Applicability and potential of wave power in China

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Master’s Thesis in Energy Systems
Preface

This study was carried out as a final thesis at the Master Program in Energy Systems at the University of Gävle.

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Abstract

Wave power is renewable energy which is environmentally friendly. Unlike most of renewable energy resources, wave energy can produce power all the year. The wave energy is stored in the ocean worldwide and highly concentrated near the ocean surface. It can be captured by wave power devices. Wave power is considered as a competitive energy resource in future.

Waves are generated by wind blows across the surface of sea. Wave energy is one kind of mechanical energy which will be used for electricity generation. Wave power can’t be used directly to generate electricity; at first the wave energy is converted into the other form of useful mechanical energy and then converted into electricity. Wave power has a high potential to be captured and used for generating electricity in future as the technology develops further.

Wave energy has been used since 1890s. There is a lot of energy stored in waves. 94% energy of the ocean stored in the wave, and the other 6% is tidal energy. Only small a part of the wave power is used for commercial electricity generation today.

The China is a developing country with a very large population which annually consume about 3073TWh electricity of which 496TWh is from renewable energy. The wave power was less than 1GWh in 2007 (reference from International Energy Agency). The World Energy Council has measured the total useful power of the ocean wave energy to be more than 2TW in the world and corresponding to 6000TWh per year. There is about 70GW useful wave power resources in China, equivalent to an annual useful wave power resource of 200TWh.

The lowest capital cost for the wave power system is today around 0.1Euro/kWh. China will in the future focus on the development electricity generation by wave power. There will be hundreds of new wave power plant built in China during the next twenty years, and the total installed capacity will be larger than 1GW at 2030, which delivers 3TWh annually. This corresponds to less than 1 percent of the total use of electricity in China.

This thesis focuses on the functionality, efficiency and economic pay-off of existing ocean wave power systems, as well as how easy the ocean wave power can produce electricity. Firstly it discusses the physical concepts of wave power, and then focus on the existing wave power systems around the world. It is concluded from the Chinese sea characteristics and the designed conditions of different wave power systems, that the Pelamis and Oyster wave power converters are the best suitable systems for China.

Key words: renewable energy, wave power, efficiency, oscillating water column.
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1 Introduction

1.1 The current status in world

In recent years the global warming problems getting more attention as well as the fossil fuel will be spent in about one hundred years. All over the world are focusing on the renewable energy utilization, trying to use less fossil fuel to decrease the green house gas emission. Under this situation it brings the greatly opportunity for the renewable energy to develop.

The renewable energy has two great advantages compared to fossil fuels. Firstly the renewable energy resources have no green house gas emission; secondly the renewable energy will be the future energy when fossil fuels are spent. The renewable energy resources include solar power, tidal power, wind power, hydro-power, wave power, geothermal power and so on.

The solar power and wind power have been widely used as the commercial energy resource, and highly developed during recent years.

1.2 The advantage and disadvantage of renewable energy resources

1.2.1 Hydro-power

The hydro-power is the most widely used renewable energy source in the world, 20% of electricity is produced by hydro-power. \[1\] Hydro-power has the highest electricity converted efficiency nearly 80% compare with the second highest bio-energy 35% (the same as the fossil fuel).

During construction of the hydro-power station it will release large amount of CO\(_2\) and other green house gases, the dam and reservoir has large influence to the local environment and ecology.

1.2.2 Wind power

The wind power is the most successful renewable energy; the wind power has nominal capacity of 159.2GW, and produced 340TWh electricity per year which is 2% of electricity use worldwide. \[2\] The wind power device is a highly developed technology; the wind turbine capacity factor (the ratio of actual electricity production in a year to the theoretical maximum) is nearly 20% which is very high in renewable resources.
The largest problem in wind power generation is the intermittent wind source, so the wind power turbines can’t operation all the time, it just could produce electricity when the wind speed is larger than 3m/s. The wind power density is not so high, it’s about 0.1kW/m² (the wind speed is 4m/s) to 0.8kW/m² (the wind speed is 7m/s). The wind device has large sound and visual impact, so it’s better to installed far away from resident.

1.2.3 Solar power

Solar power is a recently developed technology; it can be used for both heat supply and electricity production. It just provides 0.02% of the world electricity use, but the production will be double in every two years. The solar power device is very flexible; it can be installed everywhere, even on the roof of your house.

Like the wind power the solar power does not deliver electricity continuously, it can produce electricity when there is incoming sunlight. Normally in country like Sweden the maximum solar power density is near 1kW/m² at summer, but the efficiency of solar absorber device is just nearly 15% at the highest, so the solar power devices need larger ground area to get the same nominal capacity compare to other renewable energy resources. The investment for solar photovoltaic device is much higher than others, it’s about 5000Euro/kW for solar power, and it’s just 2000Euro/kW for wind power and wave power. Normally solar power device has 1000 operating hours in a year and it is 2000 hours for wind plant, that’s mean the specific investment for solar power is 5Euro/(annual delivered kWh) and for wind power is 1Euro/(annual delivered kWh). In 20 years pay back time the capital cost is about 0.38Euro/kWh for solar power and just 0.075Euro/kWh for wind power. (The calculation can be found in Appendix)

1.2.4 Bio-energy

Bio-energy is a very clean energy resource, though it will release CO₂ during burning, but the amount is very little, and will be absorb during photosynthesis by plants. And the bio-energy can be used for CHP plant just like fossil fuels, and make the efficiency very high, for electricity is nearly 35% and the rest heat will be used for district heating.

The only disadvantage of bio-energy is that the growth of plants is relatively slow, if the human use more bio-energy than its growth the local economy would be destroyed, so use the bio-energy should have a long-term perspective.

1.2.5 Wave power

Wave power has the highest power density in renewable energy resources, about 5kW/m to 100kW/m (wave power per meter width of the crest); and the wave power can produce
electricity continuously, so make wave power more suitable for electricity production. Wave power has the least environment impact and low capital cost.

The wave power is a new field, most of the technology is in a developing stage, so the efficiency of the wave power device is not high, and the cost for construction is high. Since the wave power device capture the sea water wave, the structure need to be withstanding the rough weather and the corrosive sea water. The wave power electricity generation is highly depended on the sea characteristics, which means that wave power devices should be utilized in the high wave power density area.

1.2.6 Tidal power

The tidal is generated by gravitational interaction among the earth, sun and moon. Like wave power the power density of tidal power is much higher than wind power and solar power, but unlike wave power which is varying all the time, the tidal is comparatively stable. Tidal power has higher efficiency and simpler technology (similar as hydro-power), which makes tidal power easier to produce electricity than wave power.

Like wave power, not all the tidal area is suitable for electricity generation, and the sea water is corrosive for the tidal power devices. Tidal power stations are almost always large project with large structure; this means that during construction it would influence the local environment and economy.

1.2.7 Geothermal power

Geothermal power is similar to traditional fossil fuel plant, except that geothermal plant uses geothermal energy to heat water, and fossil fuel plant burning fossil fuel to heat water. The geothermal energy can be used as CHP plant for increasing the efficiency. The technology of geothermal is highly developed, and worldwide 0.7% of electricity is produced by geothermal energy.

Because of the geothermal power mostly storage in deep earth, the construction of geothermal power plant is comparative complex. During its operation, the water will absorb some harmful gas such as CH₄, NH₃, H₂S and CO₂, and release to atmosphere during condensation.

1.3 General introduction of the wave power

The ocean waves are mechanical waves which are generated by wind blowing vastly enough over the sea surface and transferring energy from wind to wave. Because of the circulars movement of particles near surface, waves move up and down, back and forth along the surface of the sea.
In general wave power can’t be used directly to generate electricity. Wave energy should first be captured and converted into useful mechanical energy and then use this form of mechanical energy to generate electricity. All those processes perform in the wave power devices.

The wave energy is been considered as the complementary energy source to the other renewable energy resources such as solar energy and wind energy. Unlike the commercially used renewable energy, wave power just began to develop now. Wave power has the huge potential and applicability around the world, especially on the coastlines.

In Fig. 1.1 shows the wave power level all over the world. We can see that New Zealand and Argentina has the highest wave power density (100kW/m) in the coastline worldwide.

![Fig. 1.1 The approximate wave power level distribution in the world, unit kW/m. (Resource from AEA, www.aeat.co.uk)](image)

Though there is 2TW useful wave power in worldwide, equivalent to an annual useful wave power resource of 6000TWh. The practical potential to capture the wave power and used for generating electricity would be much less than this number because of some constraints, such as technical and economic problems. Still those small parts of wave power can bring us lots of energy, and become one of the most useful renewable energy resources.

The history of wave power utilization back to 1890s, but there’s still just small parts of wave power which is practically used. Portugal has the world’s first commercial wave power farm in the world, called Agucadoura Wave Park (AWP). This has total 2.25MW nominal capacity with three 750kW generation device. It has been operating since September 2008. [2]
1.4 General wave power in China

China has 18,000 kilometers long coastline, and 6960 islands with different sizes. The useful resource of ocean wave power is about more than 70GW, so there’s huge potential to utilize wave power in China. In 2007 the wave power just produced less than 1GWh electricity in China[4].

China started research wave power in 1982. At beginning China focused on the small marine wave power devices, such as lighthouse and small power devices used in the ships.

The first wave power station in China established in Guangzhou in 2005, with the installed power capacity 50kW and produces about 26MWh per year.[5]

The largest wave power station in China has a generation capacity 100kW, located in Shanwei, Guangdong province. This wave power station is in operation since 2005 and the annually electricity production is about 53MWh.[4]

China has established Department of Energy in 2009, and will focus on development of renewable energy include wave power. China prepared to construct several large wave power stations (nominal capacity larger than 1MW) in the coast of Guangdong, Fujian, Hainan, Zhejiang provinces before 2020.

1.5 The objective

This thesis described several wave power generation systems and their advantages, disadvantages. Finding out the wave power generation systems which are suitable for Chinese wave characteristics is the objective of this thesis.
2 Physical concepts

Waves are generated by wind blowing across the surface of sea. Initially wind blows along the calm surface of sea, and the tangential stress on the interface between the wind and sea cause the formation of wave, then the wind blows on the upwind side of the wave and cause pressure different between upwind and downwind of wave further cause the wave growth. During those processes the energy transfer from wind to wave.

There’re three main factors that influence the size of waves:
(1) Speed of wind,
(2) The time wind blows the wave,
(3) The fetch, the distance over which the wind excites the waves.\[7\]

The stronger the wind and over longer the time it blows the larger waves (larger wave height and velocity) emerges.

2.1 Characteristics of wave

There are four main elements in the wave which influence the wave energy characteristics:
(1) Wavelength unit meter, \( \lambda \);
The wavelength is defined as the distance between two consecutive crests or troughs.
(2) The wave height unit meter, \( H \);
The wave height is defined as the height difference between crest and trough.
(3) The period time, \( T \);
The period of the wave is defined as the time period used for two consecutive waves crest to pass though a fixed point.
(4) Seawater density unit kg/m\(^3\), \( \rho \);
The seawater density is normally a little above 1000kg/m\(^3\), around 1030kg/m\(^3\).

Fig. 2.1 below shows some elements of a typical sinusoidal wave.
**Fig. 2.1** A typical sinusoidal wave

In a period the wave just propagates through a wavelength, so the velocity \( v \) of the wave has the relationship with the wavelength and period given by:

\[
v = \frac{\lambda}{T}
\]

### 2.2 Deep water wave and shallow water wave

The deep water wave is the wave with a sinusoidal profile, and the depth of water \( d \) is larger than half of the wavelength \( \lambda \).

The shallow water wave is the wave with a sinusoidal profile and where the depth of water \( d \) is less than a quarter of wavelength \( \lambda \).

The Fig. 2.2 shows the different particle movement in both deep water (A) and shallow water (B) in ocean wave.
**Fig. 2.2** The particles movement in ocean wave. *A* is in the deep water and *B* is in the shallow water.

The movement of particle in deep water is a circle, and it’s an ellipse in shallow water. The orbits of particle movement decrease as the depth increase in both deep water and shallow water. The larger orbits contain more wave energy so the wave in deeper location has less energy. This means most wave energy is stored near the surface of the sea.

### 2.2.1 Deep water waves

Deep water waves are the wave with sinusoidal profile, and the depth of the sea is larger than half of the wavelength (\(d > \lambda/2\)). Some of the ocean wave is of this type.

The formula for the velocity in the deep water wave is shown below:

\[
v = \frac{gT}{2\pi}
\]

Where \(g\) is the acceleration due to gravity normally is 9.81m/s\(^2\).

Because of \(v = \lambda/T\), so

\[
\lambda = \frac{gT^2}{2\pi}
\]

The formula of the deep water wave power density is given by:

\[
P = \frac{\rho g^2 H^2 T}{32\pi}
\]
Where P is the wave power per meter width of the crest, unit kW/m. \( \rho \) is the seawater density.

In the deep water waves, 95% of wave energy stored between the surface and the depth equal to \( \lambda/4 \). So it is economic and optimal to capture the wave energy in this depth.

### 2.2.2 Shallow water wave

For the shallow water waves, which may found on the coastline, the depth of the sea has influence on the velocity of the wave, the less deep of sea the less velocity of the wave, according to the formula below:

\[
v = \sqrt{gd}
\]

Where \( g \) is the acceleration due to gravity and \( d \) is the depth of the sea.

From this formula, it’s noticed that the velocity of the wave is decreasing when wave is closer to the shore, due to the depth decreases from deep water ocean to shore.

The same happens with the wave power. The interaction of the seabed and the wave, means that wave energy is lose because of the friction between wave and seabed. The wave power loss is about several watts per meter of crest width, so the useful energy is decreasing. Furthermore, when wave reach the shallow water, the shore will cause breaking wave. Breaking wave appears when the wave amplitude reaches a critical point, and then lots of wave energy will transfer into turbulent kinetic energy, and will cause serious damage in the wave power generator.

Therefore it’s important to analyze the state of the wave in the shallow water before it is installed near shore wave power device.

### 2.3 Intermediate depth waves

The intermediate depth waves is between deep water waves and shallow water waves, the depth of water is between \( \lambda/2 \) and \( \lambda/4 \), and their characteristics is influenced by water depth and period.

### 2.4 Real sea characteristics

The deep water wave and shallow water wave are simply and monochromatic waves, real sea wave which is varying in the direction of wave, wave height, wave velocity all the time.

For the ocean wave in the real sea, the average power density formula is given by:
\[ P = \frac{H^2 T_e}{2} \]

Where \( P \) is the wave power per meter width of the crest, unit kW/m. \( H_s \) is so called significant wave height, unit meter, which is the average wave height of the one third of largest waves. \( T_e \) is the average period of wave, unit second.

The waves are varying all the year, so the value of \( H_s \) and \( T_e \) are not constant, leading to the wave power density (\( P \)) varying. In order to determine the annual average power level, we use the wave weight factor (\( M \)), which is the number of hours sea state is at a special power level.

The annual average power level (\( P_{ave} \)) unit kW/m is shown below:

\[ P_{ave} = \frac{\sum P_i M_i}{\sum M_i} \]

Where the wave with the power density \( P_i \) occurs \( M_i \) hours annually. [8]
3 Wave power technology

3.1 General introduction to wave power converters

Most wave power converters need constant and powerful wave flows to generate electricity, but the states of ocean are not like this. Wave power is a very unstable energy resource, so it is not so easy to capture and convert it into electricity. The wave power device should be able to convert wave energy into stable, concentrate and continuous useful mechanical energy, in order to be used for electricity generation.

There are several kinds of wave power devices which are used worldwide in the existing wave power systems, including Pelamis, Oyster and LIMPET (one kind of oscillating water column).

3.1.1 The structure of wave power device

The structure of wave power converter may be installed on the seabed or seashore with a stable frame, but some part of the structure should be able to react with the movement of the wave in order to extract the wave power. Other types of wave power structures are floating on the sea surface with a stable frame. The main part of the floating structure must remain reasonably stable, and the device inside the structure should be able to move with the wave.

The most important part of the structure of wave power converter is its physical size, because the size will affect the performance of the converter, such as the efficiency, the install capacity and the life-span and. Generally the best size of the structure of wave power converter can be estimated by measure the volume of seawater involved in the particle orbits in a wave, which can capture all of the wave energy. The wave characteristics (the wave height and time period) are varied all over the world, so building the structure of the wave power converter should according to the local wave condition.

3.1.2 Some nature shortcomings in wave power technology

The average wave power is varying from 1 to 100kW/m worldwide, and 5 to 25kW/m in Chinese coastlines and near seas. The wave power cannot be directly used for electricity generation, it has to convert to mechanical energy first, this given a low efficiency, just a few part of the wave power can be convert to electricity in the wave power devices. There is the other problem, powerful storms which are harmful for the wave power device; the corrosive salt water will bring serious problem to the wave power device too. The maintenance of the wave power devices is very expensive, and makes the selection of the optional place to install
wave power device very important. The development of the technology needs to solve those problems in wave power devices.

### 3.2 Classification of wave energy converters

The wave power converters can be classified in several ways, according their configurations, their locations, their geometry and orientations.

#### 3.2.1 Different configuration of wave power converters

According the configuration of wave power converters, they can be classified into main four types:
(1) Heaving float wave power converters;
(2) Pitching wave power devices;
(3) Oscillating water column;
(4) Surge wave power devices.

#### 3.2.2 Different in location of wave power converters

According the location of the wave power converters, they can be classified into three types below:
(1) Fixed devices on the seabed, located in shallow water;
(2) Floating devices on the surface of the seawater, located in deep water;
(3) Located in intermediate depths.

#### 3.2.3 Different in geometry and orientation of wave power converters

According the different geometry and orientation of wave power converters, they can be classified into:
(1) Terminator wave power devices;
The principal axis of this kind of device is parallel to the wave front.
(2) Attenuator wave power devices;
The principal axis of this kind of device is perpendicular to the wave front.
(3) Point wave power absorbers.
The size of this kind of device is relative small compare to the wavelength, so it’s considered as absorbing wave energy in point.
4 Oscillating water column technology

4.1 General introduction of oscillating water column

The oscillating water column (OWC) is the major type used in wave power generation in China, and it’s one of the most widely used in the world too. The oscillating water column is mostly fixed on the seabed or shoreline.

The processes that wave energy is converted into electricity in the OWC device are the following:
(1) The structure of oscillating water column captures the wave energy, and the wave energy will be converted into the compressed air (converts the wave energy into pneumatic energy) in the chamber of the OWC;
(2) Then the compressed air pass though the pneumatic turbine makes turbine to rotate (converts the pneumatic into mechanical energy);
(3) Finally the rotating turbine turns the generator for producing (converts the mechanical energy into electricity).

Since the oscillating water column devices need three processes to convert wave energy into electricity, the totally efficiency of the OWC system very low. The relation between total efficiency and the three parts of energy is shown below:
Total efficiency = Chamber efficiency * Turbine efficiency * Generator efficiency

4.1.1 The structure of the oscillating water column device

The oscillating water column device is fixed on the shore, see the Fig. 4.1 below.

Fig. 4.1 The structure of the oscillating water column device.
From Fig. 4.1, we can see that this is a simple structure of the oscillating water column. The angle of the shore surface is approximate 45° to the horizontal which is proved to be most efficiency. It consists of three main parts: chamber, pneumatic turbine and the generator.

The part of structure which is empty, and contains air, is the chamber. It allows the waves to pass into the structure, capture the wave energy and convert the wave energy into pneumatic energy. The chamber must be hermetic closed so the energy in air would not lossed due to air flows outside of chamber. The air in the chamber can just go into the pneumatic turbine or come from the pneumatic turbine.

The pneumatic turbine used in oscillating water column system usually is a wells turbine, which is a low-pressure air turbine with the incoming air vertical to the blades. There is also the other kind of pneumatic turbines called Denniss-Auld used in OWC systems in Australia.

Wells turbine is one of the best turbines which are suitable for aerodynamic, because the direction of rotation is constant and never changes, whether the direction of air is from chamber to the turbine or from turbine to the chamber. The explanation for rotation of the turbine never changed is because of the shapes of the blades (see Fig. 4.2). Independent fo the direction of the air is in or out of the turbine, the effect of the air will force the turbine to rotate in one direction.

The efficiency of the wells turbine used in oscillating water column system is usually from 0.4 to 0.7.

![Diagram of the oscillating water column system](image)

*Fig. 4.2 The wells turbine [3]*

The generator is connected to the pneumatic turbine and when the turbine is rotating, the generator will produce electricity.
4.1.2 The principle of the oscillating water column

In Fig. 4.3 we can see that the wave direction is from off-shore to on-shore, and one crest of the wave just entering into the structure of oscillating water column, and then flows in the chamber. The crest occupies some volume of the chamber (compared with the original one without wave), so the air in the chamber is compressed and the air pressure is higher than atmosphere. Now the wave energy is captured and converted into pneumatic energy.

![Diagram of oscillating water column](image)

**Fig. 4.3** The crest of wave enters into the chamber.

Due to the pressure different between chamber and atmosphere, compressed air is forced to flow though the wells turbine to the outside. When the air flows into wells turbine, the air force will make the turbine starting to rotate and the pneumatic energy is converted into mechanical energy. At the end the turbine turns the generator to produce electricity and mechanical energy is converted into electricity.

This is the whole process how wave energy converts into electricity when crest enters the OWC device.

The same happens when the trough enters the chamber, see the Fig. 4.4.

When the crest passed, the coming is trough, at this moment the chamber is emptier than before. The wave doesn’t occupy so large volume of the chamber, that’s lead to decompression of the air in the chamber. So the outside air is sucked into chamber though the wells turbine. The direction of the air passing though the turbine changed, the direction of air flow is from outside to the wells turbine, and the turbine is forced to rotation by air force.
**Fig. 4.4** The trough enters the chamber.

When the wave crest and trough continue to alternately enter the chamber, the air inside chamber is compressed and decompressed correspondingly, air is pushed out and sucked in wells turbine, the turbine always rotates in one direction and the generator continues to produce electricity. When the next crest comes the circle starts again.

### 4.2 The existing oscillating water column devices

#### 4.2.1 Oscillating water column devices in China.

The oscillating water column is the main type used in Chinese wave power generation. The Chinese first experimental oscillating water column was installed in Dawanshan Island in Zhuhai city with the capacity 3kW (maximum output). The width of the water column is 4 meters, and the length is 3 meters. The average incident wave power density is 4.4kW/m, the average height of waves is 1.5 meters and the period of wave is 6 seconds. The turbine is wells turbine with diameter of 0.8 meter, type of blades is NACA-0021, and number of blades is 10 with the rotation speed is 1500 RPM. The efficiency of the whole oscillating water column is about 1.5%. Because of the structure problem, the height of chamber is too low, so the waves sometimes entering the turbine caused damage to the device, and the station is therefore not good for long time operation. Lots of problems were solved in the 20kW wave power station.

The second experimental oscillating water column has an installed power capacity of 20kW (maximum output), the main concrete structure was finished in 1995, and the wells turbine was installed and in operation in February 1996. The annually average incident wave power
density is 4.4kW/m, the average power output is 4kW, and the average efficiency of the whole OWC system is from 2%.

The largest oscillating water column in China has the nominal capacity 100kW (maximum capacity), located in Shanwei. It has been in operation since 2005. The wave station is connected directly into national grid, the life-span of this 100kW OWC is fifteen years and can withstand the worst storm in 50 years. The width of the OWC is 20 meters, the incident wave height is from 1 to 3 meters, the wave period is from 5 to 7 seconds, and the average wave power density is 5kW/m. The power output varied from 5 to 40kW, and the annual average output is 6kW.

The total efficiency of Shanwei OWC station is about 6%. The cost for all OWC is about 4 million RMB (about 400,000 Euros) equal 4,000 Euro/kW. The wave plant can be operating 525 hours per year and the annual electricity production is 52.5MWh. The specific investment is 7.62Euro/annual delivered kWh. With 20 years pay back time, the capital cost is 0.57Euro/kWh. (The calculation can be found in Appendix)

4.2.2 The oscillating water column device in England

There is a famous oscillating water column station in island of Islay on the west coast of Scotland, called Limpet which is short for Land Installed Marine Powered Energy Transformer.

The Limpet device is built by Wavegen (Wave power company established by Professor Alan Wells in 1992 which is in the leadership in the wave power manufactory field) and Queens University Belfast (QUB). The Fig. 4.5 shows the structure of the Limpet.

![Fig. 4.5 The Limpet OWC in Scotland. (Resource from www.wavegen.co.uk)](image)

The Limpet has the nominal capacity 500kW which is a development of the 75kW experimental Limpet (operated in 1991 to 1999). It is the first shoreline oscillating water column commercial-scale station, and it sited in the best condition for electricity generation. The current wave power device is Limpet 500 which was installed in November 2000,
connected directly to the 11kV United Kingdom grid. It has guaranteed a fifteen years power purchase agreement with the Public Electricity Suppliers in Scotland. [10]

The Limpet is adapted for wave power. The Limpet contains three water columns with a water surface of 170m², the collector width of the device is 21m and the angle of the structure is 40° to the horizontal. It can capture almost the entire wave energy which enters into the water column, and convert it into useful mechanical energy, in order to produce electricity. There are two 2.6m diameter counter-rotating wells turbine installed in Limpet, each turbine drives an induction electricity generator with power 250kW, giving 500kW maximum power output. [11]

The wave enters Limpet has the annual average incident wave power density varied from 12kW/m to 15kW/m. The electricity production in Limpet is about 21kW equal 180MWh per year, which enough to power more than 400 local households. The energy efficiency from wave energy to pneumatic energy is 64%, the average efficiency of the wells turbine is about 40%, the efficiency of generator is 32%, and the average efficiency of the whole Limpet system is nearly 8.2%. [12]

The main structure is made of concrete; 1386m³ concrete material is used for constructing the Limpet. The total cost of the Limpet system is 2.4 million Euros, which means the installed cost is about 4,800 Euro/kW. The annually operation and maintain cost is about 2,600 Euro. The annual operating time of Limpet is 720 hours and the annual electricity output is 360MWh. The specific investment for Limpet is 6.66Euro/annual delivered kWh. With 20 years pay back time, the capital cost for Limpet is 0.5Euro/kWh. [12] (The calculation can be found in Appendix)

4.3 Comparison of OWC systems

There are some comparisons of sea characteristics in both Shanwei and Limpet OWC systems in table 1.

| Table 1: The sea characteristics in Shanwei and Limpet OWC systems |
|-----------------|-----------------|-----------------|
| Device          | Shanwei         | Limpet          |
| Water depth (m) | 8               | 6               |
| Wave height (Hs) (m) | 1.0 to 3.0     | 4.4             |
| Wave period (Te) (second) | 5.0 to 7.0 | 13.4            |
| Incident wave power density (kW/m) | 5 | 12 |

According to the local sea characteristics and device characteristics, the output and efficiency are different. There are some comparisons in Shanwei and Limpet OWC devices in Table 2 and Table 3.
### Table 2: Power output comparisons in Shanwei and Limpet OWC systems

<table>
<thead>
<tr>
<th>Device</th>
<th>Shanwei</th>
<th>Limpet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal capacity (kW)</td>
<td>100</td>
<td>500</td>
</tr>
<tr>
<td>Annual operation time (hours)</td>
<td>525</td>
<td>720</td>
</tr>
<tr>
<td>Annual electricity output (MWh)</td>
<td>52.5</td>
<td>320</td>
</tr>
<tr>
<td>Total efficiency</td>
<td>6%</td>
<td>8.2%</td>
</tr>
<tr>
<td>Operation time</td>
<td>January 2005</td>
<td>November 2001</td>
</tr>
</tbody>
</table>

### Table 3: Economical comparisons in Shanwei and Limpet OWC systems

<table>
<thead>
<tr>
<th>Device</th>
<th>Shanwei</th>
<th>Limpet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total cost (Euro)</td>
<td>0.4 million</td>
<td>2.4 million</td>
</tr>
<tr>
<td>Cost per kW (Euro)</td>
<td>4000</td>
<td>4800</td>
</tr>
<tr>
<td>Specific investment (Euro/annual delivered kWh)</td>
<td>7.62</td>
<td>6.66</td>
</tr>
<tr>
<td>Capital cost (Euro/kWh) 20 years pay back time</td>
<td>0.57</td>
<td>0.5</td>
</tr>
</tbody>
</table>

The current electricity price is around 0.07 Euro/kWh, the capital cost for both Shanwei and Limpet systems are too high.

Shanwei and Limpet OWC system don’t perform very well, the design operation time for both OWC systems is around 2000 hours/year, and it’s just 500 hours/year and 720 hours/year in practical. The reason lead to the low performance of those systems is the low efficiency of turbine and generator. The OWC Company in China has collected a lot of data in Shanwei OWC system, they are focusing on improving the OWC systems now. There will be four 1MW OWC systems constructing in China in next decade. Those systems will have an annual operation time more than 2000 hours, the efficiency will increase to 20% and the capital cost will decrease to 0.05 Euro/kWh.

### 4.4 Advantage and disadvantage of OWC system

#### 4.4.1 Advantage

1. OWC technology has developed for more than thirty years. It is very flexible for all sea characteristics and it can operate very efficient in low wave power density area. So it’s the most popular wave power technology.
2. The pneumatic turbines used in OWC are one direction rotation turbines which are very suitable for aerodynamic.
3. Most OWC systems are located on land off coastline, so they are very flexible to connect to the local grid.
(4) Most of OWC systems are made of steel or concrete, so they have very stable frame and a long life-span.
(5) OWC systems are all remote computer controlled.
(6) OWC system has low maintenance and operation cost.
(7) Low environment and landscape influence.

4.4.2 Disadvantage

(1) OWC systems have a very low total convert efficiency, especially the generator, because of it’s the complex converting processes and the low efficiency of the pneumatic turbine and generator system.
(2) During the construction of the OWC system there are lots of problems, the bad climate condition will damage the structure, and increase the capital cost.
(3) Most OWC systems are installed in coastline where are most shallow water areas, lead to low incident wave power density.
(4) The capital cost for OWC systems are too high, it cannot be used for commercial generation.
5 Pelamis wave power convertor

5.1 General introduction of Pelamis wave power convertor

The Pelamis is named from Pelamis Platurus (one species of sea snake), it is developed by the UK firm Pelamis Wave Power Ltd (formerly Ocean Power Delivery Ltd). Pelamis is one kind of floating and attenuator wave power device which is installed off-shore in deep water area.

![Image](image.jpg)

**Fig. 5.1** The Pelamis wave power convertor. (Resource from www.pelamiswave.com)

Pelamis is the world’s first commercial scale wave power convertor, and being used in the world’s first commercial wave power farm in Portugal in operation since September 2008. [13]

There are three processes that the wave energy is converted into electricity by Pelamis:

1. The wave passes though the Pelamis wave energy convertor and the Pelamis starts to swing upward and downward. This means wave energy is converted into mechanical energy.
2. The swings device turns the power smoothing accumulator to pump and push oil though the hydraulic turbine. The mechanical energy is converted into the other kind of mechanical energy.
3. The turbine drives the generator to produce electricity. The mechanical energy is converted into electricity.
5.1.1 Structure of Pelamis

Pelamis wave power convertor is a floating articulated structure device; consist of several cylindrical sections connected by joints. Each cylindrical section of Pelamis is 3.5 meters in diameter and 37.5 meters long. There are one electro-hydraulic power generate device in each cylindrical section. It contains one displacement turbine and two generators with rated power 125kW.

The speed of the hydraulic ram is 0.1m/s, the speed of the turbine is 1500 rpm and the working pressure of the turbine is from 100Bar to 350Bar (1Bar=$10^5$Pa). [13]

![The internal structure of joint of Pelamis.](image)

A typical Pelamis wave power convertor has an installed power capacity 750kW and is called Pelamis P-750, which consists of four cylindrical sections and three joints, giving the convertor 150 meters long, and 700 tones in weight.

Thanks to the stable frame, the Pelamis has a very good Survival capability. The life-span of the Pelamis is normally from 60 to 100 years, and it can stand against one in one hundred years storm. [14]

5.2 *The principle of Pelamis wave power convertor*

When the waves pass though Pelamis, the cylindrical sections start to swing up and down. In Fig. 5.3, we can see the crest is on the left of the picture and the trough is at the joint and the
cylindrical sections capture the wave energy. The wave energy is converted into mechanical energy.

At this moment the top hydraulic ram is pushing high pressure oil into the hydraulic turbine from one smoothing accumulator and the bottom hydraulic ram is pumping oil from the hydraulic turbine to the other smoothing accumulator. The high pressurized oil passes though the hydraulic turbine drive the turbine to rotation. The mechanical energy of the device converted into mechanical energy of the turbine.

The rotating turbine turns the generator to produce electricity. The electricity is transported though an 11kV or 33kV submarine cable to the grid. Mechanical energy is converted into electricity.

![Image](image.jpg)

*Fig. 5.3 Motion of the Pelamis.*

When the wave trough and crest alternative, the top hydraulic ram is pumping and the bottom ram is pushing, the oil passes though turbine and back to the original smoothing accumulator. Then circle continues.

**5.3 The relation between power output and wave characteristics.**

The Pelamis wave power convertor is designed to be installed in area where water depth is from 50 to 75 meters, and 5 to 10km from the shoreline. The design wave period is 8 seconds, and water height is from 5.5m to 7.5m. The design water power density is 55kW/m.

The Fig. 5.4 gives the relation between power output of Pelamis wave power convertor and the significant wave height when the wave period is 8 seconds. [13] Obviously when the wave period is constant the power output of Pelamis wave power convertor is highly dependent on the wave height, the larger wave height the larger power output. The average efficiency of Pelamis is about 20% to 40% of full nominal capacity. The investment for one P-750 is about 3 million Euros; this is equal 4000 Euro/kW. The annual operation time of Pelamis convertor is 3600 hours and one P-750 Pelamis convertor can produce 2.7GWh per year. [13] The capital cost for Pelamis is 0.083Euro/kWh which is just a little higher than current electricity price. (The calculate can be found in Appendix)
Fig. 5.4 The relation between power output and wave characteristics.

5.4 The existing Pelamis wave farm.

The world’s first commercial wave farm is in Portugal, it is 5km from the shoreline near north of Oporto, called Agucadoura wave farm. The wave farm has nominal capacity of 2.25MW; it consists of three Pelamis P-750 wave power convertors. Those three Pelamis wave power convertors cost about 9 million Euros, and support the electricity use of 1,500 homes electricity use. [15]

The cost for Agucadoura wave farm is divided into several parts, shown in the Fig. 5.5 below.

Fig. 5.5 The cost for Agucadoura wave farm.
The project at the Agucadoura wave farm will install thirty-one Pelamis wave power machine, with a total of 22.5MW electricity output in future.

5.5 Advantage and disadvantage of Pelamis wave power convertor

5.5.1 Advantage

(1) Pelamis wave power convertor is consisting of several cylindrical sections which giving it good wave capture ability.
(2) The power generating system in Pelamis wave power convertor is a hydraulic system which is highly developed and has a high efficiency.
(3) The Pelamis wave power convertor has a strong structure and can withstand bad climate condition and have a long life-span.
(4) The Pelamis is in operation in water depth from 50m to 70m, so it’s very flexible to choose the installed site.
(5) The Pelamis is constructed and maintained on land, which will not be influenced by the bad sea climate.
(6) The Pelamis works very efficient in high wave power density areas.
(7) The capital cost for Pelamis is very low, so it is very suitable for commercial investment.

5.5.2 Disadvantage

(1) The Pelamis is operating off-shore about 5 to 10km from the shore, so it needs long electricity wire to transport electricity to gird.
(2) The Pelamis is a very large machine, which is hard to transport to land to maintain.
6 Oyster wave power convertor

6.1 General introduction of Oyster wave power convertor

The Oyster is a type of pitching and terminator wave power device. It will swing backward and forward due to the wave movement. The Oyster is a hydro-electric wave power convertor, developed by the Aquamarine Power Company located in Edinburgh, Scotland. The Fig. 6.1 shows the structure of the Oyster.

![The structure of the Oyster wave power convertor](www.aquamarinepower.com)

The Oyster wave power convertor consists of two parts: The erection part which is used for capturing the wave energy is a hinged mechanical flap, and it is 16 meters height, and 20 meters width. The other part which is used for connecting the device on the seabed is base. There are two sea water pistons connected to the two main parts, and they will work when the flap swings. [16]

Due to the characteristics of Oyster, it should be installed in the seabed where the water depth is from 10 to 16 meters, so the yellow part of the Oyster wave power convertor can float on the sea surface and capture the wave energy. The Oyster should be installed in the area where the wave power density is larger than 15kW/m.

There are two processes to convert wave energy into electricity by Oyster wave power convertor:
(1) The wave passes though Oyster wave power convertor, the main part of Oyster starts to swing backward and forward. The wave energy is converted into mechanical energy.
(2) The swinging main part of Oyster leads the sea water pistons to move forward and backward, so the pistons pump water in and out into hydro-electricity generator though high and low pressure lines. The mechanical energy is converted into electricity.

Because of the simple structure and processes that convert wave power to electricity, the technology of Oyster is highly developed. The nameplate capacity of Oyster wave power convertor is 315kW. The efficiency of the Oyster wave power device is about 20%, and the estimated cost for Oyster is about 3.3 million Euros per MW nominal capacity which is equal 3300 Euro per kW. The estimate annual operation time of Oyster convertor is 2000 hours. The estimate capital cost for Oyster convertor is 0.12Euro/kWh. (The calculation can be found in Appendix)

6.2 The principle of Oyster wave power convertor.

In Fig. 6.2 and 6.3 we can see how the Oyster wave power convertor works, the direction of wave is from off-shore to shore.

![Fig. 6.2 The wave crest passes though the flap of the Oyster convertor.](image)

In Fig. 6.2 when the crest passes though the flap of Oyster wave power convertor, the force of waves is large enough to push the Oyster move to the same direction as the wave (the Oyster swings forward). The wave energy is captured by Oyster and converted into mechanical energy.

At this moment, due to the flap of Oyster moves forward, the sea water piston is pushed to pump water into high pressure flow line, and then water passes though the line enters the hydro-electricity generator. The mechanical energy is converted into electricity.

![Fig. 6.3 The wave trough passes though the Oyster](image)
As the Fig. 6.3 shows, when the wave crest passed flap of the Oyster, the wave force is decreased, so the Oyster is moving backward. The Oyster pulls the sea water piston to pump the water from hydro-electricity generator though low pressure flow line. When the next wave crest comes, the flap of Oyster is moving forward again, and pumps water to hydro-electricity generator and the circle continues.

### 6.3 The existing wave farm with Oyster

The only one Oyster wave farm is installed at Billia Croo in Orkney, Scotland. This Oyster wave power convertor has the nominal capacity 315kW. The Oyster wave farm is directly connected into National grid power in Orkney since November 20, 2009.

This wave farm just is an experimental project, and after operation and test, they will get data and design the next Oyster wave power convertor which has an installed power of 2.4MW.

### 6.4 Advantage and disadvantage of Osyter wave power convertor

#### 6.4.1 Advantage

1. The large erection part gives the Oyster a very good wave capture ability.
2. The Oyster system has the hydraulic turbine and generator which is very efficiency in power generation.
3. The design water power density of Oyster is larger than 15kW/m which is very flexible.
4. Oyster has a strong structure which can operate in bad climate condition.
5. Oyster is constructed and maintained in land.
6. Oyster has a very simple structure, and the power generation system is on land so it’s very flexible to connect to local grid.

#### 6.4.2 Disadvantage

1. Oyster just can be installed in water depth from 10m to 16m; and those are shallow water areas, so the incident wave power density is low.
2. The installed capacity of one Oyster convertor is relatively small.


7 Other wave power technology

7.1 Wave Dragon wave energy convertor

Wave Dragon wave power convertor is a floating and terminator surge device. There is one experimental project located in Nissum Bredning, Denmark. The main structure is made of concrete and steel close as a reservoir. The structure has doubly curve ramps so that the wave crest can enters in reservoir without lose energy.

Fig. 7.1 The structure of Wave Dragon. (Resource from www.wavedragon.net)

7.1.1 The principle of the Wave Dragon wave power convertor

The principle of the Wave Dragon wave power convertor is very simple; it’s the same as the conventional hydro-power station. See the Fig. 7.2 below.

Fig. 7.2 The schematic of Wave Dragon.

The main structure of Wave Dragon is floating on the sea level, and the wave trough can’t get into the reservoir. When the wave crest comes, it’s higher than the top of the main structure of
wave dragon, so some sea water will enter into the reservoir (the wave energy is captured by the wave dragon), and the level of reservoir will be higher than the sea level. Due to the gravity, the water in reservoir will pass through the hydraulic propeller turbine which is in the middle of the reservoir, and drive the turbine to rotate to produce electricity (gravity energy is converted into electricity) and go out though the turbine outlet, back into sea. \[\text{[1]}\]

There are two processes that wave energy is converted into electricity:
(1) The overtopping sea water enters in the reservoir, stored in it. The wave energy is converted into mechanical energy (gravity energy).
(2) Thanks to that the water level in reservoir is higher than sea level, the water passes through turbine and makes the turbine to rotate and back to the sea. The mechanical energy is converted into electricity.

### 7.1.2 The existing Wave Dragon wave farm

The experimental wave dragon farm is in Denmark with nominal capacity 20kW. It contains 7 low-head Kaplan turbine with a capacity of 2.3kW. It is 58 meters wide, 33 meters long and 3.6 meters height giving the volume of reservoir 55m$^3$. The wave dragon is made of ballast, concrete and steel. The total weight is 237 ton.

The water depth of the location of this wave dragon wave farm is 6m; the wave power density is significant small, 0.4kW/m. The efficiency of the wave dragon is about 20% to 30% of the full nominal capacity.

### 7.1.3 The full-scale wave dragon wave farm

The wave dragon will built a full-scale wave dragon wave power convertor in Pembrokeshire, England. The wave convertor will have a capacity of 7MW and be located 2-3 miles from shore. The water depth is 25m and the wave power density is 36kW/m. The structure of the wave dragon farm will be 300m wide, 180m long and 17.5m in height. The estimated annual electricity output will reach 20GWh.

### 7.2 Finavera wave power convertor

#### 7.2.1 The general of Finavera wave power convertor

The Finavera wave power convertor is developed by the company Finavera Renewables in Vancouver, Canada. It’s a type of floating and point absorber wave power device. It can be installed off-shore and near-shore. It has been successfully tested in the coast of Newport, Oregon.
Fig. 7.3 shows the structure of the Finavera wave power convertor. The floating part is a 6-8 meters long hull with diameters from 3m to 12m, and it consists of turbine and electricity generator. The main part is under the sea surface, contains a unique pump which is normally 20 meters long.

![Image of Finavera wave power convertor](image)

**Fig. 7.3 The structure of the Finavera wave power convertor. (Resource: form www.finavera.com)**

The unique pump in the Finavera wave power convertor is the hose pump called AquaBuoy 2.0 which is a new technical device developed by the ContiTech company Dunlop Oil & Marine. It is used for pumping sea water up into the turbine to produce electricity. [18]

The best water depth for Finavera wave power convertor is larger than 30m. The best wave power density is from 50 to 70kW/m. Under this sea characteristic, the efficiency of the Finavera can reach 35%. A 10m diameter Finavera can have the power output from 150 to 250kW, and can produce 1.5GWh electricity per year.
7.2.2 The principle of the Finavera wave power convertor

![Diagram of Finavera wave power convertor]

**Fig. 7.4** A trough passes the Finavera

The principle of Finavera wave power convertor is very simple, see Fig. 7.4. When a trough passes the Finavera, the floating part is move downward, because the high pressure in the upper pipe the piston is forced to move downwards, the sea water enter valve is opened, and the sea water enters the hose pump. The piston is a one way valve, so the water just can flow from upper pipe to the lower pipe. The sea water out valve is closed; and sea water all enters the lower pipe of hose pump. It cannot flow outside the pipe, which means the pressure inside the lower pipe is increased.

![Diagram of Finavera wave power convertor]

**Fig. 7.5** A wave crest passes the Finavera wave power convertor

When a wave crest passes the Finavera, the floating part is moved upward, the sea water out valve is open, because of the high pressure inside the lower pipe and the one way valve, sea water is forced flow though the sea water out valve into the hydraulic turbine and turns the turbine to rotation, and the rotating turbine drives generator to produce electricity. See fig 7.5.
8 Conclusions and discussion

8.1 Comparison of different wave power systems

There are some comparisons of different type of wave power systems in Table 4.

Table 4: The device characteristics of the different type of wave power systems

<table>
<thead>
<tr>
<th>Device</th>
<th>OWC (Shanwei)</th>
<th>Pelamis</th>
<th>Oyster</th>
<th>Wave Dragon (Denmark)</th>
<th>Finavera</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water depth (m)</td>
<td>8</td>
<td>50-75</td>
<td>10-16</td>
<td>6</td>
<td>&gt;30</td>
</tr>
<tr>
<td>Wave power density (kW/m)</td>
<td>5</td>
<td>55</td>
<td>&gt;15</td>
<td>0.4</td>
<td>50-70</td>
</tr>
<tr>
<td>Efficiency</td>
<td>6%</td>
<td>20%-40%</td>
<td>20%</td>
<td>20%-30%</td>
<td>35%</td>
</tr>
<tr>
<td>Capital cost (Euro/kWh)</td>
<td>0.57</td>
<td>0.083</td>
<td>0.12</td>
<td>unknown</td>
<td>Unknown</td>
</tr>
</tbody>
</table>

8.2 Applicability of different wave power technologies in China

8.2.1 Oscillating water column

China has focus on oscillating water column (OWC) since 1990s, several experimental OWC wave power plants have been operated successfully, and China will construct four 1MW scale OWC systems in different provinces. Currently the efficiency of OWC systems is too low and the capital cost for OWC systems is too high.

Fortunately the OWC have a good potential. As the development of the OWC technology (especially the efficiency of the pneumatic turbine), the wave power company in China estimated the totally efficiency of the OWC system can reach 20%. The 1MW OWC system will be built in China in next decade, and the capital cost will decrease to 0.05 Euro/kWh. At this price the OWC will be widely used for commercial generation.

8.2.2 Pelamis wave power convertor

Pelamis wave power convertor has high efficiency, good performance, long life-span and low capital cost. It is the best wave power convertor for the large wave power density areas and it is the most successful commercial wave power convertor in the world. But Chinese wave power density is relatively low (around 15kW/m), the Pelamis couldn’t be widely use, it just can be used in high power density area.
8.2.3 Oyster wave power convertor

Theoretically Oyster wave power convertor is very suitable for China. It has low limitation in wave power density and it is near-shore fixed and performance in shallow water. The capital cost of Oyster wave power convertor is much lower than OWC systems, and this price will be very competitive in future. It’s very suitable for China.

8.2.4 Wave dragon convertor

Like Oyster the wave dragon has the same advantages, flexible in sea characteristics, near-shore installed and high efficiency in shallow water, in theory it will suitable for China. But the wave dragon technology is not mature, it is just test in a small model, the practicability of the full size is unknown.

8.2.5 Finavera wave power convertor

Finavera is a very efficiency wave power convertor, but it may have low performance in China cause of the relatively low wave power density. Whether Finavera is suitable for China is unknown, it should be test in China.

8.3 The potential of wave power in China

There are some comparisons of solar energy, wind energy and wave energy in table 5.

Table 5: Comparisons of some renewable energy resources in China

<table>
<thead>
<tr>
<th>Energy resource</th>
<th>Average energy content</th>
<th>Annual operation time</th>
<th>Capital cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar energy</td>
<td>1kW/m²</td>
<td>1000 hours</td>
<td>0.375 Euro/kWh</td>
</tr>
<tr>
<td>Wind energy</td>
<td>20kW/m² [H]</td>
<td>2000 hours (on land)</td>
<td>0.075 Euro/kWh</td>
</tr>
<tr>
<td>Wave energy</td>
<td>40kW/m</td>
<td>3000 hours</td>
<td>0.083 Euro/kWh</td>
</tr>
</tbody>
</table>

Wave energy has the highest energy content and annual operation time in those three renewable energy resources. It has a big potential.

The useful wave power resources in China are about 70GW equivalent to an annual useful resource of 200TWh, but the electricity production of wave power today in China is less than 1GWh. The wave power has huge potential in China, especially in Guangdong, Fujian, and Hainan Provinces.

There will be hundreds of new wave power plant constructed in China in next twenty years, and the total installed capacity will be larger than 1GW at 2030. It delivers 3TWh annually and corresponds to less than 1 percent of the total use of electricity in China.
8.4 The future of wave power in China

Chinese policy is focus on developing renewable energy resources, such as wind power, solar power and wave power. The wave power as the least used renewable energy in China has a big potential, because of the large useful wave power resource and good wave climate in Guangdong, Fujian and some other provinces.

The technologies of wave power have been developed for a long time, but it is not very mature. The cost of the existing wave power plant is relatively high, but in future after the wave power is largely used for commercial generation, the cost for wave power generation will decrease to a rational level, and then the wave power will be an attractive energy resource in both China and the world.

No doubt the on land OWC and Oyster systems will be the most widely used wave power generation system in China. If they are combined with newer systems off-shore wave power generation system such as Wave Dragon and Pelamis, these will form the future Chinese wave power generation system.
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Appendix

1 The capital cost for solar photovoltaic system.
The investment for solar photovoltaic system is 5000Euro per installed kW.
K=5000Euro/kW

The operation time for solar photovoltaic system is 1000 hours/year in Sweden.
H=1000 hours/year

1.1 Annual productivity of solar photovoltaic system
1kW nameplate capacity in one year can produce:
W=1kW*1000hours=1000kWh electricity.

1.2 Specific investment for solar photovoltaic system
The specific investment is:
K/H=5000/1000=5Euro/(annual delivered kWh)

1.3 capital cost for solar photovoltaic system
For an annuity loan the sum of mortgage and rent is constant. It is approximately:
a=r/2 +1/n
Where r is the interest rate and n is the pay back time
Normally the r= 5% and n=20 year, and gives:
a=0.05/2+1/20=0.025+0.05=0.075
Capital cost: S=a*K/I=0.075*5=0.375Euro/kWh

2 the capital cost for wind power
The investment for wind power plant is:
K=2000Euro/kW

The operating time for wind power system on the land is:
H=2000 hours

2.1 Annual productivity of wind power system
1kW nameplate capacity of wind power system in one year can produce:
W=1kW*2000hours=2000kWh electricity.

2.2 Specific investment for solar photovoltaic system
The specific investment for wind power system is:
K/H=2000/2000=1Euro/(annual delivered kWh)

2.3 capital cost for wind power system
Under the same interest rate and pay back time, the annual loan is:
a=0.075
Capital cost for wind power system is:
$ S = a * K / H = 0.075 \text{ Euro/kWh} $

**3 The capital cost of the Shanwei OWC system.**

The nameplate capacity of Shanwei OWC is 100kW. The total cost is 400,000 Euro, and so the investment is:

$$ K = 400000 / 100 = 4000 \text{ Euro/kW} $$

The operating hours for all wave power system is 525 hours per year.

$$ H = 525 \text{ hours} $$

**3.1 Annual productivity of Shanwei OWC system**

$$ W = 100 \text{ kW} * 525 \text{ hour} = 52.5 \text{ MWh/year} $$

**3.2 Specific investment for Shanwei OWC system**

The specific investment for wind power system is:

$$ K / H = 4000 / 525 = 7.62 \text{ Euro/annual delivered kWh} $$

**3.3 capital cost for Shanwei OWC system**

Interest rate $ r = 5\% $ and pay back time $ n = 20 \text{ years} $.

The annual loan is:

$$ a = 0.075 $$

The capital cost is:

$$ S = a * K / H = 0.075 * 7.62 = 0.57 \text{ Euro/kWh} $$

**4 The capital cost for Limpet**

The nameplate capacity of Limpet is $ P = 500 \text{ kW} $. The cost is $ K = 4800 \text{ Euro/kW} $.

The annual operation time is:

$$ H = 720 \text{ hours} $$

**4.1 Annual productivity of Limpet OWC system**

$$ W = 500 * 720 = 160 \text{ MWh} $$

**4.2 Specific investment for Limpet OWC system**

The special investment is:

$$ K / H = 4800 / 720 = 6.66 \text{ Euro/annual delivered kWh} $$

**4.3 capital cost for Limpet OWC system**

Interest rate $ r = 5\% $ and pay back time $ n = 20 \text{ years} $.

The annual loan is:

$$ a = 0.075 $$

Capital cost is:

$$ S = a * K / H = 0.5 \text{ Euro/kWh} $$
5 Capital cost for Pelamis wave power convertor
Cost for a P-750 Pelamis convertor is 3,000,000 Euro

A P-750 Pelamis has 750kW nameplate capacity

The investment for Pelamis convertor is:
K=3000000/750=4000 Euro/kW

The annual operation time of Pelamis convertor is:
H=3600 hours

5.1 Annual electricity generation of Pelamis convertor
W=750*3600=2.7 GWh

5.2 The specific investment for Pelamis convertor
K/H=4000/3600=1.11 Euro/(annual delivered kWh)

5.3 Capital cost for Pelamis
The investment rate r=5%, the pay back time n=20 years, a=0.075
Capital cost:
S=a*K/H=0.083 Euro/kWh

6 Capital cost for Oyster wave power convertor
The nameplate capacity of Oyster is 315kW
The cost for Oyster is:
K=3300 Euro/kW

The annual operation time is:
H=2000 hours

6.1 Annual productivity of Oyster
W=315*2000=730 MWh

6.2 Specific investment for Oyster
The specific investment is:
K/H=3300/2000=1.65 Euro/(annual delivered kWh)

6.3 capital cost for Oyster
The loan a=0.075
Capital cost for Oyster:
S=a*K/H=0.12 Euro/kWh