Overtopping Wave Energy Converters: general aspects and stage of development

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INTRODUCTION

Wave power is the transport of energy by ocean surface waves, and the capture of that energy to do useful work, for example for electricity generation, water desalination, or the pumping of water (into reservoirs). For these and many other reasons, technologies to exploit wave resource are increasingly developing, especially in the recent years, and the wave power could potentially represent a very practical solution.

Actually, the idea of extracting energy form waves is not so recent as it can imagine, the rst patents, for example, date back to the early 18th century. In 1973 oil's crisis, resulting in sudden increase in price, has prompted many governments to consider alternative energy sources, more durable and politically stable. It is precisely in this historical moment, therefore, that ocean was identified as a major source of energy to draw from. However, with the stabilization of oil's price at the end of the 80s, the interested in renewable energy diminished and the almost absolute lack of interest on the part of government has lasted to this day. For ten years now, the incentive for clean energy has opened a new era of research and development of new and improved technologies. The reasons for this change of direction are different and multiple; for sure the increasing world population and the depletion of conventional energy sources (fossil fuel) but also the fact that the world-wide demand for electricity is expected to double within the next 20 years. This, combined with commitments to significantly reduce CO_2 emissions in the same timeframe are increasing the search for clean, socially acceptable methods of generating power. The list of countries seriously committed (figure 1) to convert wave energy in electricity is growing [I.]. Moreover, all this countries are looking, in some way, to find the greatest way to take profit by the sea respecting the variety of ocean space uses present in this moment.

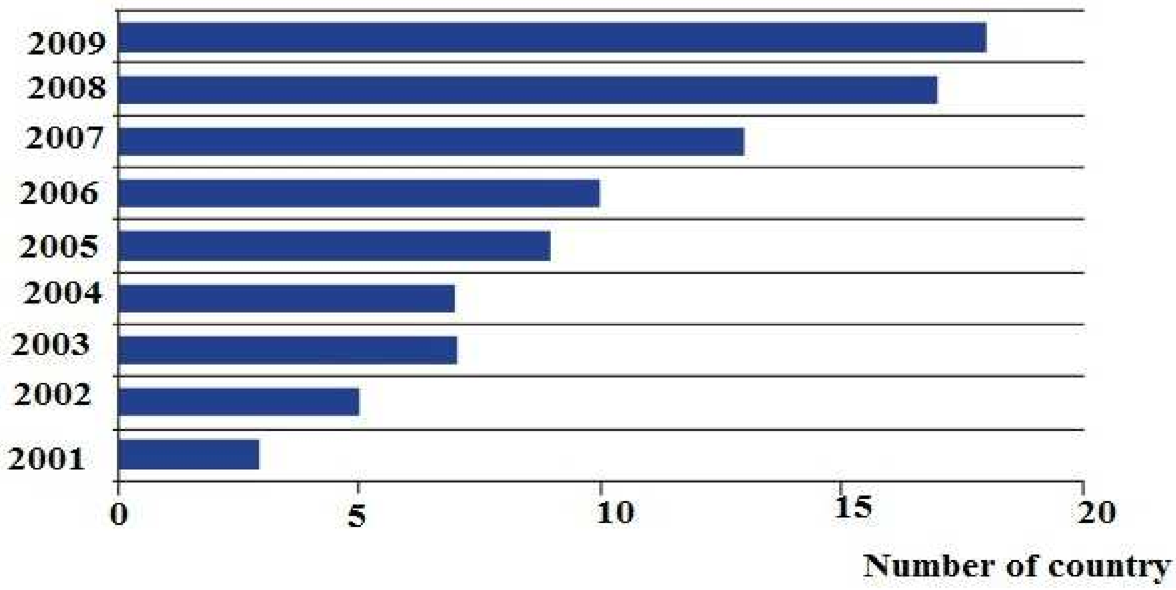


Figure 1: List of the Countries concerned in marine energy, Ocean Energy

Most governments have introduced schemes to encourage the development and uptake of renewable energy, either through direct grants or favorable tariffs for electricity generated from renewable sources. Whilst the majority of work to date has focused on the wind and solar sectors, the generation of electricity from waves, tidal currents and tides has received renewed interest as some of the complexities of practically harnessing other forms of renewable energy become apparent.
Figure 2 shows how the key areas for wave and tidal energy potential are distributed around the world. Western Europe, the west coasts of North and South America, New Zealand and Australia are the regions of the world where waves with the highest energies are found. Key regions for tidal energy include western Europe, Australia, Canada, North and South America, China and Russia.

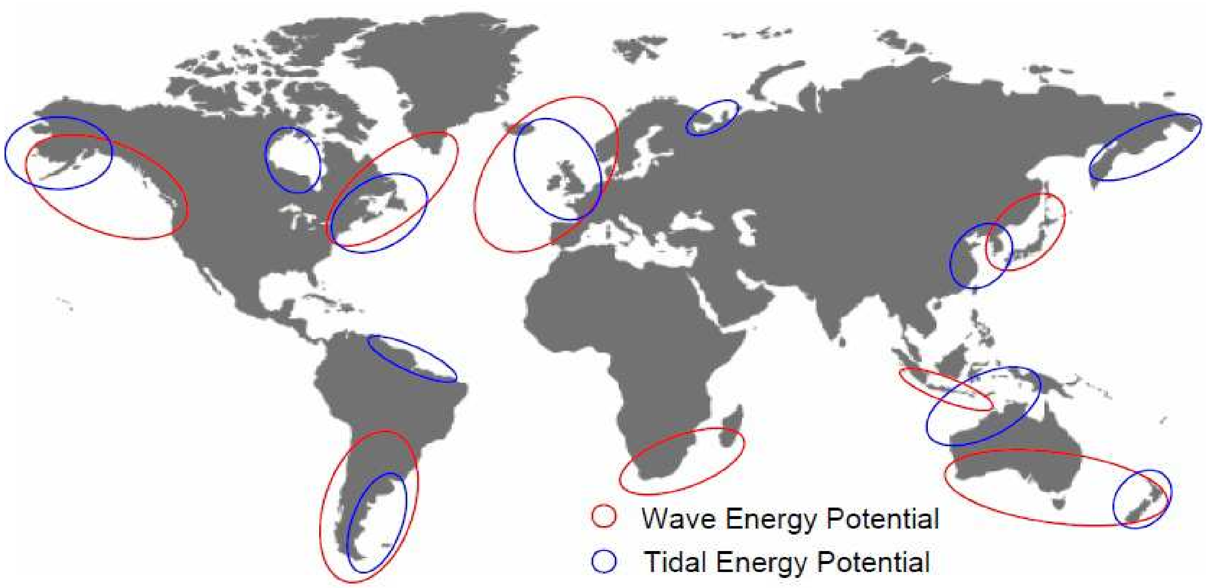


Figure 2: Areas for tidal and wave energy around the world

At the moment, in the most interesting areas for wave energy conversion, solar and wind energy are still the most competitive resource on the global market. However, looking the diagram in figure 3 below it can be seen that the utilization of wave energy is potentially higher than the wind energy and, even more, solar energy [II.].

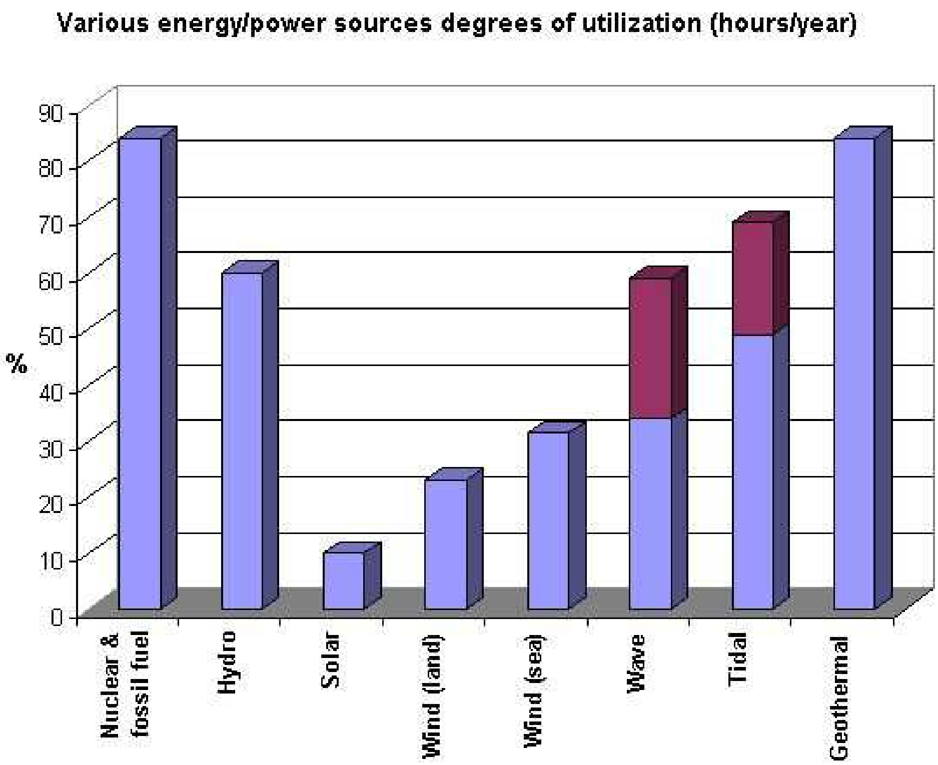


Figure 3: Degree of utilization of the main energy sources

Surely the greatest benefit comes from the fact that the resource is concentrated in specific areas all over the world with specific properties. These are, mainly, oceanic coastal zones exposed to the main directions of ocean winds and at the ends of long fetches. The wave activity in fact is intense in areas between 30°N and 60°N of latitude on both hemispheres for the presence of predominantly westerly winds. Other advantages are linked to the limited negative environmental impact in use and to the natural seasonal variability of wave energy, which follows the electricity demand in temperate climates. Last, waves can travel large distances with little energy loss; storms on the western side of the Atlantic Ocean will travel to the western coast of Europe, supported by prevailing westerly winds. The problem is that the current state of technological development is still inappropriate, due to many critical issues still unsolved. This means that the wave energy can not be economically competitive yet.

WAVE ENERGY CONVERTERS

Generality

Devices able to generate electricity exploiting the energy of the waves are commonly called Wave Energy Converter (WEC). At the moment exist a variety of technologies to capture the energy from waves; however, each is in too early a stage of development to predict which technology or mix of technologies would be most prevalent in future commercialization.

The design of a wave energy converter has to be highly sophisticated to be operationally efficient and reliable on the one hand, and economically feasible on the other. As with all renewables, the available resource and variability at the installation site has to be determined first. The above constraints imply comparably high construction costs and possibly reduced survivability, which, together with misinformation and lack of understanding of wave energy by the industry, government and public, have often slowed down wave energy development. But, in the last five years, there has been a resurgent interest in wave energy. Nascent wave energy companies have been highly involved in the development of new wave energy technologies such as the Pelamis, the Archimedes Wave Swing and the Limpet. At present the world-installed capacity is about 2 MW mainly from demonstration projects.

Classification of WECs

In contrast to other renewables the number of concepts for wave energy conversion is very large. Despite this large variation in design, WECs are generally categorized by location and type/mode of operation [III.].

a) Location

It is spoken of shoreline devices, nearshore devices and offshore devices.

Shoreline devices have the advantage of being close to the utility network, are easy to maintain, and as waves are attenuated as they travel through shallow water they have a reduced likelihood of being damaged in extreme conditions. This leads to one of the disadvantages of shore mounted devices, as shallow water leads to lower wave power (this can be partially compensated by natural energy concentrated locations). Tidal range can also be an issue. In addition, by nature of their location, there are generally site-specific requirements including shoreline geometry and geology, and preservation of coastal scenery, so devices
cannot be designed for mass manufacturing.

Nearshore devices are defined as devices that are in relatively shallow water (there is a lack of consensus of what defines 'shallow' water, but it has been suggested that this could be a depth of less than one quarter wavelength). Devices in this location are often attached to the seabed, which gives a suitable stationary base against which an oscillating body can work. Like shoreline devices, a disadvantage is that shallow water leads to waves with reduced power, limiting the harvesting potential.

Offshore devices are generally in deep water although, again, there is little agreement about what constitutes 'deep' water. 'Tens of meters' is one definition, with 'greater than 40m', and 'a depth exceeding one-third of the wavelength' being others. The advantage of siting a WEC in deep water is that it can harvest greater amounts of energy because of the higher energy content in deep water waves. However, offshore devices are more difficult to construct and maintain, and because of the greater wave height and energy content in the waves, need to be designed to survive the more extreme conditions adding cost to construction.

b) Type

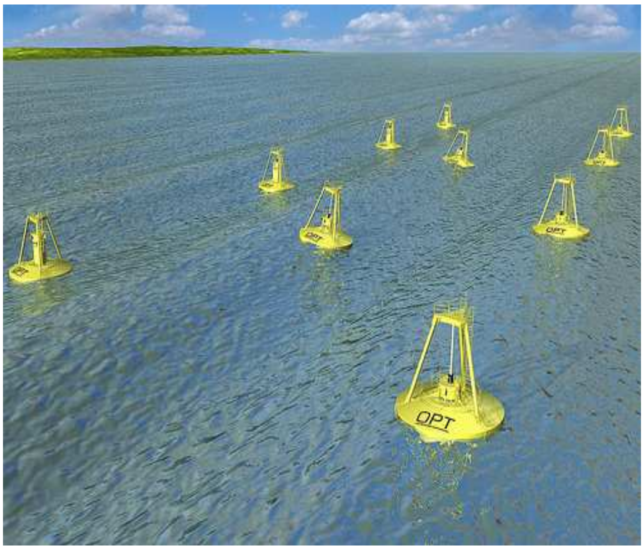
Despite the large variation in designs and concepts, WECs can be classified into three predominant types: attenuator, point absorber and terminator, depending on their orientation among the waves.

Attenuators lie parallel to the predominant wave direction and 'ride' the waves. An example of an attenuator WEC is the Pelamis (figure 4(a)), developed by Ocean Power Delivery Ltd (now known as Pelamis Wave Power).

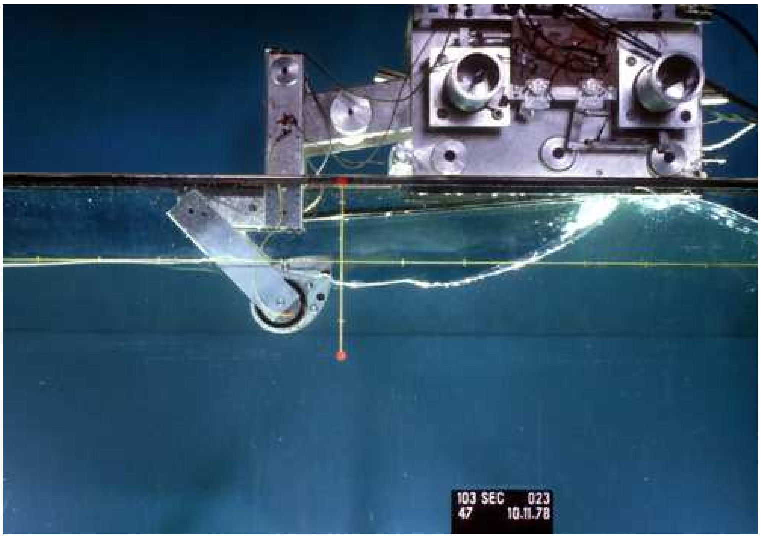
A point absorber is a device that possesses small dimensions relative to the incident wavelength. They can be floating structure that heave up and down on the surface of the water or submerged below the surface relying on pressure differential. Because of their small size, wave direction is not important for these devices. There are numerous examples of point absorbers, one of which is Ocean Power Technology's Powerbuoy (figure 4(b).

Terminator devices have their principal axis parallel to the wave front (perpendicular to the predominant wave direction) and physically intercept waves. One example of a terminator-type WEC is the Salter's Duck, developed at the Unviersity of Edinburgh (figure 4(c))

a) Pelamis wave farm



(b) Powerbuoys wave farm



c) Lab test of Salter's Duck

Figure 4: Some of the most famous Wave Energy Converters

c) Modes of operation

Within the categories identified above, there is a further level of classification of devices, determined by their mode of operation. Some significant examples are given below.

The **submerged pressure differential** device is a submerged point absorber that uses the pressure difference above the device between wave crests and troughs. It comprises two main parts: a sea bed fixed air-filled cylindrical chamber with a moveable upper cylinder. As a crest passes over the device, the water pressure above the device compresses the air within the cylinder, moving the upper cylinder down. As a trough passes over, the water pressure on the device reduces and the upper cylinder rises. An advantage of this device is that since it is fully submerged, it is not exposed to the dangerous slamming forces experienced by floating devices, and reduces the visual impact of the device. Maintenance of the device is a possible issue however. Owing to part of the device being attached to the sea bed, these devices are typically located nearshore. An example of this device is the Archimedes Wave Swing, an artist's impression of which is shown in figure 5.

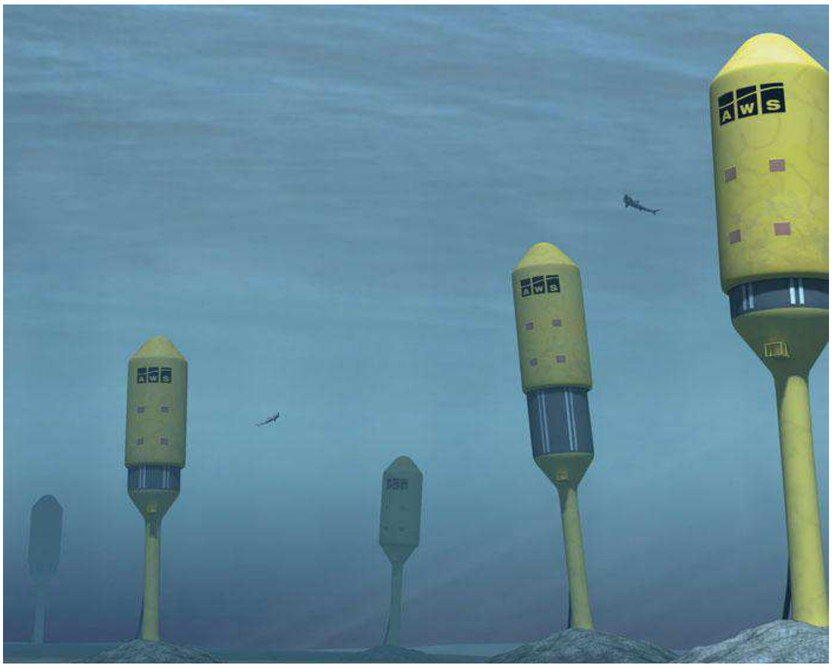


Figure 5: Archimedes Wave Swing farms

An **Oscillating Water Column** consists of a chamber with an opening to the sea below the water line. As waves approach the device, water is forced into the chamber, applying pressure on the air within the chamber. This air escapes to atmosphere through a turbine. As the water retreats, air is then drawn in through the turbine. A low-pressure Wells turbine is often used in this application as it rotates in the same direction irrespective of the flow direction, removing the need to rectify the air flow. It has been suggested that one of the advantages of the OWC concept is its simplicity and robustness. There are examples of OWCs as point absorbers, as well as being built into the shoreline, where it acts as a terminator. An example of a shoreline mounted device is the Wavegen Limpet (figure 6). The device is installed on the island of Islay, Western Scotland, and produces power for the national grid.

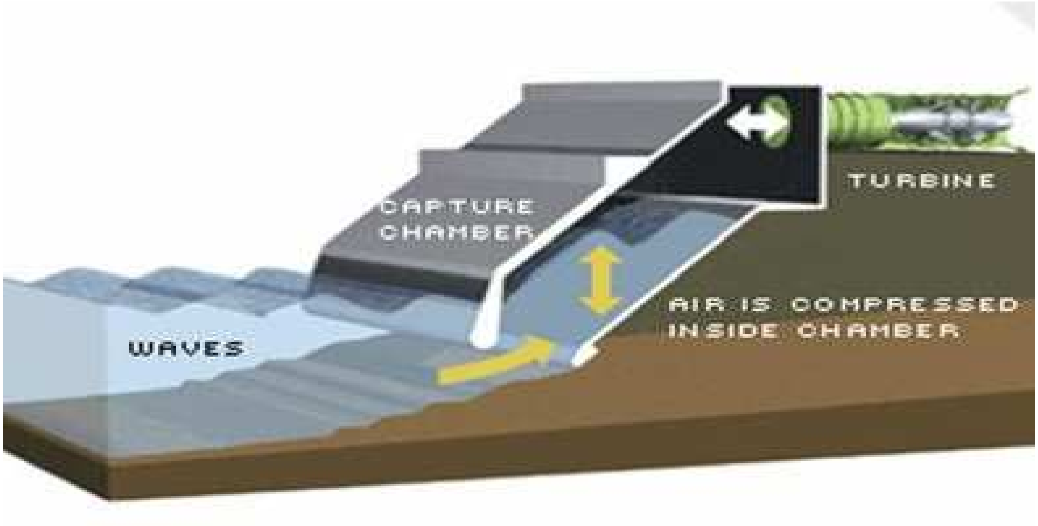


Figure 6: Sketch of Limpet

An **Overtopping** device captures sea water of incident waves in a reservoir above the sea level, then releases the water back to sea through turbines. An example of such a device is the Wave Dragon, which is shown in figure 7.

Figure 7: Frontal view of Wave Dragon in the Nissum Bredning site

This device uses a pair of large curved reflectors to gather waves into the central receiving part, where they flow up a ramp and over the top into a raised reservoir, from which the water is allowed to return to the sea via a number of low-head turbines.

OVERVIEW ON OVERTOPPING WECs

Under the Danish Wave Energy Programme a number of WECs have been suggested and tested. Among these WECs are devices like the Wave Dragon, Wave Plane, Sucking Sea Shaft, Power Pyramida and others. Furthermore a number of devices have been proposed and some built internationally. All these devices have in common that they utilize wave energy by leading overtopping water to one or more reservoirs placed at a level higher than the mean water level (MWL).

The potential energy obtained in the overtopping water is then converted to electrical energy by leading the water from the reservoir back to the sea via a low head turbine connected to a generator.

The performance of these WEC technologies are not dependant of resonance with the waves and can therefore be constructed very large. Central issues for floating overtopping WEC's are to control and stabilize the floating structure to optimize power output.

Overtopping theory

The theory [VI.]for modeling overtopping devices varies greatly from the traditional linear systems approach used by most other WECs.

A linear systems approach may be used with overtopping devices. This considers the water oscillating up and down the ramp as the excited body, and the crest of the ramp as a highly nonlinear power take-off system. However due to the non-linearities it is too computationally demanding to model usefully. Therefore a more physical approach is taken. The time series of the overtopping flow is modeled, thus, relying heavily upon empirical data. Figure 8 shows the schematic of flows for the Wave Dragon.

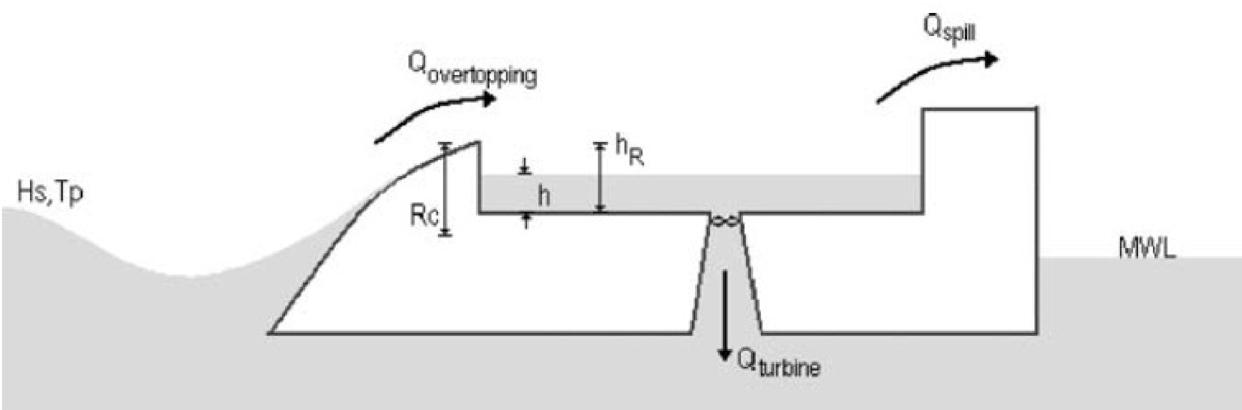


Figure 8: Schematic of flows for the Wave Dragon

Depending on the current wave state (Hs, Tp) and the crest freeboard Rc (height of the ramp crest above mean water level, MWL) of the device, water will overtop into the reservoir (Qovertop). The power gathered by the reservoir is a product of this overtopping flow, the crest freeboard and gravity. If the reservoir is overfilled when a large volume is deposited in the basin there will be loss from it (Q_{spill}). To minimize this, the reservoir level h must be kept below its maximum level (hR). The useful hydraulic power converted by the turbines is the product of turbine flow (Qturbine), the head across them, water density and gravity.

Within the field of coastal engineering there is a considerable body of work looking at the overtopping rates on rubble-mound breakwaters, sea walls and dykes.

The studies of Van der Meer and Janssen (1994) provided the basis of the theory on the average expected overtopping rate. Gerloni et al. (1995) investigated the time distribution of the flow. However this work was focused on structures designed to minimize the rate of overtopping, counter to the aims of the Wave Dragon. Kofoed (2002) performed laboratory tests on many permutations of ramp angles, profiles, crest freeboard levels in a variety of sea states, all with heavy overtopping rates. These studies showed the Wave Dragon's patented double curved ramp to be highly efficient at converting incident wave power.

When comparing results between different scales of model testing it is very useful to use non-dimensional figures to describe the variables. Results from the model scale can then simply be used for any size of device.

In coastal engineering the average flow Q is converted into non dimensional form by dividing by the breadth of the device b, gravity g and the significant wave height Hs:

$$Q_{ND}=\frac{\overline{Q}}{b\sqrt{g H_s^3}}$$

In the case of the floating Wave Dragon it has been seen that there is a dependency on the wave period. The dominant physical explanation for this is the effect of energy passing beneath the draft of the structure. Figure 9 shows a typical distribution of wave energy in the water column, with the left side showing the portion influenced by the ramp of Wave Dragon and therefore available to be exploited.

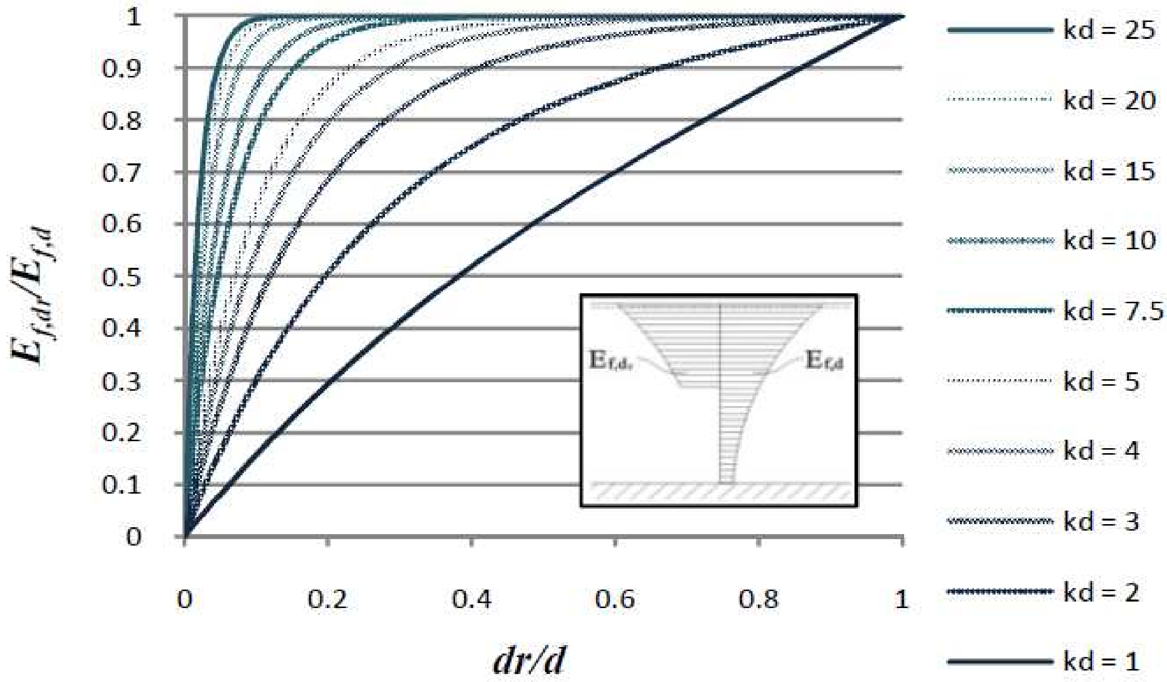


Figure 9: Vertical distribution of energy in water column (Kofoed, 2002)

As it can be seen, shorter period waves have their energy concentrated in the upper part of the water column so Wave Dragon will absorb proportionately more energy from these.

Time variation of the overtopping flow is also very important for modelling the power produced. To make the model overtopping events are assumed to be random and independent, with a Weibull distribution. With this good understanding of the overtopping flows a simulation programme is designed and is extensively used to optimize and model the overtopping WECs behavior. This programme provides as an input a randomly generated time history of waves overtopping the ramp according to a mean rate and a specified distribution. This allows modification of many attributes (such as reservoir depth and area, crest freeboard height, turbine number and type and turbine operational strategy) in order to pick the configuration which will produce the most electricity for each sea condition present at a location.

Categorization of overtopping WECs

Overtopping devices have been designed and tested for both onshore and offshore applications. So, they are categorized in two groups: coast based and floating structures [V.].

a) Coast based devices

Among the few WECs that have been built and tested is the Norwegian **TAPCHAN** (TAPered CHANnel). This device is equipped with the same machinery as a low pressure hydroelectric power station with a reservoir and a Kaplan turbine. The reservoir is fed by waves trapped by a broad channel opening that reaches into the sea. Towards the reservoir the channel is tapered and bent in such a way that the waves pile up and spill over the channel margin.

Studies have also been performed on a variation of this coast based approach where overtopping water is not used to produce power but to recirculate water in harbors (in a project called Kingston harbor pump). This approach can be useful at locations where only a small tide exists and therefore only insufficient flushing of the harbors occurs. As the coast based overtopping devices work best in areas with small tidal ranges this can be a very useful application.

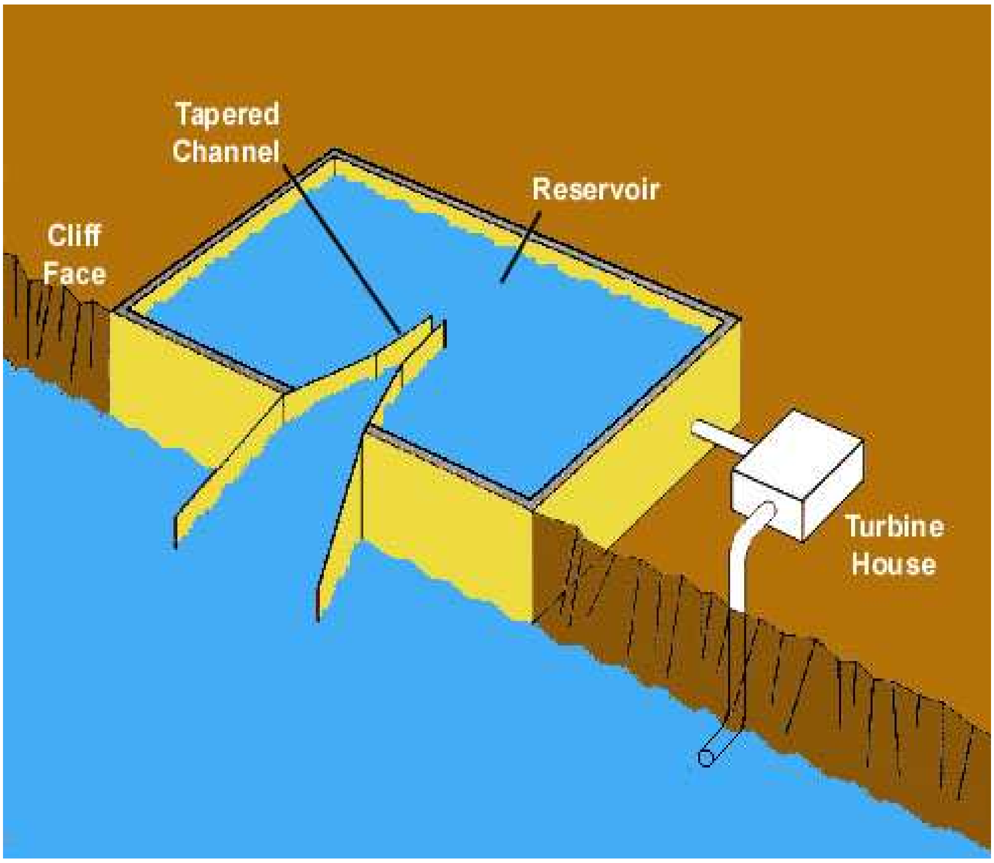


Figure 10: Scheme of TAPCHAN device

Another Norwegian project, called **Seawave Slot-cone Generator** (SSG), utilizes wave overtopping of more than one reservoir placed at different levels and is suitable for onshore application. To more detailed explanation of its principle and operation, refer to the next section

b) Floating device

The coast based devices are most applicable in coastal regions with deep water close to a rocky coastline. Therefore for countries where the coast generally consists of gentle sloped beaches, such as Denmark, the coast based devices are not appropriate as the waves lose the majority of their energy content through bottom friction and wave breaking before they reach the shore. Thus a number of floating WECs utilizing wave overtopping have been proposed. The fact that these devices are floating not only makes it possible to move them to regions with larger wave energy density but also solves problems associated with tide and enables relatively easy control of the crest level of the slope.

Among the first devices to use this approach was the **Sea Power WEC** from Sweden. This device has been tested in prototype scale.

In Denmark one of the WECs which has been most developed is the **Wave Dragon** (WD). The WD combines ideas from TAPCHAN and Sea Power and is a floating structure equipped with wave reflectors that focus the waves towards the slope.

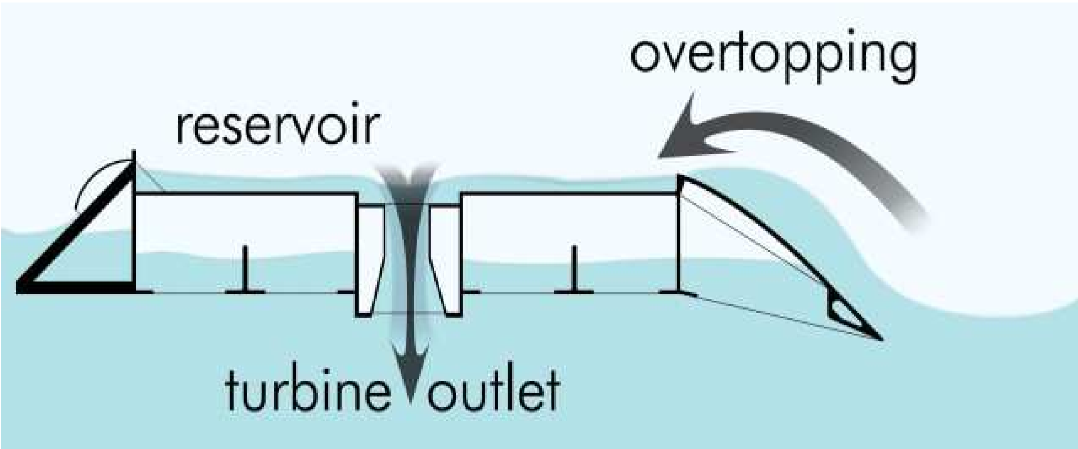


Figure 11: Scheme of Wave Dragon device

The WD has so far undergone substantial model testing of both the hydraulic performance of the structure and the performance of the turbines. For more detail on WD see the next section below.

Seawave Slot-cone Generator

The SSG (Sea Slot-cone Generator) is a wave energy converter of the overtopping type [VII.]. The structure consists of a number of reservoirs one on the top of each others above the mean water level, in which the water of incoming waves is stored temporary. In each reservoir, expressively designed low head hydroturbines are converting the potential energy of the stored water into power.

A yearly energy production of 320 MWh is foreseen for a 10 meter wide section.

A key to success for the SSG will be the low cost of the structure and its robustness. During the last 2 years such a 1350 tonnes concrete structure has been under detailed design in Norway. The construction was planned to be installed during spring and summer 2008 at a small island Kvitsoy situated near Stavanger. Unfortunately environmental issues have demanded a movement of the project to another location. The actual situation is that some breakwaters under design are being investigated as a possible places for integrating the SSG structure.

The operating principle is very simple. The incoming wave will run uphill a slope and on its return it will flow into reservoirs. After the wave is captured inside the reservoirs, the water will run through the patented multi stage turbine. Using this method practically all waves regardless of size and velocity, can be captured for energy production.

Figure 12: Cross section of a SSG Wave Energy Converter

The three-tier structure ensures a high level of efficiency and the continuous generation of energy. It is believed that this system is efficient and can be installed also on offshore structures such as oil platforms out of service.

Feasibiliy:

- **Environmental Impact**: High, if it is built on the shore, due to the high dimension, it my take completely the beach which will be installed. For offshore applications instead, the estimated impact is restricted.
- **Maintenance**: Low. Use well-proven hydraulic technology and all components are easily accessible.
- **Manufacturability**: medium-low. Require a large structure and the system is also limited to sites with steep slopes that overlook the deep sea.
- **Stage of development**: design concept.

Wave Dragon

Wave Dragon (WD) is an offshore wave energy converter of the overtopping type where each unit will have a rated power of 4-10 MW depending on how energetic the wave climate is at the deployment site. As part of the development activities towards a full size production plant in 2006 a grid connected prototype of the WD is presently being tested in a Danish fjord (a scale 1:4.5 of a North Sea production plant).

WD consists of three main elements:

1. Two patented wave reflectors focusing the waves towards the ramp, linked to the main structure. The wave reflectors have the verified effect of increasing the significant wave height substantially and thereby increasing energy capture by 70% in typical wave conditions.
2. The main structure consisting of a patented doubly curved ramp and a water storage reservoir.
3. A set of low head propeller turbines for converting the hydraulic head in the reservoir into electricity.

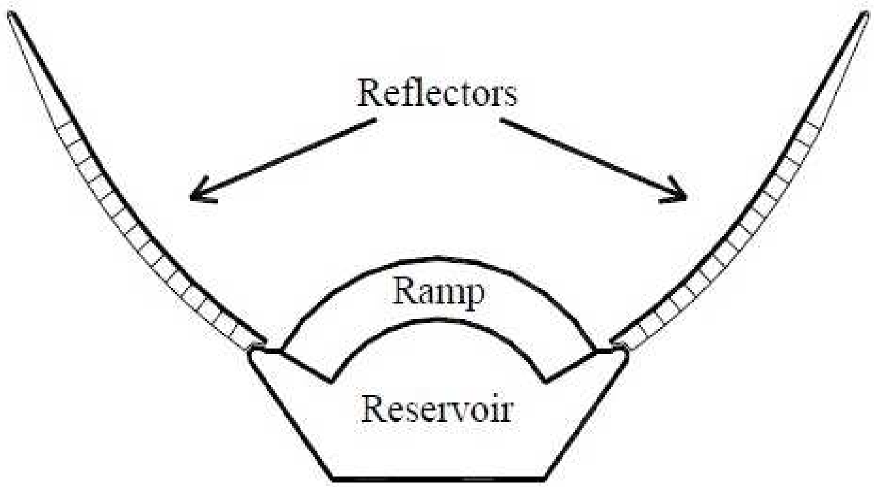


Figure 13: Main component of Wave Dragon

When waves have been focused by the reflectors they overtop the ramp and fill the reservoir, which is situated at a higher level than the surrounding sea. This hydraulic head is utilized for power production through the hydro turbines.

Figure 14: Wave Dragon prototype at test site

WD is unique among wave energy converters as it uses the energy in the water directly via water turbines, i.e. a one-step conversion system, which yields a very simple construction and has only one kind of moving parts: the turbines. This is essential for any device operating offshore where maintenance is difficult to perform and where the extreme forces, fouling etc. seriously affect any moving parts.

But yet WD represents a very complex design, where intensive efforts by universities and industry have been spent on designing, modelling and testing in order to:

- Optimize overtopping.
- Refine hydraulic response: anti-pitching and anti-rolling, buoyancy etc.
- Reduce (the effect of) forces on wave reflectors, mooring system etc.
- Develop efficient turbines for extremely low and varying head.
- Develop a turbine strategy to optimize power production.
- Reduce construction, maintenance and running costs.

All of this has been done with one goal: to produce as much electricity as possible at the lowest possible costs and in an environmental friendly and reliable way [IX.].

a) The structure

WD is moored (like a ship) in relatively deep water, i.e. more than 25 m and preferably +40 m to take advantage of the ocean waves before they loose energy as they reach the coastal area. This is in contrast to many known wave energy converters that are either built into the shoreline or fixed on the seabed in shallow water.

WD is constructed with open air-chambers where a pressurized air system makes the floating height adjustable. Thus, the crest freeboard can be adjusted to yield the maximum overtopping efficiency in different wave conditions. Furthermore, the open air-chambers reduce the movements of the main body, as the wave induced pressure on the underside of the structure compresses air rather than moving the body.

Figure 15: On the left WD prototype at launch in March 2003: the open air-chambers are used to control the floating level. On the right WD prototype in heavy wave conditions.

WD is designed to be constructed in a combination of reinforced concrete and steel. A full size unit for a 24 kW/m wave climate will have a weight of 22,000 tonnes including ballast and a width of 260 meters between the tips of the wave reflectors. The reservoir capacity will be 5,000 m^3.The size of the WD depends on the wave climate. In the table below dimensions of the WD are given for different average wave energy densities.

	Average wave energy density [kW/m]				
	0,40	24	36	48	60
Width [m]	57	260	300	390	390
Weight [t]	237	22000	33000	54000	54000
Reservoir capacity [m^3]	55	5000	8000	14000	14000
N. of turbines	1+3+6	16	16-20	16-20	16-24
Power production [Gwh/year]	-	12	20	35	43
Generators, rated power [kW]	2,5	250	350-450	460-700	625-940

Table: Dimension of WD prototype and WDs for different wave climates

b) The power take-off system

Once the overtopping water has reached the reservoir, the potential energy is harvested by the installed low-head turbines, as the ones in the figure 16.

Figure 16: The six axial propeller turbines being assembled at Kössler GmbH

The operating conditions of the turbines on the WD differ strongly from those in a normal river hydro power station. Firstly, the turbines have to operate at very low head values ranging from 0.4 m to 4.0 m, which is not only on the lower limit of existing hydro power experience, but also an extremely wide variation. Secondly, due to the stochastic time distribution of the wave overtopping and the limited storage capacity, the turbines have to be regulated from zero to full load very frequently. Lastly they have to operate in a very hostile environment, with only a minimum of maintenance being possible on an unmanned offshore platform.

Early in the project it was concluded that the turbines had to be as simple and rugged as possible, with an absolute minimum of moving parts. Thus, a design with both fixed guide vanes and fixed runner blades has been chosen. The result has been a low head turbine specially developed by the WD team and tested at the Technical University of Munich.

The resulting efficiency of the single turbine is about 91-92% in the relevant head and flow ranges.

c) Hydraulic performance

The hydraulic performance of the WD has been optimized through numerical modelling and the use of small scale models tested in wave tanks. The optimizations includes overall structural geometry, focusing especially on reflector design and the cross section of the ramp, and has almost doubled the energy capture compared to the first generation design. This has lead to overtopping expression by Hald & Frigaard, 2001 based on 1:50 scale model tests:

$$Q^* = 0.025 \exp\left(-40 \cdot R^*\right)$$

Where

$$Q^* = \frac{q}{L}\sqrt{\frac{Sop}{2\pi g H_s^3}}$$

and

$$R^* = \frac{Rc}{Hs}\sqrt{\frac{Sop}{2\pi}}$$

As indicated in figure 17 the measured prototype data compares well with the expression based on laboratory tests.

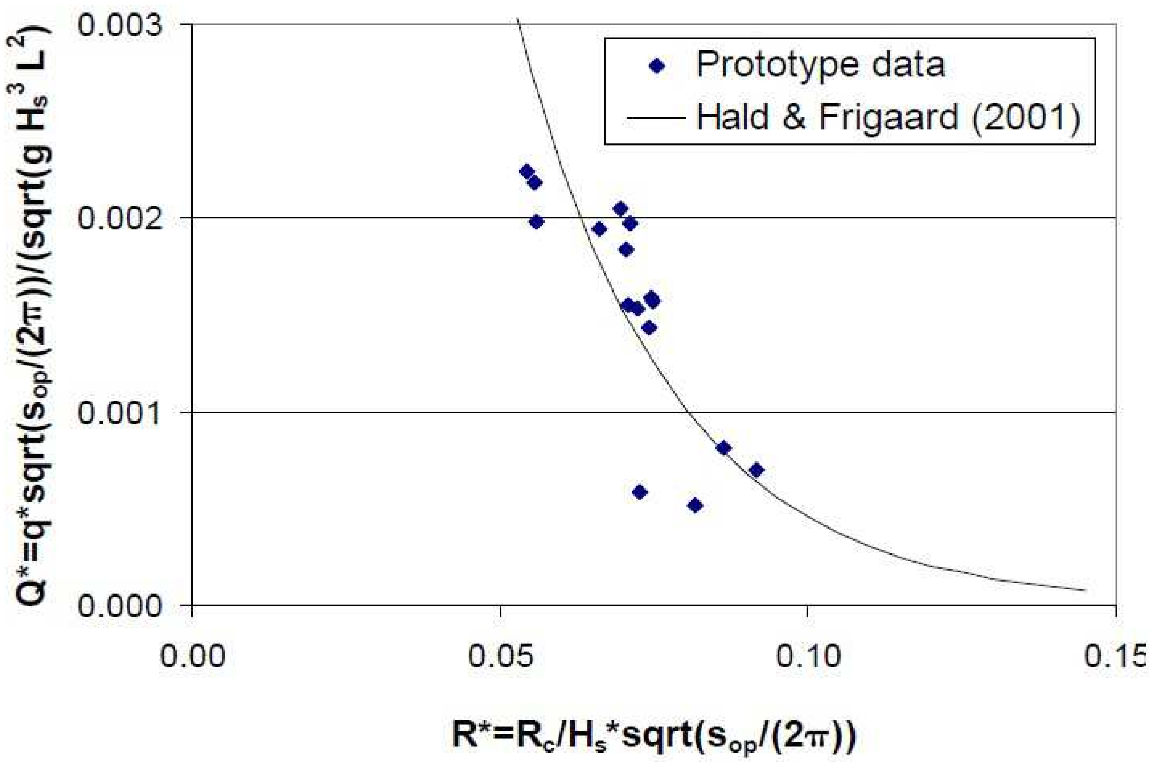


Figure 17: Comparison of preliminary prototype data and overtopping expression

With regard to survivability a lot of experiences with especially the design of the junction between reflectors and the main body have been obtained during the first year of prototype operation.

During this period the design has, due to failures, been altered, going from a delicate design where cylindrical fenders were allowed to rotate in order to act as a roller bearing, to a more rough design where the fender elements are fixed on the main body.

Measurements of mooring forces in both model scale and prototype shows good correlations. The measurements underline the importance on having an elastic mooring system in order to avoid high snap-loads.

ADVANTAGES AND CRITICAL POINTS OF OVERTOPPING WECS

In general, overtopping converters have advantages that distinguish them from other devices. Firt of all, the fluctuations of the energy produced by these devices are, in fact, relatively small, since the conversion takes place in calm conditions in the reservoir where the water is temporarily stored. The implementation of these devices, then, is associated with a higher economic feasibility. For example it is possible to combine them with other structures along the coast, such as the conventional breakwaters for coastal defense. And more, because on the back of the devices there are established calm conditions, it is possible to use this area to develop recreational activities such as aquaculture and fisheries. In addition, after the production of electricity, the water is discharged through the turbine can be recirculated in order to improve water quality, for example, in a closed door. Finally, the use of a ramp that focuses the entry of water into the basin, makes it possible to use the devices to overflow even in coastal regions are not favorable, characterized by a low density of wave energy.

On the other hand however, because these devices are usually installed offshore, they require an appropriate anchoring system. As a matter of fact high-power (80-90% capture) and high-efficiency devices require a tight mooring to react force against. Usually the mooring costs (a huge heavy platform or a tight seabed mooring) could cost easily around 200-300% more then the basic device cost (excluding the energy storage means) and requires good weather windows of opportunity to be worked or maintained.

Even excluding the costs issue, fatigue loads and survivability are still two major problems regarding any moored system. Fatigue is the most common cause of failure of any structure and mooring systems are no exception. Not only they must be able to withstand the most extreme loads (which could be extremely high), but also they must be able to resist fatigue years after years. Survivability, especially, is the most problematic aspect because is expected to greatly impact the cost of generated power passed to the consumer. For this reason, it is imperative that WECs are both highly reliable during operation, and highly survivable through extreme conditions.

A number of innovative approaches have been proposed to enable survival of WECs, including submergence and intelligent control but, as with moorings, the current state of development makes impossible to determine which of these is the best.

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