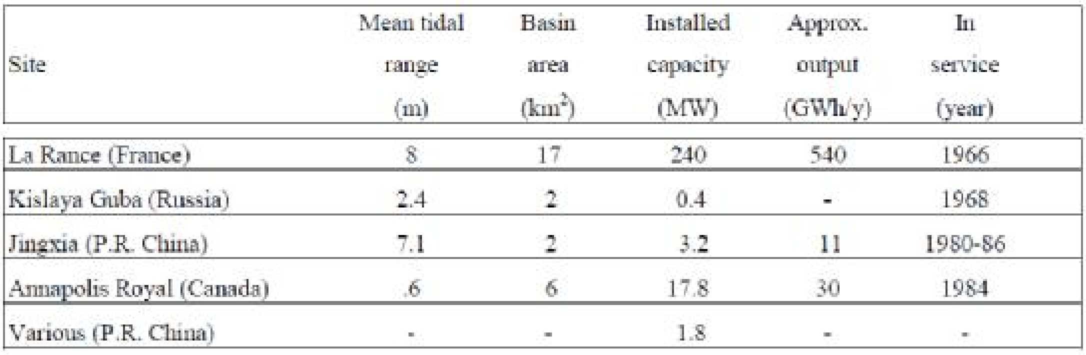
- “RWE power” is partner with the “Marine Current Turbines” to construct a tidal farm of SeaGen turbines off the coast of Anglesey (Wales).
- In 2007 the British company “Lunar Energy” together with “E.ON AG” said that they would build the world's first deep-sea tidal energy farm off the coast of

Pembrokeshire in Wales. The electricity that will be generated is expected to satisfy the demand of 5,000 homes.

- On the seabed off the peninsula of St. David, there are placed eight underwater turbines, of 25 meters long and 15 meters high. In the summer of 2008 the construction started and the tidal energy turbines, which was considered to be "a wind farm under the sea", was planned to be ready to start functioning by 2010.
- In 2009, the British “Columbia Tidal Energy Corp.” completed the development of three 1.2 MW turbines in the Campbell River and in the surrounding coastline of British Columbia (Canada).
- In the Channel Islands, around Alderney (UK) the organization Alderney Renewable Energy Ltd is planning to exploit tidal turbines in order to extract power from the significantly strong tidal flows. Up to 3GW could be extracted, according to relevant estimations. It is expected that there will be a surplus of energy as it will meet the island's demand and the rest will be exported.

Nova Scotia Power has used the OpenHydro's turbine for a tidal energy demonstration project in the Bay of Fundy, Nova Scotia, Canada and Alderney Renewable Energy Ltd for the supply of tidal turbines in the Channels Islands.

Table 1: Existing tidal energy plants [1, 10]

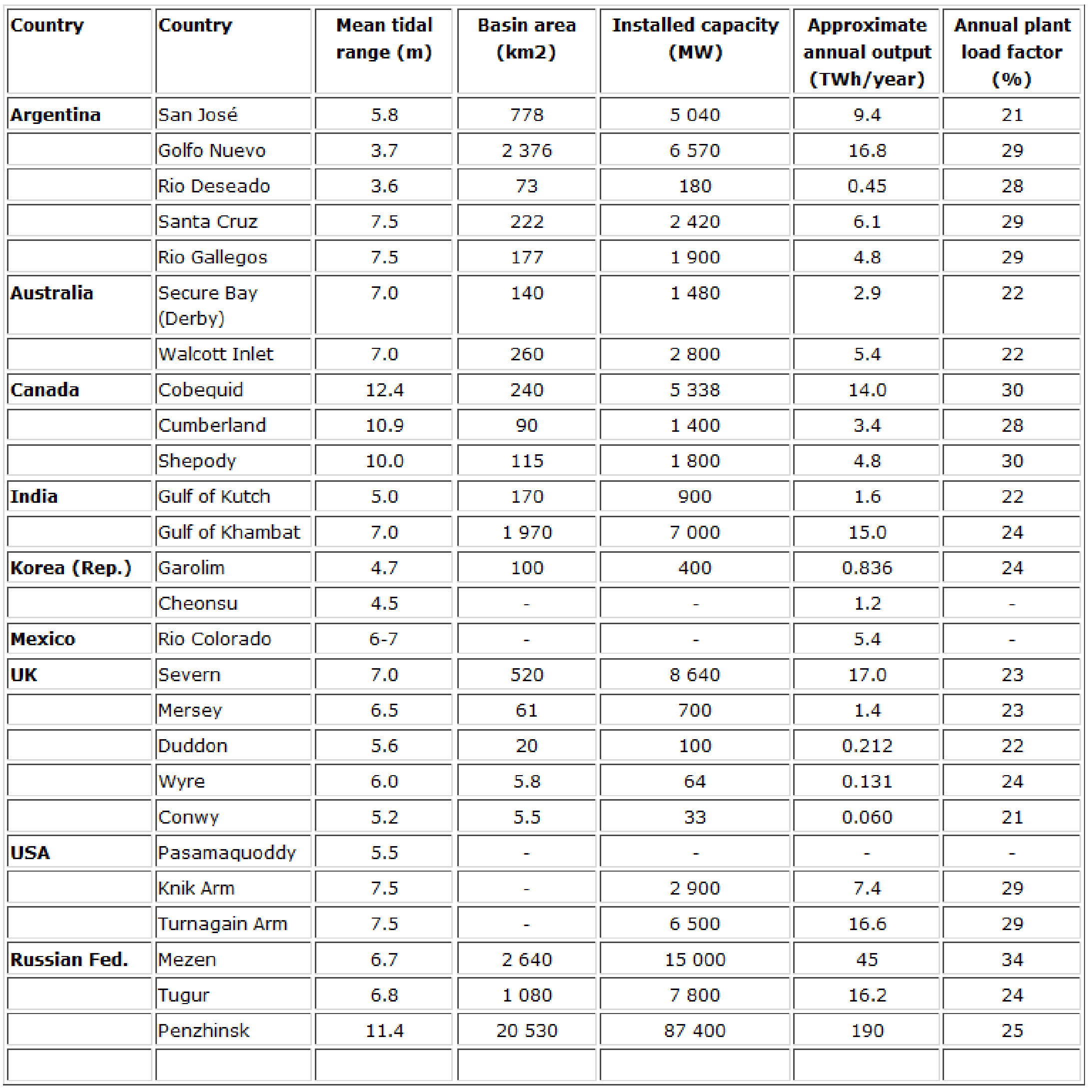


| Site | Mean tidal range (m) | Basin area ($km^2$) | Installed capacity (MW) | Approx. output (GWh/y) | In service (year) |
|---|---|---|---|---|---|
| La Rance (France) | 8 | 17 | 240 | 540 | 1966 |
| Kislaya Guba (Russia) | 2.4 | 2 | 0.4 | - | 1968 |
| Jingxia (P.R. China) | 7.1 | 2 | 3.2 | 11 | 1980-86 |
| Annapolis Royal (Canada) | .6 | 6 | 17.8 | 30 | 1984 |
| Various (P.R. China) | - | - | 1.8 | - | - |

### 2.3.4 Potential sites

The location where the tidal turbines are more appropriate to be installed is of great importance. Tidal stream systems should be installed in areas with fast currents where natural flows are concentrated between obstructions. Such places are found at the entrances to bays and rivers, around rocky points, headlands, or between islands or other land masses. For the above mentioned reasons, the following sites have a strong potential of being locations where tidal turbines can be successfully installed.

Table 2: Prospective Sites for Tidal Energy Projects [11]



| **Country** | **Country** | **Mean tidal range (m)** | **Basin area (km2)** | **Installed capacity (MW)** | **Approximate annual output (TWh/year)** | **Annual plant load factor (%)** |
|---|---|---|---|---|---|---|
| **Argentina** | San José | 5.8 | 778 | 5 040 | 9.4 | 21 |
| | Golfo Nuevo | 3.7 | 2 376 | 6 570 | 16.8 | 29 |
| | Rio Deseado | 3.6 | 73 | 180 | 0.45 | 28 |
| | Santa Cruz | 7.5 | 222 | 2 420 | 6.1 | 29 |
| | Rio Gallegos | 7.5 | 177 | 1 900 | 4.8 | 29 |
| **Australia** | Secure Bay (Derby) | 7.0 | 140 | 1 480 | 2.9 | 22 |
| | Walcott Inlet | 7.0 | 260 | 2 800 | 5.4 | 22 |
| **Canada** | Cobequid | 12.4 | 240 | 5 338 | 14.0 | 30 |
| | Cumberland | 10.9 | 90 | 1 400 | 3.4 | 28 |
| | Shepody | 10.0 | 115 | 1 800 | 4.8 | 30 |
| **India** | Gulf of Kutch | 5.0 | 170 | 900 | 1.6 | 22 |
| | Gulf of Khambat | 7.0 | 1 970 | 7 000 | 15.0 | 24 |
| **Korea (Rep.)** | Garolim | 4.7 | 100 | 400 | 0.836 | 24 |
| | Cheonsu | 4.5 | - | - | 1.2 | - |
| **Mexico** | Rio Colorado | 6-7 | - | - | 5.4 | - |
| **UK** | Severn | 7.0 | 520 | 8 640 | 17.0 | 23 |
| | Mersey | 6.5 | 61 | 700 | 1.4 | 23 |
| | Duddon | 5.6 | 20 | 100 | 0.212 | 22 |
| | Wyre | 6.0 | 5.8 | 64 | 0.131 | 24 |
| | Conwy | 5.2 | 5.5 | 33 | 0.060 | 21 |
| **USA** | Pasamaquoddy | 5.5 | - | - | - | - |
| | Knik Arm | 7.5 | - | 2 900 | 7.4 | 29 |
| | Turnagain Arm | 7.5 | - | 6 500 | 16.6 | 29 |
| **Russian Fed.** | Mezen | 6.7 | 2 640 | 15 000 | 45 | 34 |
| | Tugur | 6.8 | 1 080 | 7 800 | 16.2 | 24 |
| | Penzhinsk | 11.4 | 20 530 | 87 400 | 190 | 25 |
| | | | | | | |

# 3 WAVE ENERGY

## 3.1 General

The energy that can be extracted from waves is called wave energy and it is a renewable energy. It seems possible to take advantage of this energy in off-shore locations. Basic research for developing this technology is enriched for improving the designs of wave energy conversion in areas where high wave energy resources exist. One of these places is the Oregon coast. The wave energy is continuous but it can vary often. Despite this variation the exact characteristics of the waves can be predicted some days before.

The initial interest on wave energy started at 1970 and the main reason was the oil crisis. Although the basic research showed promising results the commercial applications came after many years because of the total cost of the investment. In 1990 there was some interest from small enterprises in UK and Norway.

The energy of the waves depends largely on the air power. Moreover, depends on the sea depth. The biggest potential is where the water is deep. It is a concentrated form of energy like solar energy. Solar power of 100W/m$^2$ is equivalent to over 1000kW/m$^2$ of wave crest length [12-14]. The suitable wind and the most workable wave power is generated between 30 and 60 degree of latitude. According to that, it is very important to know these characteristics before the decision of where the investment must be done. Finally, it is important to know the supply and demand curves for the places that the technology will be developed.

The average annual wave power levels in kW/m of wave front are depicted in figure 12 [12-14].

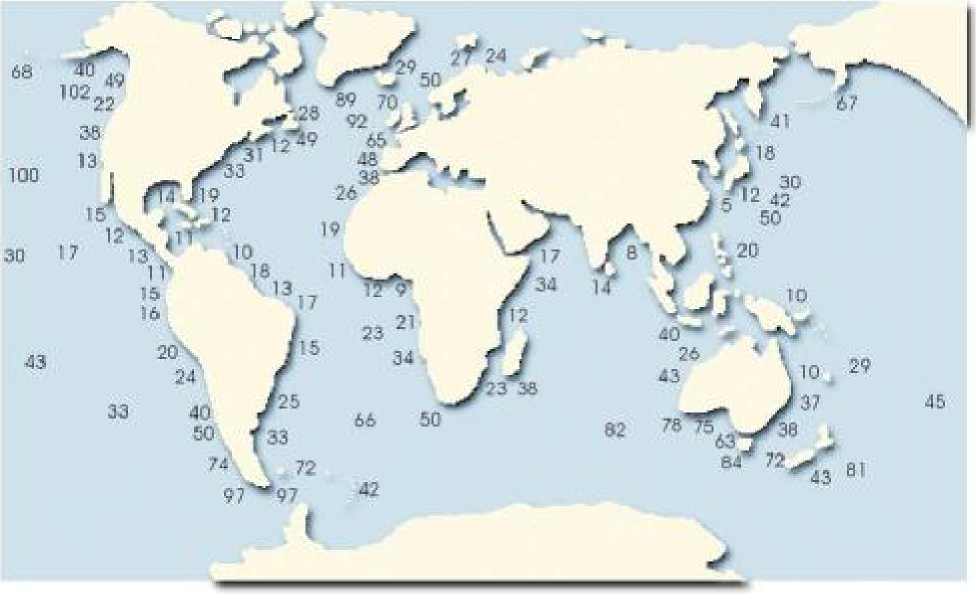


Figure 12: Average annual wave power levels as kW/m of wave front [4]

## 3.2 Types of wave energy technology

During all this years of systematic research, some integrated wave energy systems have been developed and some of them are improved day by day. These systems are described in details in the following chapters [12-14].

### 3.2.1 Oscillating Water Column (OWC)

The system is operated under the pressure of the air which is enclosed in a column. The air pressure depends upon the water level of the sea. The higher the water levels of the sea, the higher the pressure of air in the column. The air system is connected to a generator (Wells turbine) (Figure 13). The main advantage of this technology is that it can be used in both directions, upward and downward waves. It is necessary to use initial energy in order to start the Wells turbine working. The main characteristics of this technology as configured today are the following:

- A bottom-mounted, shoreline 500 kW scheme deployed by Wavegen in Scotland (Figure 14)
- A buoyant, near shore 500 kW OWC under construction for Australia

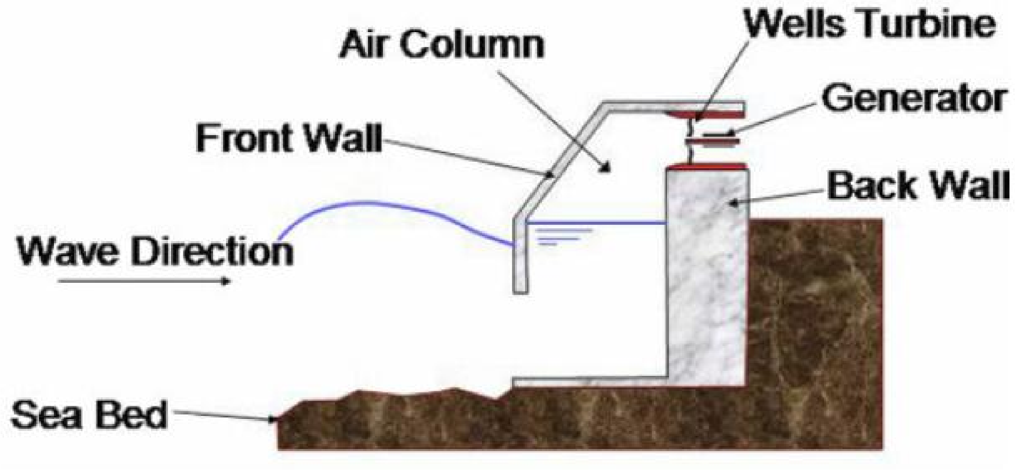


Figure 13: Schematic diagram of OWC [13]

Figure 14: OWC [15].

### 3.2.2 The Pelamis

The Pelamis system, which is depicted in figure 15, has a snake form. It consists of floated empty segments. The usual depth that is operates is more than 50m. The parts are connected each other by hinged joints. When a wave runs on the length of the systems, the energy is produced. The Joint-parts are connected with pump oil and a hydraulic generator (smoothing systems), allow movement between each section and produce electricity as the wave moves by [16].

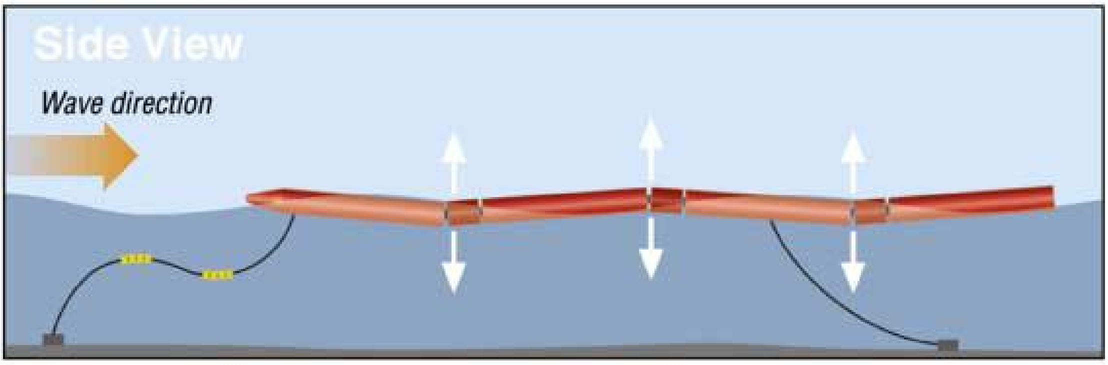


Figure 15: The Pelamis [16]

The main features about the Pelamis are the following:

Length = 120m

Diameter = 3.5m

Overall power rating = 0.75MW

Nominal wave power = 55kW/m

Annual power production = 2.7GWh

Water depth = >50m

Figure 16: Pelamis Wave Energy Converter [17]

### 3.2.3 The Wave Dragon

The wave dragon is a system based on a technology according to which the water is stored in a reservoir before it will be driven to the turbine. By this way the energy is converted to electricity. After that cycle the water returns to the source. The whole process can be categorized into three steps: absorption, storage and power take off. The process design is very complex. In order to optimize the system operation it is necessary to include the wave characteristics, such as horizontal motion.

This technology has many advantages. The major one is the sturdiness and reliability. Moreover it can be placed in the ocean zones with high potential waves because it does not need to be near the shore [16, 18].

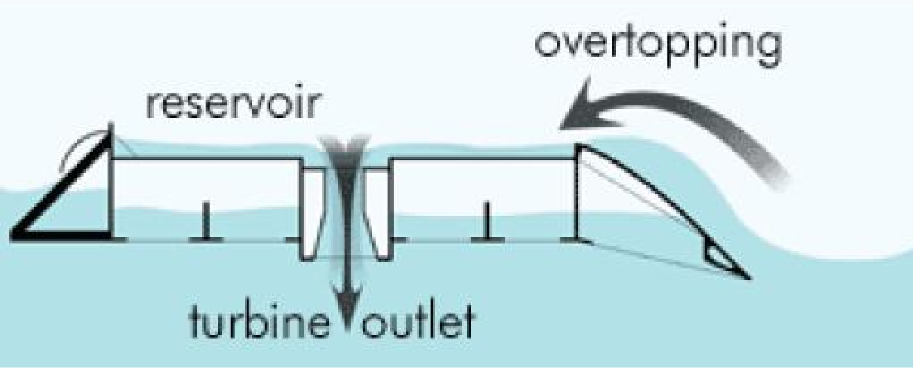


Figure 17: Schematic diagram of the Wave Dragon [16]

The Wave Dragon unit produces annually the following electricity:

in a 24kW/m wave climate = 12 GWh/year
in a 36kW/m wave climate = 20 GWh/year
in a 48kW/m wave climate = 35 GWh/year
in a 60kW/m wave climate = 43 GWh/year
in a 72kW/m wave climate = 52 GWh/year

The main features about the largest Wave Dragon are the following:

Width and length = 390x220m
Reservoir = 14,000 $m^3$
Rated power/unit = 11MW
Annual power production/unit = 35GWh
Water depth = >30m

Figure 18: The Wave Dragon [18]

### 3.2.4 The Archimedes Wave Swing (AWS)

The Archimedes Wave Swing wave energy converter is a buoy anchored to the bottom of the sea. The energy conversion process is based in the Archimedes principle. The moving part of the system is an air-filled floater. The waves produce a movement as they go up and down. The motion of the floater, due to the air pressure, converts the energy to electricity and then it is transferred to the shore. The following characteristics are needed in order to operate successfully:

- Location exposed to ocean swells - e.g. western coast of British Isles, Ireland, France, Spain or Portugal
- 40 - 100m of water depth outside of main commercial shipping lanes
- Secure electricity power grid onshore
- Industrial port within 12 hours sailing time
- Sea-bed suitable for laying power cables to shore

Today, every unit that is installed is rated at 1.2 Megawatts and produce energy, equal to the electrical demand of approximately 500 households' energy. AWS Ocean Energy installed the first machine during 2007 outside Orkney, with a budget of £250 million.

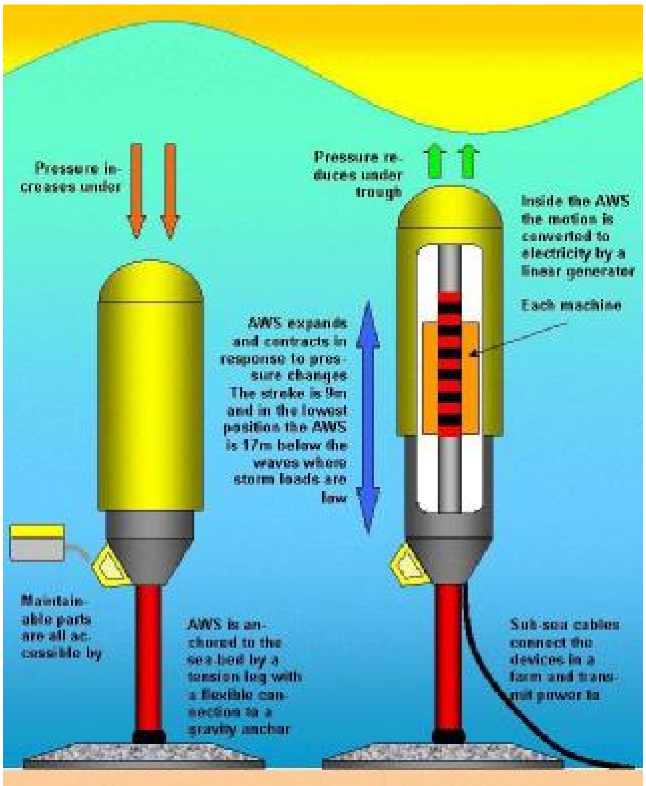


Figure 19: The Archimedes Wave Swing process diagram [19]

Figure 20: The Archimedes Wave Swing [20]

### 3.2.5 The McCabe Wave Pump

This system consists of three parts stuck together aligned to the direction of the waves.

The middle pontoon is attached to a submerged damper plate and gives the motion to other pontoons. There are hydraulic pumps which are connected to the middle and to the end pontoons.

The hydraulic fluid under pressure is used to drive a generator or to ask pressure to water for desalination using a reverse osmosis plant. The first successful plant was in Ireland in 1996 where a full-size 40m commercial device was tested.

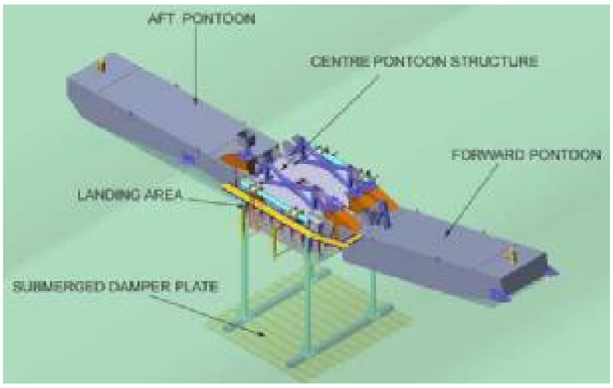


Figure 21: The McCabe Wave Pump [21]

### 3.2.6 The PowerBuoy$^{TM}$

This system is a prototype system with a submerged buoy (1m below the level of water). There is piston which can follow the wave’s movement up and down. The energy is produced from the internal generator (immobile part). By using an underwater cable the electricity is transferred to the shore. The first demonstration system was installed in 2005 and produced 40kW. In 2007, a commercial-scale system was set up in Spain producing 1.25MW.

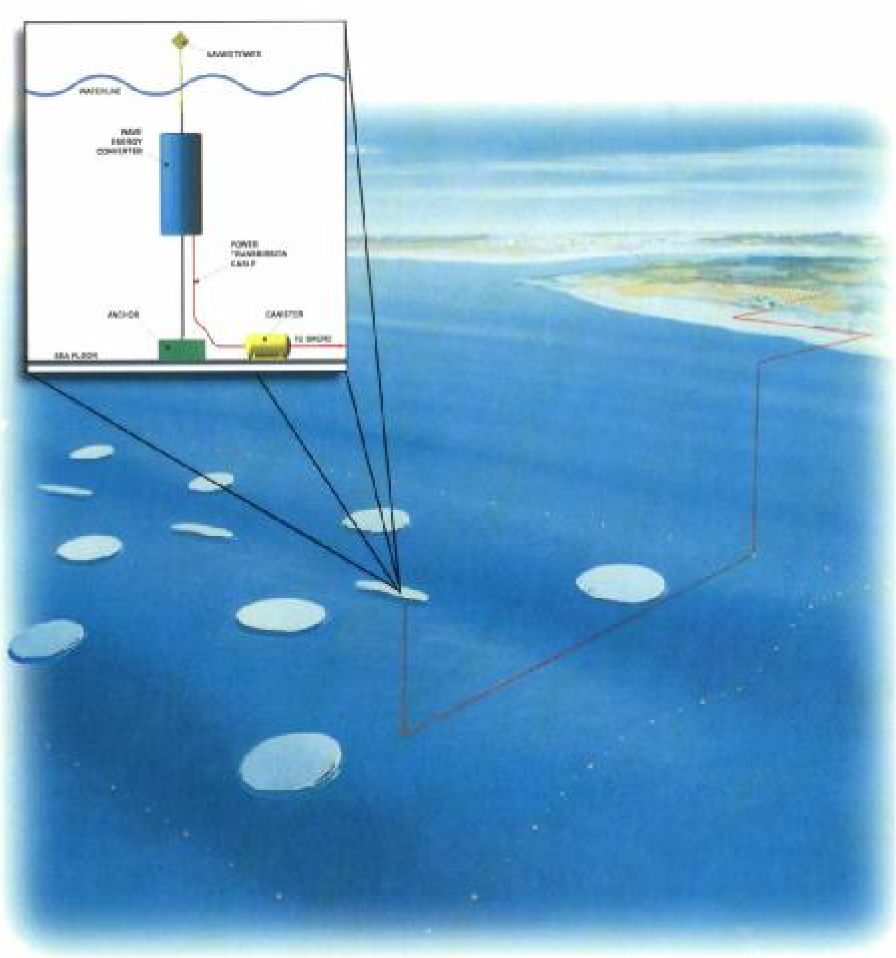


Figure 22: The PowerBuoy [22]

Figure23: The PowerBuoy in operation [13]

### 3.2.7 The AquaBuOY™

The AquaBuOY™ Wave Energy Conversion system is a prototype and is produced by the AquaEnergy Group, Ltd. This technology is based on a Swedish idea where pressure is asked in a fluid, using the wave power, in order to drive the turbine generator. In this device there is a piston which is moving up and down and elongates and relaxes a hose containing seawater, and the change in hose volume acts as a pump to pressurize the seawater. In Washington the AquaBuOY system has been tested using a full-scale prototype. Moreover, a 1-MW pilot offshore demonstration power plant is developed offshore at Makah Bay. The Makah Bay demonstration include four units rated at 250 kW placed 5.9 km (3.2 nautical miles) off-shore in water approximately 46 meters deep [23].

Figure 24: The AquabuOY™ in operation [13].

Figure 25: Schematic diagram of the AquaBuOY$^{TM}$ [13]

## 3.3 Futures Steps in Wave Energy Technology

All of the previous systems are descendants of earlier other systems more improved in an economic manner. The result of these improvements is the increasing availability of the funds from the governments. Despite this more non-technical issues need to be sorted out.

- The fact that this technology is being improved from small companies with a total investment of US$ 3-10 million each, could lead to liability problems due to prototypes failure.

- The high cost of licences, permits, and environmental impact assessments in some countries even for the development of prototypes are economically prohibitive for the prementioned small companies.

- When such a system is finally out in the markets, the competition is high because it comes against other renewable energy technologies already established and economically grown [13, 14].

## 3.4 Research and Development - the case of Greece

Despite the Greek large coastline (16,000 km), Greece's resources are relatively low. The Mediterranean also has low wave resources in general and the share of Greece stands between 1.6-4.2 kW/m. Research has shown the possibility of a rather large, for the Greek levels, resource around Crete at about 11 kW/m. Due to this fact an interest has been shown to supply electricity to some islands where the cost of production of power from diesel fuel is very high.

There is an interest for the Amorgos island also, for a full scale, semi-commercial power plant for desalinated water and electricity production. Dunlop Oil, Marine (UK), IPS, Sercon and Technocean (Sweden) have made efforts towards this direction. This project consists of three stages.

- Sea trials of a 5 kW converter in Sweden for evaluation of suitability for the desalination process.
- Constructing a prototype power and desalination plant consisting of 10 converters of 30 kW each.
- Installing a demonstration plant at Amorgos.

Greece's presence in the development of the wave energy world map was strong from the side of the Department of Marine and Shipbuilding which participated in the development of European Commission-funded MAST3 project 'Eurowaves'. This is a project tool giving information about the wave climate at maritime locations [24].

# 4 OCEAN THERMAL ENERGY CONVERSION (OTEC)

## 4.1 Introduction

Tropical sea surface, which is about 60.000.000 Km2, adsorbs every day solar energy that is almost equal to power that can be given from 250 billion oil barrels. These numbers show that it could be a great opportunity and advantage to use some of this energy in order to reduce the use of fossil fuels.

Ocean thermal energy conversion (OTEC) is a technology that operates by using the difference in temperature between shallow and deep waters, like a heat engine operates in order to produce electricity. The places that give the biggest efficiency are the places near equator, where the temperature differences between cold and warm water is more than 20 degrees Celsius. In order to take advantage of this technology the big challenge is to improve the efficiency in lower different temperatures.

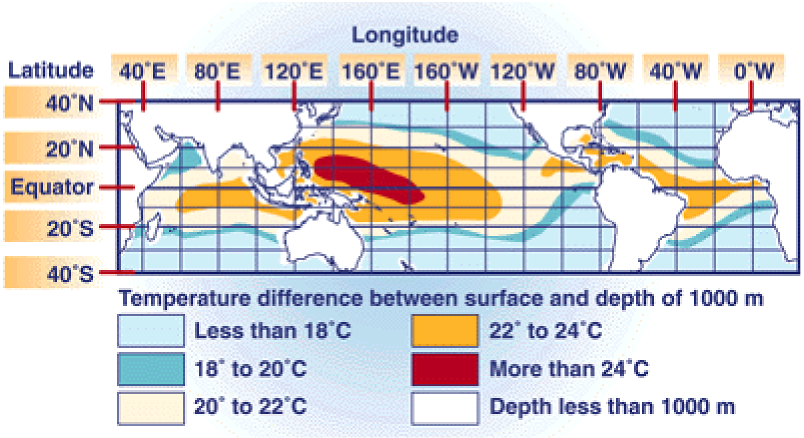


Figure 26: Map of temperature difference between surface and depth of 1000m [13]

OTEC technology can produce biggest amounts of energy than the other ocean power technologies. Although the real efficiency seems to be low, the theoretical one is much higher (7%). It is economically efficient to use the OTEC technology for other applications simultaneously with the energy production process [25-27].

Figure 27: OTEC plant in Hawaii [28]

## 4.2 Types of OTEC technology

The OTEC technologies today can be classified according to the location and cycle into three different cycles: the open cycle, the closed cycle and the hybrid cycle.

Actually the basic operating principle is the same for all systems. There is a heat engine put between a high temperature and low temperature reservoir. It works like a steam turbine, where the engine converts heat energy into kinetic energy. The operation is based in pumping the cold sea water or desalinating the water near the sea bed and then floats it up through a pipe to the surface [25-27].

### 4.2.1 Closed cycle

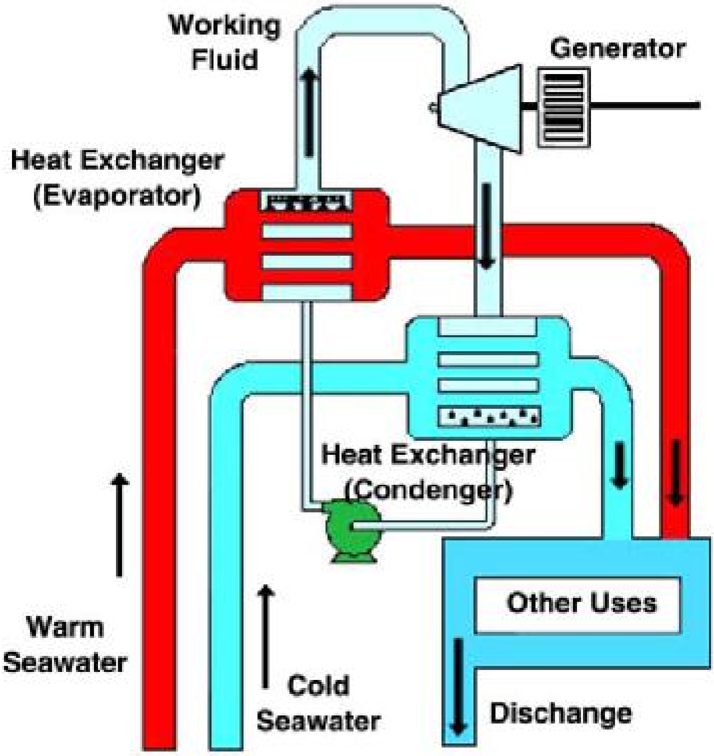


Figure 28: Closed cycle OTEC [29]

In this cycle working fluid with low boiling point is used. This is usually ammonia. In a full cycle the working fluid is cooled down and then heated up. The hot water, which is at the sea surface, is driven into a heat exchanger.  The working fluid takes the heat to change its state, and then is vaporized. After that, the vapour is driven through the turbine and generator and the electricity is produced. Then, the vapour is condensed by the deep cold water. Finally, the liquid is driven back to the heat exchanger and so on. In India there is an operating closed-cycle, floating plant of 1 MW rated power [13].

### 4.2.2 Open-cycle

According to the open-cycle process no working fluid like ammonia is used as the closed-cycle, but sea water directly. The warm water from the sea surface is used in low-pressure containers which cause the evaporation. The main operation principal is the same with the other cycles. The steam is passed into the turbine which is connected to a generator. Then it follows the production of desalinated water (fresh water) via evaporation. This steam is condensed into liquid by the deep cold water. From this operation the water finally is clean and potable. In Hawaii there is a test open-cycle plant (May 1993) which produces 50 kW of electricity.

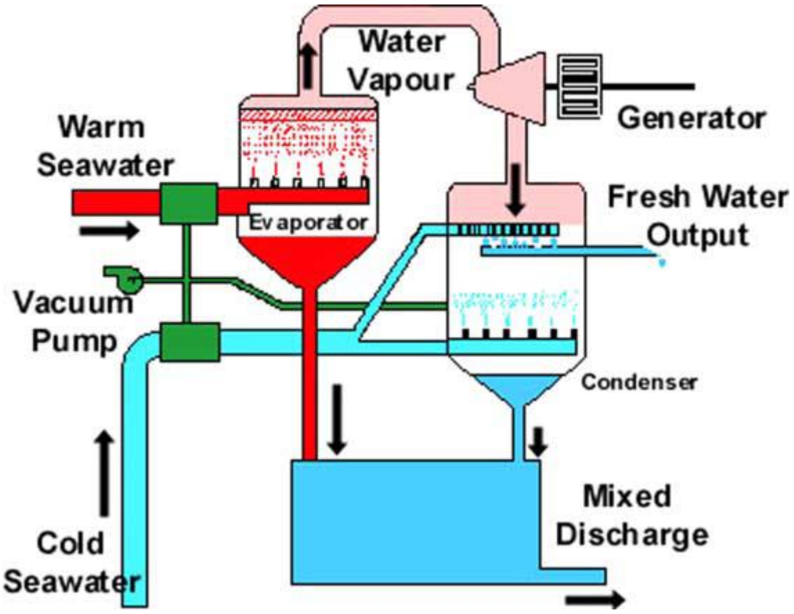


Figure 29: Open cycle OTEC [29]

### 4.2.3 Hybrid cycle

This third cycle is a combination of the two above. At first, there is the evaporation of the warm water in a vacuum chamber. Then the stream converts the working fluid into vapour which is directly driven in the turbine. In this cycle fresh water is produced.

## 4.3 OTEC applications

The OTEC technology systems analysed above in details, are mainly used for electricity production and desalination (2MW electric power plant is able to produce 4300m$^3$ fresh water every day). Moreover, there are some more applications and chemical production technologies that can be used during the operation of an OTEC plant. These are:

- Production of ammonia
- Production of $H_2$
- Use of the deep sea water which is rich in nutrients in marine-culture

The following diagram (Figure 30) shows the major by-products of electricity production.

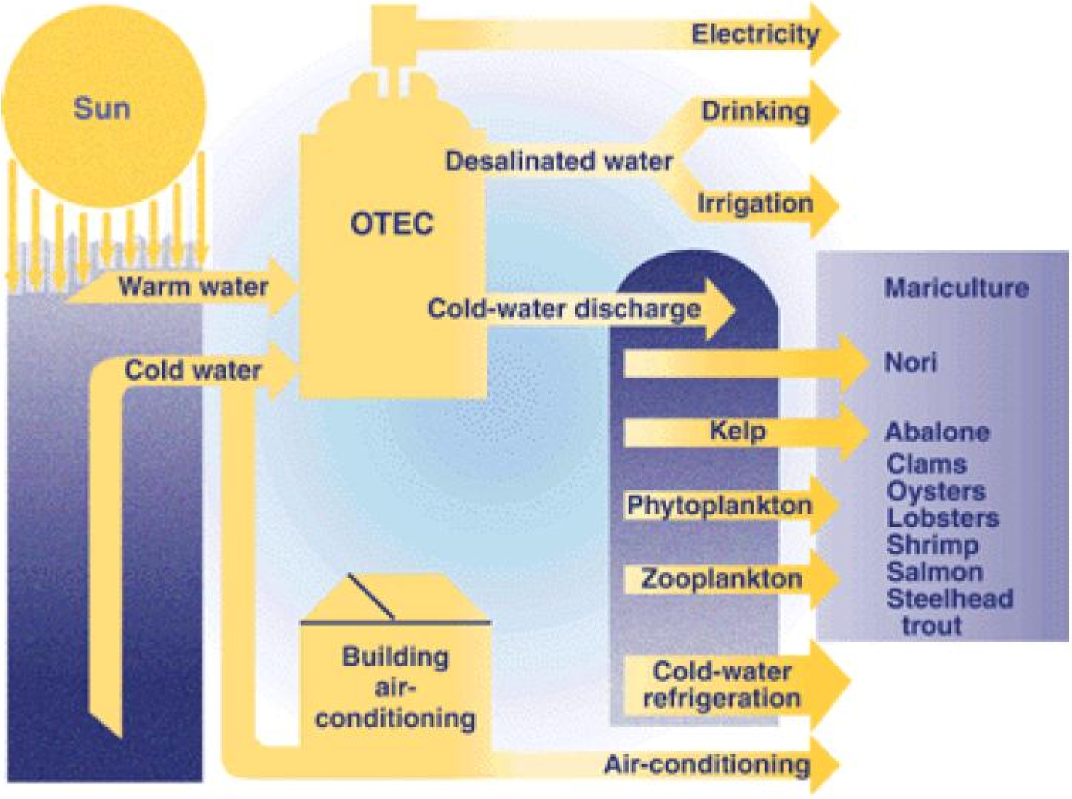


Figure 30: Block diagram of all applications from OTEC technology [13]

## 4.4 Perspectives of OTEC technology

OTEC technology is a thermal efficient technology for electricity production and for desalination of sea water. During the last decade a great turn of people and governments to reduce the use of fossil fuels for electricity generation is observed, because of the environmental impacts and the high cost. The OTEC technology is a promising technology that could be used efficiently to small islands [13, 14].

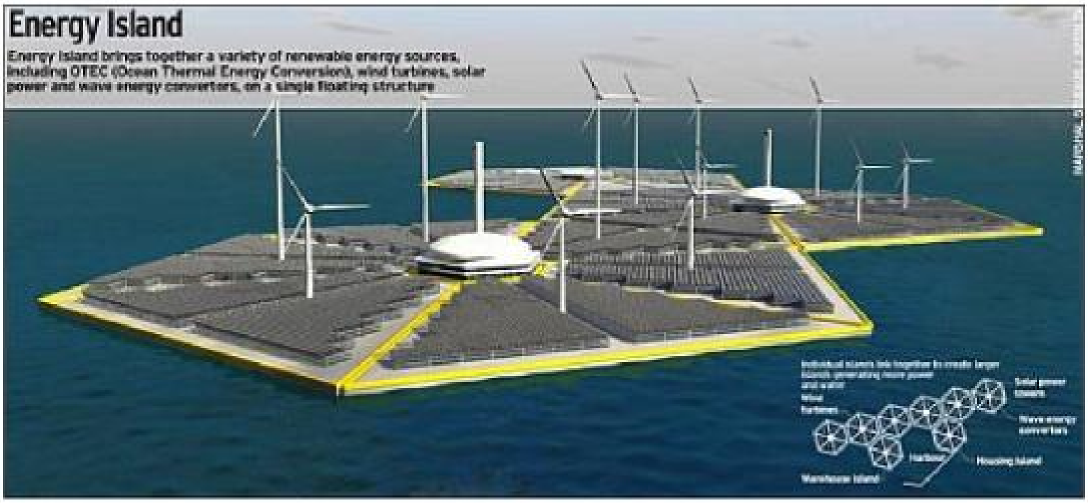


Figure 31: Futuristic project based on OTEC technology [13]

## 4.5 A Typical OTEC Design

According to the literature an example of an OTEC plant design is quoted [28]. The plant is a 10MW closed-cycle which will be located in an island in Caribbean or South Pacific. The idea for that plant was born in 1980 and year by year it is updated. Today, the main reason to develop such a technology in the islands, as is already mentioned, is the high cost of fossil fuels which is almost 75% higher than the in continental places.

Power production is achieved using two of the three 5MW power ‘pods’. In this plant more pods than needed will be used, in order to be more reliable in case of shutdown due to failure or maintenance of the pods. There are two places in the Caribbean which are chosen. The minimum temperature difference between the surface water and the cold deep water in 1.000m depth which is no more than 2.5 km from shore will be 21.8C, increasing to 23.8C at the warmest time of year

Total cost was calculated. This was the initial capital cost, the electricity production cost, the maintenance and insurance cost and the personnel cost. According to that the total cost was US$ 97 and adding the contingencies, could increase up to 25% or decrease by up to 13%.

The life of the OTEC plant was 25 years and the payback period was 10 years. The annual inflation rate was assumed at 5%.

The availability of the plant was 90% with the third pod available as standby. The electricity power generating cost was 18 cents/kWh, not including the allowance for potable water production. Using the PICHTR calculations (see Vega, 1994) as a basis, the costs for this 10 MW sized plant will fall from 18 cents/ kWh to 14 and 11 cents/kWh, corresponding to potable water credits of 40 and 80 cents/m$^3$. The potable water in these areas is very expensive and the maximum price could be almost US$ 1.60/m$^3$. So the prices from OTEC plant seam realistic. Moreover, there are and environmental benefits. In the near future there is a possibility of including in the electricity power units prices the 'Carbon tax'. This tax will benefit the renewable energy power plants.

These are the main calculations and assumptions that have been made for this demonstration plant. It is believed that after the first operation of this scale of plant, more improvements will take place in the operation efficiency and in the cost effective design.

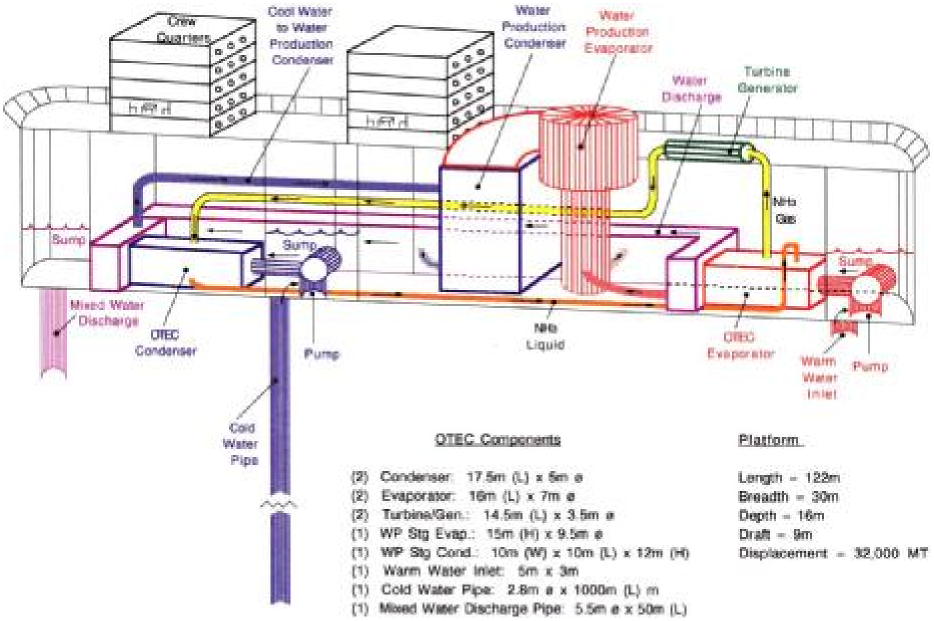


Figure 32: Schematic of 5MW OTEC pre-commercial plant [28]

Up to now, the main concern was the total cost of this kind of investment and especially the power generation cost. Moreover, the plant needs to be efficient in order to be attractive. In case of 10 MW plant described above, the rates of return are 20.4% (nominal) and 14.7% (real), which are commercially accepted.

The prospects of this demonstration plant, for both plant operator and the consumer of electricity, are looking more competitive and more interesting than in the past [28].

Figure 32 provides a schematic illustration of a 5MW pre-commercial OTEC plant, similar in general layout to the concept described above.

## 4.6 The Need for a Demonstrator Plant, Current Practice and the Market

The main problem that exists is that no demonstration power plant is yet built and so funds are very unlikely to be found. The main obstacle for this technology is not economic nor technical but philosophical. It is based upon convincing funding agencies like European Development Bank that this techno-economic values are sufficiently based.

The Countries that are interested in this technology are Taiwan and China, where extensive studies at a number of candidate sites have been done for OTEC and marinculture.

OTEC activity is taking place in India and Palau, both in cooperation with Japanese technology. A further general indication of interest in desalination of water, rather than OTEC alone, is shown in Japan where the industrial OTEC Association was succeeded by the Japan Association of Deep Ocean Water Applications.

The European Commission and the industrially-based Maritime Industries Forum have studied OTEC technology end especially DOWA application. The recommendations have been on the funding and construction of a demonstrator plant in the 5–10 MW range [13, 14].

# 5 MARINE WINDS

## 5.1 Introduction

Marine Wind Parks have the greatest development among the other ocean energy processes. This happens because it is a form of renewable energy with the lower capital investment requirements. Moreover, there are plenty of places all over the world where the marine wind parks can be developed successfully. The great advantage of the marine wind parks as opposed to the land wind parks is the reduction of the sound impact to people. Today there are many marine wind parks in Northern and Western Europe. On the other hand, there is development in this technology as described in the following chapters.

The WECS (Wind Energy Conversion Systems) started the development 50 years ago, because of the clean energy production and due to the reduction of the need to use fossil fuels. Today these systems are able to produce electricity, and most of them are commercially available.

Starting with small land parks which produce limited electrical power, the technology now is scaling up and there are big wind farms in many places. Some of them are in Northern and Western Europe: Sweden, Denmark, Germany, Scotland and the Netherlands.

Except from the land and the offshore marine wind parks there is research for developing wind farms in artificial reefs for more protection from the waves.

The land wind farms can not be developed near residential areas because of the noise produced. This problem does not exist in the offshore installations. Moreover the results of the research have shown that the potential of the offshore wind parks is much higher than the land wind farms.

Thirteen countries participated in the 2-year assessment project “Concerted Action on Offshore Wind Energy in Europe” (CA-OWEE). United States East Coast regions and Tasmania have shown real interest in this technology. The major concerns about these systems are the grid connection. Because of that, the marine wind farms cost much higher than the land wind parks.

Marine wind turbines are larger and more expensive that the land wind turbines and it is cost effective to use them in the electricity production process.

In the North Sea were placed wind turbines with 70m rotor diameter which can produce about five to six million kilowatt/hour annually. The marine wind turbines can safely turn 10–20 % faster than on land [30].

However, the marine environment is unpredictable and these devices should be very reliable. Investigations and development now focuses in wind turbines installations in deeper waters farther from shore and this is the new challenge for the next decade [31].

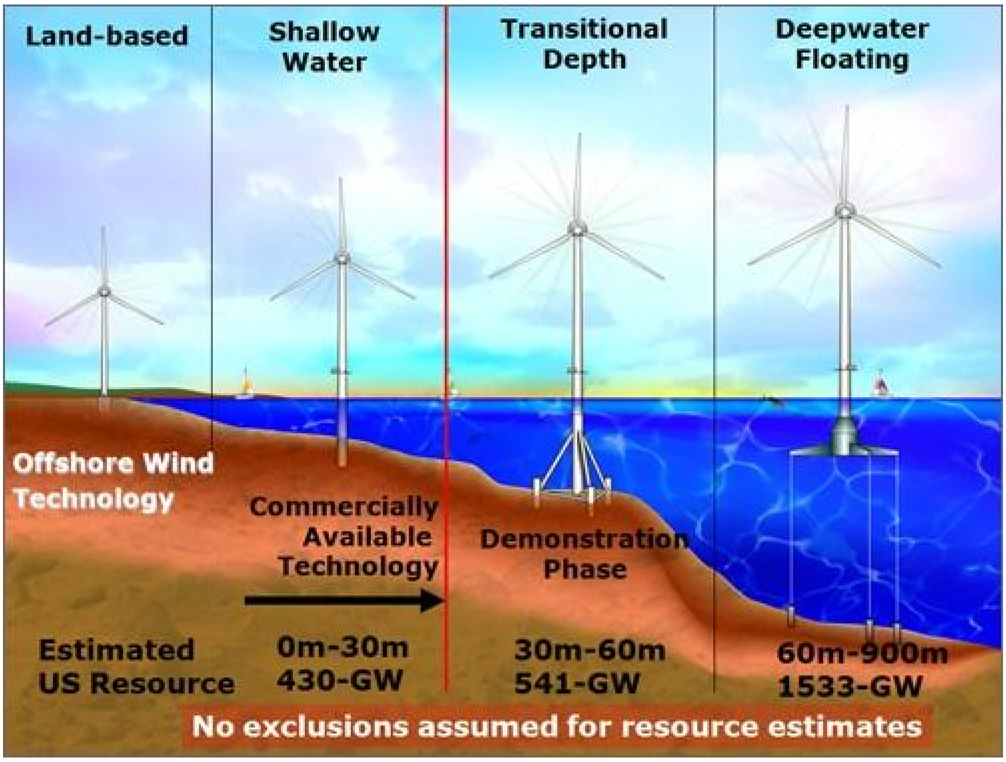


Figure 33: Research on offshore wind technologies for shallow water, transitional depth, and deepwater [31]

## 5.2 Installations

Some of the installations that already exist are the following:

- A marine wind park on the IJsselmeer, in The Netherlands

- A marine wind park in 1996 at Medemblik and Dronten

- In Denmark, some parks were built in 1991 and 1995 and the most recent is at Middelgrunden and is the largest producer with 89,000 MWh/year.

- Sweden’s installations date from 1990, 1997–1998, and the newest have been completed recently. The Utgrunden park is Sweden’s largest with 38,000 MWh/year

- The British facility in operation is located near Blyth and is a relatively small producer with 12,000 MWh/year

- The Danish Middelgrunden (660kW, and five turbines) placed along the Baldwin (Boudewijn) Canal in Bruges have a total capacity of 3MW

- There are many marine wind parks in Denmark, France, The Netherlands and Belgium.
- At Zeebrugge, Belgium (4.8MW)
- Fifty air turbines on an artificial island at 15 km off-shore from the city-resort of Knokke-Heist
- Wind power from the ocean has also been considered for providing the energy needed by pumps and desalination plants.

The German DEWI (Deutsches Windenergie-Institut) did a research and according to the results, Belgium, The Netherlands, Denmark, Germany, and Great Britain could cover their entire 923 million MWh needs from offshore wind-energy in 2000.This would, however, could happen by developing 100,000 2-MW turbines in North Sea sites.

Moreover there is more research about the already installed marine wind parks. The final goal is to enlarge them with newer technological wind turbines in order to produce efficiently more electricity power [30-31].

Figure 34: Marine wind turbines off the shores of Copenhagen. Photograph: John Nyberg [32]

Figure 35: The "Alpha Ventus" wind park, 45 kilometers (28 miles) north of the island of Borkum in the North Sea [33]

Figure 36: Wind generator [34]

## 5.3 Floating wind turbines – all the technologies

Floating wind turbines can generate electricity power in places with an average depth between 50 and 300 m. This can happen sometimes very close to shore where the continental shelf drops steeply as in the case of some European countries on the Atlantic [35].

Figure 37: Floating wind turbines [35]

Floating turbines are used in deep waters because it is not possible to use the fixed wind turbine. The idea of a floating wind turbine started from the University Of Massachusetts (UMASS) in 1972. The research continued for many years and the installations of offshore wind turbines were limited until 2003. Today there are four different types of deep water wind turbine platforms using new technologies.

### 5.3.1 Spar Platform

"Spar Platform": is a submerged system with stable ballast equipped with anchors allowing it to be simply hooked to the bottom. This system is used by Hywind for Statoil-Hydro, Technip and Siemens off the coast of Norway.

An experimental pilot unit was placed in Stavanger in 2009. The depth was about 22m and it was equipped with a Siemens 2Mw turbine. After the two year study it is about to complete.

The 100m long steel tube was used in this first "spar" installation in a Norwegian fiord. The final cost was $72 million, according to Statoil. This foundation does not rest on the bottom of the sea; it floats and is attached to the bottom only by cables having a certain freedom of movement and fixed to anchors.

Figure 38: Spar Platform [35]

### 5.3.2 Tension Leg Platform

Tension Leg Platform is a sunken platform attached to the bottom of the sea with safety. There are strings partially buried in the bottom of the sea that hold the whole system. These strings can tense according to the swell. Blue H Technologies is using this system. During the Tricase Project a structure carrying a blade turbine was constructed in the marine area of Italy at a depth of 113m. This platform was the first floating one and was disassembled 6 months later. Within the same project, Blue H engaged stage 2 of the development of a platform carrying a 2MW turbine. In the final stage of the project, at around 2014, the final construction (Figure 39) will be created in the high seas, from an unknown at the time being constructor.

Figure 39: Tension Leg Platform [35]

### 5.3.3 Semi-submersible platform (Stabilised floating)

This structure is partly sunken and visible. It is tied with chain-type strings at the bottom of the sea. American developer Principle Power Inc is using this technique in the WinfFloat platform. EDP, ASM GROUP and the pre-mentioned company are working together to create a prototype in the marine area of Portugal at 43m depth. This type is a variation of the kind of platform used by the oil and gas companies. It consists of 3 light steel lines making it extremely durable. It is attached to the bottom with 4 chain-strings. The cost is evaluated to touch the US$23million, and it is supposed to carry a 67m mast turbine with a 2 MW unit.

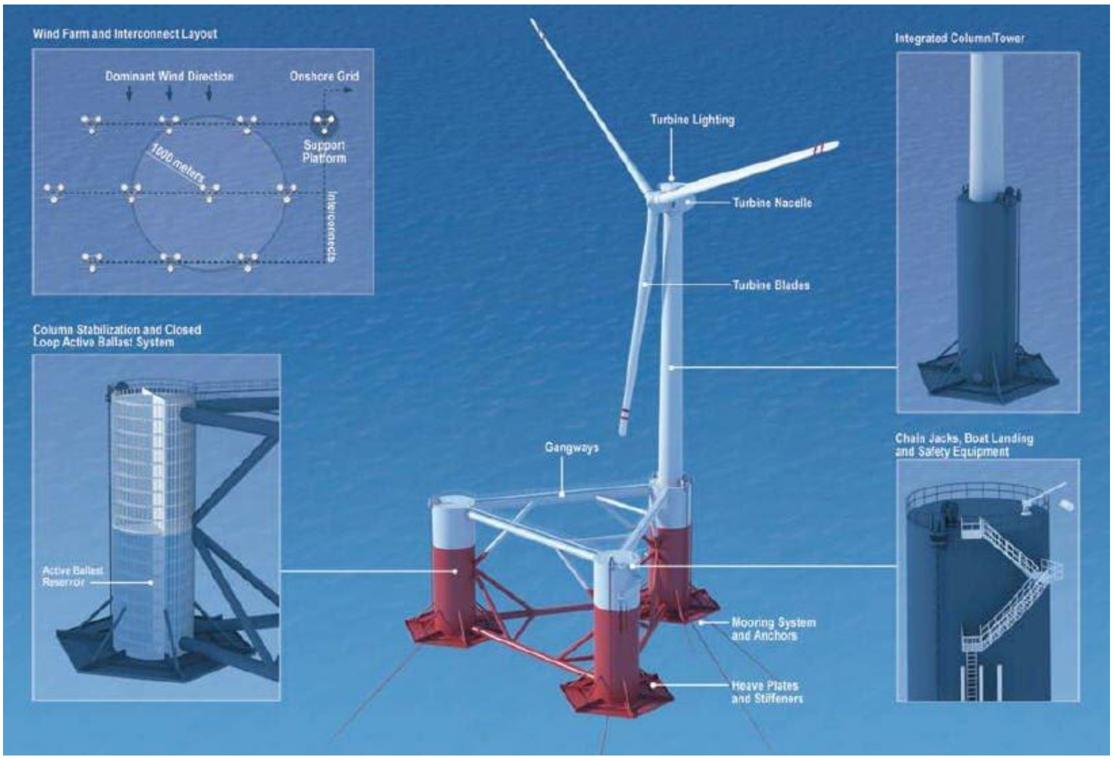


Figure 40: Semi-submersible platform. [35]

### 5.3.4 Free Floating Platform (FFP)

DCNS, Nass&Wind, Saipem and In Vivo Environnement with the support of FREMER Brest and ENSTA created a platform called WINFLO. This structure is a member of semi-submersible family also attached to the bottom of the sea with chain-strings but has several differences, a fact strong enough to create a new category called FFP (Free Floating Platform). It is lighter and more flexible as its anchorage system is not fixed, so it can be transported for service.

Figure 41: Free Floating Platform (FFP)

### 5.3.5 IDEOL

This system is a variation of the ideas above. A mechanical solution accompanied by software that calculates several parameters for the turbine’s wake effect makes this system very interesting as it is maximizing the energy production. A prototype is planned to be constructed in 2013

Figure 42: IDEOL [36]

### 5.3.6 PROSPECTIVE FLOATING WIND TURBINES

#### a) VERTIWIND

This system is a vertical-axis marine wind turbine. The main characteristic is the vertical blades that are spinning around a vertical column. The vibrations of the blades are eliminated and the height (approximately 90m) is reduced as opposed the traditional type. For this type, shallow water is needed therefore the transportation for service purposes is much cheaper. The VERTIWIND system can also float more than 200m above of the bottom of the sea [35].

Figure 43: Vertical axis offshore wind turbines [35]

b) DEEPWIND

This type is very futuristic. It is vertical axis turbine (Darrieus type) with a unique transmission and control system designed by the Danish Technical University (DTU). The project started in 2010 and has received already €3million subsidy inside the European Future Technologies Program. A generator with electronic controls put at the base of the structure is connected with electric cables. A 5Mw prototype of full scale is planned to be deployed in the marine area of Roskilde. When this stage is complete the constructors will design a unit with 20 MW turbine [35].

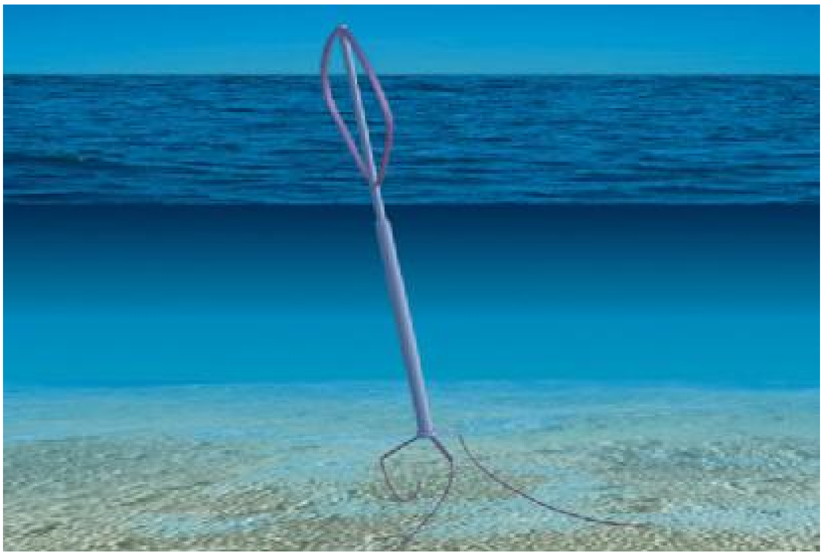


Figure 44: Deepwind [35]

c) SWAY.

This system is using the half full bottle technique. The centre of gravity of the structure is located at the lowest segment giving the stability needed for the turbine at the higher segment. A $5^o$ to $8^o$ oscillation is taking place. Garrad Hassan & Partners practice has approved this system as it's the one that behaves the best under extreme circumstances [35].

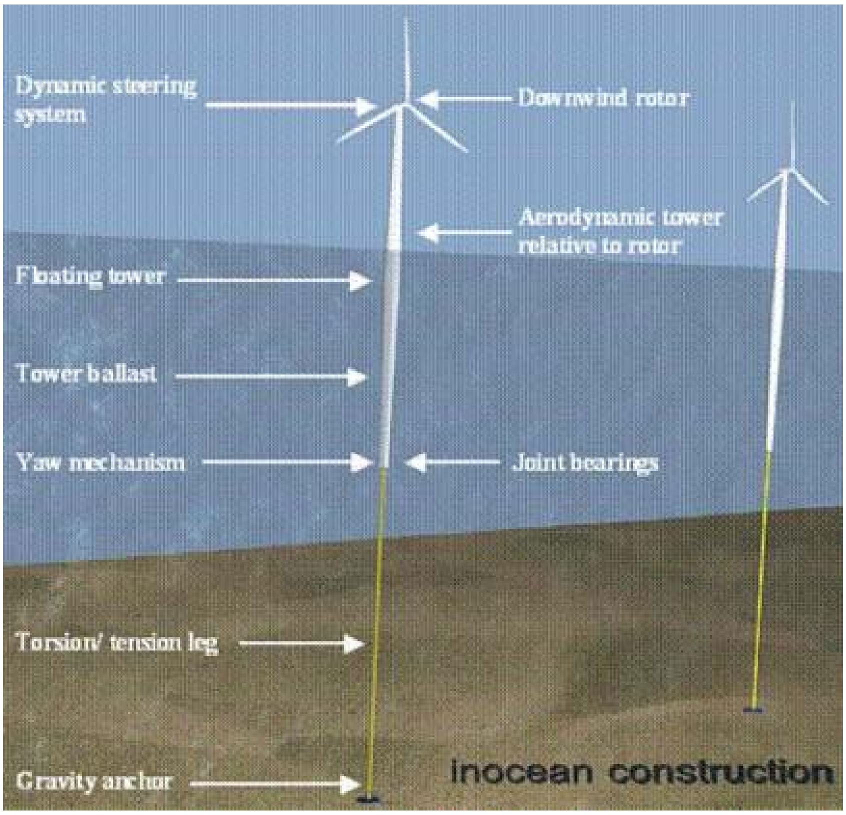


Figure 45: SWAY [35]

d) MUFOWS

The last system of the Prospective Floating Wind Turbine family is the MUFOWS (Multiple Unit Floating Offshore WindfarmS) system. The development started in the 90's, when offshore wind farms had already attracted much attention. The developers were the University College of London (UCL), W.S. Atkins and the Energy research Centre of the Netherlands (ECN). Various turbines placed in formation on semi-sub platform attached at the bottom of the sea with one string. There are two categories according the formation of the turbines, the backbone (Figure 46) and the octagon (Figure 47), both designed to hold 8 turbines. A study taken place during 2000 showed that this kind of construction was not going to be viable [35].

Figure 46: MUFOWS (Backbone) [35]

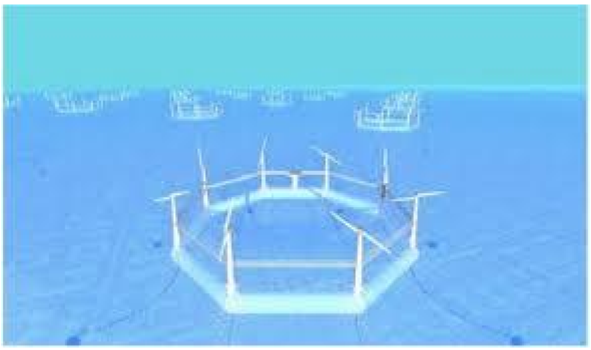


Figure 47: MUFOWS (Octagon) [3]

# 6 Economic Valuation of Ocean Energy Development

## 6.1 Introduction

The ocean energy resource can contribute in a sustainable manner to meet the increasing global energy demand [1]. However, the Ocean Energy industry is still at an early stage of development and the technology required to gain economic benefits is not yet at a level which allows broad commercial projects to be developed. Therefore, little production and historical data are available and only recently a range of reliable estimations of cost and benefits are published. A number of countries with favourable geographical characteristics (Ireland, Portugal, Australia etc.) have been carrying out economic studies to investigate the feasibility of developing an ocean energy sector and take advantage of the associated economic, environmental and social benefits [37].

The most developed ocean energy systems include: tidal energy, thermal energy (Ocean Thermal Energy Conversion or OTEC), marine currents, caused by thermal and salinity differences in addition to tidal effects, and ocean waves [1]. Regarding to the commercialisation of ocean energy technology, it appears that both wave and tidal technology can achieve full commercialisation. However, the time at which this will happen and the type of devices that will be successfully used are not yet defined, as devices which are currently at prototype stage, may not be proved to be commercially viable when they will be scaled up [37, 38].

## 6.2 General Economics for the main ocean energy sources

General economic information related to the most developed ocean energy sources are presented in this section.

### TIDAL ENERGY

Tidal power entails relatively high costs of capital and the construction period can last many years for large-scale projects. Despite of the fact that the plant lifetime can be very long (for example, 120 years for the barrage structure and 40 years for the equipment), the high costs of capital and the long construction period are still burdensome for the development of large tidal schemes [1].

The predicted cost of energy from the tidal stream devices proposed is strongly dependent on [24]:

- the size of machine
- the load factor of the power take-off system
- the running costs
- the choice of economic parameters

Preliminary estimates of the unit electricity costs from tidal stream devices vary at a range of 0.045-0.135 $US/kWh, depending on the device and the assumptions made in the evaluation. An estimated cost of less than 0.09 $US/kWh would be achievable with first generation machines in a good current regime (current velocity of 3 m/s) with load factor greater than 30 %.

### OCEAN THERMAL ENERGY CONVERSION (OTEC)

OTEC incurs high capital costs. The economic analysis has indicated that islands and communities located close to the shores requiring up to 15 MW are the early market for OTEC. According to the cost analyses, the closed cycle OTEC would be cost effective only for very large plants (greater than 40 MW). The simpler and cheaper heat exchangers of the open cycle system, given the fact that the open cycle produces large volumes of fresh water, has contributed to shift the interest to the deployment of the open cycle OTEC [1].

### MARINE CURRENTS

Factors which have significant impact on the energy unit costs are the size of machine, the choice of economic parameters and the running costs, in addition to the load factor that is very crucial. According to the preliminary estimates, the unit costs of electrical energy can vary between 0.045 and 0.135 $US/kWh. The assessment of the European Commission has indicated that costs less than 0.09 $US/kWh could be achieved with first generation machines in a good current regime (current velocity of 3m/s) with load factor larger than 30% [1, 24, 38].

### WAVE ENERGY

It is difficult to reliably estimate the unit costs of electrical energy produced from the waves, given that the few existing schemes are prototypes and there are additional costs at such a preliminary stage of development.

However, the estimated costs have shown a steady decrease with time, despite the little financial support received in recent years. It should be mentioned that the cost of energy produced is a function of local wave climate and, as regards the shoreline devices, is site specific. There have been significant reductions in the predicted generating costs of several devices, which are capable of providing cheaper electrical energy for small islands and remote near-shore communities that depend on expensive Diesel generation [1, 24].

## 6.3 Developing an Ocean Energy Economic Model

This subsection presents the basic parameters that are taken into consideration when assessing the value of developing ocean energy industry. The economic models described below have been used in relevant studies in order to analyse potential economic benefits.

### 6.3.1 Basic Elements of an Economic Model for Ocean Energy Valuation

According to [37], an Ocean Energy economic model:

- ü incorporates the current status of country's and global Ocean Energy industries in terms of installed capacity and employment
- ü predicts the likely volume of installed capacity over time (in the country and global)
- ü estimates the possible level of jobs and value associated with various installed capacities
- ü combines the above analysis to provide an overall picture of the jobs and value arising

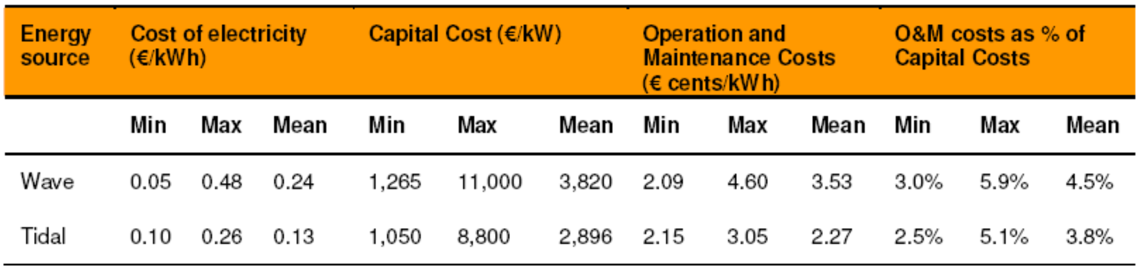
The Ocean Energy economic model used by analyses potential economic benefits under nine different wave and tidal scenarios: each run using optimistic, central or pessimistic technology development and deployment scenarios - onto each of which an additional set of three scenarios for export potential are superimposed [37]. The nine scenarios therefore examine sensitivities and differing scales of wave and tidal device deployment and varying export opportunities. A number of evidence-based assumptions have been used to build up the scenarios including: potential deployment patterns for wave and tidal devices; likely costs of deployment and electricity generation, expected learning rates for wave and tidal technology development, likely future grid capacity, subsidy offerings for Ocean Energy technology development, and the potential job requirements in the Ocean Energy supply chain. The sensitivity analysis is used in order to vary these assumptions and to provide an evidenced economic valuation.

### 6.3.2 Review of technology costs

Statistics Summary for technology costs

Information on the estimated costs of deploying wave and tidal technologies can be extracted from a number of reports as mentioned for the Irish case in the relevant study [37]. The table below provides a summary of the maximum, minimum and mean results for a number of cost parameters (cost of electricity, investment cost, operation and maintenance costs) as reported in previously published research documents.

Table 3: Costs for Tidal and Wave energy



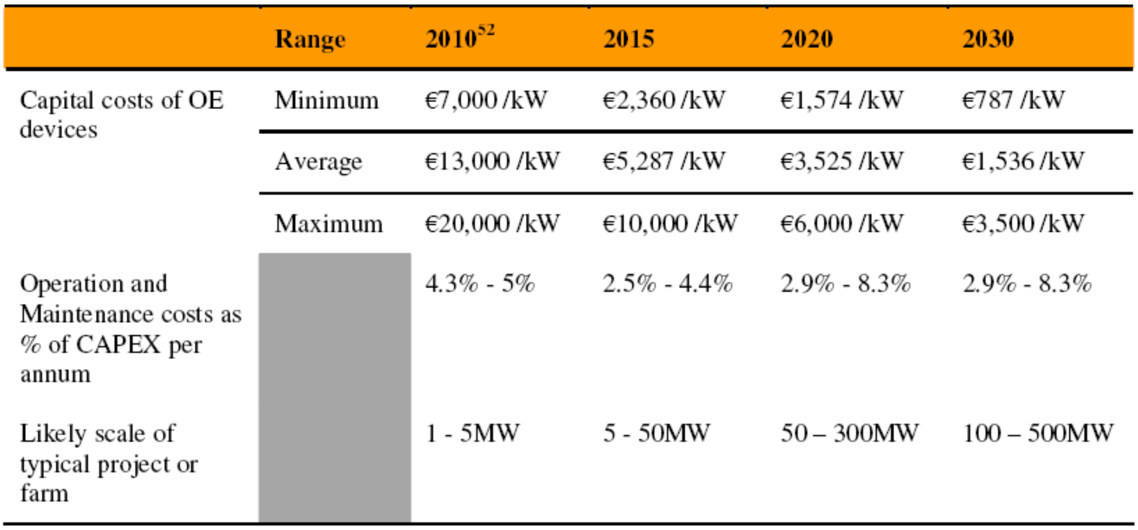
| Energy source | Cost of electricity (€/kWh) | | | Capital Cost (€/kW) | | | Operation and Maintenance Costs (€ cents/kWh) | | | O&M costs as % of Capital Costs | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Min | Max | Mean | Min | Max | Mean | Min | Max | Mean | Min | Max | Mean |
| Wave | 0.05 | 0.48 | 0.24 | 1,265 | 11,000 | 3,820 | 2.09 | 4.60 | 3.53 | 3.0% | 5.9% | 4.5% |
| Tidal | 0.10 | 0.26 | 0.13 | 1,050 | 8,800 | 2,896 | 2.15 | 3.05 | 2.27 | 2.5% | 5.1% | 3.8% |

The Irish report examined the specific parameters from which the economic value of Ocean energy (wave and tidal) could be determined [37]. The broad range of information required was derived from questionnaires that were addressed to various stakeholders in Ireland and can be listed as following:

- Capital costs (investment cost)
- Operation and maintenance costs
- Irish and global deployment plans
- Appropriate aids and subsidy required
- Employment

It should be noted that there was no visible differentiation between wave and tidal energy in terms of cost, capacity and the appropriate subsidy and aids, as they are both at an early stage of development. However, at a further stage future economies of scale may vary widely.

Table 4: Estimated ocean energy costs and project size [37]



| | Range | 2010[52] | 2015 | 2020 | 2030 |
|---|---|---|---|---|---|
| Capital costs of OE devices | Minimum | €7,000 /kW | €2,360 /kW | €1,574 /kW | €787 /kW |
| | Average | €13,000 /kW | €5,287 /kW | €3,525 /kW | €1,536 /kW |
| | Maximum | €20,000 /kW | €10,000 /kW | €6,000 /kW | €3,500 /kW |
| Operation and Maintenance costs as % of CAPEX per annum | | 4.3% - 5% | 2.5% - 4.4% | 2.9% - 8.3% | 2.9% - 8.3% |
| Likely scale of typical project or farm | | 1 - 5MW | 5 - 50MW | 50 – 300MW | 100 – 500MW |

<u>Comparison of technology costs for wave and tidal ocean energy with offshore wind energy</u>

It is also worth comparing costs related to wave and tidal energy with some of the most recent estimates for onshore and offshore wind, as the latter are renewable technologies that have a great potential to compete with Ocean Energy development and deployment. According to the European Wind Energy Association (EWEA), on average, the expected <u>investment costs (capital costs)</u> for a new offshore wind farm are currently in the range of 2.0 to 2.2 million €/MW (€2,000 to €2,200 per kW). Whilst this is lower than the mean value seen across the data sources reviewed for wave and tidal energy (€3,820/kW and €2,896/kW) it is significantly above the minimum values observed: €1,265/kW and €1,050/kW for wave and tidal respectively. The EWEA have also provided estimates for the <u>operation and maintenance</u> costs of offshore wind farms in 2006 and for 2015, being 1.6 €cents/kWh and 1.3 €cents/kWh respectively (based on a capacity factor of 37.5%). These values are approximately 23% and 37%

lower respectively than the minimum estimated value recorded for wave or tidal energy [37, 38].

### 6.3.3 Charges for transportation and export of ocean energy

Ocean energy does not involve or require fuel transportation or storage. However, as with other alternative methods of generating electricity, ocean energy processes need transmission capacity to make them a viable power source. Electricity generated off shore by OTEC and deep-water wave systems typically would send the power through an underwater cable to the electrical grid onshore.

Additionally, all transmission lines can involve issues of access, rights of way and property ownership [4, 38].

Exporting ocean energy entails transmission charges, especially related to the use of the interconnectors (interconnector costs) which have a significant burden on the end-price of such electricity. In Ireland, for example, the access to most interconnectors is determined by yearly capacity auctions where bidders bid for a certain MW capacity. In particular, there are no separate ‘use of interconnector’ charges for the transit of electricity, across the Moyle interconnector and instead, auctions proceeds from the purchase of electricity pay for the annual operating costs of the interconnector [37].

### 6.3.4 Learning rates

Technology learning rates quantify the cost evolution of a technology as it matures and improves. A learning rate is often set as a percentage cost reduction with each doubling of capacity. Factors which determine the learning rate are [37]:

- Economies of scale in production and operation
- Learning and technology improvement in knowledge
- Improvement in investment and financial, management and terms

- More efficient regulation
- Experience

### 6.3.5 Government Support

The critical variables to achieving success are (at least initially) directly within the influence of Government, namely those factors associated with enabling efficient and timely capacity growth: electrical grid capacity; supply chain; efficient regulation, consenting and licensing. To determine whether an intervention may be considered as 'value for money' it is important to ensure that (a) the objectives of intervention are met and (b) the benefit to cost ratios (BCRs) are sufficient [37].

In terms of the objectives of an intervention in Ocean Energy, it is clear that carbon savings, increased security of supply and additional employment are achieved by an island of Ireland OE sector, however the cost of doing so against the counterfactual or indeed competing technologies is better measured or compared by means of BCRs. The results of the Irish report are noted to be highly dependent on the extent of the export market captured [37].

## 6.4 Valuation of Energy Produced and estimations of economic benefits

The economic benefits from the development of the ocean energy industry can be estimated under a number of headings including the energy produced, the environmental benefits through lower emissions, avoidance of hidden subsidies to fossil fuels, regional development, full time employment and gross value added.

### Energy Value

Placing a value on the energy produced is straightforward since it is equal to the cost of electricity that does not need to be produced by other means. The most commonly used approach for estimating the value of the pollution avoided by renewable energy is to place a value on the tradable credits that would be produced in the existence of a developed market for the trading of such credits. The UK has led the way in developing this market. Initial estimates suggested that these credits could be worth in the region of €15,000 per GWh55. This would give a value of about €43 per tonne of CO2. Obviously, such estimates are subject to considerable error as the market is not mature, but the evidence to date from the UK suggests that these values are being exceeded by the prices being paid in the traded green credits market. However, the prices currently being experienced include a high-risk premium and, as the market develops, the risk will gradually be removed and the price will fall [37, 38].

### Hidden Subsidies to Fossil Fuels

Subsidies granted to fossil fuels in the global market keep down the price of electricity generated from oil and gas. Research shows that the total value of subsides to renewables is substantially below what is given to fossil fuels and is probably less than what is provided to nuclear energy alone. In total, it is estimated that, while renewables in the EU receive in the region of €4 billion per annum, subsidies and other supports to fossil fuels amount to over €70 billion, while the nuclear industry receives a further €10 billion. Transfers and tax reliefs to fossil fuels in Ireland have been estimated to exceed €90 million, split between solid fuel and oil and gas, with only around €10 million going to renewables. Thus, the energy output of the ocean energy sector would reduce the cost of these transfers, however it is impossible to accurately estimate this [37].

### Regional Development

An important non-marketed hidden benefit of the development of ocean energy would be its potential to create incomes and employment in lagging regions of the country [37].

In particular, the development of an Ocean Energy industry is expected to provide a benefit through the creation of additional jobs (direct and indirect) and additional investments. The economic impact model used in the Irish Report converts the estimated wave and tidal energy output into estimates of net full time employment and net GVA impacts (Net Gross Value Added (GVA) = the total value of goods and services produced by the economy minus the value of goods and services used to produce the final products). In order to convert the installed capacity into jobs, it is necessary to estimate the number of jobs per MW of energy generated. For both wave and tidal it is assumed that in the early industry there would initially be 15 FTE jobs per MW and that the number of jobs per MW would fall over time in line with the rate of reduction in cost by using the same learning rate [37].

## The Value of Knowledge

Additional value can be created through the prospect that ocean energy generation can become a very valuable wealth creating sector in the future. R&D output is very difficult to evaluate. However, in general, charges on technology development in the ocean energy may be expected to yield returns in the form of:

- A better understanding of the ocean resources and its commercial development.
- Improved and realistic understanding of the cost and timescale implications of ocean energy development
- Potential for exporting ocean energy with consequential improved employment and wealth creation opportunities.
- Consulting, project management and project development expertise with import substitution and export potential.
- Improved university teaching resources in the several technological fields that can be applied in ocean energy research [37, 38].

## 6.5 Environmental Impacts

The long-term environmental impacts of commercialized ocean power are yet unknown. Concerns include interference with sea life migrations, silt build up, sediment deposits. Careful site selection along with rigorous monitoring will be necessary. Certainly, in the area of air quality, ocean power has less impact than most other forms of electricity generation. Once the devices are in place, they produce electricity without emissions [4].

In many parts of the world, particularly those with interests in wave energy, a formal environmental review (in some cases an Environmental Impact Assessment) is needed in any deployment [24]. Lack of knowledge can cause uncertainty for the planners and environmentalists, and therefore potential difficulties in permitting even technically sound and well-developed proposals. While formal environmental reviews may be required for each site, a generic understanding of the issues can contribute to planning efforts around the World.

These generic issues include:

- Impacts on marine life— and especially noise and interactions with fish and sea mammals.
- Effects on coastal processes—such as changes to sedimentation transport and deposition systems.

Environmental Impact Assessments (EIAs) should always be carried out on a site-by-site basis. However, a generic understanding of the issues is important in maximising the effectiveness of the EIAs [24].

The rest of this section reviews the environmental impacts of the main ocean energy sources.

Like most renewable sources of energy, tidal energy is non-polutant and displaces fossil fuels. A tidal barrage protects against coastal flooding within the basin during very high tides, by acting as a storm surge barrier. However, a tidal energy scheme can result in significant changes to the estuarine ecosystem. For each project, a site-specific environmental impact assessment is considered necessary. In the upper estuary away from the immediate effects of the barrage, salinity will diminish because of the reduction in the volume of seawater which enters the estuary. The tidal range, currents and the intertidal area inside the basin are reduced by about half. These hydrodynamic changes can in turn affect both water quality and the movement and composition of bed sediments. Any reduction in water turbidity that may occur can cause increase in the primary biological productivity, with consequences throughout the food chain. Increases in the low-water levels and a general reduction in currents and turbidity will make the enclosed basins more attractive for water-based recreation. In particular, at large sites, the opportunity to build a road across the dam would be very beneficial [1].

The environmental impacts of submerged marine current turbines are expected to be low. Major concerns arise in particular as regards the navigation and fishing. Installations of large-scale, whereby the downstream current velocity is altered significantly across the width of an estuary, may affect the transport of sediments and downstream ecosystems. In the development of demonstration as well as in later commercial plants, site-specific environmental impact assessments are also necessary in order to reliably estimate such consequences [24, 38].

The main areas of environmental concerns related to the ocean thermal energy conversion (OTEC) are the likely change in the oceanographic properties of seawater caused by pumping. Chemical pollution arising from working fluid leaks and corrosion creates environmental concerns. On the other hand, structural effects promoting artificial reef formation, entailing nesting and fish migration can be positive [1].

There is also a potential that OTEC can affect the temperature of the water near a power plant and, when desalinated water is a by-product, it is possible to require disposal of the removed salts [4].

Wave power generation is generally considered environmentally benign. For shoreline power plants, the major negative impacts are visual intrusion and noise from air turbines. Near-shore and offshore plants may constitute obstacles to coastal marine traffic and, when deployed in large numbers, may promote modifications to coastal dynamics. Other consequences, namely on the ecosystems, on fishing and on recreation and tourism, may also occur. Most of these burdens can be minimised and, in some cases, eliminated. In order to assess all these consequences, a detailed environmental cause-and-effect study of any intended deployment is needed. A strategy for the assessment and quantification of environmental impacts needs to be developed [1, 24, 38].

## 6.6 Cost-benefit analysis

Cost-benefit analysis attempts to measure all costs and benefits of an intervention in monetary terms, adjusted for the time value of money (known as discounting), in order to provide the ‘present value’ of all costs and benefits, which may then be expressed as a Benefit-Cost Ratio (BCR). BCR values greater than one indicate that the monetary value of the benefits of the intervention outweigh the costs of setting it up and running it. In economic theory, the policy/intervention under investigation should be adopted if it has a positive net benefit.

Some of the advantages of CBA described in [37] include:

- it can give an indication of costs and benefits over time and provides estimates of what costs and benefits are expected to be, thus, it informs investment decisions by providing robust appraisal

- it allows comparison between different scenarios
- it provides a sound value for money technique, which is becoming increasingly important as part of public sector investment decisions on projects and programmes
- it supports the more efficient allocation of resources

In general, the cost of generating electricity from ocean energy mostly involves the research and development of prototypes and, later, the construction or purchase of equipment and facilities. Operations and maintenance carry significant costs as well. Some in the industry hope that the long experience of the off shore oil and gas extraction industry could help them produce durable equipment to survive the harsh conditions in the sea. The predicted costs of wave power, in particular, have been falling against that of fossil fuels [4].

In the Irish economic study the costs and benefits were discounted using a discount rate of 3.5%, guidance in order to bring all of the monetary cost and benefit values into present values which can be compared against each other [37]. For both the wave and tidal industries, it is clear that the benefits created are significantly greater than the subsidy costs required by 2030. The benefits from tidal although very positive under some scenarios are lower than those from wave. This is due to the more limited tidal resource, and that Northern Ireland GVA figures are slightly lower than those for the Republic of Ireland. It is expected that as the Ocean Energy industry develops the number of Full Time Employment jobs per MW will decrease in line with greater efficiencies and economies of scale. The modelling has taken this into account by reducing the employment intensity (FTE jobs/MW) at the same rate as the technology learning rate. It would also be expected that GVA per head would increase under these circumstances to a level proportional to the associated Ocean Energy economic value per MW of installation or output [37, 38].

The World Energy Council estimates that electricity from “arrays of mature devices located in promising wave energy sites” could cost from 5 cents to 10 cents per kilowatt-hour (kWh). 17 In fact, the Limpet, an on-shore oscillating water column device, began commercially generating electricity in Scotland in late 2000. At the time, the expected cost of Limpet's electricity was 7 cents to 8 cents per kWh, already nearly competitive with the non-renewable price of about 5 cents. And according to the Electric Power Research Institute (EPRI), the cost of ocean electricity production will drop significantly as the volume of production increases, as usually happens in the development and commercialization of any new technology [4].

However, as regards the appropriateness of using the method of cost benefit analysis in the case of ocean energy, there are some concerns. Some of the challenges and difficulties of using CBA include:

- estimating total costs – accounting for different types of costs is difficult and it should be recognised that this CBA has only taken into account the governmental cost of providing the subsidy. There is no consideration of private or social costs.
- capturing benefits – in terms of performance against selected outcomes; and in dealing with persistence effects (estimates of how long the benefits will last) and discounting over time
- benchmarking the findings to establish relative returns compared to initiatives seeking to achieve similar outcomes, and ensuring that BCRs are used in an informed way, e.g. in the context of understanding the non-monetary outcomes that may be delivered by projects [37].

Two difficulties are identified when adopting a highly formalised approach such as cost benefit analysis in the case of ocean energy [37]:

a) Only those effects that can be quantified are included in a formal Cost Benefit Analysis (CBA). Important non-quantifiable impacts such as the contribution to a better regional balance of economic activity or the improvement of the security of supply cannot reliably measured. Besides, the most difficult according to [37] is the evaluation of R&D expenditure, since it entails a cost to the economy but simultaneously provides the value of the knowledge created as a benefit.

b) The second difficulty arises due to the long payback period and the extreme uncertainty that would exist in relation to a policy to develop this industry. A time-period of 20 years would be quite normal for the evaluation of capital expenditure, where recognisable annual returns could be identified for the period.

However, in the case of ocean energy, the returns really depend on the outcome of the process and cannot be predicted with any degree of confidence.

# 7 Conclusions

Each system has its own advantages and disadvantages. Several common points to these four main technologies stand out.

The advantages are:

- Reduction in the use on fossil fuels.
- Source of energy is free, renewable and clean.
- Energy is free once the initial costs are returned.

The disadvantages are:

- At the time being, the amount of the produced electricity costs more than the one produced from fossil fuels.
- It has impact on the wild life.
- Technologies are still being developed.
- It is hard to send the produced electricity onshore

Tidal and wave power

Advantages

The advantages of tidal and wave energy use over fossil fuels are many. Some impressive benefits are the following.

- High efficiency: Coal and oil are at 30% and tidal and wave power is about 80%.
- Protection of the shoreline through the whole procedure
- Small optical impact.
- Continuous exploitation.

Disadvantages

It can only be used only where there is enough tidal or wave motion.

Barriers need to be constructed of salt resistant parts and therefore there is a higher cost.

- Prevention of the movement of large marine animals and ships due to the large size.
- Prevention of the fish migration.
- Disruption of the fishermen's lives.
- Energy can only be produced if there is enough tidal differential.
- It is limited because the tide's speed is never being increased or decreased.
- Very high cost
- Potential flawed devices if constructed with cheap materials.
- Extreme weather conditions can create unexpected situations.
- Very few locations (at around 20) are considered suitable for this kind of stations [39-44].

OTEC

Advantages

- Parallel products can be produced such as potable water.
- inexhaustible supplies of energy because of the solar energy received by the tropical ocean surface

Disadvantages

- This kind of technology can only be implemented at locations with 40 degrees Fahrenheit difference.
- Disruption of marine life.
- Low interest in funding, due to small scale test of these applications [45-47].

### Offshore wind energy projects

It is a very new technology in the stage of development, so further improvement should be made in order to become more competitive against it's main competitor, the inland wind farm.

Studies have shown that the payback percentage can be quite high, which gives investors insurance. The world wide investment on this kind of technology was increased during the 2009-2010 period.

#### Advantages

- There are more powerful winds offshore than inland at 40% percentage.
- Less visual impact than the inland wind farm because of the distance from the shore
- Easier transportation of the parts at the construction stage because of the advantages of the ships over the trucks or trains when moving very large cargo.

#### Disadvantages

The main disadvantage of this techology is the high cost. Such structures should be extremely durable to withstand extreme weather conditions that may occur away from the coast. The installation cost of such project in 2010 was appriximatelly $5 million per megawatt of capacity, when the corresponding project on land cost the half [48, 49].

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