Ocean power conversion for electricity generation and desalinated water production

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Abstract: Ocean power is a promising source of renewable and alternative energy used to fuel human activities. Generated energy from ocean power devices can be converted into electrical or mechanical energy, which can in turn be used as a driving force together with the desalination and water treatment by reverse osmosis processes. In this article, applications of high pressure wave energy converters (WEC) and hydrokinetic turbine for current energy conversion (TEC), described in Estefen et al [1], are presented. Due to its conceptual design, these ocean energy converters (OEC) are able to transform the hydraulic energy available from the sea into mechanical energy and then in turn into electricity generation, reverse osmosis desalination or as the driving force for hydraulic machines. A theoretical production estimation of wave and currents devices was conducted, which considered their performance from laboratorial tests associated to ocean parameters. Results are promising and indicate that it is indeed possible to supply domestic, industrial and agricultural demands of electricity and/or water, respecting the corresponding standards required.

Keywords: *Ocean power, Wave power, Current power, Desalination, Isolated communities.*

1. Introduction

In recent years, several kinds of ocean power converter prototypes have been developed, according to the expertise of each inventing team and/or specific issues from the local sea where it was planned for. This amount of prototypes indicate that the most suitable technology is not defined yet, i.e., which amongst will be applied to commercial purposes. The conversion technology from ocean power has been developed or adjusted from experience and knowledge in hydraulic and wind projects, besides from the activities performed in the offshore oil industry. According to the classification of Brooke [2] and Pontes & Falcão [3], Wave Energy Converters (WEC) can be sorted by the location in shoreline, near shore and offshore devices or by technology in Oscillating water column systems, Overtopping Systems, Point absorbers systems, Surging devices and other devices.

Tidal energy converters (TEC) can be classified into three main groups: horizontal axis turbines (axial flow), vertical axis turbines (cross flow) and oscillating hydrofoil. The former is based on hydrofoils impulsion from lift force caused by tidal current flow. In the sequence, hydraulic cylinders are driven, which in turn causes the electricity generation. Furthermore, the classification proposed by Bryden and Couch [4] includes Venturi systems, based on turbines endowed with a diffuser to increase the pressure difference.

The concept of high pressure wave power converter, described in Estefen et al [1], is based on the use of an hyperbaric chamber, which stores wave power converted from highly pressurized water. The first version, denominated onshore, works as a bi-supported beam with one beam fixed deep down into the soil and the other on a buoy, which follows the waves´ movement. Once a wave passes by the buoy, it causes beam displacement, which is joined with a hydraulic pump and then pressurizes the water. This pressurized water is stored in a high pressure system, consisting of a hydro-pneumatic accumulator and hyperbaric chamber.

The chamber works as a hydraulic accumulator. When the pressure inside the accumulator reaches its operational level, the water is delivered, through a valve to a hydraulic turbine, which is linked to an electrical generator in order to produce electricity.

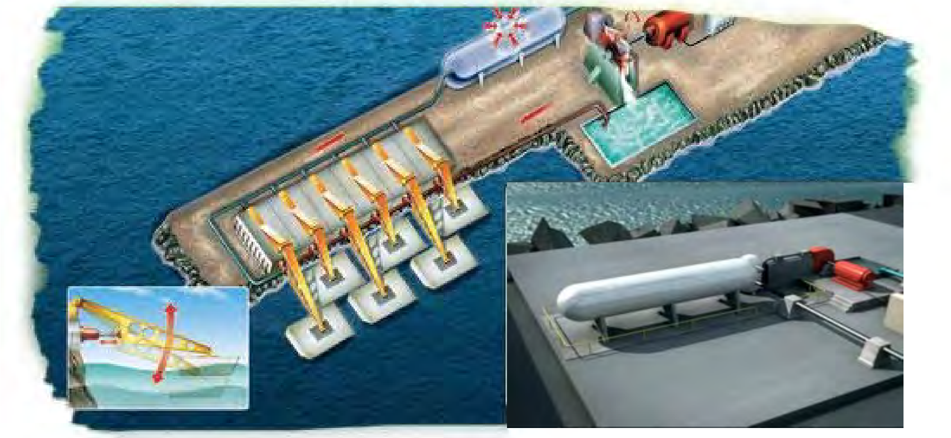

*Figure 1: Wave power plant using high pressure system as described in Estefen et al [1]
In detail the high pressure system including hyperbaric chamber and accumulator*

Power harnessed by ocean devices can be converted into electrical or mechanic energy, and applied as a driving force for engines or even, in the desalination and water treatment from the reverse osmosis process. The produced drinking water can supply households, industries and agricultural irrigation. For domestic use, salt concentration around 300 mg/L is required, including other quality parameters which can be achieved through the reverse osmosis conventional process, pre and post-treatment. Power consumed to pressurize water could be totally supplied by the ocean energy converter system. In industrial processes, e.g. thermo electrical plants, salinity standards similar to humans, around 300 mg/L is required in order to avoid the corrosion of equipment. Finally, in agricultural use, it is possible that large amounts of desalinated water can be produced, allowing irrigation of between 1 to 3 hectares per unit, at severe conditions of hydric demand typical in semi-arid regions.

Power supply is considered to be one of the main issues for economic and social development, since it is applied during the whole process of production and services, providing the basics necessities of modern life. For example, according to Pereira et al [5], Brazilian households without access to electricity stands at 2.8%, the majority of which are from isolated communities and rural areas, limiting electrical supply under conventional means. Such restrictions lead to a large expense of these families incoming in fossil fuels or to employment of old and inefficient techniques to generate power [5]. On the other hand, the same regions which lack electricity beholds a significant amount of alternative and renewable energy sources, for example, solar, wind, hydraulic, tidal and biomass energy. In regard to tidal current power, there are feasible possibilities of supply for isolated communities spread throughout Brazilian and South American territories.

2. Methodology

In order to estimate the amount of power extracted by an Ocean Power Converter (OEC), uneven wave or tide conditions must be considered, but also the device characteristics, the power take-off system, and the control strategy to name a few [6]. The power comprised in the wave incident to a device, according to EPRI [7], is based on two parameters: the significant wave height and its peak period, see Eq. (1).

$$E_u = 0.42 \times (H_S)^2 \times T_P \qquad (1)$$

where E_u is the power of each meter of wavefront in kW/m
H_S is the significant wave height in meters
T_P is the peak period in seconds, being the inverse of frequency where spectra reached its maximum value
The coefficient 0.42 varies according to the wave spectra considered for a specific sea state.

The Eq. (1) can be employed to estimate the amount of power incident from a wave with H_S and T_P known. On the other hand, each device will be able to convert a fraction of wave incident power. In order to estimate the production of each device, a table must be created in which the cell represents the amount of power converted by the device for specific conditions of wave height and peak period. Generally, these results have been obtained through laboratorial or field tests, therefore it reflects only their performance on a small scale.

The wave parameters used as a reference for the calculations below have a significant wave height of 1.6 m and peak period of 6 seconds. The performance of the wave energy converter was obtained in tests with a reduced model, and these conditions reached a level of 18 kW of converted hydropower. The average energy absorbed in each conversion cycle, equivalent to the work done by the piston pump with each passing wave period, is calculated in Eq. (2).

$$\Delta W = \int_0^T P(t)dt = \int_0^T F_P(t)y(t)dt \qquad (2)$$

where F_P is the periodic force exerted on the piston;
y is the piston displacement, consisting of a term of steady state and another transient.

Similarly, the generation of electricity through the power of tidal currents, the potential energy is calculated from Eq. (3).

$$\Delta W = \int_0^T \frac{1}{2} C_P \rho A_{turb} v^3(t)dt \qquad (3)$$

Where C_P is the power coefficient;
A_{turb} is the transversal area of the turbine;
v is the speed sinusoidal of the current.

An energy converter of currents around 7 meters in diameter working in a tidal current speed with a sine wave amplitude of 1.8 m / s and power co-efficiency of 35%, will absorb an amount close to the energy converted by the WEC in the wave conditions presented, equivalent to an average of 18 kW. This amount of energy is absorbed primarily by the drive which is available in the oceans. From this point on, this energy is stored in the form of pressure and can be directed to the generation of electricity in a Pelton turbine or a module of reverse osmosis to produce desalinated water.

The desalination and water treatment for drinking can be accomplished through the process of reverse osmosis coupled with the energy converters of the sea. Reverse osmosis is a water treatment process that uses synthetic semi-permeable membranes to intercept components of water, especially salt particles. Unlike the phenomenological natural osmosis, in reverse osmosis the goal is to produce water with low salt concentration obtained from the introduction of energy in the system. This energy is transformed into a driving force for pumping the water of higher salt concentration through a semi-permeable membrane, thus producing potable water.

In this sense, the pressure reached by the system must be sufficiently greater than the osmotic pressure between the two different salt concentrations before and after the membrane, not only to reach the balance in osmotic pressure, but also to produce a reasonable flow of water permeated, reversing the flow. In the case of converting energy from the high sea pressure [1] these pressure levels are easily achieved through the sizing of pumps attached to the primary conversion module, which provides power to the system.

The salty sea water with salinity levels of 33‰ and temperature of 24ºC has an osmotic pressure equivalent to 27.5 bar. According to marketing literature, working pressure levels of about 55 bar are required to obtain significant flow of desalinated water in the reverse osmosis process. The flow of desalinated sea water, depending on the energy converted from the sea and made to the system can be estimated by integrating the van't Hoff formula for the osmotic pressure, described in Eq. (4). This energy converted by the converter device serves as a driving force, allowing the seawater admission and pumping it to a reverse osmosis module.

$$\Delta W = -\int_{V_1}^{V_2} \pi dV = N \cdot R \cdot T \cdot \ln(V_1 / V_2) \qquad (4)$$

where ΔW is the required energy per pump cycle
N is the number of moles of salt in seawater
R is the universal gas constant
T is the temperature in Kelvin
V_1 e V_2 are the initial and final volumes of the pump piston, their difference represents the volume of water actually pumped.

The energy required to pump a volume through a semi-permeable membrane can be calculated by Eq. (5). The liquid pressure achieved by the system must be greater than the osmotic pressure between the concentrations before and after the membrane, coupled with a pressure associated with the flow of permeated water.

$$W = \int_{V_1}^{V_2} (P_S + \Delta P) dV = \left[\frac{P_{sea} \cdot (1-\alpha/2)}{(1-\alpha)} + \Delta P \right] \cdot \Delta V \qquad (5)$$

where α is the recovery rate of the desalination system.

For the recovery rate of 45%, the energy required to desalinate a liter of water would be 6.5 kJ/L. Taking the energy available in the system to the conditions of wave and current previously calculated as 18 kJ per second and the complete cycle of pumping of 6 seconds, can be obtained from the flow pumped by each cycle in Eq (6).

$$\Delta Q = \Delta V \cdot (1/cycle) = 235 m^3 / day \qquad (6)$$

The reverse osmosis modules available on the market specifically for the desalination of sea water have recovery rates of 40 to 50%. The number of modules to be used for each energy converter device of the sea was estimated from information of a type widely sold for this purpose. Table 1 shows the main parameters of this model.

Table 1. Parameters of the module of reverse osmosis desalination for seawater

Membrane area	35 m²
Unit permeated flow	14 L/hour/m²
Number of elements per pressure vessel	Up to 7
Recovery rate	45%

The production of each element will be 490 L/h and the number of elements required will be obtained by the ratio between the flow obtained by Eq. (4) and this unit flow, resulting in 20 elements. Pressure vessels can include up to seven elements of desalination in the series, which represents the need to install at least three pressure vessels coupled with each module of ocean power converter device. Whereas the recovery rate to feed flow rate will be 521 m³/day of seawater from the sea.

On the other hand, in the reverse osmosis process, as well as in other processes of desalination, wastewater is produced with higher concentrations of salt than the average salinity of the sea. The final disposal of these effluents should be studied carefully to avoid causing damage to the immediate environment, especially marine biota. Studies using models of hydrodynamic circulation and transport of water constituents are desirable for evaluation of local impact. In any case, the use of sea energy for desalination by reverse osmosis is configured as a viable cost effective alternative, especially for locations where there is a scarcity of drinking water, such as on islands and coastal areas which are far from large sources of freshwater.

3. Results

3.1. General applications for the OEC devices

Possible applications for tidal and waves energy are similar to any other energy source, which can be to provide for the electrical system, the seasonality of supply and daily peak time consumption. It can also serve as a complement to thermal energy to replace pollutants in places where few options for energy supply exist. Remote markets and isolated spots, such as villages on islands, coastal and riverside population, units of offshore oil, scientific research and the military, marine farms and fisheries.

3.2. Applications for electricity

In the case of electricity production, each high-pressure ocean power convertor, e.g. described at [1], is able to supply the demand of an average 36 households, considering the wave or current conditions described above with an average residential consumption of 12 kWh/day. Electricity produced from the sea energy converters can be used in a variety of projects, either as a principal supply, or as a supplement to other sources. The first application is domestic supply, especially in residences near marine resources located on the coast where waves or tidal estuaries are present. In South America, there is sparse population along the coast and inland waters, poor supply of electricity can benefit from these types of project. Other applications include the use of electricity in scientific and military bases located on islands and remote locations, hotels and resorts in exploiting the tourist appeal of the device itself and also drive the production of clean and renewable energy.

3.3. Applications for desalinated water

The applications of water treated by reverse osmosis from sea power converters include residential, industrial and agricultural processes through irrigation. The production capacity of treated water per converter module of wave energy or currents has a power equivalent to 18 kW and an average of 235 cubic meters per day, as shown in Eq. (6), which allows for the supply of approximately 940 people.

As an example of industrial use, the water process in power plants must meet very stringent standards for salinity in order to prevent corrosion of equipment. The salinities suitable for this purpose is 300 mg/L, similar to that required for human consumption. The unit consumption of treated water per megawatt hour produced in power plants varies from 180 to 720 U.S. gallons or 0.68 to 2.72 m^3, depending on the fuel coal, gas or nuclear power and technology of the cooling tower [7] as shown in Fig. 2.

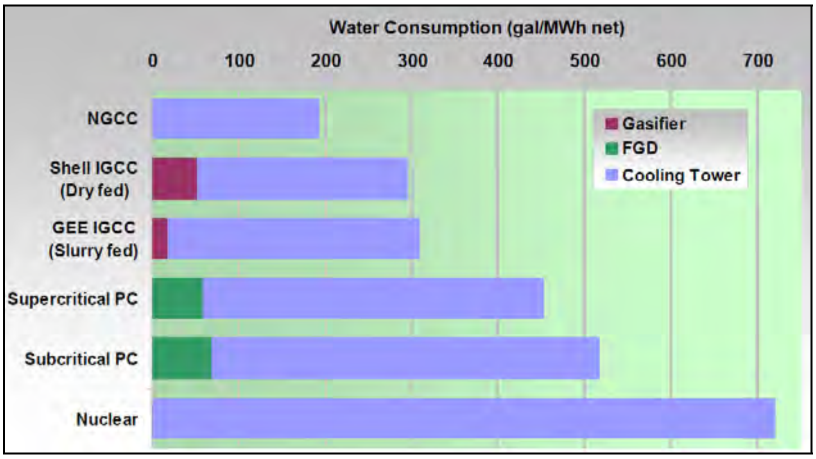

Fig. 2. Water consumption in the processes of coal-fired, gas and nuclear applications. Source: Gerdes and Nichols [7]

Considering the average production of treated water for ocean energy converters of 235 cubic meters per day, you can meet the thermoelectric consumption for the values shown in Table 2.

Table 2. Production of OEC to supply the thermoelectric water consumption

	Combined cycle (dry Tower)	Simple steam cycle (dry tower)
Water consumption	0,11 L/s	0,27 L/s
Power attained for No. of OEC modules	24 MW/Module	10 MW/module

Another application of desalinated water from OEC's is for the service of irrigated crops. Agricultural irrigation is water consumptive, due to the fact high water demand from the crops throughout the growth phase and the planting and irrigation techniques have low levels of efficiency in water management. The quality of irrigation water is usually based on the total content of dissolved salts, measured by the electrical conductivity and sodium adsorption ratio (SAR), assessing the risk of sodicity in soil [8]. The required concentration of dissolved salts in irrigation water is limited to the potential impact on soil structure, corresponding in terms of electrical conductivity to between 250-750 micromhos/cm and, in some cases, 2,250 micromhos/cm. In terms of salt concentration, the values are between 160 and 480 mg/L.

To illustrate this application, the water requirements for cultivation of cane sugar in a Brazilian region characterized by lack of rainfall during summer in the Southern Hemisphere will be described below, along with the possibilities that this demand can be met by OEC modules. The observed rainfall in the Alagoas region during 2008 is presented in Table 3.

Table 3: Average monthly rainfall (mm) in the region of Alagoas (Brazil)

JAN	*FEB*	*MAR*	*APR*	*MAY*	*JUN*	*JUL*	*AUG*	*SEP*	*OCT*	*NOV*	*DEC*
41	206	214	257	256	261	276	238	76	48	12	41

The months of November, December and January show a significant drop of rainfall, resulting in severe consequences for water users in this region. In Fig. 3 (a), the curve shows the agrometeorological cane ratoon, the evolution of the crop water demand throughout its growth in the months of the planting period, August through to July, the harvest season.

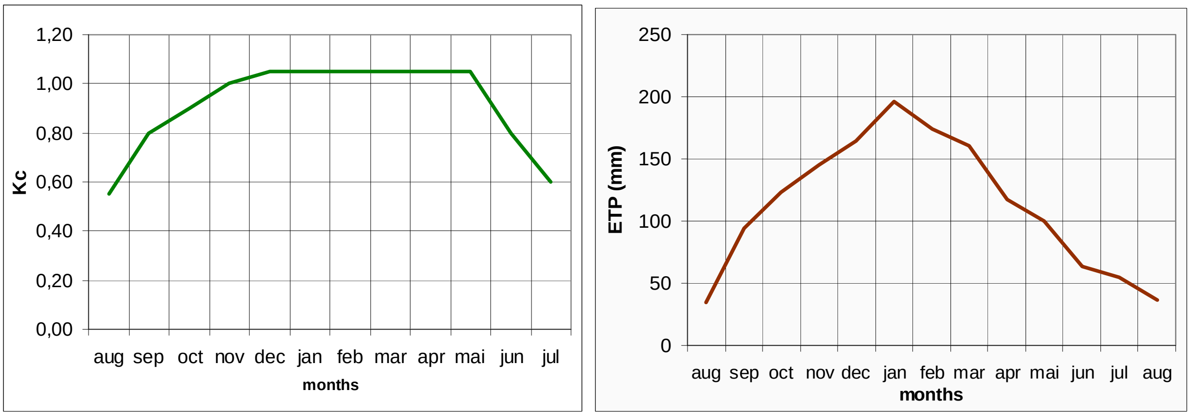

Fig. 3. (a) Agrometeorological curve (Kc) and (b) Evapotranspiration of the sugarcane ratoon (mm)

Thus, the water demand in each month of sugarcane ratoon crop irrigation can be calculated by the difference between the amount of water precipitated and crop evapotranspiration. The amount of irrigation water demand is presented in Table 4.

Table 4: Monthly water demand for irrigation of sugarcane ratoon (in mm)

Month	*AUG*	*SEP*	*OCT*	*NOV*	*DES*	*JAN*	*FEB*	*MAR*	*APR*	*MAY*	*JUN*	*JUL*
Lamina (mm)	85,1	-18,25	-74,8	-133,2	-123	-155,1	32,1	53,6	139,8	156,2	197,2	221,9
Daily irrigation flow (m^3/day/ha)	0	6,1	24,9	44,4	41,0	51,7	0	0	0	0	0	0

As shown in Table 4, negative values mean that there was a demand for irrigation in the corresponding months. The daily flow irrigation during the critical months was calculated taking into account the water depth required. Based on a water salinity content of 300 mg/L and the flow of irrigation in the most critical month of January, it shows that the production of water from ocean energy converter of 18 kW is capable of supplying irrigation in 4.5 hectares of cultivation.

4. Conclusions

An estimation of wave and tidal current power converter production was conducted, which focused on a high pressure system concept [1] developed by Submarine Technology Laboratory at UFRJ (Brazil). The WEC is an oscillating body type, which pumps water to the hyperbaric chamber and uses conventional Pelton turbine coupled with an electrical generator. Also, the hydrokinetic turbine is connected to a hydraulic pump and from this stage it is similar to the architecture described above. Due to its conceptual design, these ocean energy converters (OEC) are able to transform the hydraulic energy available at sea into mechanical energy and then into electricity generation, reverse osmosis desalination or as a driving force for hydraulic machines. As a reference, the energy amount converted by this WEC in a typical wave condition was used for the following calculations, and it was compared to the similar amount generated by the TEC. The estimate indicated that for a significant wave height of 1.6 meters, the WEC can generate 18 kW or 235 m^3/day of desalinated water and the same production can be obtained by the hydrokinetic turbine at a current speed of 1.8 m/s.

Electricity, fresh water and driving force resulting from OEC can be employed in domestic, industrial and irrigation uses, especially in regions which lack these natural resources, *e.g.* islands, coastal and riverside isolated communities. Additionally, industries and agricultural irrigation settled near to the coast can be potential users of treated water and electricity generated by the mentioned OEC. The water supply for each case is simulated herein. For domestic use, each module of WEC or hydrokinetic turbine can supply 940 people. The industrial application was illustrated by the water demand of a thermoelectric plant, providing values of each 10 MW in the Combined Cycle can be supplied by one OEC module, and in the Simple, each 5 MW. The irrigation use was demonstrated through the water consumption of sugarcane cultivation during a critical month associated with low precipitation. In this case, up to 5 hectares of cultivation can be irrigated by the production of one module. Harnessing ocean power is a way to provide decentralized electricity generation which could supply remote sites, promoting the diversification of energy matrix and becoming an economical development vector, especially in coastal communities of developing countries.

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