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# PRELIMINARY STUDY OF OCEAN THERMAL ENERGY CONVERSION (OTEC) PLANT IN BRAZIL

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***Abstract.****One way to generate sustainable energy is through solar energy. In tropical areas, the oceans are big solar energy accumulators in their surfaces and this energy can be converted in electrical energy by means of the process denominated Ocean Thermal Energy Conversion (OTEC) plant. The operating principle of OTEC plant is from temperature difference of seawater between surface and a point at a depth of 1,000 m. In tropical areas, the seawater average temperature is 25 ºC, while the depth seawater average temperature is 5 ºC. In this condition, the water of ocean surface is utilized in the evaporator as a heat source and the seawater depth is used as a condenser. In this way, three thermal cycles can exist: open, closed and mixed. In all of these cycles, many byproducts can be generated, such as considerable quantities of fresh water, marine-life-based industrial products, sea foods, as well as chilled-water for air conditioning. In locals where the difference of temperature is more than 20 °C, the ability to produce energy can be around 10 MW, in a small plant. To optimize the difference of temperature, can be installed solar collectors, where the hot water or work fluid will increase its temperature. This work presents a literature review about OTEC plant and how is the process for energy generation, as well investigates the possibility of installation in Brazilian coast. Moreover, the potential areas in Brazilian coast in which OTEC plants can be installed are presented as well as the methods utilized to determine the efficiency in these areas.*

***Keywords:*** *energy, ocean thermal conversion, sustainable plants.*

## 1. INTRODUCTION

One way to generate clean energy is through solar energy which can be harnessed the light and heat to convert it in mechanical and electrical energy (Baptista *et al.*, 2006). In tropical areas, the oceans are big solar energy accumulators in their surfaces. Oceans accumulate energy in the form of solar radiation. This energy is equivalent to 250 million barrels of oil, that can be converted in electrical energy by means of the process denominated Ocean Thermal Energy Conversion (OTEC) plants (Etemadi *et al.*, 2011).

Takahashi and Trenka (1992) say that the concept of the process to convert the thermal energy from oceans into electricity was first proposed by French engineer J. A. d'Arsonval more than a century ago, in 1881. In 1930, G. Claude, a d'Arsonval's former student, field tested a model at Matanzas Bay, in northern Cuba. His model has generated 22 kWe, but it consumed more power than it generated because the design had many problems.

Years later, Claude launched his second attempt. His project has been a floating plant aboard a cargo ship moored off the Brazilian Coast, but the waves broke the cold pipe when it was being installed. Claude never got his aim of generating energy with OTEC system.

An OTEC plant is able to produce 3 MWe it was designed to be built on the west coast of Africa in 1956 by French engineers but this project was abandoned due a various reasons. In 1960 decade, J. H. Anderson and his son initiated some studies about OTEC and ten years later W.E. Heronemus and C. Zener from the University of Massachusetts and Carnegie-Mellon University joined them, respectively. In 1972, the National Science Foundation granted the technical and economic viability evaluation to University of Massachusetts. The earlier research work was unheralded. In 1973, with the oil embargo, the OTEC technology has advanced because the urgent demands to find alternative sources of energy led engineers to reexamine its potential. Thus, since that year, the researchers have brought its technology to a commercial scale (Plocek and Laboy, 2009).

According to Bharathan (2011), the production capacity of OTEC plant is between 1and 40 MWe, depending on the installation area. In Hawaii, an OTEC plant generates 10MWe, but it offers a potential market for a nominal 40 MWe, because the ocean surface average temperature around Hawaii is high. Nowadays, the biggest OTEC plant is being built in China for production of 10MWe and it will be ready to operate in 2017.

This type of electricity generation plant has many advantages and few disadvantages. The advantages are the energy resources for OTEC that are vast and naturally self-renewable and non-polluting. Furthermore, it can produce several byproducts, such as considerable quantities of fresh water, marine-life-based on industrial products, seafoods, as well as chilled-water for air conditioning (Crews, 1997). Fig. 1 shows how the byproducts can be obtained.

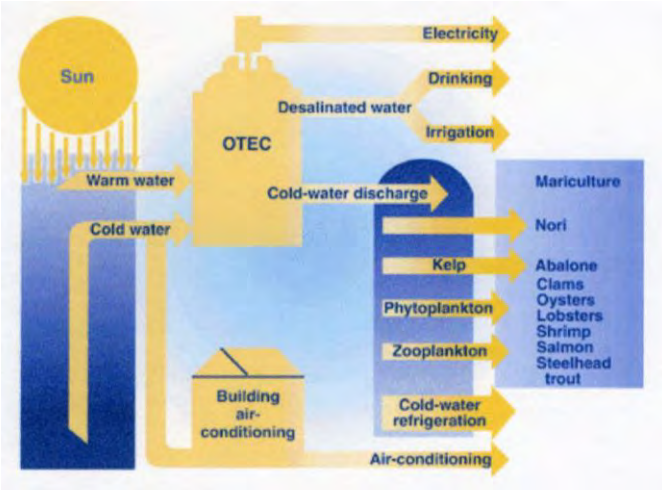


Figure 1. How OTEC plant gets byproducts.
(Available at http://www.nrel.gov/tech_deployment/state_local_activities/pdfs/tap_webinar_20080213.pdf)

Tahara *et al.* (1995) say that a 100 MW OTEC system can reduce the amount of $CO_2$ emissions by 140,000 t-C/year. The energy payback time is 0.46 year, which is supposed to build a large-scale system is more feasible than many small-scale systems. The energy conversion has a small efficiency, but it might work without stopping generating clean energy.

The disadvantages of this power plant are few. One of them is the requirement of a large initial investment, in the range of 50 to 100 million dollars for constructing a 10 MWe plant.

According to Fujita *et al.* (2012), although not emitting carbon to the atmosphere, the environment impacts of OTEC plants must be investigated. They say, for example, the condenser need large quantities of cold water gotten in the depth. This cold water, when discarded, could go down the sea surface temperature around the installation and entrain a large number of microorganisms that live in the depth, affecting the biodiversity. Another environment problem is if ammonia leaks the closed cycle (Etemadi *et al*., 2011), but all of this environment impacts need more studies.

## 2. HOW AN OTEC PLANT WORKS

According to Etemadi *et al.* (2011), an OTEC plant works with the difference between surface seawater and a point at a depth of 1,000 m. In the tropical areas, this temperature gradient is around of 20º C. This difference occurs because the seawater gets colder as the depth increases (Reis and Souza, 2012). Fig. 2 shows the variation the seawater temperature with the depth.

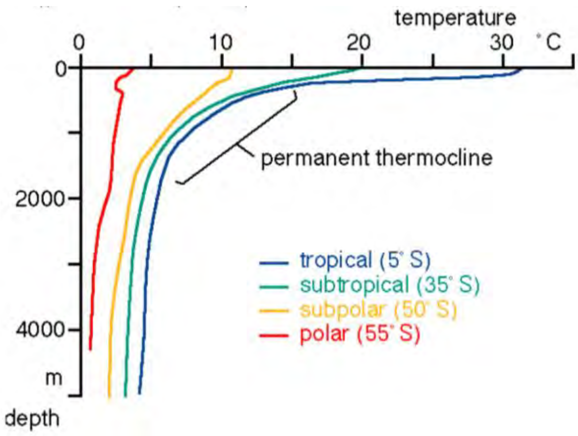


Figure 2. Typical ocean thermal structure in tropical areas (Reis and Souza, 2012).

The thermal system is based on three cycles: open, hybrid and closed (Takahashi and Trenka, 1992). These three cycles will be described in the sequence.

### 2.1 Open cycle

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According to Takahashi and Trenka (1992), in OTEC open cycle the warm seawater from ocean's surface is the working fluid, which is pumped into a flash evaporator where the pressure allows the water to boil at temperature ambient. The warm water steam drives the low-pressure turbine coupled to an electricity generator. After leaving the turbine, the steam passes by a condenser, in which it is cooled by the deep seawater. This process can produce desalinated water, minerals and life based food. Fig. 3 shows the open cycle process.

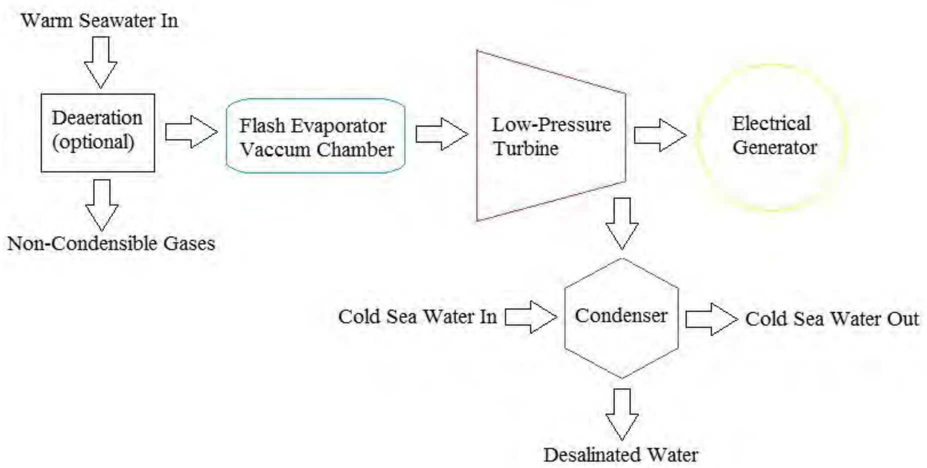


Figure 3. Schematic of an open cycle OTEC system (Takahashi and Trenka, 1992).

**2.2 Closed cycle**

The OTEC closed cycle system produces electricity using the principles of a Rankine cycle (Faizal and Ahmed, 2013). The working fluid is a fluid with low boil temperature such as ammonia and freon. Bharathan (2011) recommends more studies about the efficiency of thermal system using propylene. This Rankine cycle consists in two heat exchangers, one steam turbine and one pump. The warm seawater is taken from the ocean's surface and it is pumped into the heat exchanger and the working fluid will boil increasing its temperature and entropy. The steam produced drives the turbine and the working fluid is condensed in the condenser, which exchange heat with the cold seawater of the depth and the working fluid is pumped back to the evaporator (Faizal and Ahmed, 2013). Fig. 4 illustrates the schematic system of OTEC closed cycle.

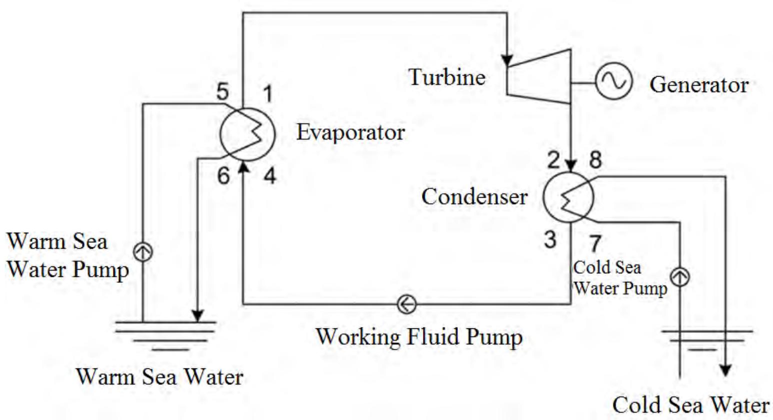


Figure 4. Schematic of a closed OTEC cycle (Faizal and Ahmed, 2013).

Bharathan (2011) has used in his Rankine cycle simulation the resources conditions shown in Tab. 1 and the efficiencies of equipment, such as pumps and power turbine, are shown in Tab. 2. The heat exchanges minimums approach are shown in Tab. 3 and the overall hydraulic system lost are shown in Tab. 4. With these parameters and conditions, was obtained a nominal 10 MWe using ammonia as working fluid and modeling the system using the commercially available software ASPEN Plus.

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Table 1. Resources conditions utilized in Bharathan's Rankine cycle simulation (Bharathan, 2011).

| | |
|---|---|
| Warm water temperature (ºC) | 26 |
| Flow rate (kg/s) | 50,000 |
| Cold water temperature (ºC) | 4.5 |

Table 2. Efficiencies of equipment utilized in Bharathan's Rankine cycle simulation (Bharathan, 2011).

| | |
|---|---|
| Water pumps | 0.72 |
| Working fluid pumps | 0.72 |
| Power turbine | 0.75 |
| Generator | 0.94 |

Table 3. Heat exchanger minimum approach utilized in Bharathan's Rankine cycle simulation (Bharathan, 2011).

| | |
|---|---|
| Evaporators (ºC) | 1.2 |
| Condenser (ºC) | 1.0 |

Table 4. Overall hydraulic system loss utilized in Bharathan's Rankine cycle simulation (Bharathan, 2011).

| | |
|---|---|
| Warm seawater loop (bar) | 0.3 |
| Cold seawater loop (bar) | 0.72 |
| Evaporator (bar) | 0.06 |
| Condenser (bar) | 0.06 |

To increase the efficiency of the thermal system, Yamada *et al.* (2009) describes another method that utilizes not only the ocean thermal energy, but also solar thermal energy gotten through its radiation. This method was named Solar Boosted Ocean Conversion Energy (SOTEC) that consists in a solar thermal collector plate installed in a closed cycle. There are two ways of installation these solar thermal collectors. One way is before the evaporator (indirect SOTEC). Thus, the warm water pass by the solar collector, increasing its temperature in until 20º C. Fig. 5 shows the indirect SOTEC system.

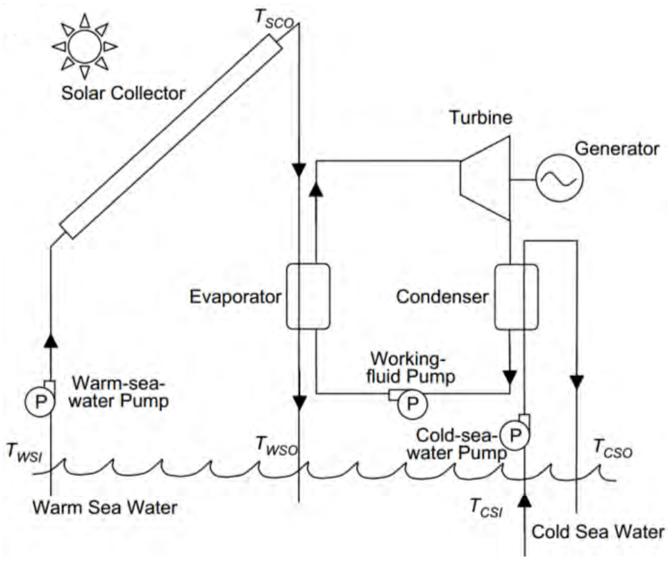


Figure 5. Schematic indirect SOTEC with warm seawater pass by solar thermal collector (Yamada *et al.*, 2009).

Another way is installing the solar collector after evaporator (direct SOTEC), but the working fluid that will pass by increasing its temperature and entropy before driving the turbine. The Yamada *et al.* (2009) simulations have concluded that the annual net thermal efficiency of direct SOTEC is 1.5 higher than the conventional OTEC. The SOTEC system is indicated to subtropical areas or to enhance the efficiency in the tropical area. Fig. 6 illustrates the direct SOTEC system.

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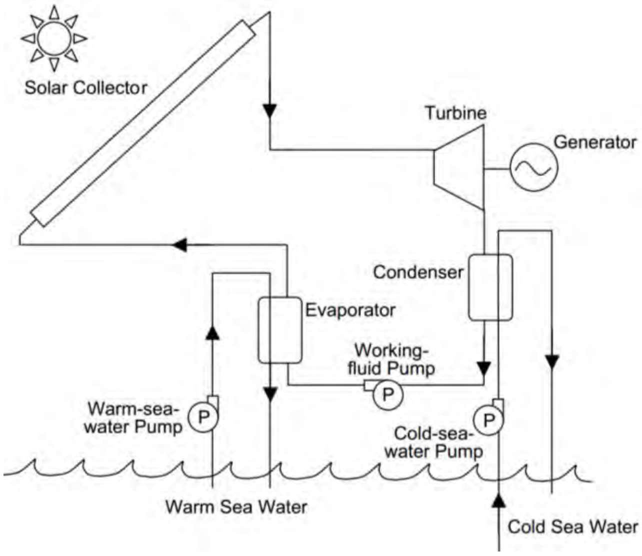


Figure 6. Schematic direct SOTEC with warm seawater pass by solar thermal collector (Yamada *et al.*, 2009).

### 2.3 Hybrid cycle

The hybrid cycle mixes the two others cycles: opened and closed. This configuration might enhance the OTEC efficiency and maximize the byproducts production. According to Etemadi *et al.* (2011), the hybrid cycle might mix the working fluid vapor and water steam traveling through the turbine and then the working fluid is separated from the water steam. The working fluid returns back to closed cycle and steam water is condensed into fresh water. Takahashi and Trenka (1992) gave another description. In their description, the vacuum flash evaporator is integrated in the closed cycle evaporator. The warm seawater is boiled by means that low its pressure and its steam exchange heat with the working fluid and the water is condensed as fresh water.

## 3. POTENTIAL AREAS

For getting the maximum efficiency of the OTEC power plant, the temperature difference between seawater surface and depth seawater should be more than 20º C. According to Nihous (2007), half of the tropical waters of the Atlantic Ocean are appropriate for a good OTEC operation. The first step to consider in an OTEC installation is the ocean surface temperature and if the local is suitable for that (Straatman and van Sark, 2008). Fig. 7 shows the world's oceans surface temperature.

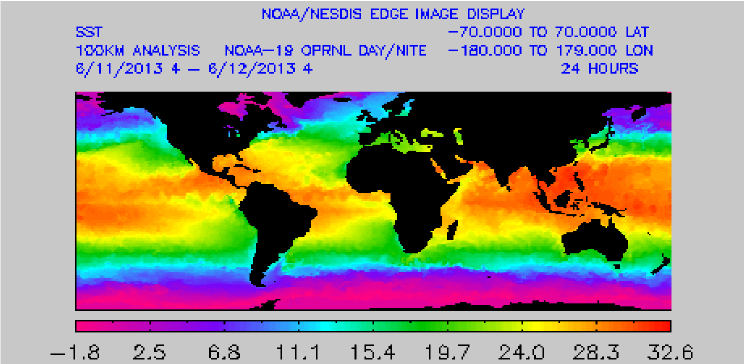


Figure 7. Sea surface temperature around the world.
(Available at: http://www.ospo.noaa.gov/data/sst/fields/FS_km10000.gif)

Takahashi and Trenka (1996), say there are 99 nations and territories with capacity for OTEC resources. These 99, only 61 countries or territories are situated in the orange or yellow zone in the Fig. 6, being 15 nations in America's Mainland, 23 in America's Islands, 18 in Africa's Mainland, 5 in Africa's Island, 11 in Indian/Pacific Ocean Mainland and 27 in Indian/Pacific Ocean Islands (Crews, 1997). However, with more detailed studies, this number will decrease because was only consider their sea surface temperature.

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In America's mainland, Crews (1997) listed 15 territories where OTEC plant could be developed. They are: Mexico, United States, Belize, Costa Rica, El Salvador, French Guiana, Guatemala, Guyana, Honduras, Nicaragua, Panama, Suriname, Colombia, Venezuela and Brazil. Brazil has a great potential of OTEC's installations in its coast, as it's possible to see in the Fig. 8, mainly in shoreline site along on a 1,100 km the eastern coast, starting from the north of Natal, in Rio Grande do Norte, and finishing in the south of Salvador, in Bahia.

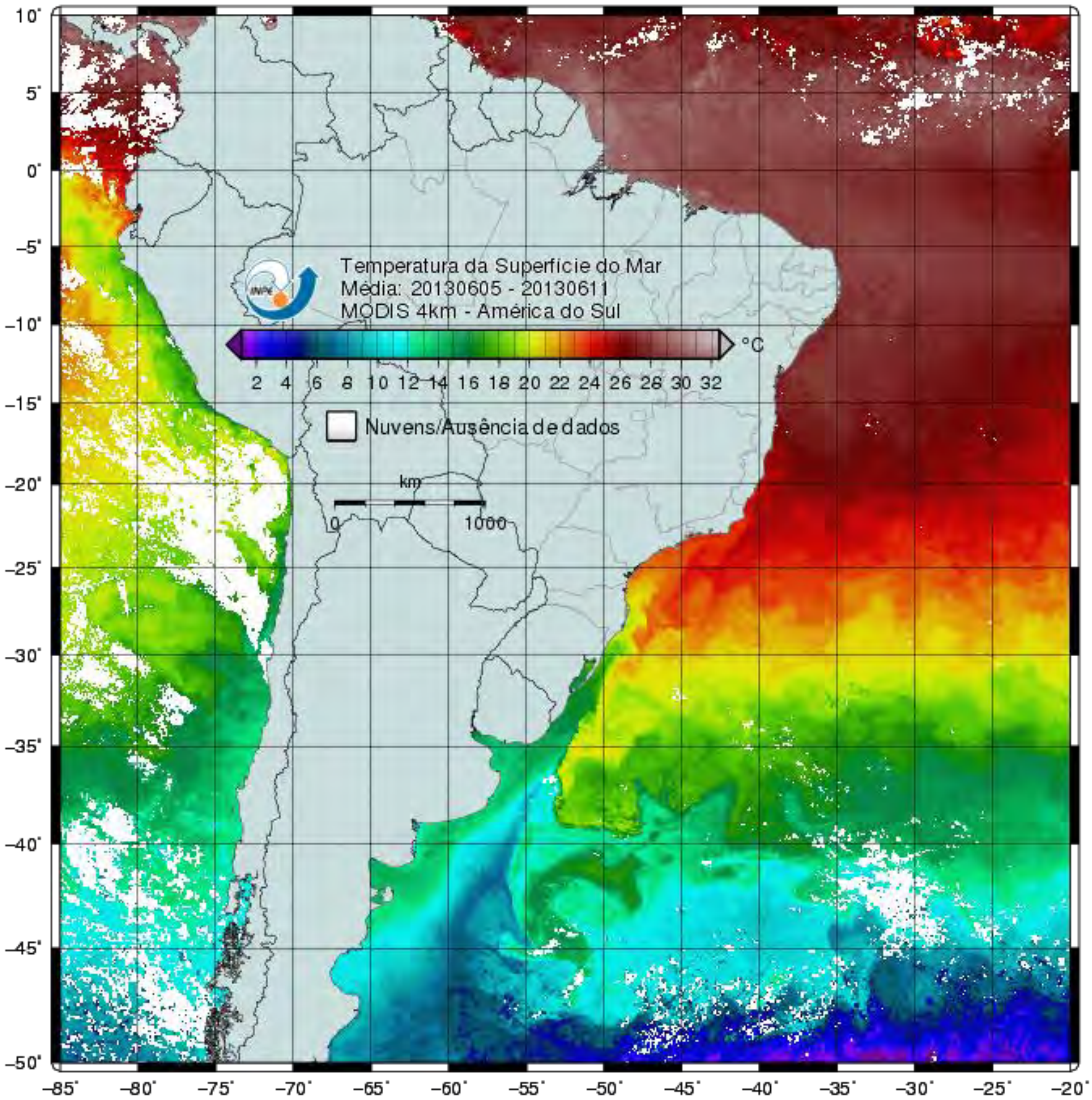


Figure 8. Sea surface temperature on Brazilian coast.
(Available at: http://satelite.cptec.inpe.br/acervo/imgacervo.jsp?idProd=3401).

In the Fig. 7 the average of the seawater surface temperature is shown in the Brazilian's coast in the last four months. It can be observed in the figure, the Brazilian's northeast coast had in turn of 28º C. It is very good surface temperature for the installation of OTEC plant. Fernando de Noronha Island would be a good local for it too.

Crews (1997) says to build a shore based OTEC plant the deep ocean area must be nearly, within until 10 km or 6 miles. Although, the maximum cold-water-pipe length should be at most 2 or 3 km. Above this length, the cold water temperature could increase more than the good point for using it in the condenser, making the system lost its efficiency due the frictional forces (Straatman and van Sark, 2008). In areas where the distance of the shoreline to a point in depth of 1,000 m are bigger than 3 km, the power plant can be installed at remote offshore areas and the electrical energy produced can be utilized to produce hydrogen and storing it in fuel cells (Kazim, 2005).

After analyzing the sea surface temperature and the distance until the deep ocean, some political, geographic and infrastructural considerations must be evaluated. These considerations, according to Crews (1997) are: What is the tropical climate? The local have several storms? Does the local have another electricity generation source? Are there prohibitive ecological constraints? What are the local infrastructure for transport of products, the local per-capita

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income and authorities? What is the shoreline construction base? And another many questions must be answered before starting to build an OTEC plant.

## 4. CONCLUSION

OTEC plant is a great form to generate clean energy with a very low rate of Carbon emission. Looking at an ecological and sustainability side, it is also a very good alternative. The plant have three kinds of working. In each of these kinds, energy and many byproducts can be generated. Despite their efficiency are lower than others ways to producing energy, it might work without breaks, generating considers quantities of fresh water, chill-water for air conditioning systems or producing Hydrogen to applications in fuel cells. The OTEC's hybrid cycle has the best theoretical application, but there are few studies about it. A good alternative to locals where more energy generation is needed is a SOTEC plant, it can also be used to increases a plant's efficiency.

As the objective of this study is the capacity of power generation of OTEC plant and applicability in Brazil, where there are few studies about its application in the country, is possible to see there are a vast area (from north of Natal to south of Salvador) that could be potential candidates to installation of this plant. This potential should be avail, because this region needs more investments in electricity generation. The fresh water, one of the OTEC's byproducts, could be used to feed the lack of water in dry areas in the country part of the State where would be installed the plant.

For future works, will be done the OTEC and SOTEC plants simulation using IPSEpro software, the Bharathan (2011) initial parameters and two working fluids: ammonia and propylene, such as recommend. Is expected good results about the simulations and the feasibility of OTEC plant installation in Brazil.

## 5. ACKNOWLEDGEMENTS

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## 6. REFERENCES

Baptista, A.S.C., 2006. *Análise da viabilidade econômica da utilização de aquecedores solares de água em resorts no nordeste do Brasil*, Master Degree Dissertation. Federal University of Rio de Janeiro, Rio de Janeiro, 171 p.

Bharathan, D., 2011. *Staging Rankine cycles using ammonia for OTEC power production*. National Renewable EnergyLaboratory. Technical Report NREL/TP-5500-49121, <http://www.nrel.gov/docs/fy11osti/49121.pdf>, 18 p.

Crews, R., 1997. "OTEC Sites", 18 Jan. 2013, <http://www.trellis.demon.co.uk/reports/otec_sites.html>.

Etemadi, A., Emdadi, A., AsefAfshar, O. and Emami, Y., 2011. Electricity generation by the ocean thermal energy. *Energy Procedia*. Vol.12, pp.936-944.

Faizal, M. and Ahmed, M.R., 2013. Experimental studies on a closed cycle demonstration OTEC plant working on small temperature difference. *Renewable Energy*. Vol. 51, pp. 234-240.

Fujita, R., Markman, A.C., Diaz, J.E.D., Garcia, J.R.M., Scarborough, C., Greenfield, P., Black, P., Aguilera, S.E., 2012. Revisiting ocean thermal energy conversion. *Marine Policy*. Vol. 36, No. 2, pp. 463-465.

Kazim, A., 2005. Hydrogen production through an ocean thermal energy conversion system operating at an optimum temperature drop. *Applied Thermal Engineering*. Vol. 25, No. 14-15, pp. 2236-2246.

Nihous, G., 2007. An estimate of Atlantic Ocean thermal energy conversion (OTEC) resources. Ocean Engineering. Vol. 34, No. 17-18, pp. 2210-2221.

Plocek, T.J. and Laboy, M., 2009. "Ocean thermal conversiton (OTEC): Technical viability, cost projections and development strategies". In *Proceedings of the Offshore Techonology Conference.* Houston, USA.

Reis, R.A.N and Souza, R.B., 2012. *Climatologia da estrutura termal do oceano Atlântico sudoeste a partir de dadosobservacionais de XBTS.* Scientific Iniciation Final Relatory, CRS/INPE - MCTI, Santa Maria, RS, 7 p.

Straatman, P.J.T., van Sark, W.G.J.H.M., 2008. A new hybrid ocean thermal conversion - Offshore solar pond (OTEC-OSP) design: A cost optimization approach. *Solar Energy*. Vol. 82, No. 6, pp. 520-527.

Tahara, K., Horiuchi, K. and Kojima, T., 1995. Ocean thermal energy conversion (OTEC) system as a countermeasure for $CO_2$ problem - Energy balance and $CO_2$ reduction potential. *Energy Conversionand Management,* Vol. 36, No. 6-9, pp. 857-860.

Takahashi, P.K. and Trenka, A., 1992. Ocean thermal energy conversion: It's promise as a total resource system. *Energy*, Vol. 17, No. 7, pp. 657-668.

Takahashi, P.K. and Trenka, A., 1996. *Ocean thermal energy conversion*. John Wiley.

Yamada, N., Hoshi, A. and Ikegami, Y., 2009. Performance simulation of solar-boosted ocean thermal energy conversion plant. *Renewable Energy*. Vol. 34, No. 7, pp. 1752-1758.

## 7. RESPONSIBILITY NOTICE