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A preliminary study about methods for harvesting energy from marine resources

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Abstract

The greatest increase in demand for energy coming from newly industrialized countries where large- scale electricity generation will be required, the environmental requirements for zero or low CO_2 emission sources and the need to invest in a sustainable energy mix, involve the development of new energy sources. Wave, tidal and marine current energy could be available as a future energy option and should be able to acquire a significant role in providing a sustainable, secure and safe solution to tackle European and global energy needs. Sun and wind are predictable, but not constant: photovoltaic panels and eolic turbines could barely support alone the peaks of the power request from the grid, and the contribution of hydroelectric seems to have already reached its limits in some European countries. For this reasons, in order to become independent from fossil fuels, it will be fundamental to harvest energy from the largest number of natural phenomena, especially ones that are predictale with high precision, as tides, and ones that are almost constant, as ocean currents.

Acknowledgements

I thank my family that helped me in inspecting the English language, and my friends who discussed with me with propositional attitude on the themes of this work.

Especially my deepest gratitude goes to prof.ssa Sparavigna, who has ever been helpful, explained me some of the physical principles on which marine energy technologies work and got interested with me in the topics: she was really the best final work tutor I could ask for.

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1. HISTORICAL NOTES

1.1 Tides and tidal mills

Ancient people from different ages showed several interests towards natural phenomena linked to the seas and the oceans, and they gave different explanations of them. The event related with seas that probably mostly stimulated the minds of the ancient philosophers and astronomers is the one of tides. The observation was suitable for all, as large expanse of land were periodically submerged by water, conditioning the life of people who lived in these areas: the changing level of water could create problems with boats, as it still does, or prevent the access to some areas of the shore.

The first to give a partially correct interpretation of tides is probably the Greek explorer Phyteas, who travelled to the British Isles around 325 BC and was stunned by the higher intensity that tides had on the ocean rather than on the Mediterranean sea. The description of his voyage was well known in the past, but unfortunately it has been lost in the years. However, some writers and historians ascribed to Phyteas the relation of tides to the phases of the Moon.

In the 2nd century BC Seleucus of Seleucia, a Babylonian astronomer, supposed that tides were due to the attraction of the Moon. He used also this explanation of tides to argument the Heliocentric theory of Aristarchus of Samos, which stated that the Earth rotated around its own axis which in turn revolved around the Sun.

Pliny the Elder (23-79 A.D.), who made an important work of collection of previous scientific texts, in the second book of his Naturalis Historia made some important statements about tides:

1) the presence of the Sun and the Moon are the causes of the flux of water linked to tides[1];

2) the influence of the Moon is higher if the planet is more near to Earth[2].

Reaching the modern scientific thought, Isaac Newton used his theory of universal gravitation to explain the lunar and solar attractions as the origin of the tide-generating forces.

Another important work about the study of tides has to be attributed to William Thomson, the Irish physician also known as Lord Kelvin: he produced the first systematic harmonic analysis of tidal records, starting in 1867, and built a tide-predicting machine with his collaborators (Figure 1-I) [1].

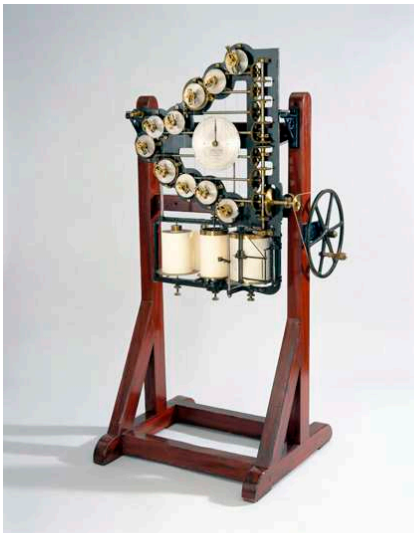

Figure 1-I: The tide predicting machine by William Thomson

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[1] "Et de aquarum natura complura dicta sunt, sed aestus mari accedere ac reciprocare maxime mirum, pluribus quidem modis, verum causa in sole lunaque", And about the nature of bodies of water many things have been told, but the rise and fall of the tides of the sea is extremely mysterious, at all events in its irregularity; however the cause lies in the sun and moon.
Plinio il Vecchio, *Naturalis Historia, Liber II*

[2] "Eadem in aquilonia et a terris longius recendente mitiores quam cum in austros digressa propiore nisu vim suam exercet", When the moon is northward and retiring further from the earth the tides are gentler than when she has swerved towards the south and exerts her force at a nearer angle.
Plinio il Vecchio, *Naturalis Historia, Liber II*

Besides studying and trying to understand the causes that originated tides, humans tried also to use the energy carried by tides: tide mills were similar to ones built on streams, but they had the disadvantage to work only about 10 hours a day and people who wanted to use them had to adapt themselves to the timetables of the high and low tide. However, they were built where there was lack of water streams and they had the advantage to work every day in every season, while some mills built on rivers and creeks operated depending on the flow of water and the season. For a description of the ancient tide mills, we mention Terry S. Reynolds, professor of history at the Michigan Technical University, who, in his “Stronger than a hundred men: a history of the vertical water wheel” (1983) illustrates the techniques applied in the past to generate mechanical energy from tides:

“Tide mills could be constructed in many ways. The earliest may have been merely anchored or moored boat mills. When the tide came in, their wheels would be pushed in one direction; when the tide went out, in the other. But the form of the tide mill that came to most widely applied was more complex. It required impounding the water of incoming tides by means of dams and gates placed across the mouth of a river, creek, or bay. The gates would be open to an incoming tide, but closed when the tide went out, creating large tidal reservoirs. The water from these reservoirs would then be released through a mill race onto the blades of a water wheel. Tide mills were not as convenient as conventional watermills. They could be used only six

to ten hours a day, and the hours when they could be operated varied from day to day as the tides changed. But where conventional mills could not be used, they were applied, and they did have the advantage of never freezing over” [2].

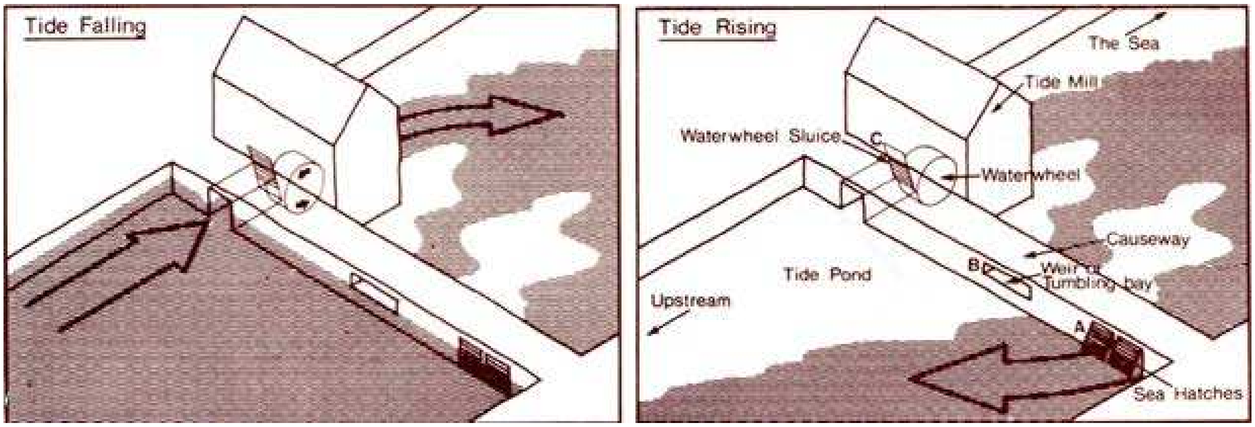


Figure 1-II: Tide mill with dams and gates

Initially, tide mills were probably made up of just a wheel that was connected to a mechanical system and directly used the water flow created by tides. Reynolds, in his work, tells that the most part of tide mills were built using dams to increase the productivity of the system: if the water can enter through large gaps and is blocked into a reservoir, when the tide starts decreasing it will be possible to canalize all the water collected through the mill; the quantity of energy obtained will depend on the quantity of water and on the height of the gap between the reservoir and the sea level to use a larger difference of potential energy opening the dams when the tide is near to its lowest level.

Indeed, as written by Richard Duffy in "Tinkham Brothers' Tide-mill" (1999):

"*The most efficient operation of the mill occurred when the tide fell to a point below the level of the entire waterwheel, allowing it to "run clear." The wheel would continue to turn until either the water behind the dam fell below the level of the sluice, or more frequently, until the water level in front of the dam rose above the sluice at high tide*" [3].

One more question arises almost spontaneously: where were tide mills established in the Middle Ages? To answer this question we refer to a work of W.E. Minchinton, “Early tide mills: some problems”, where it is analysed the possibility of finding Middle Ages tide mills in various sites.

We know for sure that tide mills were in operation at Basra, a coastal town on the Persian Gulf, where they were used mostly for grinding corn. Minchiton mentions the words of a Muslim geographer of the 10th century, al-Madisi Shams al-Din, who wrote: “The tide is a marvel and a blessing for the people of Basra. The water visits them twice every day, and it enters the rivers and irrigated the orchards and carries the ships to the villages. And when the tide ebbs it is also useful for the working of the mills because they are all situated at the mouth of the river and its tributaries. So when the water goes out to sea it turns them around”. Besides telling us that tide mills were used at Basra, the geographer also gives us some information on how they worked; he tells that they were activated when the tide ebbed, that means they were of the type earlier described, with dams and gates.

For what concerns the Adriatic sea, the Franciscan father Girolamo Zanetti wrote that Venetians set up mills on boats whose wheels were driven by the tide in the mouths of the river in the lagoons of Venice. In this case, we are in front of floating mills (or ship mills): they were probably simpler to be built, but also less efficient and more difficult to be used. However, they could be placed without the need of dams and gates at the middle of an estuary, where the current is stronger than on the sides. Finally, it is doubted whether a conventional tide mill could operate in the Adriatic Sea, because of the really limited tidal range (about 1 meter): the advantages obtained by its use would not have been enough against the high costs of construction.

Looking at France, in the 12th century there were tide mills in the neighborhood of Nantes, the old capital of Brittany, and in Bayonne (Pays Basque); however, in the 13th century they were probably widespread all along the Atlantic coast and on many islands of Brittany.

The first tide mill to be built in England was probably the one in Dover in 1082, and many others have been constructed in the following centuries. In particular historians estimate that in England in the 12th century six tides mills have been built and even twenty-seven in the 13th century; moreover, studies on the early history of tide mills inform us that in England remains of 169 tide mills have been found , and 105 of them had been built before 1700.

Minchiton gives also information about tide mills on the Atlantic coast of the Iberian peninsula: in particular while English and French mills used to have vertical wheels, the Portoguese ones, starting from 1290, had horizontal wheels. Tide mills are known to have existed in Spain too, but there isn't any evidence yet of tide mills built in Middle Ages; however, for sure they existed in the 19th century [4].

To end this introduction on the use of tides to produce mechanical energy, we propose some study sparks mentioned in "Early tide mills" by W.E. Minchiton: should the high number of tide mills, built especially in England before 1700, highlight the necessity of mechanical energy for a power hungry society, or should it show the convenience of using tide mills instead of normal watermills, whose productivity can be strictly related to the flow? The answer is not simple and a possible solution would be found in the comparison between the number of normal watermills and tide mills in a specific region, but the result could be affected by the fact that also river estuaries on Oceans are often subjected to tides, and it could be impossible to use watermills on large streams.

Figure 1- III (left): Tide mill "Berno", Ile d'Arz, Britany

Figure 1- IV (right): Tide mill in Olhao, Portugal

1.2 Waves

Ancients seemed to be less interested in finding a scientific explanation for waves than for tides, as it is much more difficult to find historical information for the former than for the latter. However Romans and especially Greeks, that where great sailors, saw in Poseidon (or Neptune) the cause of storms: the strength and height of waves were then linked to his frame of mind.

The use of waves to produce energy is much more recent than the one of tides, as the motion is not constant but it is an oscillation. In 1799, during the Napoleonic period, monsieur Girard and his son obtained in Paris a patent for a machine that they had designed to mechanically capture the energy in ocean waves: they envisioned to use it taking advantage of vessels' bobbing and connecting their device to land. In this way mechanical energy could be used to run pumps, sawmills and the like. However, there is no evidence that they ever carried out their plan [5].

A "wave motor" system was invented and patented by P.Wright in the USA in 1898 (Figure 1-V). It was made of a hinged float which rode the waves and, thanks to mechanical connections, could operate a hydraulic pump able to power various machineries.

An early wave device to produce electricity was built by a French, Bochaux-Praceique, in 1910 (Figure 1-VI). The goal was basically just to light his house, and his device is considered to be the first oscillating water column type wave device.

The research on the use of wave power grew rapidly from mid 1800s to late 1900s: 340 license were filed just in the UK between 1855 and 1973. As we will explain up ahead, there are many different wave energy devices that are studied nowadays, and none of them has definitely exceeded yet the others for efficiency or convenience [6].

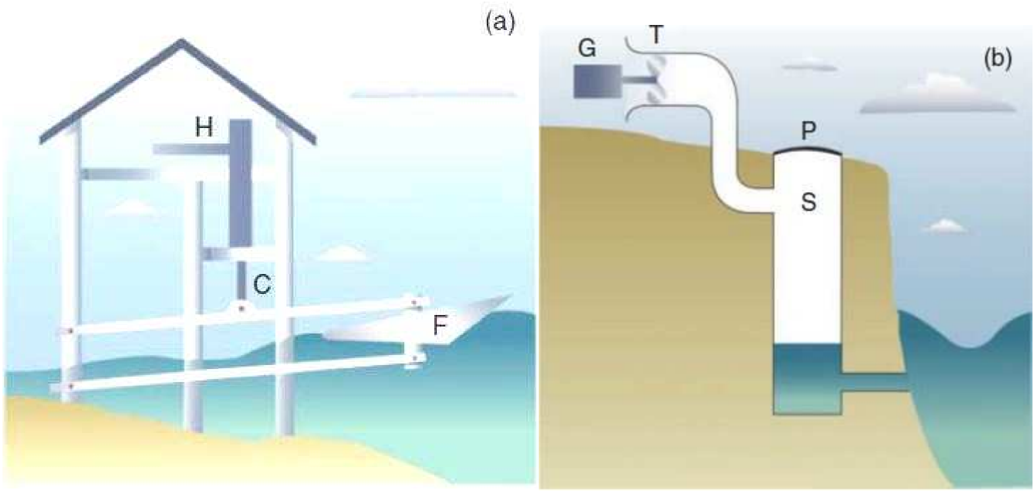


Figure 1-V (left): Wright's Wave motor of 1898

Figure 1-VI (right): Bocheaux-Praceique Oscillating water column of 1910

1.3 Ocean currents

Many people think that the idea of harvesting energy from ocean currents is recent, however it is a conception that is 100-year old at least. As written by A.C. Sparavigna in her work "Emilio Salgari and the Energy Harvesting from Gulf Stream", E. Salgari, an Italian writer of adventure novels and science fiction, described in his novel “The wonders of 2000” an hydropower plant for extracting energy from the Gulf Stream. Salgari depicts future society and its huge technological progress; moreover, he explains how this society is gaining its energy from oceans.

Figure 1-VII: The cover of “The wonders of 2000”, E. Salgari, Bemporad, 1907

Thanks to literary fiction, the writer represents future society through the experience of James Brandok and Toby Holker who discovered in 1903 how to suspend their vital functions and travel in time. They were kept in a sort of hibernation in a bunker near New York. They awoken in 2003 by one of Holker's grandchild, and they started living again in a very different society. Sparavigna mentions the section of the book in which the hydropower plant is illustrated: Brandok, Holker and his grandchild, after having travelled to a polar colony and moved to Europe, they got on an electric train and on the “Centaur”, a flying vessel. After that they passed though an underwater city. Finally they found the plants [7]:

"Now you'll see another of the most marvelous inventions of our scientists, - said Holker - you will see what profit men of the third millennium are gaining from this great stream that men of your time neglected. It seems impossible that your scientists never dealt with such an immense force in these waters". Then Toby asks, "What have you done with this river in the ocean? You told about mills." "Yes, uncle, - Holker answered - as you know, all our machines are powered by electricity, so we need a huge force from gigantic dynamos. North America has its famous waterfalls, the South, its numerous rivers. Europe a few streams with poor waterfalls, so it is insufficient. Therefore, what have the scientists thought? They have resorted to the Atlantic Ocean and have fixed their eyes on the Gulf Stream. And, in fact, an immense force can be drawn from this stream! They built huge floating islands, made of steel, equipped with huge wheels similar to those of your old mills, and towed up to the Gulf Stream, mooring them firmly. Nowadays there are more than two hundred, spread out near the coasts of Europe and almost as many in the Gulf of Mexico, with a mandate to administer, with almost no expenditure, the force required by factories in Central America and also in the northern coast of Guyana, Venezuela, Columbia and Brazil." "How is the force transmitted? By overhead wires?" "No, uncle, with submarine cables, similar to those that you used for transatlantic telegraphy." "What is the speed of the Gulf Stream?" asked Brandok "Five to eight km/h," said Holker. "Can those islands resist hurricanes?" "Each one is strongly moored and even if one broke its moorings, the men on them who are in charge of surveillance run no risk, since those islands, or rather, vast vessels are unsinkable." "And each of them how much force can provide?" "A million horsepower” [8].

We mentioned this Salgari's novel because he correctly predicted that 21st century would have been profoundly dependant on electric power and the need of collecting energy from ocean currents is one of the effects of this matter of fact. Salgari also seems to make a description of plants able to harvest the current energy not so far from what researchers are nowadays building; he probably failed the dimensions of the plants, which nowadays are much smaller than in his description, but he afterall pointed out that they worked with wheels similar to those of the mills.

Using ocean currents to produce energy seems to be more difficult than using tides or waves, but the great advantage of this source of energy is its constancy and regularity. Despite the fact that research on current energy harvesting is not mature yet, we'll try to give an idea about the studies that are being made and of the areas where the plants could be installed in the future.

2. GENERAL STATEMENTS AND PRINCIPLES ON WAVE ENERGY CONVERSION

2.1 Classification of wave energy converters and their comparison

There's a really wide range of Wave Energy Converters (WECs) based on different mechanical principles, but none of them has really yet overcame the others for efficiency or functionality in the production of energy. In this chapter we'll consider the technologies using the oscillatory nature of the resource, and we will mention the collectors operating with a collecting chamber based on an overtopping principle. We'll make a general description of the different types of WECs, with specific references to some existing devices.

Many different methods have been suggested in order to classify WECs; the most intuitive classification system is probably the one based mainly on the principle of operation (Figure 2 – I):

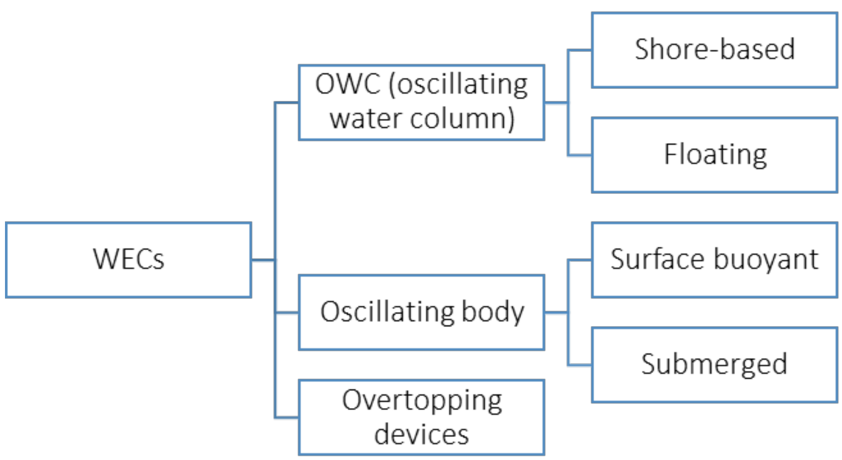


Figure 2-I: Scheme of classification of Wave Energy Converters

- OWC (oscillating water column): these energy converters use water motion to induce varying pressure levels between the air-filled chamber and the atmosphere; an air turbine, thanks to its design, rotates in the same direction both during the filling and the emptying of the chamber, and produces energy. These devices can be “shore based” or “floating”.
- Oscillating body: in this case, the mechanical energy from the relative motion of two bodies is used by the power take-off system to produce electrical energy. The bodies are normally on the surface of the sea, but some devices are also devised in order to work submerged. In this group there are also some newer near shore devices of large dimensions: they are wave-powered pumps, which push high pressure water to drive an onshore hydro-electric turbine.
- Overtopping devices: water from waves is collected in a reservoir, and then its potential energy is transformed into electrical energy passing through a hydraulic turbine. As hinted, this system does not directly work on the “oscillating nature” of waves, but it just uses it to obtain regularly potential energy. We’ll concentrate our interest on the “oscillating devices”.

A different but accurate classification mostly considers the geometry of the device and the way it absorbs energy (Figure 2 – II); if we take into account the propagation direction and the wavelength (λ), we can find [9]:

- Point absorbers, devices with a vertical symmetrical axis and with a small relative size to the wavelength of the incident waves; they can use the energy of waves in all the directions and are relatively simple to study as their size makes negligible the scattered waves;

- Attenuators, which have a dominant dimension in the direction of the waves;
- Terminators, whose dominant dimension is perpendicular to the waves direction.

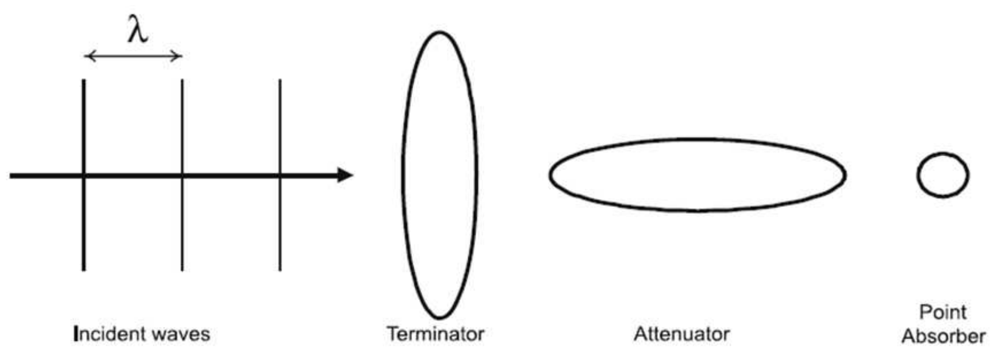


Figure 2–II: Classification of WECs according to the device geometry

Since the first studies on WECs have been started, researchers felt the necessity to ascertain the quantity able to evaluate the ability of a device to catch and use the energy of waves. The fundamental property is the Capture width, that, at a given frequency, is defined as the ratio of the total mean power absorbed by the body to the mean power per unit crest wave width of the incident wave train, where “mean” refers to the average value per wave period for regular waves or per energy period for irregular waves [9]. Capture width has the dimension of a length, and can also be called Absorption length or Absorption width. The Maximum capture width of a device is related to the properties of the power take-off mechanism: this will involve a strict relation of the capture width to the input frequency: the highest efficiency is only achieved with a certain frequency of waves. The Bandwidth curve is obtained after having fixed the power take-off parameters, comparing the behaviour of the device to different frequencies; a device with a broad bandwidth will work well over a wide range of conditions, while it will be the opposite for a device with a tight bandwidth. The importance we must give to these properties depends on the characteristics of the waves in the selected area, therefore the choice has to be done after their measurements and some preparatory work.

In the next paragraph we’ll describe the energy transported by a wave, so that, knowing the absorbed power by a particular device, we can get an expression for the capture width.

2.2 Energy of marine waves

In order to give a description of surface marine waves, it’s important to point out that they aren’t longitudinal nor transverse: the trajectory of a sea water particle is elliptical. This is a consequence of the incompressibility of water, and if somewhere the height of water is raising (and a crest is forming), somewhere else water is flowing away (and a trough is developing).

Marine waves, moreover, are dispersive: this means that the wavenumber is not directly proportional to the pulsation. What is essential to be known is that this relation depends on restoring forces, which are essentially (for marine waves) the surface tension and the gravity. The former is influential for very short wavelengths and we can neglect it, as this type of waves is not the aim of our study; however, the latter affects considerably water waves of medium and long wavelengths, and we’ll consider it.

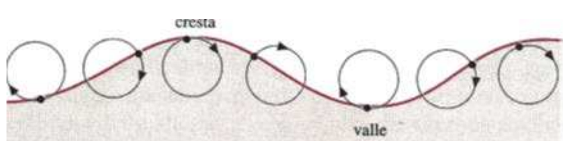


Figure 2–III: Circular trajectory of water particles in a wave

In order to describe the gravity affecting the restoring forces of waves, we’ll make some simplifying hypothesis: we imagine to be into deep sea without considering the effect of currents.

These two preconditions will permit us to neglect the dissipative effects of the sea bottom (h>>λ, where h is the water depth and λ is the wavelength); moreover, we will approximate the elliptical trajectory of particles to a circular trajectory between the crests and the troughs of the waves (Figure 2 – III).

Each marine wave is made of the overlapping of many sinusoidal waves: for this reason the representation of a marine wave can turn out to be difficult. If we analyse only one sinusoidal wave in deep sea and we employ the Bernoulli Equation between its crest and trough, we obtain:

$$p + \frac{1}{2}\rho {v_t}^2 + \rho g h = p + \frac{1}{2}\rho {v_c}^2 + \rho g(2A + h) \ ,$$

where p is the atmospheric pressure, ρ is the water density, h is the water deep, A is the amplitude of the wave, v_t and v_c are the trough and crest velocity. Bernoulli equation requires to be used along a streamline (requirement satisfied by the circular trajectory of water particle) and an (that the) incompressible irrotational and stationary flow. Simplifying the equation, we will obtain:

$${v_t}^2 - {v_c}^2 = 2gA \ .$$

If $v_f = \frac{\omega}{k} = \frac{\lambda}{T}$ is the velocity of propagation of the wave, with ω angular frequency, we can rewrite v_t and v_c in function of r (radius of the circular trajectory) and T (period both of the wave and the rotation):

$$v_t = \frac{2\pi r}{T} + v_f \ , \ v_c = \frac{2\pi r}{T} - v_f .$$

The radius r will be the equal to the amplitude of the wave, then A=r. Joining the expressions obtained and the definition of velocity of propagation of the wave, we have obtained the expression:

$$v_f = \sqrt{\frac{g\lambda}{2\pi}} \ ,$$

that states the velocity of propagation of one wave independently of the period T [10]. This velocity is called phase velocity and reduces as λ increases.

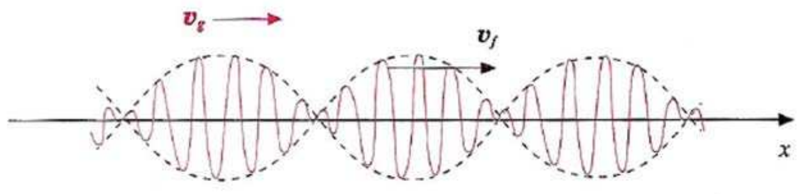


Figure 2-IV: Overlapping of two sinusoidal waves

Actually, marine waves are formed by the overlapping of many waves with different frequencies: this generates a group of waves called "wave train" (Figure 2 - IV). The velocity of each singular wave, called phase velocity, doesn't correspond to the travelling velocity of all the wave train: we have to formulate the group velocity, that states how fast the propagation of the wave train is. The group velocity is defined as:

$$v_g = \frac{d\omega}{dk},$$

and it can be equal or different to the phase velocity, depending on how much dispersive the medium is.

It is demonstrated that for marine waves the dispersion relation is:

$$\omega^2 = kg \tanh(kh);$$

as we chose to make our study in deep sea, h tends to infinite, and $\lim_{h\to\infty} \tanh(kh) = 1$, so that

$$\omega^2 = kg.$$

The phase velocity of each wave will be, as already stated is:

$$v_f = \frac{\omega}{k} = \sqrt{\frac{g\lambda}{2\pi}},$$

and the group velocity is:

$$v_g = \frac{d\omega}{dk} = \frac{1}{2} v_f.$$

We've found out that, with reference to marine waves in deep sea, the group velocity is always half of the phase velocity of each crest of the group. Moreover, the group velocity of a wave train in a dispersive medium it also represents the speed with which energy propagates.

We finally have what we need to describe the energy transported by a marine wave and to give an expression in order to calculate the capture width. For a regular incident wave in deep sea the power per unit length of crest is:

$$P_w = \frac{1}{2}\rho g a^2 v_g \;\; [W/m].$$

Called P [W] the mean power absorbed by a certain device, its capture width is:

$$L(\beta, \omega) = \frac{P}{P_w}.$$

Therefore, the device that we considered can catch an amount LP_w from the wavefront [9], [10], [11].

Looking for a dimensionless measure of the absorption characteristics of a device, we can divide the quantity L by the front length of the system (for example, for a point absorber, it could be the diameter D): this should represent an objective evaluation of the absorption capacity of a certain type of device, independently from its measures (a very large device will surely catch more energy than a small one, but it will also involve structural and safety problems that should be solved) [9].

2.3 Oscillating body

The right approach to study the WECs is researching the performance in power absorption: the response to extreme sea conditions is certainly important, but it will have no significance if the device doesn't conveniently work in normal conditions. Moreover, for the majority of WECs, the main objective in extreme conditions is not the production of energy, but rather the "survivability" of the whole system.

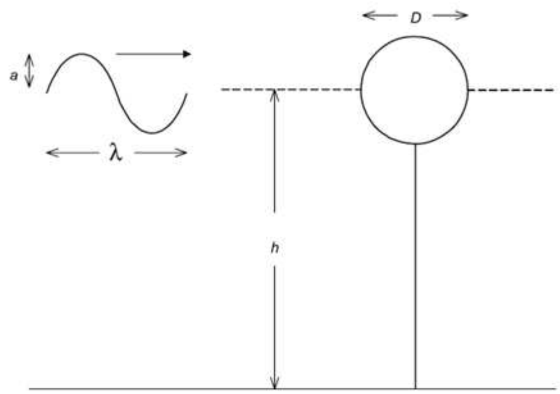


Figure 2-V: Point absorber

Looking at the forces acting on an oscillating body device, here represented as a point absorber (D < λ) berthed to the sea bottom (Figure 2-V), and neglecting the components in the sway motion direction (perpendicular to the paper surface), we obtain:

- F_f (t), that includes all the fluid induced forces: F_H (t), that is the buoyancy force; F_S (t), that is the scattering force (indicating the force that the body would experience if it was held fixed in his mean position and is mainly dependant of incident waves); F_R (t), the radiation force, corresponding to the force experienced by the body due to its oscillatory movement, without considering any incident wave;
- F_{ext}, the sum of the external forces applied to the mooring system and the mechanisms that allows to convert energy.

The motion of the floating oscillating body is given by the equation:

$$m\ddot{X} = F_f(t) + F_{ext}(t),$$

where m is the mass of the body and $\ddot{X}$ is its acceleration [9].

After having described the devices allowing to harvest the energy of waves it is necessary to examine the systems which permit the practical use that kind of energy: the power take-off systems (PTO) are generally indicated as the mechanisms that permit to convert the waves into mechanical and, then, electrical energy. Moreover a further classification should be done between linear generators and hydraulic power take-off systems. In general, linear generators are associated with point absorbers devices and hydraulic systems with the other types of devices, but this is not necessarily a strict rule.

2.3.1 Linear generators

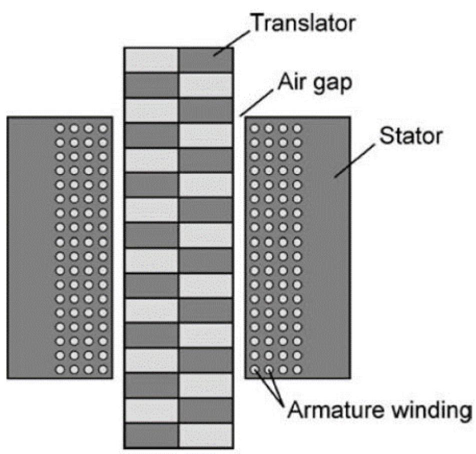


Figure 2-VI: Linear generator

The use of a linear generator (Figure 2-VI) as PTO permits to spare money for the mechanical components, but it also brings some important issues linked with the extent of the system and the connection at the electrical grid.

The energy absorbing part (floating body) is directly coupled to the moving part of the linear generator, called translator and on which magnets are mounted with alternating polarity. The translator moves linearly (up and down) inside a stator (Figure 2-VII) containing windings of conductors, and the difference of tension is created according to the Faraday-Lenz law applied at a coil of wire:

$$\varepsilon = -\frac{d\varphi}{dt},$$

where ε is the electromotive force, φ is the magnetic flux through a single loop and N is the number of turns of conductor wire; between the translator and the stator there is a little air gap.

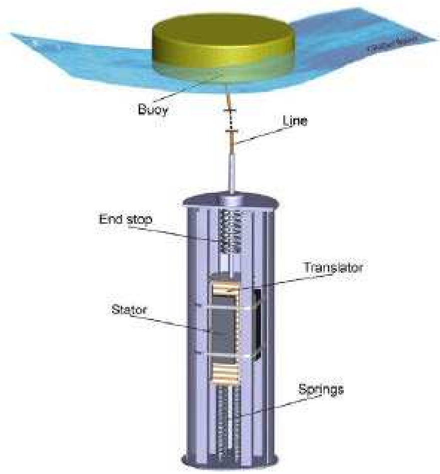


Figure 2-VII: Translator and stator of a linear generator device

The waves consist in the driving force of the oscillating system, and the generator acts as damper. The capacity of absorption of the device depends on the damping of the generator: this is influenced by the dimension of the absorber, its weight and the scillation speed of the body (and of the translator). In general, linear generators are characterised by a slow speed because the speed of the input source is slow: the vertical speed of the sea surface normally varies between 1 and 2 m/s, whereas rotational generators rotates at a speed 15-50 times higher. In consequence, the linear generators must be 15-50 times larger than the rotational ones in order to give an equal output power.

The translator has a ceaselessly varying speed and the same it occurs to the output power; consequently the power generated by a oscillating body WEC with a linear generator will vary either on a short timescale, because of the varying speed of the translator, or on a long timescale, due to the change of the wave conditions. Other consequences of the oscillatory motion in the generator are that the induced voltage frequency will vary and the order of the phases in a multiphase machine will be interchanged. This prevents from connecting a linear generator directly to the electrical grid: the current needs to be rectified and then converted into 50-60 Hz AC [9].

2.3.2 Hydraulic systems

There's a group of devices that works on the principle of oscillating bodies and uses hydraulic systems. The first of these devices, Duck, was designed by Stephen Salter in 1974 (Figure 2-VIII); it was made of different parts connected each other, and its section had the form of a cam. The apparatus took advantage of both the kinetic and potential energy of waves, and was characterised by a high efficiency. Unluckily, although Duck was well designed and many researchers worked on it, only some prototypes have been made and tested in sea: the technology used was really expensive at that time and the device has never been produced [10].

Figure 2 – VIII: Salter’s Duck

Pelamis

Pelamis (Figure 2-IX) is an ocean wave converter produced by Ocean Power Delivery Ltd., a Scottish company; as Duck, it’s made of many moving parts and riminds of a form of a snake. In particular, the four semi-submerged cylindrical corps are interconnected by mechanical joints: waves cause the relative up-and-down movements between the corps and some joints activate pistons pumping high pressure oil through hydraulic motors. Stiffness of joints have to be regulated according to sea conditions, and the device needs to be orientated in parallel to the wave direction through a complex mooring system.

A few Pelamis machines have been installed since 1998, when the company was founded:

- In 2004 it was installed and tested its first full scale prototype at the EMEC, the European Marine Energy Centre in Orkney, Scotland; Pelamis became in this occasion the first commercial scale, offshore, wave power machine generating electricity into the national grid.

- In 2008 Ocean Power Delivery Ltd. sold three 750kW commercial machines to the global investment company Babcock & Brown,that installed them in Portugal; the three Pelamis machines produced electricity for a short period of time, as the acquiring company went into liquidation.

- In February 2009, after having changed its name in Pelamis Wave Power, the company received an order from Germany for a new generation of wave converters, called P2. The machine was installed at EMEC in 2010, and has been tested there for three years under a series of different weather conditions with progressively higher wave heights; this approach permitted a progressive study of risk management of the technology used and development of the ability to handle all the unexpected technical issues [12].

Tests on P2 machines have been completed at EMEC, but in November 2014 the company ended in administration to assess the options for future development. To understand the difficulties that Pelamis and other promising projects encountered in getting fulfillment and complete fruition, we quote the words by Dr Richard Yemm, the founder of Ocean Power Delivery, interviewed by the Herald Scotland Journal:

“It's a challenging time in the whole industry. We are in a very big period of uncertainty because of electricity market reform [the constantly-changing price and incentivisation regime surrounding the decarbonisation of the electricity market]; there's no getting away from the impact this has on investment confidence for renewable in general. Those like us at the riskier end of the renewable portfolio are hit hardest, while the most mature technologies at the lowest costs will still proceed. That background pervades the whole industry, not just in the UK” [13].

Figure 2-IX: Pelamis

2.4 Oscillating water column

As floating devices are often developed according to particular needs of a determined area (for example the prevalent direction of waves, or the influence of marine currents on the area considered), OWCs (oscillating water columns) have quite similar technical features independently of the area where they must be installed. The majority of OWCs is shore-based or floating near the coast, and this makes the connections to the grid less expensive; moreover they don’t have mechanical parts in contact with water, so the maintenance of the plants is generally less expensive than for other types of devices. On the other hand, experimental studies on WECs are not easy to perform, because it is complex to quantify the influence of vortex and viscous-effects with small-scale models. For this reason, the mathematical modelling of oscillating water columns holds a fundamental importance.

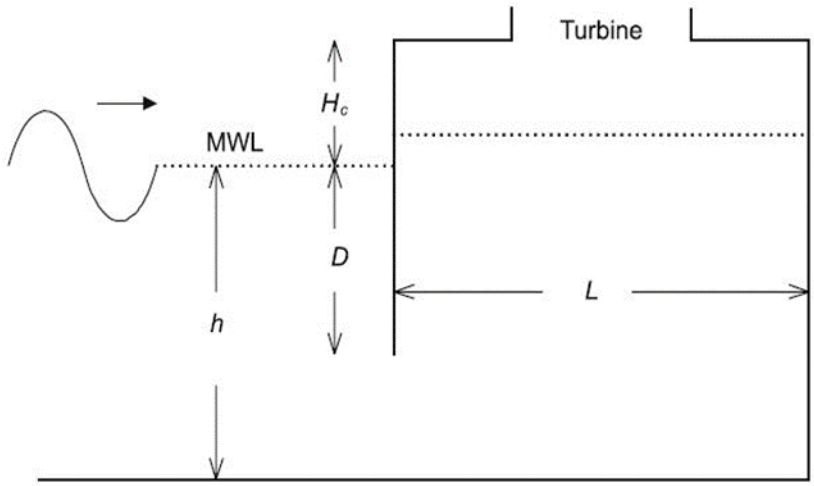


Figure 2-X: Oscillating water column scheme 1

Incident waves create a time-varying pressure field inside the air chamber; the resulting time-varying air flux activates a self-rectifying turbine connected to an alternator. Self-rectifying turbines were developed to be applied to Oscillating Water Columns at the end of the 70's by Alan Wells at the Queen's University of Belfast. Wells low pressure air turbines rotate continuously in one direction independently of the direction of the air flow and use some symmetrical airfoils. The main disadvantage of these devices is a low efficiency of the turbine, as they don't have a true fixed point of operation. In 2009 a new bidirectional turbine, the Hanna turbine, was developed: the main difference with Wells turbines is the asymmetrical shape of the airfoils with a lower angle of attack that produce a greater lift and smaller drag resistance [14].

For what concerns shore-based devices, it's very complex to give account of its incident-wave field as it is non-linear; in the next lines we'll try to specify the power received by the turbine of an OWC from an established stated wave. The air outside the chamber will be at atmospheric pressure pa, that is considered constant, whereas the internal pressure $p_c(t)$ will change harmonically; the inside and outside pressure will be related by the expression:

$$p_c(t) = p_a(t) + p(t),$$

where p(t) is the difference between the chamber and external pressure. If W is the width of the chamber, we denote with $V_c(t) = LH_cW$ the volume of air in the chamber and with $V_w(t) = LDW$ the water volume contained in the chamber above the barrier (Figure 2-X); these two quantities will be related by:

$$V_w + V_c = L(D + H_c)W \qquad \text{and} \qquad \frac{dV_w}{dt} = -\frac{dV_c}{dt}.$$

Indicating with ρ_c and ρ_a, respectively, the density of air inside and outside the chamber, and with γ the ratio of specific heats, for the adiabatic gas law we have

$$\frac{\rho_c(t)}{\rho_a} - 1 = \frac{1}{\gamma}\left(\frac{p_c(t)}{p_a} - 1\right) = \frac{p(t)}{\gamma},$$

that results to be valid if the pressure and density inside the chamber are not far from their ambient values. The air mass in the chamber $M_c(t)$ will change, and considering the air volume flux at the turbine $Q_t(t)$ positive in an outward direction, its time derivative will be:

$$\frac{dM_c}{dt} = \frac{d}{dt}(\rho_c V_c) = -\rho_a Q_t(t)$$

Combining the former equations, and indicating with Q(t) the rate of change of the water volume inside the chamber, we can obtain another expression for $Q_t(t)$:

$$Q_t(t) = \frac{\rho_c(t)}{\rho_a} Q(t) - [L(D + H_c)W - V_w(t)]\frac{1}{\gamma p_a}\frac{dp}{dt}.$$

This expression for the volume rate is nonlinear: we can obtain a more simple form replacing $\rho_c(t)$ by $\rho_a(t)$ and $V_w(t)$ by LDW:

$$Q_t(t) = Q(t) - \frac{LH_cW}{\gamma p_a}\frac{dp}{dt}$$

The instantaneous power at the turbine is finally:

$$P(t) = Q_t(t)p(t) = \left(Q(t) - \frac{LH_cW}{\gamma p_a}\frac{dp}{dt}\right)p(t) .$$

This relation expresses the power received by the turbine (that will surely be higher than the electrical power in output) in function of the dimensions of the chamber, of the rate of the water volume inside the chamber and of the rate of pressure due to the oscillation of the water column inside the chamber. It's not simple to establish the term Q(t), and specific knowledge on the modelling of marine waves would be required. However, it's important to take note that, despite the characteristics of OWCs are quite similar for devices built in different areas, the dimensions of the air chamber depends on the rate of change of the water volume inside it, and on the prevalent features of the waves in the chosen area, in order to limit the risk of the resonance phenomenon inside the chamber, that would nullify the air flux at/ to the turbine [9].

Most part of OWCs are shore based or near to shore devices and the choice mostly depends on the capital expenditure required because shoreline devices are usually more expensive than floating ones. However, with a considerable high wave motion and with high differences of water level due to tides, anchored devices should be more indicated in order to be able to regulate the length of the cables and to give a correct response to the variation of water level. Despite all this, shoreline based devices result more firm and stable and they can offer a higher resistance to waves, that is a higher efficiency in the production of energy.

OWCs are quite extended devices: the section of the chamber can vary between 100 and 400 m^2, the height is included between 10 and 20 m, and the diameter of the turbine is in the order of 2-3 m. Currently, the output power of OWCs can be up to 1 MW, that doesn't represent a high power for a quite expensive and extended plant. In Europe, the two main projects of OWCs are the plant of *Pico* (Figure 2-XI), in Azores (a Portuguese archipelago in the Atlantic Ocean), which has a turbine of 400 KW of power, and the *Limpet* (Figure 2-XII) in Islay (UK), with a power of 500 kW.

Despite OWCs have been studied for a long time (since the 70's, when the Wells turbine was developed), most of these devices are prototypes because of the necessary high capital and operating expenditures (cost) and the very longterm investment comeback. The possibility of integrating the systems with breakwater structures (for example at the entrance of harbours) should be in future a good opportunity to reduce the cost of these kinds of plants.

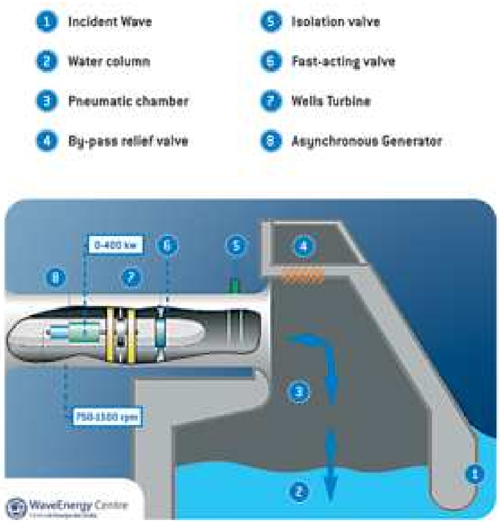


Figure 2-XI (left): Pico OWC scheme

Figure 2-XII (right): Limpet OWC

3. TIDAL RANGE ENERGY

In this chapter we'll first describe the phenomena of tides and its different typologies in various areas of the world, thereafter we'll focus the attention on the power generation from tides and on the case study of the Rance tidal power plant.

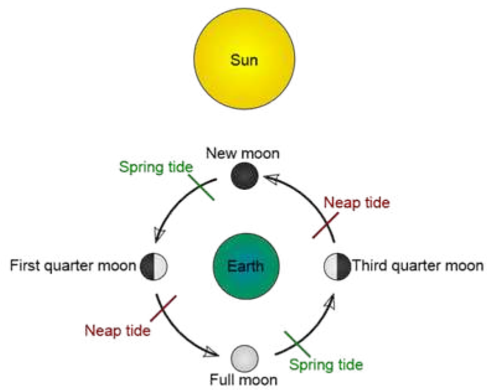
As it is possible to produce energy either using the potential energy of the body of water moved by the tide or the kinetic energy of the tide stream, we will first focus on the former way of energy production, the one that uses barrages and lagoons. We will consider the latter kind of energy production in another chapter concerning the devices producing energy through ocean currents and tidal streams.

3.1 Tides

The word "tide" refers to the rise and fall of sea level in connection to the land. The extent of the phenomena differs according to seasons, astral alignment and the morphology of the interested area. The forces that generate tides are the gravitational pull of sun and moon and the centrifugal force linked to Earth rotation. Let's give a look at Newton's law of universal gravitation between two bodies of masses m_1 and m_2 at a distance r:

$$F = G\frac{m_1 m_2}{r^2},$$

where G is the gravitational constant (6,67E-11 Nm^2/kg^2). As the term r appears with the exponent 2, if the body considered has a large extension the gravitational force is not constant across it: on this basis, there will be different attraction by celestial bodies on particles of water on different sides of Earth. Regions on Earth nearer to the celestial body considered will undergo a stronger attractive force towards it than further regions. In particular, even if the gravitational attraction of Sun is 179 times stronger than the one of Moon, the latter exerts a stronger influence on tides. Indeed, the diameter of Earth (12˙742 Km) is comparable with the distance Earth-Moon (384˙400 Km) but it’s much shorter than the distance Earth-Sun (149˙600˙000 km); however, due to its giant mass, also Sun’s tide force is influent, and it is equivalent to about 45% of the Moon’s tide force [15].



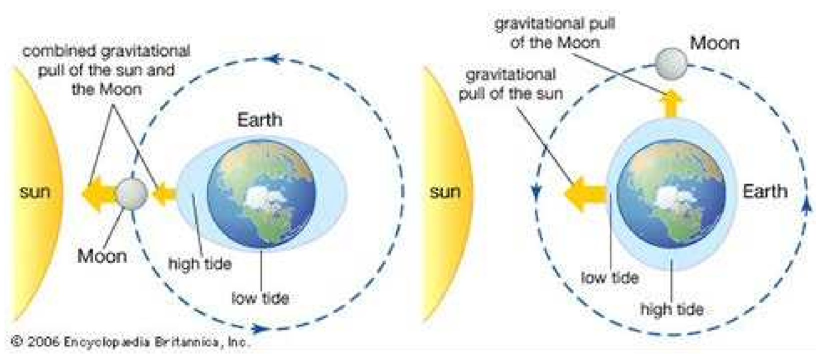


Figure 3-I (up): Tides and moon cycles

Figure 3-II (down): Tidal force as sum of vectors

As first approximation, the overall tide force is then the vector sum of the two named forces, and the intensity of the tide in each moment depends on the relative position of Moon, Sun and Earth: if Moon and Sun are in conjunction or opposition the tide will be strengthened and we’ll call it spring tide. If the two celestial bodies are in quadrature the tide will be weakened and we’ll call it neap tide. As a result the amplitude of tides increases and decreases cyclically, in a period of about two weeks.

There are different types of tide in various areas of Earth [16]:

- Diurnal tides, which are the ones we can meet for example on the coasts of Korea and Alaska; they display one high and one low in a tidal day. The lunar day differs from the earth day, and so the tidal day does; their mean life span is 24h 50' 24.9''.
- Semidiurnal tides, when in a tidal day two high and two low tides occur. We can observe them on the Atlantic coast of Europe and North America for instance. There is normally just a little difference between successive tides of the same phase, and two high tides are 12 h 25' distant on the average.
- Mixed semidiurnal tides show peculiarities of both diurnal and semidiurnal tides. We can encounter them on the Pacific Ocean coast of the United States, and they're characterized by a large diurnal variance; for example, there should two low tides and two high tides of different heights in the same lunar day.

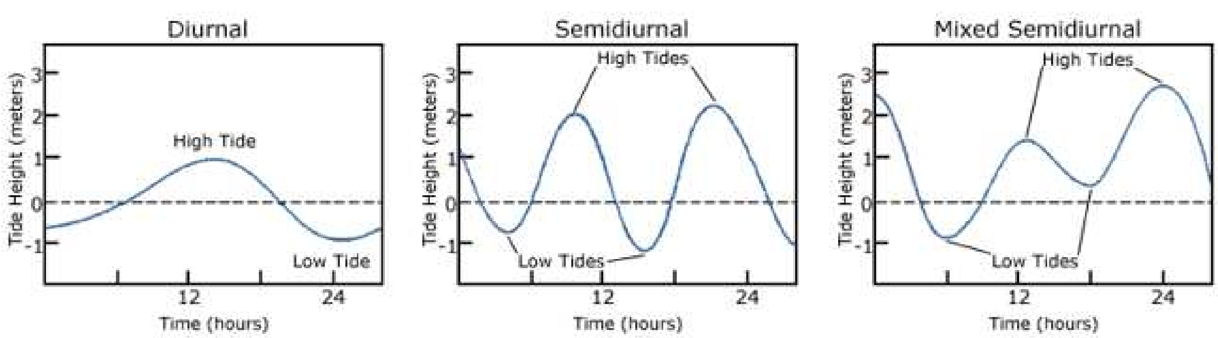


Figure 3-III: Diurnal, semidiurnal, mixed semidiurnal tides

Tidal force, as hinted, depends mostly on the lunar and solar position and the extent of the water mass, but also Earth's rotation and bathymetry (the underwater depth of ocean floors) influence it. The way in which water moves and the consequent type of tide also depend on the specific morphology of the area.

Therefore, it would be useful to consider the different ways in which tides are calculated: the current procedure used to analyze tides and to predict them in order to give notice of the phenomena is directly obtained from the method of harmonic analysis by William Thomson. Motions of sun and moon determine a large number of component frequencies: each frequency has a component that produces tidal motion, but the response of the system differs from place to place on Earth. Therefore the tide heights are measured for a period of time sufficiently long (usually more than one year) to know how the response is in specific areas to each tide-generating frequency. Tide heights follow the tidal force with a constant amplitude and a delay phase for each frequency component; as astronomical frequencies and phases can be exactly predicted, also tide heights can be predicted if we know the particular response on a specific geographic area [16].

Most tide tables used by sailors indicate the levels of high and low tide in a certain locality and their corresponding times, so in a single book you can find many data referring to several localities. For what it concerns semidiurnal tides, the most common tides in Europe, seafarers make use of the “rule of twelfths” to estimate the height of water at any time. The rule has been proved to indicate a good approximation and it assumes that the flow rate of a tide smoothly increases to a maximum halfway between high and low tide before regularly decreasing to zero again .

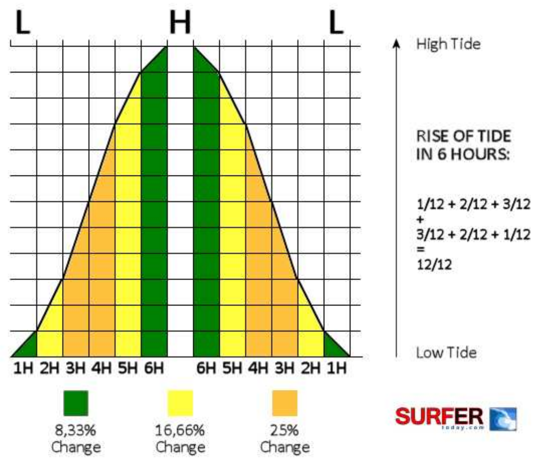


Figure 3-IV: Rule of twelfths

If we divide the period of time between low and high tide into six intervals, the rule says the water level will rise of one twelfth of the range in the first interval, two twelfths in the second one, three twelfths in the third and fourth ones, again two twelfths in the fifth interval and finally one twelfth in the sixth interval.

3.2 Tidal barrage plant

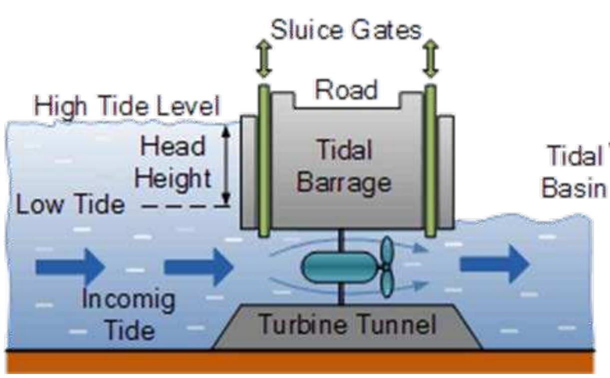
A tidal barrage is a dam-like structure used to capture the energy from masses of water moving in and out of a bay or river due to tide; it allows water to flow into the bay or river during high tide and to flow back during low tide. Sluice gates, where turbines capturing the water potential-kinetic energy are placed, are opened and closed at key times of the tidal cycle. When the water level outside the basin or lagoon changes in connection with the water level inside, the turbines are able to produce power.

The area where a tidal barrage plant can be built needs a high average tide range of at least 10 to 15 m to make the plant economically sustainable; moreover a large area where water can be stored is required, so broad bays and river estuaries are particularly suitable to this use [17].

There are several different barrage schemes and types of tidal barrages: ebb generating systems, flood generating systems, two-way generation, and double-basin tidal barrages.

Ebb generation

By this method the flood tide is allowed to fill the bay through a series of sluice gates (E→B). Once high tide is reached, the sluice gates are closed in order to trap the water within the estuary (B→C). As the tide outside the barrage flows out, the water within the bay is held in place until a sufficient head difference is created. At this point the sluice gates are opened, releasing the water through a series of low-head turbines and generating electricity (C→D). This generation continues until the pressure head drops to a level at which the turbines can no longer operate efficiently [17].



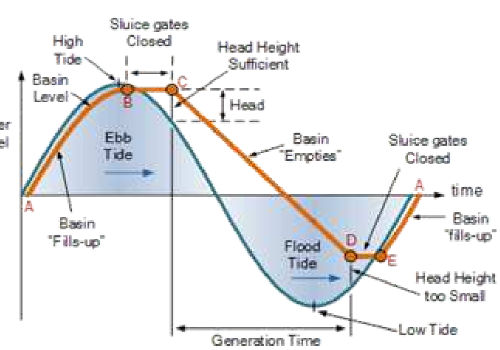


Figure 3-V (left): Ebb generation barrage scheme

Figure 3-VI (right): Ebb generation time

In addition to these schemes, turbines in the barrage can be used to pump extra water into the basin at periods of low demand; this usually coincides with cheap electricity prices, generally at night when demand is low or there is an overproduction from other sources (for example nuclear). The company therefore buys the electricity to pump the extra water in, and then generates power at times of high demand when prices are high so as to make a profit; this technique has been already used in many hydroelectric plants.

Flood generation

This method of generation is similar to ebb generation except that it harnesses the energy of the incoming flood tide. After the water has been allowed to flow out of the bay, the sluice gates are closed at ebb tide. As the tide begins to flood back in, the pressure head is built up on the seaward side of the tidal barrage. Such as the ebb generation method, the sluice gates are opened when a sufficient hydrostatic head has been achieved. [17]

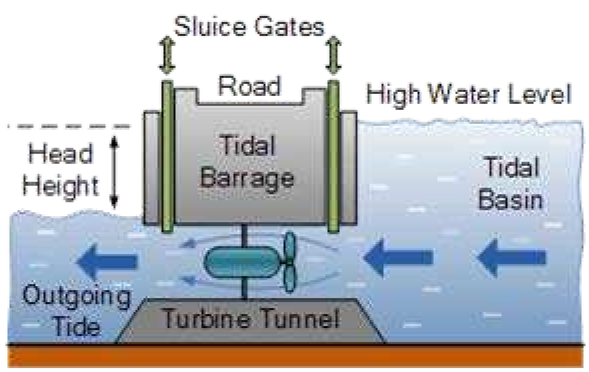


Figure 3-VII: Flood generation barrage scheme

Two ways generation

Two-way generation harnesses the power of both the incoming flood tide and outgoing ebb tide. The sluice gates are kept closed until the end of the flood cycle. When a sufficient pressure head is achieved the gates are opened, allowing water to flood into the bay through the turbines. Once high tide is reached within the bay the sluice gates are again closed in order to create a hydrostatic head with the ebb tide. Again, once a sufficient head difference is achieved the gates are opened, allowing the water to turn the turbines and generate electricity. [17]

With the two-way generation, the period of non-generation is greatly reduced; however this production of energy is usually less efficient than one-way flood or ebb generation because the head height is smaller and bi-directional tidal turbine generators designed to operate in both directions are generally more expensive and less efficient than dedicated uni-directional tidal generators. Finally, the choice between the two-way generation scheme and the ebb generation scheme depends on the amount of the available capital and the required pay-back time, that are both higher in the two-way generation scheme, and the availability of energy storages.

Double-basin generation

Another kind of energy barrage configuration is that with two basins, in which one is filled at high tide and the other is emptied at low tide; between the basins there are reversible turbines. Two-basin schemes offer some advantages compared to normal schemes as the generation time can be adjusted with high flexibility and it is also possible to generate almost continuously: a portion of the electricity generated when the first basin empties is used to pump water into a secondary holding basin.

Normally two basin schemes are very expensive to build due to the cost of the extra length of barrage. There are some appropriate geographic areas, however, which are well suited to this kind of scheme.

Tidal barrage plants make often use of bulb turbines, an evolution of the Kaplan turbines built to reduce the environmental impact and the civil works needed for hydroelectric plants. Bulb turbines are indeed a type of low head hydro turbine in which the entire generator is mounted inside the water passageway as an integral unit with the turbine, so that there are significant reductions in the size of the powerhouse. These turbines can have swiveling blades in order to produce energy in both the directions of the flow.

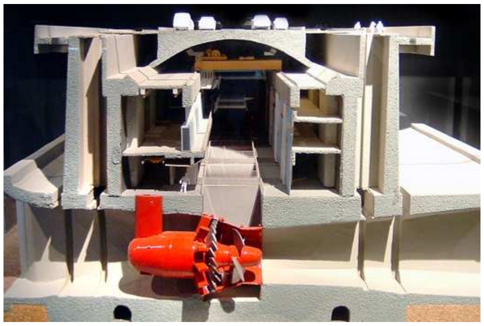


Figure 3-VIII: Swiveling turbines of Rance TPP

3.3 Available power and energy

The rise and fall of tides dissipates all over the world an amount of energy, called tidal power potential, in the range of 3 TW, and one third of it is supposed to be located in relatively shallow waters. We should harvest just a part of this quantity (that contains both the tidal range energy and the tidal current energy); however, considering the development of low head turbines and the correct choice of the opening and closing time of tide gates, we can state that most part of tidal power potential in shallow waters could be transformed in electrical energy.

The energy available from a tidal barrage is dependent on the volume of water that the basin contains. The potential energy contained in a volume of water is:

$$E = \frac{1}{2} A\rho g h^2,$$

where:

- h is the vertical tidal range, that means, in case of ebb generation, the starting difference of height between the water in the basin and outside the basin (that is equal to the difference between the high tide and the low tide)
- A is the horizontal area of the barrage basin
- P is the density of water = 1025 kg/m^3
- g is the acceleration due to the Earth's gravity = 9.81 m/s^2

The factor 1/2 is due to the fact that the difference of height h decreases as water passes to the other side of the dam: the maximum head h is only available when the gates are closed, before water starts flowing.

As the available power varies with the square of the tidal range, a barrage is best placed in a location with very high-amplitude tides. Suitable locations are found in Russia, the USA, Canada, Australia, Korea, and the UK. The map gives an idea of the areas in the world where the tidal amplitude is higher.

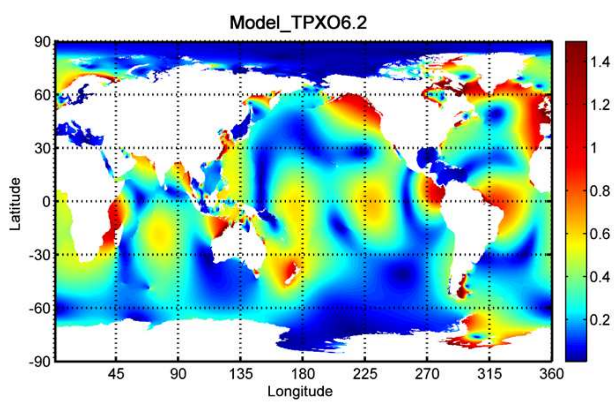


Figure 3-IX: Intensity of tides in the world

3.4 Case study: Rance tidal power plant

There are currently only two operating tidal barrage plants with a capacity in the order of hundreds MW: the Rance Tidal Power Station (1966) in France, with a peak capacity of 240 MW, and the Sihwa Lake Tidal Power Station (2011) in South Korea, with 254 MW of peak capacity. Another enormous plant, the Incheon Tidal Power Station is being built in South Korea: it will be operative in 2017 and it will have a peak capacity of 1320 MW [19].

Figura 3-X: High angle view of Rance TPP

Description and datas

The Rance TPP (Tidal Power Plant) has been built in an area where several tide mills had been used for centuries. It was designed in 1959 and it became operative seven years later; it was the first tidal plant of large dimensions and high production, even if some other little power stations had been working both in Europe and USA in the years before. The peak output of the plant is of 240 MW; as the average output is 62 MW, the plant has a capacity factor of about the 26%, and it produces around 500 GWh per year.

The barrage is 750 m long and is situated on the estuary of the Rance river, south of Saint-Malo, and it creates a basin of more than 22 km2. The power plant portion of the dam is 332,5 m. and consists of 24 bulb turbines with four swiveling blades each; each turbine has its own alternator inside the bulb. In normal conditions, on each turbine the rate flow is of 260 m3/s, and each turbine rotates with a speed of 93 rpm. As the turbines can be swiveled, the plant has the scheme previously described as "two-way generation": it produces energy both when the tide is rising and decreasing. Moreover, water can be also pumped up in the basin as the turbines are reversible; EDF, the French company of electricity, overproduces energy especially at night because of its high number of nuclear plants and when the tide is rising the Rance plant is used as "energy storage" [18].

Environment and economics

We'll now give a look at the environmental and economic aspects of the Rance TPP, keeping in mind that it has been built about 50 years ago and that, nowadays builders of new tidal plants can make use of better and more modern techniques.

The building of the plant lasted three years, and the river was "cut" by two temporary stoplogs during the first two. The ecological impact of the building works has been remarkable, as the construction almost destroyed flora and fauna. In spite of this ten years after the construction, in 1976, the Rance estuary was considered richly diversified again: a new different biological equilibrium was established and water life was flourishing again. In general the fauna is now mainly formed by species of little and fast fishes because they can move through the turbines, while the bigger and slower ones cannot. The estuary of the Rance river is now submitted to tide movements that depend on the choices and necessities of EDF, and the period of time in which there isn't any current in the basin is now more than one hour, while it was of just 5 minutes before the construction of the plant: all this has profoundly modified the sea bottom and the sea currents in the area. The basin is also loosing 1% of its capacity each year due to the stockpile of mud coming from the river that the barrage provokes; this fact is also at the origin of accumulation of mud on the beaches that were covered with white sand.

Figura 3-XI: Construction of Rance TPP

The cost of this construction has been remarkable: 94.5 million, and it took about 20 years for the plant to pay itself; thanks to the long life the plant is having, the electricity being produced in the plant has the really low cost of 1,8c/KWh (versus the 2,5 c/KWh of the nuclear).

Nowadays 28 people work in the plant, and it has been created the COEUR, the Operation Committee of Elected Representatives and Users of Rance: this committee works in contact with the local administration and EDF to improve the quality of water and the navigability of the basin. The plant has also become a tourist appeal, and it contains a museum: "Decouverte de l'usine maremotrice de la Rance". A year after the opening of the electrical plant also the road over the barrage has been opened: it allowed people to go from Saint-Malo to Dinard driving 15 km only, instead of the previous 45 [19].

4. TIDAL CURRENT AND MARINE CURRENT ENERGY

As hinted in the previous chapter, we will finally take into consideration the production of energy by tidal and marine current. Even if their origin is different, the way in which tidal and ocean currents reveal themselves and their energy is the same, and also the devices used to harvest this energy can be the same. Generally speaking there are many prototypes and a few devices which nowadays produce energy from tidal currents, while for what concerns marine currents researchers are still working on prototypes only.

4.1 Tidal currents

We've already written about tides and their origins in the previous chapters: the gravitational pull of the moon and the sun and the rotation of the earth. The current rise and fall of tide is accompanied by a regular movement of water: this phenomenon is the tidal current. Tidal currents and tides are obviously related to each other, but the relation between them is complex to identify and, especially, it is variable.

While nearshore water seems to move forward and backward, offshore the direction of the flow of the tidal current is not restricted by barriers: the result is a rotary movement (Figure 4-I). When tidal currents are directed toward the land, water levels rise in harbors and rivers and these are called flood tides. Tidal currents flowing seaward with falling sea levels are called ebb tides. Between flood and ebb tides there are slack water periods (little or no horizontal movement) [17], [20].

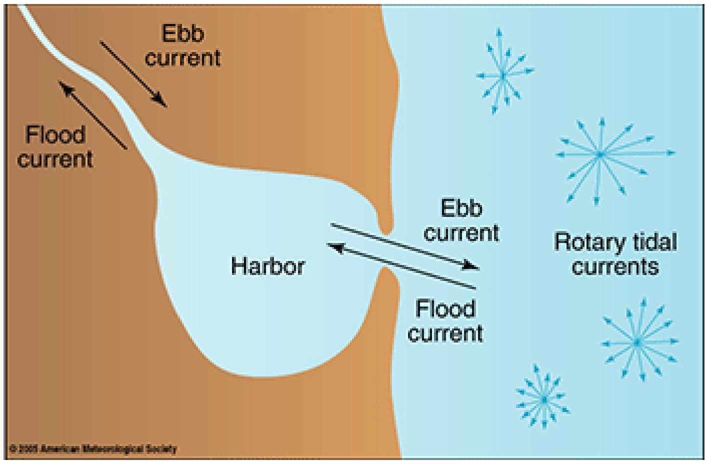


Figure 4-I: Tides nearshore and offshore

The current at anytime and anywhere in the ocean is a combination of tidal and non-tidal currents: the observation of tidal currents is not simple at all because of the superimposition of other currents. As tidal barrages could produce energy both with the rise and fall of the tide, both the flood and the ebb of the reversing nearshore current can produce mechanical energy.

4.2 Marine currents

Marine currents are constant movements of water and can be described as big rivers that flow through the oceans; these moving masses of water are characterized by different temperatures and salinity levels compared to the surrounding water and their speed varies from 2 to 10 km/h. Currents can be originated by the action of wind on water surface or by the differences of atmospheric pressure and of water density, salinity and temperature.

Marine currents are caused by differences in physical properties of water and can occur both on surface and/or in deep water, and they can be classified as:

- Hot currents, which have a higher temperature than the surrounding water;

- Cold currents, which have a lower temperature than surrounding water.

Marine currents that flow all together for long distances generate the ocean conveyor belts, cyclical motions of water playing a dominant role in determining the climate in many regions upon the earth.

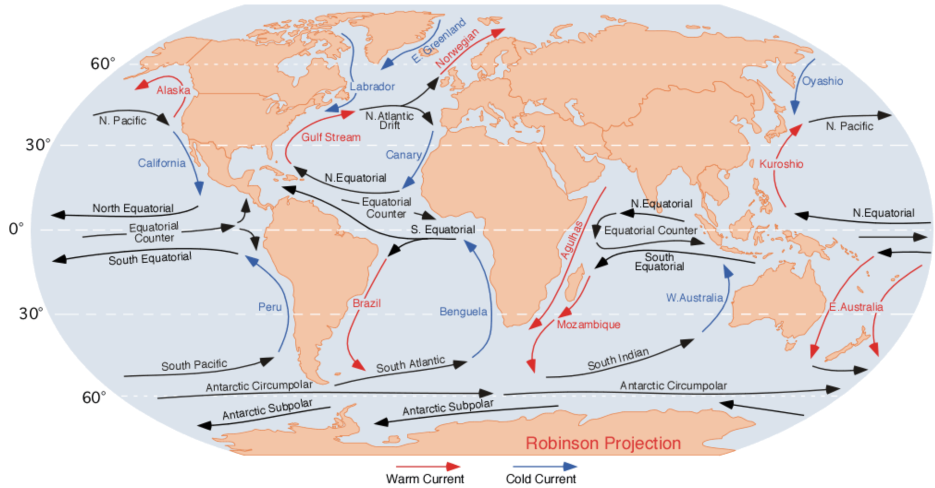


Figure 4-II: Global ocean surface currents

Water masses at Polar Regions have a higher density because they are subjected to the cooling down effect, and they tend to sink at high depths, they move in depth at more temperate latitudes where they warm up and, consequently, they raise. This movement clears new space at Polar Regions, and this causes warm water from lower latitudes to move on the ocean surface towards the poles, where it cools down and becomes more dense: the cycle starts again.

Transferring heat from tropical regions to polar ones, ocean currents mitigate the climate of some areas: for example, Norwegian ports during winter are not frozen because of the warm Gulf Stream, a North Atlantic current that brushes against the coasts of the Scandinavian Peninsula. On the other side, the Canadian Labrador peninsula, at about the same latitude of Norway, is affected by the cold Labrador current and it has its ports frozen over for many months during the year. Another effect of the Gulf Current is spotted on the south coast of Ireland, where it's even possible to find some sub-tropical plants [20].

The intensity of wind and the energy of sun are the main causes of ocean currents. However, the Coriolis force has a great importance to their direction: water masses in the northern hemisphere are drifted right, and they move clockwise; water masses in the southern hemisphere are drifted left, and they move anticlockwise.

Here is a list of the main marine currents:

- Alaska Current: a surface current coming from a branch of the North Pacific current; its temperature is around 4°C, so it's hotter than the water of the Alaska Gulf. Although it's in the north hemisphere, this current is one of the few directed anticlockwise because of the shape of the Alaskan peninsula.
- Aleutian Current: a surface current that flows towards East between the Aleutian islands and the 42° of latitude North. When it arrives near the coasts of North America, it splits into Alaska Current and California current. Its temperature and salinity are low.
- Agulhas Current: a surface current of hot water (around 20°C) that flows through the Indian Ocean. It passes in front of Africa with south-west direction and then it turns back to east.
- Brazil Current: a hot (19-27°C) and salted current of the southern Atlantic that flows towards south in front of Brazil. It then turns east before the far end of the southern American continent.
- Canary Current: a cold surface current that springs from the northwestern Europe and flows towards south, passes the Iberian Peninsula, the northern African coasts and in front of Senegal it flows into the North equatorial Current.

- Caribbean current: a powerful hot current that flows towards west through the Caribbean Sea and comes from the North equatorial Current. Its average velocity is between 38 and 43 cm/s.
- Gulf Stream: a system of ocean currents that moves along the western edge of northern Atlantic Ocean. It's part of the continuous circular motion of anticlockwise currents of the North Atlantic, and it's probably the most interesting example of the phenomena of ocean currents. Its high speed can surpass the 250 cm/s on surface. It takes origin from the North equatorial current and goes towards the Mexican Gulf and the Florida Straits, where it becomes more powerful. It continues towards north, becomes larger (around 150 km wide), and before Canada starts flowing towards Europe; at East of the Great Banks, it becomes the large North Atlantic East, that influences the climate of a large part of Europe [21].

4.3 Available energy

The aim of the devices described in the following pages is to transform the kinetic energy of ocean and tidal currents into electricity, and their technology is based on the same physical principles of wind converters. The velocity of ocean water and the quantity of its motion move the rotor that is mechanically linked to a generator to produce electricity. Sea water is 832 times more dense than air and this fact gives ocean currents an extremely high energy density, which means that tidal turbines need a smaller rotor size than an offshore wind turbine of equivalent power rating.

Betz's principle states that it is not possible to extract all the kinetic energy from the current flowing through the turbine: indeed, the speed of the fluid overflowing the turbine cannot be null, otherwise water would not flow away. In the picture shown in the figure below, we can see Betz's ideal model, where V_1 is the flow speed before the turbine, V_2 the flow speed after the turbine and S the surfaces. $V_2<V_1$, so S_2 must be higher than S_1 in order to maintain the same amount of fluid rate:

$$\dot{m} = \rho S_1 V_1 = \rho S_2 V_2 = \rho V S,$$

where ρ is the water density. If we assume that the average speed through the rotor is the mean between the speeds V_1 and V_2 before and after the turbine, we'll obtain that the flow rate is:

$$\dot{m} = \rho S(\frac{V_1+V_2}{2}).$$

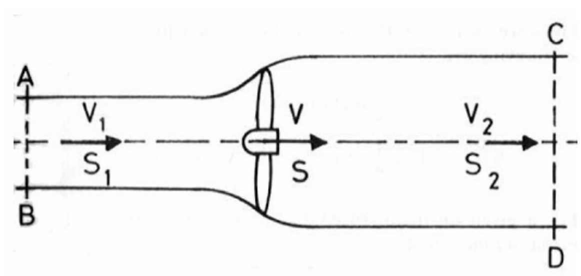


Figure 4-III: The Betz's law

The power extracted by the rotor from the water flow is equal to

$$W = \frac{1}{2}\dot{m}(V_1^2 - V_2^2),$$

and if we substitute the equation obtained for the flow rate

$$W = \frac{1}{4}\rho S(V_1 + V_2)(V_1^2 - V_2^2).$$

As the theoretical power available from the flow is…

$$W_{teoric} = \frac{1}{2}\rho S V_1^3,$$

we obtain that the ratio between extracted power and available power will be

$$\frac{W}{W_{teoric}} = \frac{1}{2}(1 + \frac{V_2}{V_1})(1 - \frac{V_2^2}{V_1^2}). \qquad (1)$$

Setting $y = \frac{W}{W_{teoric}}$ and $x = \frac{V_2}{V_1}$, we obtain the equation $y = \frac{(1+x)(1-x^2)}{2}$. Deriving and making equal to zero to obtain the maximum of the equation (1), we obtain $3x^2 + 2x - 1 = 0$, whose solutions are $x = \frac{1}{3}$ and $x = -1$ (the second one is physically unacceptable). We have then $V_2 = \frac{V_1}{3}$, and substituting into (1)

$$\frac{W}{W_{teoric}} = \frac{1}{2}\left(1 + \frac{1}{3}\right)\left(1 - \frac{1}{9}\right) = \frac{16}{27} = 0{,}593.$$

This means that we can harvest from a moving fluid just the 59,3% of its energy. The calculation is made considering an ultrathin and ideal rotor, with an infinite number of blades and absence of friction; for a real dimensioned rotor the captured ratio energy/available energy can be much lower than 0,593 [22], [23].

4.4 State-of-the-art technology

Ocean and tidal current energy can be harnessed using submerged rotors as hinted in the previous paragraph. Ocean and tidal current turbines are closely based on the wind turbine model, and many devices also have pitch and yaw regulation typical of big wind turbines, that means that the blade angle and the orientation of the system can be controlled and varied depending on the characteristics of the flow. In general, regulation seems to be essential for all devices working with tidal streams and other uneven streams, while non-adjustable systems can be suitable where all year long constant streams are available.

Because of the much higher density of water than the density of the air, water turbines are subjected to stresses also ten times more intense than wind turbines, and that’s why it is necessary to make extensive endurance testing for this type of devices. High pressure, differential stresses, inevitable corrosion, the possibility of collisions, and biofouling by marine are the main challenges for engineers who design water current turbines: large part of the research is devoted to find materials equipped to resist all these solicitations and assure high productivity. Furthermore mooring and anchoring systems require much attention as well as they must bear high traction forces.

The Experimental ocean current turbine by SMREC

Researchers of SNMREC (Southern National Marine Renewable Energy Centre) at the Florida Atlantic University (FAU) are studying some devices which could be able to harvest energy from the Gulf Stream, in particularly they are trying to demonstrate their commercial viability. Their first challenge has been to identify the turbine locations: in an academic article presented in 2012, the Ph.D student Alana Duerr and Dr. Manhar Dhanak, from the FAU's Department of Ocean and Mechanical Engineering, described how they assessed the potential of the Gulf Stream opposite Florida coasts. Their work required observations on the current speed, that varies with depth, season, spatial location and the amount of turbulence of the flow and its direction, mainly northward but locally variable, especially near coastal areas. Thanks to this data, Duerr has created a method that estimates the hydrokinetic power source over time and space. The results of this research suggested that the best turbine location was in the "core" of the Current, an area with the highest current speed (and the highest amount of available power) that can be sometimes near the shoreline or sometimes further offshore and it occurs at various depths, from the surface to several hundred meters below. In a few words we can say that there isn't a generic rule to identify the best location for a device extracting power from marine current, but it is necessary to take into consideration each case evaluating all the collected data .

However, the choice of a location doesn't depend on the power density of the stream only, but also on the technical and economic aspects of the installation and maintenance of the device. Duerr produced a method for developing a cost-benefit analysis for siting turbine locations in which the variables considered are the power density, the distance from the shore and the depth of the sea: as the first increases, the overall cost decreases, while as the other two increase, cables and mooring installations become more expensive and complex. The number of potential sites reduced further after this study, and each location has been identified with different values of the three variables mentioned.

The following step for researchers at FAU has been to evaluate the type of turbines to be used and the number of turbines to include in an array. In general, because of the speeds of the flow, the best turbines to be used are ones with low cut-in speeds and large diameters. Among these, Duerr says, "the only way to determine what type of turbine to employ in a specific array is to compare the acquisition, operating and maintenance costs of each". Moreover, to extract portions of the available power able to justify the costs of installation and of the cables, arrays need to have large numbers of turbines. However, the number of turbines in an array depends also on their type and size: the more turbines are installed, greater would be the power extracted, but each turbine could be less effective due to turbulences produced in the flow [24].

From the website of the SMREC, the Southeast National Marine Renewable Energy Centre of FAU, we read that, at present time, prototype devices are being lowered into the Florida Current from a vessel berthed to a surface buoy with a permanent mooring (Figure 4-III), and then recovered for shore-based engineering analyses.

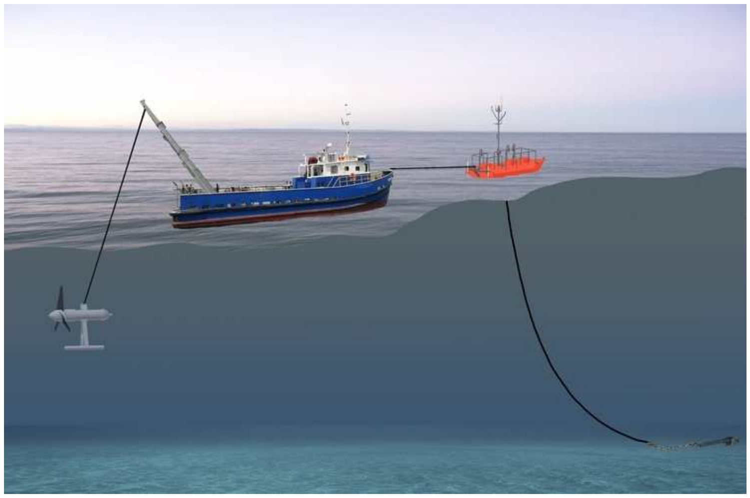


Figure 4-III: Prototype devices of the SNMREC project

These procedures must be refined and perfected, and environmental assessment considering the answers of the marine fauna to the presence of this type of turbines must be made; after that researchers will be able to consider long-term deployments of prototypes [25].

SeaGen

SeaGen is the first large scale commercial tidal stream generator. The first device of this type was installed in Northern Ireland and connected to the grid in July 2008, and nowadays generates 1,2 MW for 18-20 hours a day. SeaGen has been developed by Marine Current Turbines Ltd, a Siemens company, and its predecessor study was SeaFlow, made of a single rotor turbine and not connected to the grid. SeaGen, instead, has two rotors with a diameter of 16 m, each one is connected to a gearbox and a generator, not differently from a wind turbine. The device can operate in both flow directions, that means in this case, both for ebb and flood tides. The company that produced the generator is now looking for other sites to install a bigger device with a power of 2 MW.

Figure 4-IV (up): SeaGen in Northern Ireland

Figure 4-V (down): SeaGen rotors can be raised above surface for maintenance

5. CONCLUSIONS

In this work we've illustrated how great the potential of the three most important marine energy sources is. We have just examined some of the projects that have been started in the last decades, and it is important to specify that many others are being developed all around the world. Regrettably, except for tidal range plants, it is difficult for new marine technologies to produce energy at comparable costs to the current cost of energy from fossil fuels; however, the development of innovative renewable.sources technologies has started in areas where fossil fuels are more expensive because of very high cost of transport, such as on islands.

The number of archipelagos and little islands that are organising to satisfy in a short span of time all their own demand for energy from renewable sources is increasing year by year; in most cases wind turbines produce large part of the energy needed, but wave and tide devices are starting to integrate the production. The most operative example is probably the one of Orkney Islands, an archipelago situated off the north coast of Britain: years ago, a polluting and expensive diesel generator produced electricity for the inhabitants, but nowadays the islands have a grid with over 700 renewable energy generator. Among them, there are some of the most advanced wind turbines, as well wave devices and tidal turbines. Moreover the archipelago hosts the European Marine Energy Centre, where new marine devices are being tested, thanks also to favorable sea conditions. Orkney Islands and other archipelagos are playing a global and significant role in the development of wave and tidal technologies, and of renewable energies in general [27]. Looking at these best practices, it will be necessary in the next decades to apply the same principles to the complex urban environmennts, in order to create a low impact living.

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