Tidal Energy Harnessing System with Multiple Lagoons

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Abstract — With this work it is intended to analyze hydric resources that are different from the established conventional ones, in particular the tidal resources of the estuary of Tejo river. The development of this work aims to analyze the behavior of a system with multiple tidal lagoons. These ones make part of old tidal mills that was located in this estuary, more precisely in Barreiro, Lisbon. In order to make this study we develop a model from which we can simulate the behavior of the multiple lagoons system and also can analyze the energy production that we can do taking advantage of the tidal range in the system. So through a simulation model of communicant water tanks we can stablish a simulation model of the tidal lagoons and the river estuary. To simulate the energy production in this system we used two calculation modes – one through the theoretical equations to predict the available power in a hydropower plant, and other using the equations that describes the water turbine, used in this cases, behavior in the power conversion. In the end we established a few simulation scenarios to analyze the economic viability of the system simulating he energy selling that the system provides in the Portugal energy market.

Keywords — Energy Markets; Water Turbines; Tidal Energy; Tidal Lagoons; Tidal Range.

I. INTRODUCTION

The big humanity evolution in technological, economics and social of the last years were based in the fossil fuels. Due to the excessive use of these type of fuels environment degradation has been increasing in the Earth.

Production of electric energy is one of the main reasons to the fossil fuels utilization once Man has a big dependence on these to survive and to do their daily activities.

In Portugal due to the low energetic resources like fuel, gas and coal. Introduction of renewable resources in the electric energy production has been increasing throughout the years, and now they have a great impact in the sector.

The most used renewable resource in Portugal to produce electric energy is water through the conventional hydroelectric power plants.

Beyond the traditional methods to produce energy through the hydric resources there are more methods to harness this resource. These methods are the harnessing of the tides and the waves.

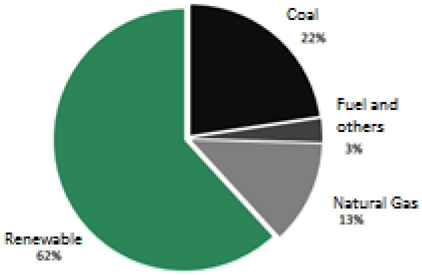

Figure 1- The amount of energy produced by each source in the year 2014 in Portugal. Adapted from [1].

Focusing on the tidal energy, this can be obtained by two ways:

- **Tidal range energy** – obtained through the potential energy created by the constant oscillating level of the waters due to the tide.
- **Tidal current energy** – obtained through the kinetic energy created by the tidal flow.

This type of harnessing is already exploited in several places. The first tidal power plant of the world was constructed in La Rance, France, on 1966. This power plant has an installed power of 240 MW and an annual production of 540 GWh.

In Portugal there are many places where the tidal energy can be exploited to produce electric energy. Therefore, appears the idea of analyze the potential of a tidal multiple lagoons system located at the estuary of the Tejo river, in Lisbon. To analyze this potential a simulation model of the real system was developed.

In the simulation model developed is introduced the energy production calculation. In order to approximate it to the reality model of the water turbine that would be used in this harnessing were made. This turbine was modulated in order to make simulations in the normal operation mode and simulations where it is included the pumped hydroelectric storage. This process has been included in many hydroelectric power plants to increase the energy production. So a model of a reversible turbine to include in the multiple tidal lagoons system was made.

II. TIDAL ENERGY INTRODUCTION

A. *Physical Principle of Tidal Energy*

The tidal energy is the dissipated energy in the movement of them. The origin of the tides are the gravitational forces of attraction established between the Earth, Moon and the Sun [2]. These forces create a cyclic movement where the water ocean levels go up and go down in every places of the Earth, creating the tides.

The gravitational and centrifuges forces established can cause that in Earth there are locals where the water concentration is higher, so the water levels in these places are higher and there are locals where the water concentration is lower, so the water levels in these places are lower, at the same time. This can cause that in Earth can exist two places that at the same time present different water levels.

Figure 2 – Gravitational force influence in the tides. Adapted from [4].

It is possible to define two maxims levels that the tides can reach:

High Tide: when the tide reaches the maxim water level in the final of the flood period.

Low Tide: when the tide reaches the minimum water level in the final of the ebb period.

In general tides are influenced by the moon behavior and they present a time period of 12 h and 25 min [2], that match with the lunar cycle. The range of the tides change with the lunar month, that have approximately 29.5 days [2]. Due to the tides period of 12 h and 25min they change day by day, because every day has a delay of 50min.

B. *State of art*

1) *History*

Since early tidal energy has been used by Man. The first records of this tidal harnessing systems date from the middle age and can be found for every world and for many different utilizations [5]. Although the old records of tidal energy harnessing, the studies and the first project for a tidal power plant only began in the XX century.

So the first tidal energy power plants were build and put into operation after the second world war, still being in operation until present days. Examples of this first tidal harnessing are:

-La Rance, França (1966)
-Kislaya Guba, Rússia (1968)
-Annapolis, Canada (1984)
-Jiangxia Creek, China (1985)

In 2011 became operational the most recently and bigger tidal power plant in the world in Sihwa South, Korea.

2) *Conversion Principles of Tidal Energy*

Due to physical characteristics of tides, there are kinetic and potential components, Constant oscillation of the tides water level create the tidal flows. It is possible to define two types of technologies for the tides energy harnessing and they are:

-Tidal range technologies - These type of technologies harnesses the range between the two tides, the flood tide and the ebb tide, to convert the potential energy into electric energy like in the conventional hydroelectric power plants.

-**Tidal flow technologies-** Harnesses the kinetic energy present in the tidal flows to convert into electric energy, like is made in the wind energy.

3) *Tidal Range Technologies*

The technologies used to produce energy form the tidal range are similar to the used in the conventional hydroelectric power plants, because in both the operation principle are the same.

The bigger difference between these harnessing's are that in the conventional method water flows only in one way and the range between the two sides of the power plant is the same every time, but in the tidal harnessing the water can flows in two ways and the range oscillates because of the tides flow.

The structures of these power plants can take different configurations and they can have characteristics that make them more profitable to the point of view of the energy production. These structure configurations can include pumping storage processes, the use of multiple lagoons to increase the storage and so produce more energy.

So the tidal range power plants can have different configurations according to the number of tidal lagoons that make part of the system. A system with only one lagoon is defined like single basin system and a system with multiples lagoons is named of double basin system and these, in general, didn't have more than 2 lagoons of storage [2].

In the single basin systems, is possible to define three operation modes:

-Ebb Operation: Here the basin stores water into the flood flow of the tide and the energy production is during the ebb flow of the tide, like is represented in the figure 3 by the red curve (C-D).

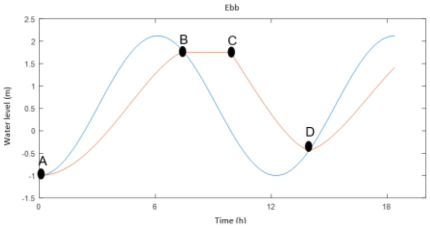

Figure 3- Ebb operation.

- Flood Operation: Here during the flood flow of the tide the sluices of the system, located between the ocean and the tidal lagoons are closed to increase the range between the two sides and when this range are great the sluices are open and the energy production can begin. This operation mode is the less used because in this is where the energy production is lower. The energy production is represented in the figure between the point B and C.

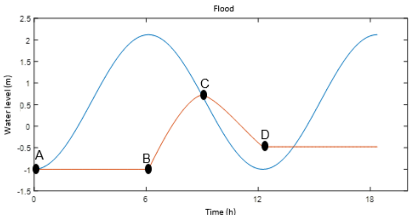

Figure 4- Flood Operation.

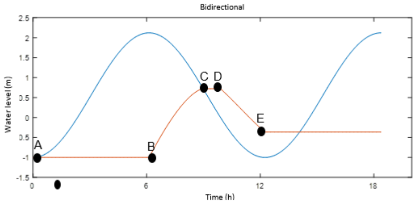

Figure 5- Bidirectional Operation.

-Bidirectional Operation: Here the energy is produced in the flood flow and at the ebb flow of the tide so the utilization factor of the power plant is higher than in the other operating modes, but this mode isn't more efficient that the ebb operation mode because the ranges between the two sides of the system are lower and the production for tide cycle is similar to the ebb mode.

The double basin system, in general, are composed by two lagoons and can present different configurations to take more profitable of the tides range. In many cases the pumping process are installed in this systems.

4) *Tidal Stream Harnessing Technologies*

The tidal streams can create the movement of big water flows. These water streams can be a great energy resource and they are another method of pull out energy from the tides.

The water turbines used in this type of tidal harnessing converts the kinetic energy produced by the tidal flows movement into electric energy like the wind turbines does with the wind movement, but the turbines used here present some differences, because the characteristics of operation to the wind and to the water are different [5]. The big difference is that the density of water is 800 times bigger that the air density and it makes that a tidal turbine and a wind turbine with the same nominal power presents different sizes, because a tidal turbine with less size that a wind turbine and rotating at a low speed [5] generates same energy that the wind turbine.

In the last years the technologies used to apply in the tidal streams harnessing have been studied and tested, what lead to a great evolution of them. To test and study these technologies in real conditions in 2005 was created the EMEC (*European Marine Energy Centre*), in Scotland. Through the information that this test center provides an ideal turbine type it has not been found, but they say that the two major types are the horizontal turbines and the vertical turbines.

The **horizontal turbines** exploit the horizontal movement of the water streams to pull out energy of them, like in the wind energy [5] [11]. So the runners of the turbine, rotate through an horizontal shaft that is parallel to the water stream. This is the principal type of tidal stream turbines choose by the investigators to study because they have efficiency peaks higher than the vertical turbines. An example of this type of turbines is the Seagen, presented at the figure 6, and developed by the company Marine Current Turbines Ltd.

Figure 7- Seagen Turbine. Adapted from [13].

The **vertical turbines** exploit the stream movements of the water streams like the horizontal, the difference is that they rotate trough a vertical shaft that was placed perpendicular to the stream movement [11], for this the vertical turbines can be named like cross-flow turbines. These turbines present an efficiency peak lower that the horizontal but due to their design they have some advantages [5], one of them is that they can rotate in every direction what makes that the turbine can run whatever the tidal stream direction. One disadvantage is the size of them because they can have diameters of 16-18m. An example of this type of turbines are the Kobold platform, developed by the company SeaPower.

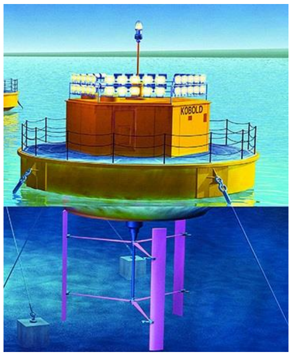

Figure 6- Kobold Turbine. Adapted from [14].

5) *Energy Markets*

The energy power plants can be classified trough the period of their operation and can be classified like peak plants and base plants. The peak plants are the plants that operate in the load peak period and the base plants are the plants that operate in every period. These different periods make that the energy cost at the market be different at the different load periods. In the figure below it is presented a diary diagram of consumed and produced energy in a normal day in Portugal.

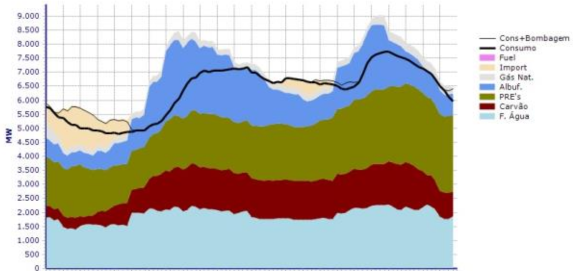

Figure 8- Consumed and Produced Energy Diary Diagram. Source: REN

Through the figure it is possible to observe that there are periods where the energy consumed is higher than others. The energy demand factor is the principal motive of the costs variation of this in the market. So trough the energy demand we can define three different periods where the energy cost is different, and they are:

-Peak period – this period occurs in the hours of high demand of energy, and is where the peak load is registered. In this period is where the energy cost is higher.

-Full period – Is the period where the energy demand is high but don't register the peak load values.

-Empty period– This period occurs in the hours of low demand of energy. In this period is where the energy cost is lower.

So the power plant can be classified according to the period that they operate.

III. SYSTEM PRESENTATION AND MODULATION

The tidal range harnessing to product energy can be classified like the conventional hydroelectric power plants, with the same classifications established for these. Generally tidal power plants are low head plants once the range of the tides are not too high, in the point of view of the installed power they can have any classification, it depends only the capacity of the tidal power plant and the conditions of the local of the installation.

1) Hydroelectric Harnessing's

a) Energy calculation in a hydroelectric harnessing

For definition in this type of energy production the principal characteristics to make the theoretical prevision of the available power are: the water flow and the water level difference between the two sides of the power plant. [15] [16] [17]. The equation that describes the available power in an hydroelectric harnessing is the following:

$$P_{disp} = \rho g Q H \quad (1)$$

Where ρ (in Kg/m^3) is the specific mass of the water or the water density, Q (in m^3/s) is the volumetric water flow, H (in m) is the gross height between the two sides of the dam.

The energy available can be expressed by:

$$E = \int_0^T P_{disp} dt \quad (2)$$

The equation (1) describes the available power in a hydroelectric harnessing, but don't take in an account the loses of the system. So the expression of the available power taking in account the losses is:

$$P_{efet} = \eta_{Turbine} \rho g Q H_u \quad (3)$$

Other losses can be considered in the turbine efficiency like generation efficiency, transformer efficiency, losses related to the hydraulic circuits and other system losses.

b) Water Turbines

The principal machine that we have to define in a hydroelectric harnessing is the turbine to install in the system, and this choice have to be made with carefully because the turbine choice influences all the efficiency of the system and the cost of this machine many times represents a higher investment.

For the different type of hydroelectric power plants, we can define different types of turbines and each type is adequate to a different type of power plant. So the choice of the appropriate turbine for the harnessing result of the analysis of three fundamental parameters: the head height, the water flow and the power that we pretend to install [16]. Many times, in a first stage, to choose of the turbines results of the analysis of the head-flow curves provided by the manufactures, like is presented in figure 9.

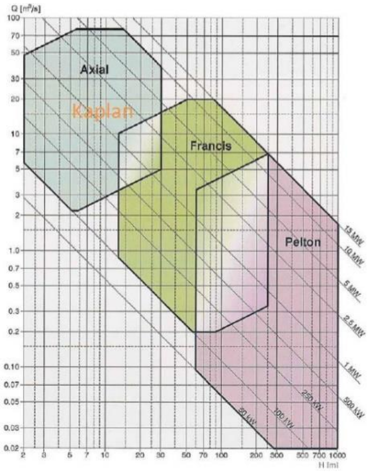

Figure 9- Head-flow turbine curves. Adapted from [18].

The main parameter that influences the turbines efficiency are the relation between the incoming water flow and the nominal value defined to the turbine. Like it's possible to view in figure 10, there are turbines where this relation have a great impact on his efficiency.

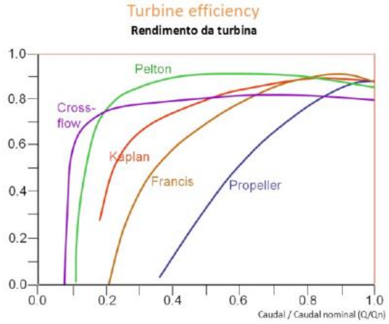

Figure 10- Efficiency curves turbines related to the water flows. Adapted from [18].

The most used turbines in the tidal harnessing are the Straflo and the Bulb which are variations of the Kaplan turbines. The most used of this two is the Bulb because have a better efficiency that the Straflo and can operate in reverse mode. However, Bulb turbines are very sensitive to the variations of the water flow like it's observable in figure 10. Through figure 10 it is also possible understand that the turbines have exploration limits and below of them the turbine go off of operation. To the Bulb this limit is expressed by:

$$Q_{min} = 0.65 Q_N \quad (4)$$

2) Bulb turbine Modulation

The Bulb turbines are variations of the Kaplan turbines and the runners design is similar on the two types once these turbines are both axial [16]. The water flow directions can be defined for the same way in these two turbines. So we can define that the equation that describes the power transferred to the turbines rotor of a Bulb turbine is the same that for the Kaplan turbine and is given by [15] [19]:

$$P_T = \rho Q (c_1 u_1 \cos \alpha_1 - c_2 u_2 \cos \alpha_2) \quad (5)$$

Where, ρ (Kg/m^3) is the specific water mass or the water density. Q (m^3/s) is the volumetric flow of water.c_1 and c_2 (m/s) are the absolute velocities of the water input and output, respectively, of the turbine rotor. u_1 e u_2 (m/s) are the linear velocities of the water input and output, respectively, of the turbine rotor blade and generally are the same. α_1 and α_2 (°) are the incident angle and the output angle of the water through the rotor blade.

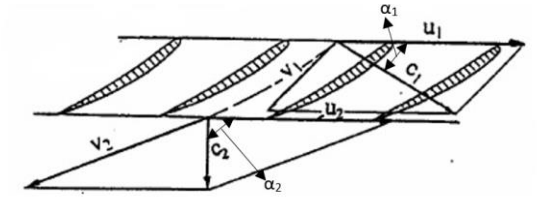

Figure 12 – Velocities diagram in a rotor of a Kaplan turbine. Adapted from [25].

Knowing that a turbine runs with an angular velocity, ω, and this is related to the linear blade displacement velocity, u, through the radius, r, of the rotor, we can define that:

$$u = \omega r \quad (6)$$

So we can redefine the equation (5) and we obtain:

$$P_T = \rho Q \omega (c_1 r_1 \cos \alpha_1 - c_2 r_2 \cos \alpha_2) \quad (7)$$

To obtain the absolute velocities c_1 and c_2 we have to know the velocities, v_1 and v_2, of the flow and the respective angles, β_1 e β_2, that presented in the velocities diagram presented in the figure 13.

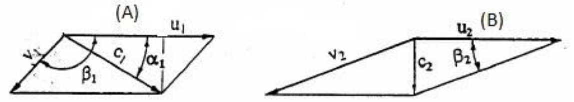

Figure 13- (A) Inlet velocities diagram (B) Outlet velocities diagram. Adapted from [25].

In order to obtain the absolute velocities through the diagrams we can see that if we apply the triangles symmetry in the diagram A we can obtain that:

$$c_1 = \frac{v_1}{\tan \alpha_1} \quad (8)$$

Through the diagram B we can obtain that:

$$c_2 = v_2 \sin \beta_2 \quad (9)$$

Knowing the ω we can obtain the torque which is given by:

$$T_{mec} = \frac{P_T}{\omega} \quad (10)$$

So the Bulb turbine is modelled through the equation (7) which represents the power that the rotor can pull off of the water flow.

3) Multiple Lagoons System

The multiple tidal lagoons system to model is constituted by two tidal lagoons and for the river's estuary. The river estuary can be approximated to a lagoon of higher dimensions in comparison to the other two lagoons, so it is possible to obtain a system of three communicant water reservoirs like is presented on figure 13.

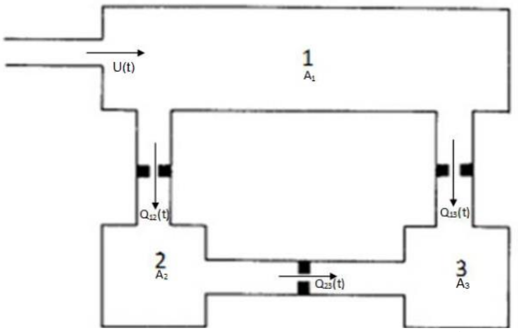

Figure 11- Multiple Lagoons system. Adapted from [11].

a) Water Tank Model

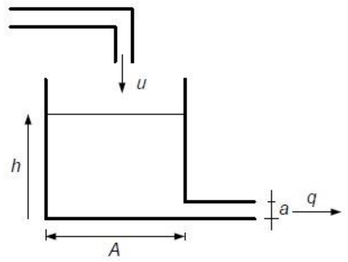

Figure 14- Water tank scheme. Adapted from [21]

To model a single tidal lagoon, it is possible to approximate it of a water tank and say that this model is the same of the water tank model. So we can describe the tidal lagoon model with the two equations bellow [20] [21]:

$$A \cdot \frac{dh}{dt} = U(t) - q(t) \quad (11)$$

$$q = a\sqrt{2gh} \quad (12)$$

With the equation bellow the evolution of the water level in the tank or lagoon can be observed [20] [21].

$$\frac{dh}{dt} = \frac{U(t) - q(t)}{A} = \frac{u(t)}{A} - \frac{a\sqrt{2g}}{A} . \sqrt{h(t)} \quad (13)$$

b) Multiple Lagoons System Model

According to the figure 12 the system lagoon to lagoon can be described [22]:

-Lagoon 1

The principal equation and the one that describes the evolution of the tidal is:

$$\frac{dh_1}{dt} = \frac{U(t) - Q_{12}(t) - Q_{13}(t)}{A_1} \quad (14)$$

Where $Q_{12}(t)$ e $Q_{13}(t)$, are:

$$Q_{12}(t) = sgn\big(h_1(t) - h_2(t)\big) a_1 \sqrt{\left|2g\big(h_1(t) - h_2(t)\big)\right|} \quad (15)$$

$$Q_{13}(t) = sgn\big(h_1(t) - h_3(t)\big) a_2 \sqrt{\left|2g\big(h_1(t) - h_3(t)\big)\right|} \quad (16)$$

The equation that represents the tidal evolution is:

$$U(t) = A_U \cos\left(\frac{2\pi}{T_m} t\right) \quad (17)$$

Where A_U is the range of the water flow that simulates the tidal and T_m is the tide period.

This lagoon simulates the river estuary so to represent this like a lagoon a bigger area than the others lagoons should be created. Therefore, to achieve this area following equation is used:

$$A_1 = A_U \frac{\Delta t}{A_m} \quad (18)$$

Where A_1 is the lagoon area, A_m is the amplitude of the tide and Δt is the time interval that the tidal takes to go from zero to A_m.

-Lagoon 2

The principal equation and the one that describes the evolution of the water level in the lagoon is:

$$\frac{dh_2}{dt} = \frac{Q_{12}(t) - Q_{23}(t)}{A_2} \quad (19)$$

Where $Q_{12}(t)$ is described by the equation (15) and $Q_{23}(t)$ is equal to:

$$Q_{23}(t) = sgn\big(h_2(t) - h_3(t)\big) a_3 \sqrt{\left|2g\big(h_2(t) - h_3(t)\big)\right|} \quad (20)$$

-Lagoon 3

The principal equation and the one that describes the evolution of the water level in the lagoon is:

$$\frac{dh_3}{dt} = \frac{Q_{13}(t) - Q_{23}(t)}{A_3} \quad (21)$$

Where $Q_{13}(t)$ is described by the equation (15) and $Q_{23}(t)$ by the equation (20).

4) *Complete Model*

a) Turbine introduction

To incorporate the turbine model into the tidal lagoons model the influence of them in the water flow has to be taken in account. Thus, it is considered that the energy extraction by the turbine in a time interval, Δt, is equal to the difference into the energies of the flow when don't exists a turbine in the duct and the flow energy when exist a turbine extracting energy in the duct, like is described below.

$$E_1 - E_2 = E \leftrightarrow \frac{1}{2} m v^2 - \frac{1}{2} m v_t^2 = P_T \cdot \Delta t \quad (22)$$

Through the development of this equation, it is possible to achieve the equation that describes the influence of the turbine in the water flow when the turbine is extracting power from them. So the water flow output velocity is given by:

$$v_t = \sqrt[3]{v^3 - \frac{2P_T}{\rho a}} \quad (23)$$

With this equation the turbine influence on the water flow of the system is introduced.

b) Pumping

In order to simulate the pumping process, power has to be introduced into the turbine to make it rotate in reverse mode and increase the velocity of the water flow to store the water. To simulate this process, the equation (23) was used and to simulate the power injection into the turbine a $P_T<0$ is added in the equation.

Nowadays this process to store more water can produce more energy, presenting efficiency values around the 80%. This efficiency is obtained by [24]:

$$\eta_{pump} = \frac{E}{E_{cons}} \quad (24)$$

IV. SIMULATIONS RESULTS

A. *Simulation System Characteristics*

Previously a simulation model of a multiple tidal lagoon system was described. To apply this model in this study and analyze the potential of the tides in the Tejo river estuary, Portugal, a real system in this place was simulated. This place is constituted for 2 tidal lagoons that make part of two old tidal mills placed in Barreiro.

So the real system that was simulated to study the potential of tidal energy in the river Tejo is composed by:

-The estuary of the river;
-The tidal lagoon of the Big Mill, Barreiro;
-The tidal lagoon of the Little Mill, Barreiro.

In the figure 15, obtained through the *Google Earth web application*, is displayed an aerial view of the place where the: 1 is the river estuary, 2 is the Big Mill lagoon and 3 is the Little Mill lagoon.

Figure 15- Aerial view of the lagoon system.

In the table 1 some system parameters used to simulate the system are presented. These parameters are equal for every simulation.

Table 1- Simulation Parameters.

Simulation	
T (h)	12,25
Msz	T/30000
A2 (m2)	55200
A3 (m2)	7250
Au (m3/s)	3×10^5
Z (m)	3
Δt (h)	6,125
a (m2)	1,767146

B. *Scenario 1*

In this first scenario only the operation of the tidal lagoon of the Big Mill was simulated in order to observe the results of the energy production for the three operation modes Ebb, flood and Bidirectional. These simulations are to understand what is the best operation mode to apply to this system. The results are showed in the table 2. The produced energy has been calculated with the theoretical equations.

Table 2- Energy produced results.

Operation Mode	*Ebb*	*Flood*	*Bidirectional*
Produced Energy (kW.h)	355	207	363

Through the results presented in the table 2 it is possible to view that from the three modes the worst one is the flood mode, like expected. The other two modes have a similar production but the bidirectional produce more 8 kWh than the ebb mode. The production difference between them is not too much significantly and to operate in the bidirectional mode a reversible turbine which is more expensive is needed. Thus the use of the bidirectional mode is not too much profitable in this case because of the production difference in relation to ebb mode is not too much higher and does not pay the increase of the turbine cost.

Then the best operation mode in this system is the Ebb mode.

C. *Scenario 2*

Through the result of the scenario 1 the Ebb operation mode was adopted and in this scenario the energy production of the two individual lagoons was simulated. On the last one it was simulated the two lagoons in a communicant system where they change flow. When the two lagoons in a communicant system are simulated only one point of energy production is considered located into the Big Mill lagoon and river estuary. Thus we consider that the system just have one turbine. The energy produced calculation is through the theoretical equations.

For the individual simulations the results are presented in the table 3.

Table 3- Individual production results.

Lagoons	*Big Mill Lagoon (Lagoon 2)*	*Little Mill Lagoon (Lagoon 3)*
Produced Energy (kW.h)	355	34

It is possible to observe that lagoon 2 produce more energy that lagoon 3 and this is due to the area of the lagoon 2 is much greater than the area of the lagoon 3.

For the results where the lagoons are together in the system the result is showed in the table 4.

Table 4- Two comunicant lagoons system results.

Lagoons	*2 and 3*
Produced energy (kW.h)	415

Through this results it is possible to understand that the system simulated with the two lagoons together can produce more energy than with them separately, so this configuration of the system is the better.

D. *Scenario 3*

The third scenario simulated is equal to the last simulation of the scenario 2 but on this the turbine model in the system was incorporated. So in this case the calculation of the energy produced are made through the turbine equation (7). To do this calculation some nominal parameters has to be defined, like flow and useful height, so it is possible to define the nominal power of the turbine. The nominal power of the turbine is choose with the help of the curves like are presented in the figure 9.

In table 5 the nominal parameters and some project parameters are defined to the turbine are presented.

Table 5- Nominal and project parameters of the Turbine.

Nominal Parameters of the Turbine		*Project Parameters of the Turbine*	
P_N *(kW)*	200	α_1 *(º)*	50
H_u *(m)*	2	α_2*(º)*	80
Q_N *(m^3/s)*	11	β_2 *(º)*	20
Q_{min}	$0.65Q_N$	r_1 *(m)*	0,75
		r_2 *(m)*	0,2

Therefore the results of the scenario simulation are presented in the table 6 where are also presented the results of the scenario 2 in order to make a comparison.

Table 6- Two comunicant lagoons system results.

Lagoons	*2 and 3*
Produced Energy, Scenario 2 (kW.h)	415
Produced Energy, Scenario 3 (kW.h)	400

Through the results presented in the table 6 it is possible to observe that with to different methods to calculate the produced energy it is possible to achieve similar results. In scenario 2 it is used the theoretical method and in the scenario 3 it is used the turbine equation. Comparing the results, it is possible to conclude that exist an error of 4% between the two results.

E. *Scenario 4*

To analyze the pump storage process and the add value that this can bring to the system in the point of view of the energy production, the system presented in the scenario 3 was simulated but with this process included in the simulation.

Because of the inclusion of the pumping process in the system new parameters to the turbine were defined and these are presented on the table 7.

Table 7- Nominal and project parameters of the Turbine

Nominal Parameters of the Turbine		***Project Parameters of the Turbine***	
P_N *(kW)*	500	α_1 *(º)*	50
H_u *(m)*	4	α_2*(º)*	80
Q_N *(m^3/s)*	21	β_2 *(º)*	20
Q_{min}	0.65Q_N	r_1 *(m)*	0,85
		r_2 *(m)*	0,3

To simulate the pumping process, there's a need to put energy in the turbine so it is possible to increase the velocity of the water flow into the lagoon and also increase the water level on them. Water level in the lagoon are limited to 3 meters because of the nature of them. So water should be pumped until the water level achieve his limit. For this the turbine a is set to a power of 300kW and it was assumed that the turbine in reverse mode has an efficiency of 70%.

The results of the simulation of this scenario are presented in the table 8 along with the results of the scenario 3 so it is possible to perform comparison.

Table 8- Results of the scenario 3 and 4.

Scenario	***Produced Energy (kWh)***
Scenario 3	400
Scenario 4	922

Through these results it is possible to understand that pumping produces more energy since with this process it is possible to obtain a higher water lever in the reservoir. With the pumping process it is possible to produce more 522 kWh than when this process is not performed.

However, to analyze the efficiency of the process the energy spent by the process and for the pumping period with the parameters referred above was observed. A consume of energy of 741 kWh was calculated. Therefore to do the calculation of the efficiency of the process the energy produced has to be divided by the energy consumed like in the equation (24), and the following is obtained:

$$\eta_{pump} = \frac{E}{E_{cons}} = \frac{522}{741} = 0.7$$

It is possible to observe that there is an efficiency of 0.7. which is in agreement to the theoretical values referred in [26].

F. *Economic Analysis of Simulated Scenarios*

To made the economic analysis only scenario 3 and 4 were considered which represent the process without pumping and with pumping, respectively.

As stated in this study the energy markets have, in a day, periods where the energy has different cost values because of the differences in the energy demand by the consumers. So to calculate the revenues that the tidal power plant installed in the estuary of the river Tejo could have the prices of the energy practiced in the market has to be known. With the data available in the OMIP (Iberian Markets Organization) virtual platform a medium value for every hour of one normal day was obtained. In the figure 16 a medium value for the energy price in every hour during the year 2015 is presented.

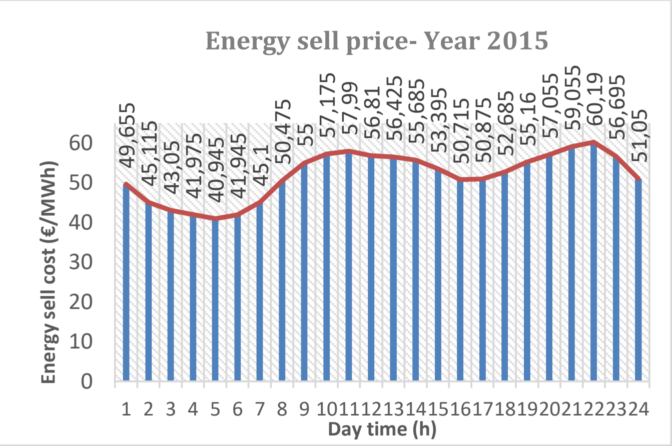

Figure 16- Hourly medium sell price of energy during the year 2015. Source: OMIP.

With this values the profitability of the power plant can be evaluated when facing a normal operation scenario with the characteristics of the scenario 3 and adding the pumping process to the operation of the power plant, with the same characteristics of the scenario 4. So for an operation like in the scenario 3 the economical results presented in the table 10 are obtained.

Table 9- Obtain results for energy prodution in the different periods, with the characteristic of the scenario 3.

Simulation	**Produced Energy (kWh)**	**Production period (h)**	**Market period**	**Production time(h)**	**Sale price (€/MWh)**	**Revenue (€)**
1	400	3	Empty	3→4	41,975	15,6
				4→5	40,945	
				5→6	41,945	
	400	3	Full	15→16	50,715	19,5
				16→17	50,875	
				17→18	52,685	
2	400	3	Full	7→8	50.475	22.5
				8→9	55	
				9→10	57,175	
	400	3	Peak	19→20	57.055	24
				20→21	59,055	
				21→22	60,19	

So the simulation 1 is when the producing period correspond to the empty period of the market and twelve hours later when occurs production again the full period is achieved. In this situation it is possible to conclude that in a day the revenues are 31€.

In the case of the simulation 2 it is considered that the producing period of the power plant match with the peak period and the other producing period match with the full period. It is possible to achieve 46.5€ of revenues in this simulation.

With these results it is possible to conclude that if energy is produced only in peak periods there will be achieved more revenues, like expected. However due to the tidal cycles the power plant cannot produce only on the peak periods because the tides change day by day and they are not constant in time.

In order to add more value to the revenues of the power plant the pumping process can be executed to produce more energy and to obtain more profitability to the power plant. So in the table 10 the results obtained when pumping process is added are presented.

Table 10- Obtain results for energy prodution with pump process, in the different periods.

Simulação	**Energia Produzida (kWh)**	**Período de Produção (h)**	**Período de Produção**	**Horário de Produção (h)**	**Preço de Venda (€/MWh)**	**Ganho Total (€)**
1	922	3h 25min	Vazio	3→4	41,975	41.5
				4→5	40,945	
				5→6	41,945	
				6→7	45.1	
	922	3h 25min	Cheia	15→16	50,715	48.1
				16→17	50,875	
				17→18	52,685	
				18→19	55.16	
2	922	3h 25min	Cheia	7→8	50.475	53.4
				8→9	55	
				9→10	57,175	
				10→11	57,99	
	922	3h 25min	Ponta	19→20	57.055	54.6
				20→21	59,055	
				21→22	60,19	
				22→23	56,695	

As expectable once the pumping process increase the energy produced for the simulation characteristics, as described for the simulations done previously, revenues are increased and the energy producing is more profitable when produced in the peak periods.

However, these results don't take into account the cost of the pumping execution. Thus to analyze the results taking this into account the cost of the energy consumed to execute the pumping has to be calculated. For this calculation, the cost of the energy in the different periods of consumption should be known. In Portugal the authority that imposes this cost is the ERSE (Energy Services Regulatory Authority). Then with available data at the virtual platform the cost of the process for the different periods defined was calculated and these results are presented in the table 11.

Table 11 – Cost of the pumping process in the different period

Consumed Energy (kWh)	**Pumping period (h)**	**Market period**	**Energy Cost (€/kWh)**	**Cost (€)**
741	2h 42min	Super Empty	0.0198	14.3
741	2h 42min	Empty	0.0206	14.9
741	2h 42min	Full	0.0374	27.1
741	2h 42min	Peak	0.0432	31.3

So with the energy cost per period the cost of the pumping process execution can be calculated and like it is possible to understand this cost is different for the different periods. The periods are defined with the same base that the markets periods, in other words the periods are defined according to the energy demand. In the extend version of these master these at the attachment 2 the hours where every period occurs are presented.

With these results it is possible to observe that the best periods to execute the pumping process are the first ones because the energy cost is much lower than in the other two periods. So this process has to be executed in the empty period or in the super empty period.

In order to evaluate the complete process and achieve the balance between the revenues obtained with the energy production and the costs added by the pumping two simulations were performed. The simulation 1 is where the power plant produce energy in the peak period and do the pumping in a empty period in order to get greater revenues. At the simulation 2 the power plant produce energy at the peak power and do the pumping at the peak period too.

Table 12- Results for the best and worst prodution periods.

Simulation	**Produced Energy (kWh)**	**Market period**	**Revenue (€)**	**Consumed Energy (kWh)**	**Pumping period**	**Cost (€)**	**Balance (€)**
1	922	Peak	54.6	741	Empty	14.9	39.7
2	922	Peak	54.6	741	Peak	31.3	23.3

So in the simulation 1 a profit of the process in about 73% can be achieved and in the simulation 2 a profit of 43% can be achieved and this faces the expectations because in the simulation 2 the cost of the pumping process is the double that in the simulation 1.

As conclusion it possible to observe that to get the higher profit of this tidal power plant the producing periods have to be managed as well as the pumping periods in order to do these like in the simulation 1, because it is the conjugation of the period’s results where it is possible to obtain the greater profit.

Although this managing of the periods leads to that the power plant keeps out of operation for many hours until the tides periods and the market periods are favorable to the production of energy, what is not easy to get because of the tide cycles oscillation in the time.

V. CONCLUSION

The first conclusion, and the most important one, that it is retired of this study is that the multiple tidal lagoons located in the estuary of the Tejo river are profitable to the energy production process. However, due to the low dimensions these systems are turned into a low scale system when compared with a tidal power plant like La Rance, in France. This fact makes that the results obtained through the different simulation scenarios display low values to the energy production.

Although this study has been developed to the tidal range harnessing in the estuary of the Tejo river and to a system where the storage areas are low, the results obtained can help to comprove that if it is possible have payback to a low dimension system it is possible to have payback in a higher dimension system in the same place.

However, this place can be exploited to install an experimental project of tidal harnessing, like already exists in Portugal to the waves energy in Pico island, or to develop technologies related to the tidal range power plants. As referred, the technologies related to the tidal range harnessing in previous times didn’t have evolved too much because have big cost and the investors don´t want to risk, and implement always the technologies that have been test and have good results. So this study can work with the purpose of develop and test new technologies to these type of harnessing's like is made in the EMEC.

Thus it is possible to conclude with the economical analyze that the system with multiple tidal lagoons is not a viable project in the point of view of the economical payback because as referred the dimensions of the system are to small when we compare with other systems of tidal range harnessing.

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