

## VARIOUS ASPECTS OF THE EXPLOITATION OF MARINE CURRENT ENERGY WITH TIDAL TURBINES

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### ABSTRACT

*The main purpose of this paper is to present a short review of the actual progress on the tidal energy and on the tidal energy convertors: turbines, dam systems, oscillating wings and their operation characteristics. The energy of the oceans: the tides, the waves, the difference of osmotic pressure between the fresh water and that of the oceans, the thermal gradient in the depths of the oceans, the sea currents, represents a huge reservoir of electricity estimated at an annual production of 120.000 TWh. The energy of the tides could provide a lot of electricity, but a power station of this type causes damage to the environment of the estuary where it is built and to its wild life because it prevents the passage of fish. Tidal turbines could be an alternative solution in environment protection..*

**Keywords:** tidal energy, tidal turbines, oscillating wings

### 1. INTRODUCTION

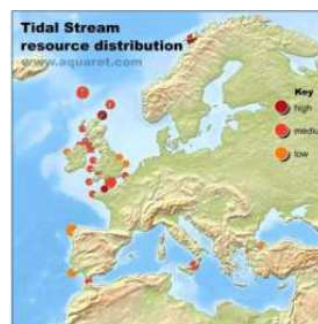
All movement is energy. Tides, ocean waves and rivers flowing around the world contain kinetic and potential energy that can be used to run turbines and generate electricity, reducing our dependence on fossil fuels. One can even take advantage of the differences in salinity (salt content) and temperature that characterize water bodies to create dynamic forces capable of producing electricity.

These different forms of renewable marine energy are available as long as tides continue to rise and fall, and rivers and streams continue to flow.

Tidal energy is obtained by the movement of the tides which is formed under the influence of the gravity of the Sun and the Moon. It can take two forms: the tidal current and the tidal range.

A major European Commission study assessing current tidal energy resources for

106 locations across Europe, with predefined features making them suitable for tidal energy exploitation, estimated an exploitable resource from these sites of 48 TWh per year (European Commission). The total capacity of this site selection is an installed capacity of over 12,000 MW marine current turbines.



**Fig.1.** Resource distribution of tidal currents

A more recent Black & Veatch (Black & Veatch for Carbon Trust) study suggests a UK extractable resource estimated at 22 TWh for a tidal stream, using a modified and

more accurate methodology. Other countries with exceptionally high resources are Ireland, Italy, the Philippines and Japan. Figure 1 shows the average tidal range for 237 locations along European coastal lines. These locations are between 50 and 100 km offshore and the distance from one location to another is of approximately 100 km.

## 2. CHARACTERISTICS OF TIDES AND OTHER MARINE CURRENTS

The use of tidal energy is old, as evidenced by the many tide mills. The recovery can be done in its potential forms: sea level variation and exploitation via a dam, or kinetics: direct exploitation of currents by turbines placed directly in the flow, like submarine wind turbines, also called tidal turbines. These two principles thus give rise to two families of tidal systems. One of the advantages of the tides is their high predictability, which facilitates planning and makes it possible to better integrate such production systems into networks, even if there is no correlation between availability and demand. With dam systems, the storage effect in upstream and downstream basins can be used to make storage, possibly by pumping in the advantageous parts of the cycle.

Depending on the location, there are different types of tides. The most energetic have about 2 cycles per day with a period of about 12.5 hours and an amplitude that varies substantially, sinusoidally, on a cycle. Tidal ranges or amplitudes (between high and low levels) can vary considerably depending on the location and the tidal coefficient (20 to 120). The tidal coefficient is a factor to be applied to determine the tidal range with respect to a site-specific reference value. For example, the reference tidal range of the Mont Saint Michel is 11 m, the highest coefficient is reached at the equinoxes and leads to a maximum tidal range of 13 m. This French region is one of the first sites in the world, with the highest known tidal range being reached in Fundy Bay in Canada with a

value of 16 m. Figure 2 shows changes in the tidal coefficient, during a year, on a site.

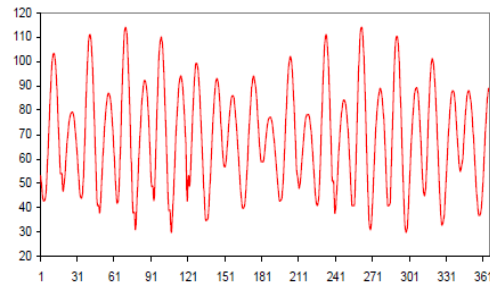


Fig.2. Examples of the tidal coefficient variation over a year

Tidal currents are more intense when the depth is low and their intensity is maximum at the surface to reach a zero value at the bottom by effect of "boundary layer". The evolution of the velocity  $v$  as a function of the distance  $z$ , counted from the surface, is of the type:

$$v = v_0 \cdot \left[ \frac{z}{H} \right]^\alpha \quad (1)$$

where  $v_0$  is the velocity at the surface and  $H$  is the depth (typical value of  $\alpha$ : 1/7).

Tidal phenomena are not the only ones causing marine currents. The rotation of the earth, temperature differences, density gradients (salinity function) create continuous currents, such as the Gulf Stream, whose average annual velocities (there are indeed seasonal variations), in certain places and regions, are high enough to indicate a possible commercial exploitation. This is particularly the case off the coast of Florida where we observe currents reaching speeds of 2 m/s. The tidal currents could thus be described as alternating currents and the others as continuous currents. We only insist that continuous currents play a decisive role in the climate and that they already seem to be affected by global warming, so we cannot consider their exploitation on a large scale without taking into account the ecological consequences it could have.



- then the groups are stopped, the valves are opened to accelerate the filling of the basin until the level of the sea reaches its average value;

- finally, we return to the operation of the single-action cycle where the water accumulates in the basin until the sea returns to its average level.

In the double-acting cycle, the water level in the basin varies almost sinusoidally with a phase shift of a quarter of a period compared to that of the sea and its maximum value remains lower than that at sea. Today, the experience gained has made it possible to automate operation and make the most of the installation.

The hydraulic units of the Rance plant are of the horizontal axis bulb type, they are composed of Kaplan turbines (diameter 5.35 m) with 4 blades and variable pitch, each coupled directly to a synchronous machine, which is itself electrically coupled to the network without electronic converter (fixed speed of 93.75 rpm, 32 pairs of poles). In the Sihwa plant, the technology will be roughly the same with 10 groups of 25.4 MW, an annual productivity of 0.55 TWh, or 2100 hours equivalent to full power (2250 h for the plant of the Rance).

## 2.2 Artificial lagoons

One way to overcome topographic constraints may be to create an artificial lagoon and thus an offshore tidal power plant. That's what Tidal Electric Ltd. offers. Feasibility studies have been carried out, such as that of Swansea Bay in the United Kingdom where there is an area of 5 km<sup>2</sup> in which the depth of the seafloor at low tide is between 1 and 5 m, which makes possible the construction of a circular dike. The average accessible power is proportional to the square of the tidal range and the basin area. Thus, in Swansea Bay, with a lagoon of 5 km<sup>2</sup> and tidal ranges up to 7 m, we can expect a power of 60 MW and an annual energy of about 0.187 TWh with bidirectional groups exploiting the double-acting cycle previously described for the

Rance plant. But this technology must prove itself, especially as regards the resistance of the dike.

## 2.3 Marine currents energy recovery systems

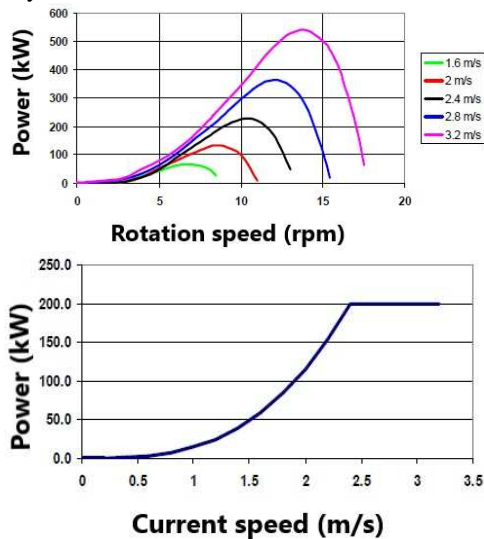
The free currents recovery technique is very close to that of the wind turbines, except that the direction of the currents is constant, that their direction is alternative (effects of tide) or continuous and that the turbines are in salt water (this technology has already been tested in freshwater, especially in the Amazonian rivers). We thus find two large families of turbines, depending on whether the axis of rotation is vertical or horizontal, but also other more original technologies such as the one using oscillating flat wings functioning in the image of the tail of the marine mammals, or floating systems of the "impeller" type.

Apart from the Gulf Stream's energy extraction projects with huge power: 400 turbines of 15 MW or 4000 turbines of 2.5 MW, most of the projects current issues concern tidal currents. We will focus our attention on technologies adapted to alternating tidal currents, knowing that they are mostly adapted to DC currents. The mechanical power, and the electric power (because the yields of the generators are close to 100%), of a free-flow turbine is expressed by:

$$P = \frac{1}{2} \cdot C_p \cdot \rho \cdot v^3 \cdot S \quad (W) \quad (3)$$

where  $C_p$  is the hydrodynamic power coefficient, limited by the 59% Betz law,  $\rho$  the density of the water,  $v$  the velocity of the current (m/s) and  $S$  the surface swept by the turbine. When the speed of currents varies sinusoidally, the power of the resource varies as the cube of this speed. Even if the speed fluctuations are not comparable to those of the wind, it can be interesting to level off the power beyond a nominal speed. This speed is an important parameter of a technico-economic optimization determined according to the characteristics of each site. Off the coast of Brittany, currents have maximum

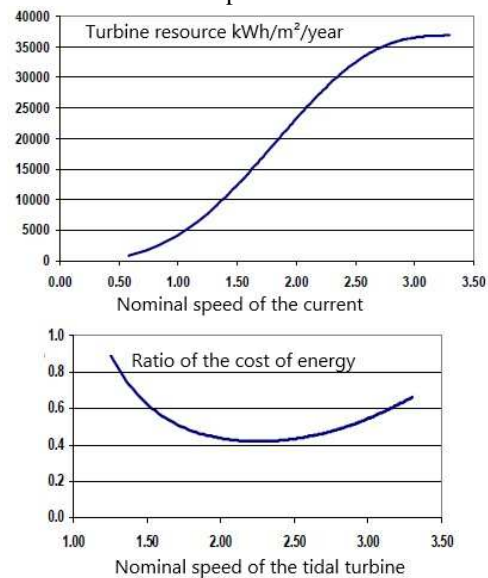
speeds of 0.5 to 3 m/s, at Raz Blanchard (La Hague peak) they reach 5 m/s, and in some Norwegian fjords speeds are measured for peaks of 7.8 m/s. With a minimum hydrodynamic efficiency ( $C_p$ ) of 30% (pessimistic: the values in the water are between 0.35 and 0.5), for 3 and 7 m/s the power per unit of turbine area is respectively 4 and 50 kW/m<sup>2</sup>. The characteristics of the turbines are exactly the same as those of wind turbines or those used in oscillating column hougenerators. Figure 4 highlights the interest of varying the speed of rotation to maximize power recovery when the speed of the current changes according to the tide cycle. This same figure shows the electric power characteristic obtained by a variable pitch turbine and variable speed electric generator assembly. The variable speed makes it possible to fully exploit the possibilities of the turbine below the nominal speed (here 2.4m/s) and the variable pitch makes it possible to level off the power beyond this value.



**Fig.4.** Network of power characteristics of a tidal turbine according to the speed of rotation and the speed of the current. Typical power curve of a tidal turbine including power levelling off

The existence of an optimum nominal speed of the current (from which the power is

leveled off) was highlighted in order to minimize the design cost of a tidal turbine. Although the kinetic power increases substantially with the cube of the speed of the current, it is advantageous to level off the power of the turbine to the strong currents (beyond a so-called nominal speed), which makes it possible to optimize the dimensioning of the current complete system considering that high velocity currents have a low occurrence. Figure 5 shows the effect of the "nominal" speed of the current above whose power is leveled off on the annual energy productivity. The study shows an economic optimum around a speed of 2.2 m/s, a value for which the energy produced would thus have the lowest cost price.



**Fig.5.** Influence of Design Nominal Speed (Current) on Annual Energy Productivity and Investment Cost to Production (called the "Energy Cost Ratio")

There are four categories of marine hydrogenerators:

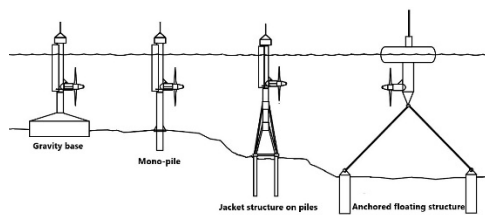
- horizontal axis turbine
- vertical axis turbine
- swinging or oscillating wings
- floating wheel





**Fig.6.** Types of marine hydrogenerators.  
From left to right: horizontal axis turbine (HydroHelix), vertical axis turbine (Gorlov) and oscillating wing (Stingray).

Most of the imagined systems are completely submerged, except for HydroGen, which uses paddle wheels that float on the surface. The small power submersible generators can be floating, placed under a barge, which makes it possible to settle more easily the problem of the variations of heights due to the tides themselves and to make sure that the machines always remain in the vicinity of the surface. They can also be floating buoys and moored, as proposed by the company SMD Hydrovision or Ponte de Archimede with its KOBOLD turbine with vertical axis. This principle is already exploited in rivers. Hydrogenerators can also be placed on the bottom gravity base (Lunar Energy and HydroHelix) or carried by a metal monopile like those of Seaflow. In fact, the choice of bearing structures is mainly dictated by the depth and nature of the funds. Figure 7 shows, in a simplified way, the various media technologies. The monopoy is reserved for depths between 20 and 40 m. It is driven into the ground (sand) by thrashing. Offered in the offshore oil and gas industry, jacket structures, made of welded tubes that provide a wide surface hold, provide access to higher depths and / or rocky soil. These are also the technologies used or envisaged in offshore wind farms.



**Fig.7.** Different technological solutions for supporting hydrogenerators

The different prototypes or systems at the pre-industrial stage have powers of a few tens to a few hundred kW. The tidal turbines of Marine Current Turbines Ltd (MCT), which have been the subject of much advanced work (Seaflow project), are analyzed more precisely . The Seaflow project consisted in installing in the Bristol Channel (20 to 30 m deep) a two-bladed turbine (composite blades) of 11 m diameter, with a variable pitch up to 180° on a 42 steel pile, 5 m long and 2.1 m in diameter (mass 80 tons). The nacelle can move along the pile, fact which facilitates maintenance. The maximum power of 300 kW is reached at equinox tides. The turbine drives a variable-speed 450 kVA cage generator (690 V and 3 pairs of poles) through a geared mechanical multiplier (ratio 1:70). As in the case of wind turbines, the two-bladed rotors are less efficient than the three-bladed ones and induce more force pulsations but allow a lower mechanical simplification and cost, at least in this phase of development. Tests conducted have revealed significant power fluctuations (30 to 50 kW) due to the blades passing in front of the pile (approximately every 2 seconds). Eventually, MCT provides monopiles supporting two two-bladed hydrogenerators of 500 kW each arranged on each side of the pile and whose flows will no longer be disturbed by the passage of the blades in front of the pile.



**Fig.8.** MCT Seaflow Hydrogenerator photos (in maintenance and service)

Figure 8 shows two photographs of the MCT Seaflow system with the emerged (for maintenance) and submerged (in operation) platform.

An estimate of the production potential has been made in the area between the English Alderney Island and the Pointe de la Hague (strong currents). The diameter of the turbines has been defined so that the lowest point is at a distance from the bottom equal to 25% of the depth and the highest point at 7m below the surface (value taking into account hollows of swell 4 m and 3 m uncertainty). The complete hypotheses are defined with dual rotor machines (MCT type) of power 12, 24 and 38 MW (diameters of 14, 20 and 25 m respectively), a cumulative installed capacity of 3243 MW, annual energy yield reaches 7.4 TWh, giving an equivalent annual duration at full power of 2280 h.

The diversity of vertical axis machines is significant. These machines do not need to be oriented relative to the current and can quite easily associate matrix. They have a low "Tip speed ratio" ( $\lambda = R.\Omega/v$ ), therefore the optimal rotation speeds are low. Three categories of turbines are presented: Darrieus (of which the Kobold are part), Gorlov (see figure 6) and those from the LEGI whose blade tips have a break to reduce turbulence and improve hydrodynamic efficiency. Here, there is also presented the Enermar project of the Italian company Ponte di Archimede, experienced since 2002 in the Strait of Messina (between Sicily and Italy) where currents reach 1.5 to 2 m/s with a depth of 20m. The Kobold turbine is suspended from a floating platform, 10m in diameter, anchored 150m from the shore. The turbine is 3 blades carbon fiber 5 m long (height) and 40cm of corde and the diameter is 6 m. It drives, via a multiplier (ratio 90:1), a synchronous generator three-phase 4-pole (1500 rpm). The maximum power (130 kW) is provided with a current of 3 m/s and a speed of rotation of 18rpm. The tests, however, were performed with a current of 1.6 m/s and the power was of only 16 kW.

"Hydrofoil" winged oscillating systems are the last family of marine hydrogenerators, with the Stingray device as the most successful representative. The leading edges of one or more hydrofoil wings with parallel planes are arranged facing the current. The angle of attack of the wings is adjusted so that their lift is maximum and remains in the same direction as the movement. Hydraulic cylinders dampen the movement by compressing oil in a high pressure tank, the oil is turbined in a hydraulic motor that drives a variable speed electric generator.



Fig.9. Stingray system with hydrofoil wing: drawing, photograph of the prototype and view of an underwater farm

The angle of attack of the blades needs to be optimized incontinuously (hydraulic control) during vertical oscillations to maximize recovery. The set is designed to be laid and anchored at the bottom of the sea. A prototype 150 kW single wing (actually two half-wings aligned) was built, it occupies a floor area of 280 m<sup>2</sup> and weighs 35 tonnes (185 tonnes including ballast). The half-wings are 7m long and 3m long and offer a total support surface of 42m<sup>2</sup>. The support arm, 11m long, allows oscillations of +/- 50° or a vertical deflection of about 17m and a catch section facing the current of 235m. The control of the movements requires a fine optimization of the function of evolution of the angles, in particular of the period. In a current of 2 m/s, a cycle period of 24 s leads to a power of 117 kW. The system has been tested and a 500 kW version with 3 superimposed wings is planned.

### 3. CONCLUDING REMARKS

The projects of the tidal development are characterized by very large investments, long periods of construction and long periods of recovery of the investment.

Feasibility studies related to the installation of tidal power plants have estimated a considerable reduction in future energy production costs, due to new technological solutions for converting tidal energy. Assuming that it will be possible to exploit tidal currents with speeds over 3.5 m/s and that the development of this technology continues, it is estimated that in the future, in practice, it will be possible to achieve low costs for obtaining electricity from tidal energy.

Tidal energy has several advantages:

- Hydropower is a renewable green energy. Its operation emits a very small amount of gaseous pollutants;
- The dam is used to channel the water level in the estuary during periods of high flood;

- The tidal coefficient is known several years in advance, allowing technicians to optimize the daily productivity of turbines.

Tidal energy has also some disadvantages:

- The ecological impacts are sometimes disastrous, the presence of the dam can upset the ecosystem of the estuary where it is located;
- Its implementation requires investments as well as significant operating costs;
- Electricity generation is not homogeneous all year round, as it depends on the level of the tide.

The energy of the tides represents an important source of renewable energy that has been expanding in the last years and which is expected to progress rapidly since a lot of development projects had reached their maturity.

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