Design of an OTWEC-OC plant to produce desalinated water and electricity in Ensenada. B.C.

Leandro Daniel Balan Pool[1], Lucero Isabel Castro Meneses[2], and Eva Sofia Cetzal Chay[3], and Estela Cerezo Acevedo[4]

1,2,3,4. Universidad del Caribe, Cancun, Q. Roo. Mexico.

Keywords— Desalination, **OTEC Open Cycle, Thermal water.**

I. Introduction

From a global perspective, ocean water accounts for 97% of the total water on Earth. Currently, approximately 10% of the population lives in Low Elevation Coastal Zones (LECZ), which are areas less than 10 meters above sea level and represent 1.8% of the total land area. From 2010 to 2100, it is expected that the population residing in LECZ will increase from 704 million to over 1 billion [1].

Ocean Thermal Energy Conversion (OTEC) is a technology designed to harness energy from the temperature differences between surface and deep ocean waters. The thermal gradient starts at the ocean surface and exponentially decreases as depth increases. OTEC generates electrical power through the Rankine thermodynamic cycle by extracting the energy potential from the thermal gradient between warm surface waters and colder deep waters (up to 1,000 meters deep). It is recommended to operate in areas where the thermal gradient of the water column exceeds 20°C to ensure higher system efficiency [2].

However, there are areas of opportunity that have not yet been explored by OTEC technology, and this is to take advantage of the thermal gradient present in geothermal anomaly areas that are close to the coast. The theory suggests that if a thermal gradient exists, it is possible to create a system capable of converting that energy into electricity. OTEC has variations, including the open cycle, which has been tested and implemented in countries such as India, Hawaii, and even Cuba, where experimental trials and operational plants have been used to desalinate ocean water for the benefit of local communities.

In this project, the design of a new variant of OTEC called OTWEC (Ocean Thermal-Water Energy Conversion) is being developed. It operates based on the Rankine cycle and can produce desalinated water and electrical energy using the thermal gradient between a geothermal anomaly and seawater.

In 2021 the first study of Playa la Jolla in Ensenada [3] was conducted, revealing a geothermal anomaly with temperatures of up to 93°C at just 20 cm depth. Sufficient data was collected to create an initial design that considers the thermodynamic balance under certain steady and ideal conditions. However, it is also observed that the design is competitive in size with other OTEC plants currently in operation worldwide.

The municipality of Ensenada faces water scarcity issues, and energy demand projections exceed the installed capacity, making it necessary to consider renewable energy sources. Due to the water and energy needs in the city of Ensenada, this project proposes harnessing the thermal gradient between the thermal waters of Playa La Jolla and the surface seawater of the Pacific Ocean to produce desalinated water and electrical energy through an OTWEC-OC. To achieve this, data on the temperature gradient and flow rate of the thermal waters, as well as the average temperature of the surface seawater, are utilized to conduct the mass and energy balance of the plant. This allows for the sizing of water and electricity supply to the city, estimation of greenhouse gas emissions reduction compared to other types of plants, and assessment of potential environmental impacts of the plant.

II. Methods

The FEL methodology (Front End Loading) is used. According to [4] FEL is a methodology used in investment projects, and its foundation lies in considering a progression of factors to guide the strategy in the development of a project. The phases of the FEL methodology are: Visualization Phase (Opportunity identification), Conceptualization Phase (Alternative selection), and Definition Phase (Project planning). This provides the specific requirements to support detailed engineering.

The rates of energy transfer and energy production in a basic operating cycle of an OTEC (Ocean Thermal Energy Conversion) system are obtained using the following equations [5]

$$w_{turbine} = h_3 - h_2 \quad (1)$$

$$w_{tr} = \eta_T w_{turbine} \quad (2)$$

$$q_{ev} = h_2 - h_1 \quad (3)$$

$$\dot{Q}_{ev} = \dot{m}_{st} q_{ev} \quad (4)$$

$$q_{cond} = h_4 - h_3 \quad (5)$$

$$\dot{Q}_{Cond} = \dot{m}_{st} q_{ev} \quad (6)$$

On the other hand, Avery [6] presents the following equations for the basic open cycle (eq. 7 to 8), assuming that the effect of sensible heat on vapor production is negligible, and combining energy and mass balances in the flash evaporator, turbine, and surface:

$$\dot{Q}_{ev} = \dot{m}_H C_\rho (T_H - T_W) \quad (7)$$

$$P_g = \eta_T \dot{Q}_{ev}(1 - T_c/T_H) \quad (8)$$

$$P_n = P_g - P_{pump} \quad (9)$$

$$\eta = P_n / \dot{Q}_{in} \quad (10)$$

In table 1 are showed variables and units for OTWEC mass and energy balance.

TABLE I
VARIABLES AND UNITS FOR MASS AND ENERGY BALANCE

Symbol	UNIT	Quantity
$w_{turbine}$	kJ/kg	Ideal work of turbine per unit mass
h	kJ/kg	Enthalpy
h_1	kJ/kg	Enthalpy at evaporator inlet
h_2	kJ/kg	Enthalpy at evaporator outlet
h_3	kJ/kg	Enthalpy at turbine outlet
h_4	kJ/kg	Enthalpy at condenser outlet
w_{tr}	kJ/kg	Real work of turbine
q_{ev}	kJ/kg	Heat transferred to evaporator per unit mass
η_T		Efficiency of turbine
$\dot{m}_{st}$	kg/s	Mass flow of steam
$\dot{m}_H$	kg/s	Mass flow of thermal water
$\dot{Q}_{ev}$	kJ/s	Heat flux to evaporator
q_{cond}	kJ/kg	Heat to condenser per unit mass
$\dot{Q}_{Cond}$	kJ/s	Heat flux to condenser
C_ρ	kJ/kg·°C	Specific heat of water
T_H	°C	Temperature of thermal water
T_W	°C	Temperature of thermal water in evaporator outlet (brine)
T_C	°C	Temperature of surface water
P_g	W	Gross power
P_n	W	Net power
P_{pumps}	W	Pumps power

For the utilization of thermal water, it was considered that all thermal water natural flow in La Jolla can be captured and stored in a tank, this water has a temperature greater than 26 °C, as measured at surface [3]. The volumetric flow rate (L/s) of water with different temperatures at a depth of 20 cm was based on measurements conducted by Carbajal et al.

As part of the FEL methodology in its second phase, the concept of OTWEC-OC for Playa La Jolla is developed, based on the methodology. The researched information is used for the design of the plant, considering the site's characteristics, needs, and available technology. The basic engineering is achieved by conducting mass and energy balances of the plant and assessing its effects on the social and environmental aspects.

According to SEPROA (Secretaría para el Manejo, Saneamiento y Protección del Agua) [7], the percentage of the population without access to water service is 15.04%. Based on historical censuses from INEGI (Instituto Nacional de Estadística Geografía) [8], it has been projected an estimation of the population in the municipality of Ensenada for the year 2030, the water deficit and the projection of the maximum energy demand for the year.

For the environmental impact assessment of the OTWEC-OC plant and its resizing, the Leopold Matrix method was chosen. This method is a qualitative tool used for the assessment of environmental impacts from project planning to construction. It allows for the evaluation of potential environmental impacts and helps in decision-making processes to mitigate or minimize those impacts.

Additionally, the same procedure is followed to obtain a second OTWEC-OC plant that serves as an alternative to the previously calculated one. However, this alternative plant is designed to address the water deficit in Ensenada by supplying desalinated water.

III. RESULTS

The OTWEC-OC plant diagram is created using the AUTOCAD design software (see figure 1). The cycle begins with the thermal water from Playa La Jolla being stored in a tank, where fluids of different temperatures are mixed and reach a final equilibrium temperature. The water from the storage tank is pumped to the flash evaporator (line 1), where the pressure is lower than the saturation pressure corresponding to the equilibrium temperature of the thermal water mixture. A small fraction of the water turns into saturated vapor and continues the cycle through line 2, heading towards the turbine. The remaining fluid exits the system through line 2'. The saturated vapor passes through the turbine, which is connected to an electric generator, and then goes to the condenser as a saturated mixture (line 3). In the condenser, the vapor mixture exchanges heat and condenses into saturated liquid by utilizing the surface seawater, which is pumped through line 5 and returned to the ocean through line 6. The desalinated liquid water exits the system through line 4. Thermodynamic process is showed in figure 2.

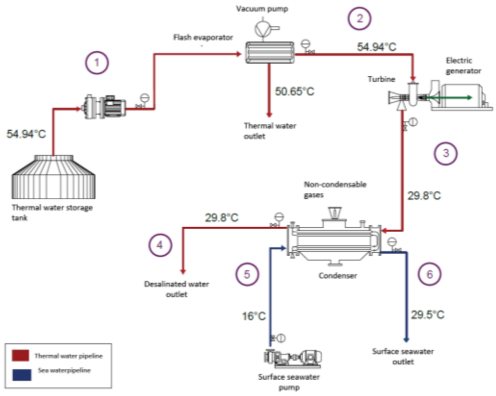

Fig. 1. OTWEC-OC Plant Diagram.

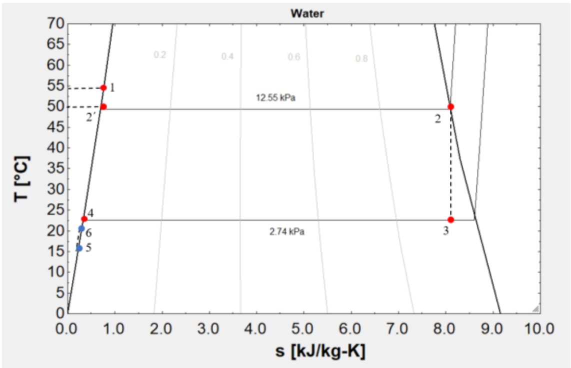

Fig. 2. Thermodynamic states in the OTWEC-OC plant represented in a temperature-entropy diagram.

Table 2 showed the results for mass and energy balance from first and second plant designed for supply water deficit by 2030.

TABLE II

VARIABLES AND UNITS FOR MASS AND ENERGY BALANCE

VARIABLE	UNIT	OTWEC-OC PLANT	ALTERNATIVE OTWEC-OC
η_{carnot}		11.87 %	11.87 %
η_{OTWEC}		4.898	4.898
$x_{2,3r}$		0.96049	0.9649
$\dot{m}_H$	kg/s	325	21,207.24
$\dot{m}_{exit}$	kg/s	322.5625	21,048.1857
$\dot{m}_{evaporator}$	kg/s	2.4375	101.43
$\dot{m}_6$	kg/s	273.9103	21,048.1857
$\dot{m}_{desalinated}$	kg/s	2.4131	157.4638
$\dot{Q}_{evaporator}$	kW	5756.689	375,641.467
$\dot{Q}_{condenser}$	kJ/s	5729.493	373,866.876
$\dot{W}_{turbine}$	kW	357.311	23,315.632
$\dot{W}_{generator}$	kW	321.58	20,984.069
$\dot{W}_{pumpev}$	kW	29.6	1,903.72
$\dot{W}_{pumpcond}$	kW	10.42	680.361
$\dot{W}_{net}$	kW	281.56	18,399.988

The OTWEC-OC plant, with a production of 2.4131 L/s of desalinated water, produces 208,492 L/day. Considering that an average resident in the municipality consumes 140.2 L/day, the plant can meet the daily needs of 1,487 people. On the other hand, the alternative OTWEC-OC plant with a production of 157.4638 L/s could supply 97,039 people. In Figure 3, the dotted line represents the projected population in the future, while the orange and blue areas represent the percentage of total population coverage for their respective years by OTWEC-OC and its alternative. As observed, the alternative plant always exceeds the water deficit, and until 2030 it is equal to the deficit.

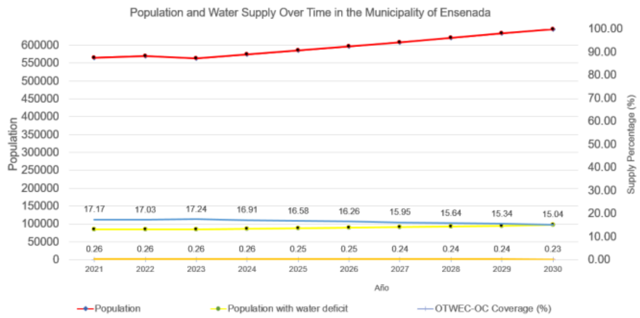

Fig. 3. Percentage of water supply compared to the water demands in the municipality of Ensenada and the Baja California power grid for the year 2022 and the projection for 2030 is shown.

In Figure 4, the percentage of energy supply in the Baja California electrical grid is shown by year, and both plants are below 1%.

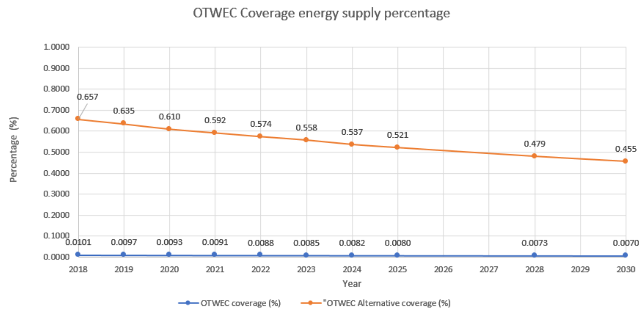

Fig. 4. The percentage of energy supply in the Baja California power grid per year is below 1%.

The annual energy production of each type of technology that is part of the Baja California power grid is presented in Figure 5. This value depends on the capacity factor and installed capacity. As can be seen, most of the energy is produced by combined cycle power plants. Figure 6 shows the same data with a logarithmic scale.

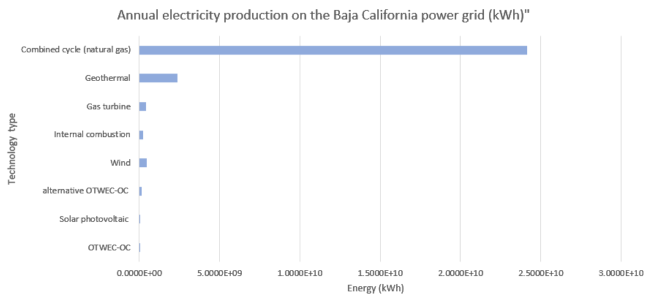

Fig 5. Annual energy production in Ensenada, B. C.

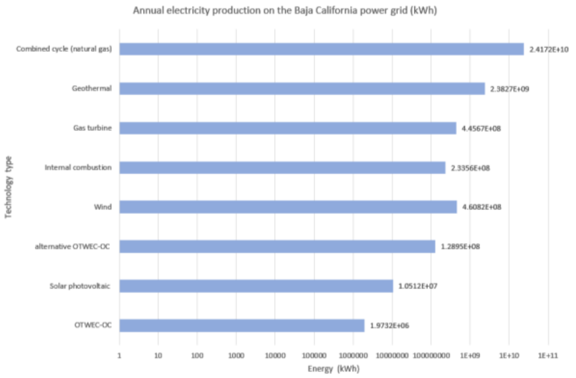

Fig 6. Annual energy production in Ensenada with a logarithmic scale.

In Figure 7, the blue bars represent the annual kWh production for each technology, and the red line represents CO2 emissions. As observed, wind energy has the best ratio between energy produced and CO2 generated, followed by photovoltaic solar and OTWEC-OC.

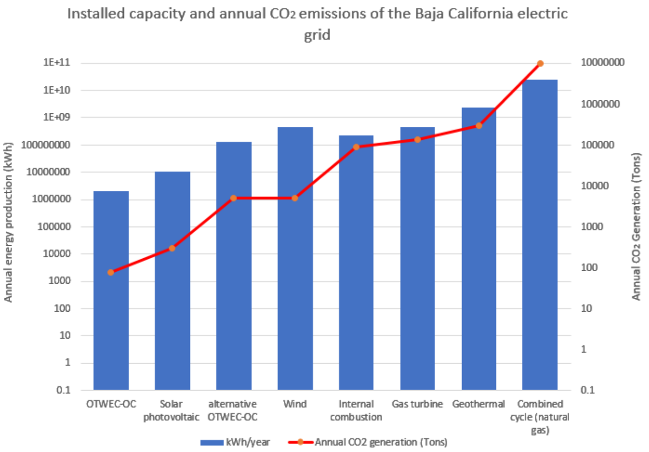

Fig. 7 Production Capacity vs. CO_2 Emissions

The discharges from the OTWEC-OC plant would directly impact the temperature of the beach, creating a thermal shock. However, there are additional options to consider, one approach is to employ a heat exchanger that utilizes surface water to cool down the hot water before releasing it into the environment. This method not only ensures that the discharged water is at a more environmentally acceptable temperature but also minimizes the impact on aquatic ecosystems. Another innovative solution is to explore the potential of using the hot water for heating systems, this not only maximizes the energy efficiency of the process. Additionally, the brine discharged from the flash evaporator of the OTWEC-OC plant would have a concentration of 35.26 ups, which is 0.75% higher than the salt concentration in seawater. This slight increase in concentration can be disregarded.

IV. DISCUSSION & CONCLUSION

The design of an OTWEC-OC plant to produce energy and desalinated water was carried out, harnessing the thermal gradient between the thermal waters of Playa La Jolla and the surface seawater of the Pacific Ocean, based on other studies conducted on the geothermal anomaly. This resource utilization proposal addresses the water and energy needs of the Ensenada region.

The OTWEC-OC plant (281.56 kW, 2.41 L/s) would have a daily generation of 208,224 m^3 (60,801.41 m^3 annually, considering an 80% capacity factor) of desalinated water. It would be self-sufficient in energy for its operation and would have a net surplus that could be used for other purposes. Despite being relatively small compared to the local demand, it would emit 75.96 tons of CO_2, making it one of the least polluting technologies in the region during operation.

Among the most significant problems in the region, the water needs of the municipality were identified. A deficit projection was made for 2030, and the OTWEC-OC plant was resized to cover the resource shortage by 100%. It would have a daily production of 13,604.87 m3 of desalinated water (4,965,778.3968 m^3 annually) and emit 4,964.47 tons of CO_2 into the atmosphere, which is 65.35 times more than the initial design. Despite the increased emissions, it would still be considered one of the plants with lower CO_2 emissions compared to other technologies in the Baja California power grid.

This study serves as a valuable decision-making tool in the energy industry, as it provides insights into electricity generation behaviour and opens avenues for further research. The interpreted data are ideal for exploring the energy potential of thermal gradient systems, which, while showing lower CO_2 emissions, are known to have different potential site maps compared to other energy sources.

The environmental impact generated by the proposed plant in this project is minimal compared to plants in India and other proposed plants. This is due to the scale of the plant and the proposed technology, as the impacts are directly related to the production and scale of the plant. Potential impacts on the marine system and thermal sources were identified; however, further studies are needed to determine their extent. Similarly, the onshore proposal considers less impact in the design and planning of the plant, as it would not involve deep-sea cold water intake pipes, minimizing nutrient entrainment and impacts on marine biota. Mitigation and control measures are proposed for potential impacts on organisms during water extraction, as well as variations in salinity and temperature. The discharge of brine from the flash evaporator and the outflow from the condenser would not represent a massive impact on the surface seawater. Therefore, it is determined that the qualitative assessment of the construction and operation of the OTWEC-OC plant near Playa La Jolla in Ensenada, Mexico, would not pose an extraordinary environmental impact compared to other desalination plants or their equivalents along the Ensenada coast.

Upon completing the basic engineering of an OTWEC-OC plant and its resizing, relevant topics are left for future research as complementary work to this project. The following are listed:

- Study of the water quality in the thermal sources.
- Development and research on open cycle OTEC technology.
- Study of the environmental impact of water extraction from the thermal sources at Playa La Jolla, Ensenada, Mexico.
- Study of the impacts on marine and thermal biota due to the operation of an OTWEC-OC plant.
- Measures for cooling the brine from the flash evaporator before releasing it into the surface seawater with a heat exchanger using cold seawater at 16°C.

REFERENCES

[1] Silva, R., Martínez, M., Hesp, P., Catalan, P., Osorio, A., Martell, R., Fossati, M., Miot, G., Mariño, I., Pereira, P., Cienfuegos, R., Klein, A., y Govaere, G. (2014). *Present and Future Challenges of Coastal Erosion in Latin America.* Journal of Coastal Research, 71(sp1), 1-16, https://doi.org/10.2112/SI71-001.1

[2] Garduño, E., García, A., Rodríguez, A., Bárcenas, J., Alatorre, M., Cerezo E., Tobal, J., Romero, V., y Silva, R. (2017).*Conversión de energía térmica oceánica (OTEC) estado del arte.* Colección Energías Renovables del Océano. doi:10.26359/EPOMEX.CEMIE012017

[3] Carbajal, D., Peiffer, L., P., Diamond, L., Fletcher, J., Inguaggiato, C. y Wanner, C. (2021) *Exploration of orogenic, fault-hosted geothermal systems using an integrated, multi-disciplinary approach.,* EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-13261, https://doi.org/10.5194/egusphere-egu21-13261, 2021.

[4] Valles, J. (s.f.). *La Metodología FEL en la Gerencia de Proyectos Logísticos.* Recuperado de: https://www.academia.edu/37445321/La_Metodolog%C3%ADa_FEL_en_la_Gerencia_de_Proyectos_Log%C3%ADsticos?source=swp_share

[5] Cengel Y., y Boles, M. (2012). Termodinámica. Nueva York, EE. UU. McGRAW-HILL/INTERAMERICANA EDITORES

[6] Avery W. y Wu Chih. (1994). *Renewable Energy from the Ocean: A Guide to OTEC.* Nueva York, EE. UU: Oxford University Press, Inc.

[7] Secretaría para el Manejo, Saneamiento y Protección del Agua [SEPROA]. (2022). INDICADORES DE GESTION ORGANISMOS OPERADORES DE SISTEMAS DE AGUA POTABLE Y ALCANTARILLADO. Recuperado de http://www.cea.gob.mx/documents/indicadores/INDICADORESMARZO2022.pdf

[8] INEGI. (2021). *Comunicado De Prensa Núm 30/21.* Recuperado de: https://www.inegi.org.mx/contenidos/saladeprensa/boletines/2021/EstSociodemo/ResultCenso2020_BC.pdf