

Feasibility of OTEC in Arabian Sea

Syed Muhammad Sabih ul Haque¹, Ali Muhammad Hadi¹, Sohaib Ahmed¹, Abdul Rehman¹
and Ammad Fareed¹

¹National University of Sciences and Technology (NUST), Pakistan

Abstract: *Pakistan faces a looming energy crisis with a shortfall that is crushing the entire economy. This study aims to find a sustainable solution that is renewable in nature and provides a long-term remedy for the power shortages in the region. Purpose of this research study is to analyze the potential of Ocean Thermal Energy Conversion (OTEC) in Pakistani Coastal Areas. Pakistan enjoys vast coastal areas with warm waters all around the year, therefore, there is a need to exploit this resource and utilize the thermal gradient for electricity generation. The paper discusses oceanic data; encompassing annual & monthly temperature and depth relationship at different sites along Pakistani coastlines, providing the basis for identifying the optimal location of an offshore facility; 56km from Gwadar. This research provides the basis for the selection of an off-shore OTEC plant in Pakistan's EEZ.*

Keywords: *OTEC, Oceanic data, Arabian Sea, Open Cycle, Feasibility.*

1. Introduction

1.1. Energy Crisis in Pakistan and its Causes

As a developing country, Pakistan's energy needs are climbing and consequently the country suffers power outages. The energy crisis is killing an already feeble economy. This situation has eaten up 4% of GDP and has caused countless industries to stop operating resulting in unemployment and increased imports. If we look at the bigger picture 55% of households in Pakistan don't have electric power [1]. At present, Pakistanis are facing blackout problems due to shortage of 5000 MW power supply. It is therefore imperative that Pakistan develops a self-sufficient energy policy and counters the energy crisis [2].

Pakistan, since long is fighting this complex and multifaceted problem. There are several main causes that leads to this energy crisis, for engineers its due to improper equipment, distribution network and power theft. A politician blames the government and the energy policy, and an economist claims the power outage is mainly due to circular debt. After assessing the energy mix, there is an imbalance with oil & gas comprising of a whopping 64.12% and renewable sources making up only 0.41%. As Pakistan's energy mix is heavily reliant on oil and gas, the fluctuating prices and dwindling of fossil fuels along with changing climatic patterns in the past few years have greatly affected the energy sector [3]. Pakistan has numerous renewable resources which can play an important part in solving the imminent energy crisis.

Solar, wind, hydel, biomass and geothermal are the major renewable sources which are utilized in different ways to generate power. Ocean Thermal Energy Conversion is an appealing option, and is the topic of this research study.

1.2. Why Prefer OTEC

The oceans can provide an inexhaustible amount of energy absorbing radiations which has the same heat content as 250 billion barrels of oil each day [4]. Pakistan borders 1046 kilometres with the Arabian Sea in the

south. This strategic location provides an ideal opportunity for the establishment of an Ocean Thermal Energy Conversion (OTEC) system.

OTEC system is capable of producing 10-1000 Tera Watts of electricity if all oceans are considered. [5] One major advantage that OTEC holds over other renewable energy resources like solar photovoltaic and wind power is that it can be integrated into national grid as it generates constant electric power which is unaffected by seasonal climate changes and day to day variations in wind speed and solar intensity due to clouds and solar angle. Thus, it offers a green and uninterrupted power source with no harmful emissions.

The added advantage of an OTEC plant is the possibility of provision of potable water that can prove to be fruitful for different applications. [6].

1.3. What is OTEC?

The electricity generated today comes from heat engines of various kinds. A heat engine utilizes a working fluid that expands via a turbine to a lesser pressure and temperature thus producing work. The greater the difference in temperature of the working fluid and condensing fluid, the higher the efficiency and more the work extracted. Similarly, Ocean Thermal Energy Conversion (OTEC) harness electric power indirectly from the sun by making use of the temperature differential but unlike a heat engine, no fuel is burnt to achieve the gradient in temperature.

Ocean waters are a major source for the accumulation of solar radiations in tropical regions, this allows the seas to enjoy a surface temperature of around 25-28°C all year round. As the depth increase the intensity of the radiation incident decrease and so does the temperature, at about 1000m the temperature is 4-5°C. The two layers that is warm surface water (100-200m) and the colder water at depth are separated from one and other due to a phenomenon called stratification. For a viable operation of an OTEC plant a gradient of 20°C is necessary. Therefore, the performance of an OTEC power cycles is limited by this temperature gradient [7] [8].

Ocean Thermal Energy Conversion power systems have numerous designs, all are based upon three elementary types: Closed Cycle, Open Cycle & Hybrid Cycle. These OTEC plants can be either constructed on land that is near the sea shore or an OTEC facility can operate off-shore. A Closed cycle utilizes a low boiling point working fluid like Ammonia which circulates in closed path for electricity generation, hence the name, Closed cycle. On the other hand, open cycle utilizes pure steam that expands in a turbine to generate electricity. Steam is generated when it flash-evaporates in a flash chamber and is then condensed in a condenser, thus producing potable water.

2. Research Methods

The selection of the study area was the Arabian Sea, focusing on Pakistan's Exclusive Economic Zone (EEZ), as there is a potential of electricity generation through OTEC. The selected area was extensively studied to identify exact locations for an OTEC plant. In totality, four locations near Gwadar; two locations near Karachi; two locations near Pasni and two locations near Ormara were chosen for this study. Out of these locations, the most optimum location was picked for the OTEC facility. After deciding the location, an analysis was done to determine whether the facility should be off-shore or land based. The study also explains whether an Open Cycle OTEC or a Close Cycle OTEC would be ideal for the selected location in particular and for Pakistani coastal areas in general with the latitude 21° 3' 32.9" N - 25° 36' 49" N & the longitude 61° 25' 0" E - 68° 11' 52.1" E.

Data collected from National Oceanic and Atmospheric Administration (NOAA) assisted us in obtaining oceanic data at different locations in Arabian Sea adjoining the coastal cities of Karachi, Gwadar, Ormara and Pasni. Using this data relation between temperature and depth was established. Moreover, the distances from these particular locations were measured using digital maps. The climatic data was obtained from World Ocean Atlas 2013 (WOA13). WOA13 contains oceanographic data observed at different locations throughout the oceans to map and then interpolate to standard depths on 5°, 1° and 1/4° grids for monthly, annual & seasonal assessment of temperature all around the world. In this study data on 1/4° grid was analyzed for precise and

accurate measurement of temperatures at standard depths. These categorized data were utilized in visualizing the relation between temperature and depth at various locations along the coastline of Pakistan.

OTEC cycle has a certain maximum theoretical efficiency; Carnot efficiency. The temperatures at the surface and at a certain depth dictates the efficiency, attained by calculating Carnot efficiency at various locations. Net output from an OTEC plant is limited due to small ΔT and hence, the efficiency of cycle is quite low. The Carnot efficiencies varies between 6-9% while the actual efficiency in a working commercial plant is about 2-4%. The limiting thermodynamic efficiency makes OTEC seem impractical and insignificant, but this can be overlooked as OTEC system requires no fuel for its operations [8] [9]. The equation provides a relationship between the cycle efficiency and the physical properties. In this case the governing properties are the temperature of source (T_W) and the temperature of sink (T_C). Carnot efficiency will be deciding factor for the selection of OTEC site in this research study.

$$\text{Carnot Efficiency} = 1 - \frac{T_C}{T_W} \quad (1)$$

where:

η = Carnot efficiency

T_W = Temperature of the warm water

T_C = Temperature of the cold water

3. Analysis and Result

The feasibility of OTEC in Pakistani Coastal Areas was the focus of this study. For this purpose, meticulous research conducted to obtain oceanic data that governs the practicality of OTEC. Keeping in mind that the optimal temperature gradient that is about 20°C for viable operation of OTEC facility, different locations were assessed throughout the Pakistani economic zone to determine the best locations.

To find this temperature difference, analysis was done both for the surface and at a depth of up to 2000 m. For the representation of this data graphically, graphs were plotted at different locations to determine whether these locations meet the temperature gradient or not. These graphs show the relationship between the annual mean temperature and depth at various locations.

Throughout the Arabian Sea, the surface temperature and its variation with depth can be observed through oceanic data made available by NOAA. It is represented in the Fig.1 below.

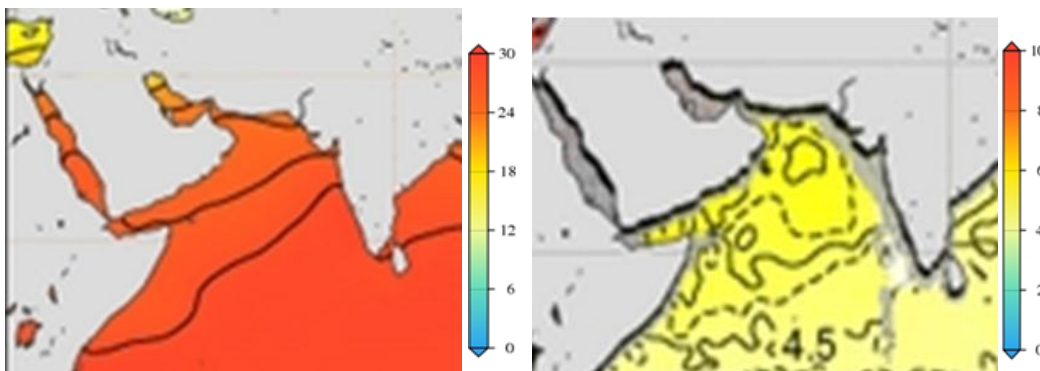


Fig. 1: International borders of Pakistan's EEZ at surface (left) and at 1500m depth (right). [10]

As observed, the Arabian Sea enjoys sunlight throughout the year and therefore it has the potential for the implementation of OTEC technology which requires a temperature gradient of 20 C which is available at certain depth.

Coastal areas near Karachi were considered. The first location was 50 km from the city with the coordinates 24.375° N, 66.375° E and the second location was 196 km from Karachi with the coordinates 23.875° N, 65.125° E. The graph shows annual mean temperature to be between 23°C - 25°C at the surface and as the depth increases the temperature decreases due to low thermal radiation. Graphs of Karachi are shown in Fig.2 below.

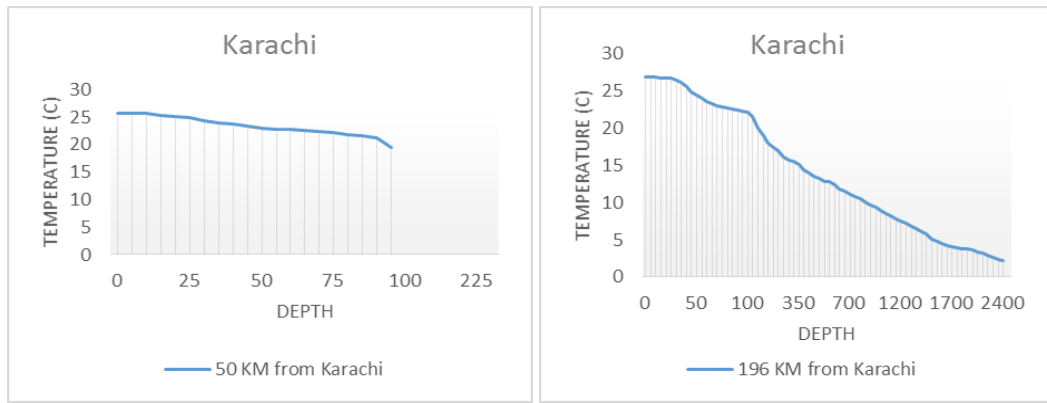


Fig. 2: Temperature depth relationship at Karachi. [11]

Next the coastal areas of Pasni were taken into account. The first location was 47 km from the city with the coordinates 24.875° N, 63.375° E and the second location was 68 km from Pasni with the coordinates 24.625° N, 63.625° E. Through graph, it can be observed that annual mean temperature is between 26°C - 27°C at the surface and decreases with increase in depth. Fig. 3 below shows the temperature distribution with depth near Pasni.

Two locations at Ormara were assessed located at 73 km and 104 km from the city with the coordinates being 24.625°N , 64.625°E and 24.375°N , 64.625°E respectively. The annual mean temperature ranges between 26°C - 27°C as shown by the graphs in Fig. 4.

Finally, four locations were studied at Gwadar with distances and coordinates as follows: 33 km from Gwadar at 24.875° N, 62.625° E. 56 km from Gwadar at 24.625° N, 62.375° E. 87 km from Gwadar at 24.375° N, 62.375° E. 112 km from Gwadar at 24.125° N, 62.625° E. An annual mean temperature ranging between 26°C - 28°C is observed through the graphs shown in Fig.5.

After analyzing the relationship between temperature and depth at different locations, it was decided based on the data above that which locations would be feasible for an OTEC plant. Locations associated with Karachi were discarded due to long distances from the sea. The locations with depth of 1000m or more have the potential to station an OTEC plant providing the necessary temperature gradient.

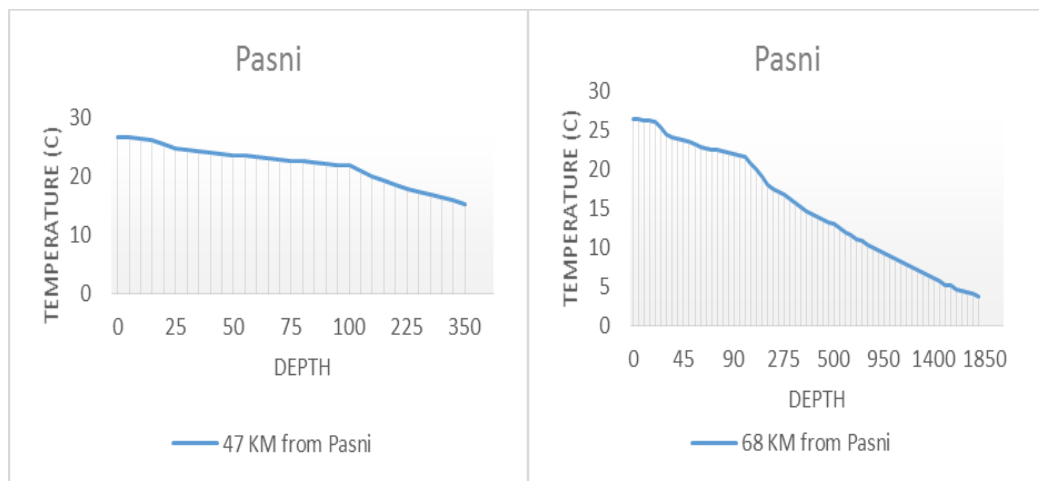


Fig. 3: Temperature depth relationship at Pasni. [11]

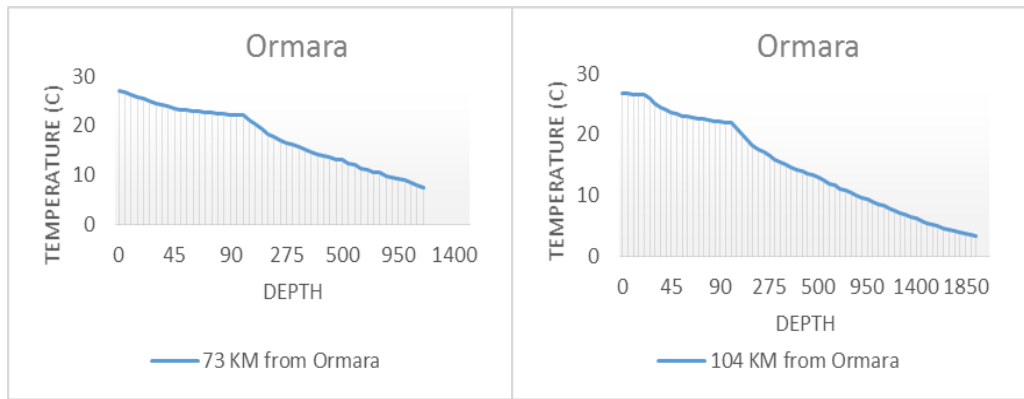


Fig. 4: Temperature depth relationship at Ormara. [11]

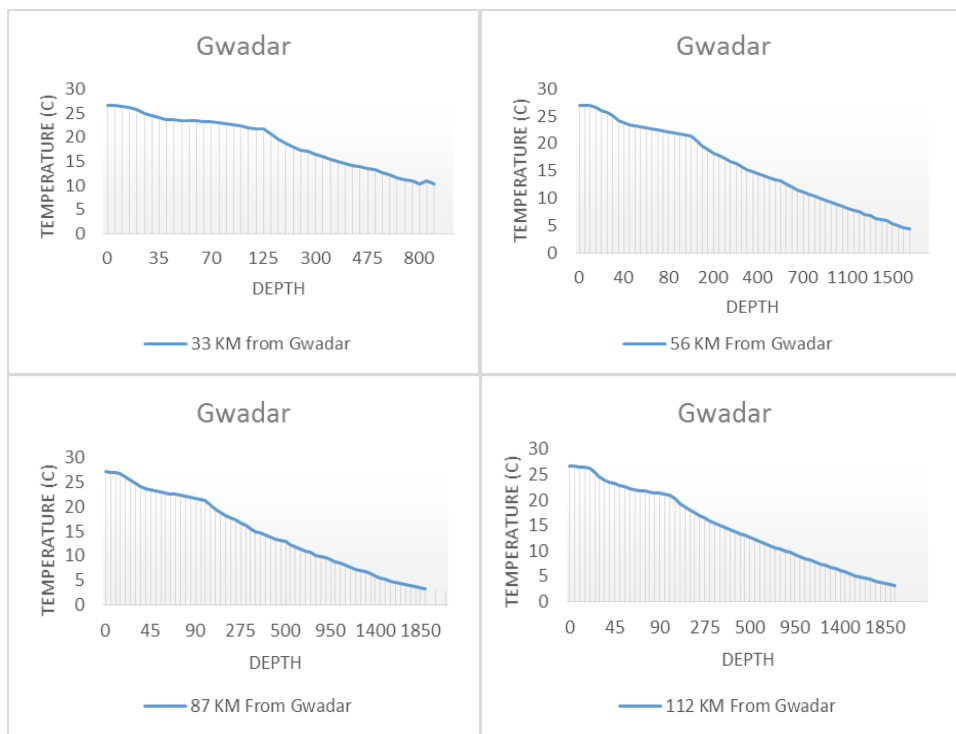


Fig. 5: Temperature depth relationship at Gwadar. [11]

In order to observe the seasonal variation in temperature, the data has been compiled in TABLE I to determine whether there is any significant change in temperature or not.

Based on the results shown in TABLE I, the temperature distributions gathered for the locations near Gwadar shows the mean surface temperature in all the seasons was 27.10°C, whereas the temperature difference between the surface and at a depth of 1000m was 18.23°C and at a depth of 1500m was 21.84°C. When sea water near Pasni was considered, the mean surface temperature throughout the year was 26.79°C, and the temperature difference between surface and a depth of 1000 m was 17.76°C and at a depth of 1500m 21.48° C. For locations near Ormara, mean annual surface temperature was 27.03°C and the temperature difference between surface and depth of 1000m was 18.17°C and at a depth of 1500m was 21.86°C, as depicted in Fig. 4.

As claimed earlier, there is no prominent change in temperature that will hinder the use of OTEC in the selected areas. The table shows, there is little to no difference in the temperatures at various locations whether it be at the surface or at a depth of 1000m or 1500m. This proves that a steady and continuous OTEC cycle can be

operated at any of the considered locations.

TABLE I: Seasonal Data of Surface Temperatures, Temperatures at Depths and the ΔT

Season	SW Temperature (°C)			CW Temperature at 1000m			CW Temperature at 1500m			ΔT at 1000m (°C)			ΔT at 1500m (°C)		
	GW	OR	PS	GW	OR	PS	GW	OR	PS	GW	OR	PS	GW	OR	PS
Summer	28.55	28.08	27.52	8.86	8.80	8.98	5.19	5.10	5.20	19.69	19.28	18.54	23.35	22.98	22.32
Spring	28.28	27.99	28.27	8.89	8.78	9.17	5.08	4.80	5.10	19.39	19.21	19.11	23.19	23.19	23.17
Fall	27.02	27.99	26.80	8.82	8.92	8.83	5.42	5.43	5.51	18.19	19.07	17.97	21.60	22.56	21.29
Winter	24.05	24.03	24.32	8.91	8.96	9.06	5.42	5.47	5.51	15.14	15.06	15.26	18.63	18.55	18.81

The temperature-relationship graphs pointed out locations with considerable temperature gradient. Next it was imperative to calculate Carnot Efficiencies at different depth to properly assess the potential available at each location. A tabulated data showing annual mean temperatures of surface and varying depths at different locations along with Carnot efficiencies is given below in TABLE II.

TABLE II: Carnot efficiencies at different selected locations

Location	SW Annual Mean (°C)	CW at 1000m (°C)	CW at 1500 m	ΔT at 1000m	ΔT at 1500m	Carnot Efficiency 1000m	Carnot Efficiency 1500 m
56 km Gwader	26.971	8.858	5.422	18.113	21.549	6.038	7.184
87 km Gwader	27.108	8.844	5.211	18.264	21.897	6.086	7.296
110 km Gwader	27.281	8.782	5.548	18.499	21.733	6.161	7.238
68 km Pasni	26.436	8.879	5.186	17.557	21.250	5.863	7.097
107 km Pasni	26.917	8.837	5.567	18.080	21.350	6.028	7.119
73 km Ormara	26.984	9.050	5.500	17.934	21.484	5.978	7.162
104 km Ormara	26.820	8.912	5.441	17.908	21.379	5.973	7.131

Based on above table it can be observed that Carnot efficiencies of Gwadar's locations are greater than 6% at 1000m and greater than 7% at 1500m depth. Only one selected location at Pasni attains above 6% efficiency at 1000m while both locations have above 7% efficiency at 1500m. Locations at Ormara on the other hand have Carnot efficiencies slightly below 6% at 1000m depth while at 1500m, its Carnot efficiency reaches above 7%. Based on this data, it can be established that these locations can be utilized for energy production via OTEC as the required Carnot Efficiency of 6-8% is achieved along with the annual temperature difference between surface and selected depth that is around 21°C.

At the end of this extensive analysis throughout the economic zone of Pakistan, a decision is to be made to opt for an ideal location that will support and meet the technological and climatic requirements of Ocean Thermal Energy conversion. A location 56 km from Gwadar with the coordinates 24.625° N, 62.375° E has been chosen that will assist the OTEC facility. This location was decided after careful consideration of various parameters. The first governing parameter was the attainment of a temperature gradient of 20°C. The second requirement was to have a Carnot efficiency in a preferable range and thirdly to have a minimal distance from a coastal city. The location selected is within the selection parameters while others were discarded because they were not as feasible as the one with coordinates 24.625° N, 62.375° E.

To decide between an open or closed cycle parameters, the emphasis was given to the provision of water for a location like Gwadar which is present in an open cycle. Hence an open cycle is preferred despite having an actual efficiency a percent less than closed cycle.

For a location 56 km from shore, a platform is necessary. For this distance, a floating type plant with semi-submersible platform is selected. These structures have enough weight to remain upright under stormy conditions and can be used for depths up to 3000m. Also an added advantage is the possibility of repositioning

since the platform is not hard anchored to the ocean floor. Based on this feasibility study, if an OTEC facility is considered for this area, it is highly probable that it will operate steadily all year around with no carbon emission and fuel costs.

4. Discussion and Conclusion

With the shortfall in electricity expected to rise in Pakistan, it can be established that addition of renewable resources can supply considerable power to the national grid, and in the process reducing the dependence of fossil fuel imports thus improving the environment in the region. However, the selection of optimal location itself doesn't entirely indicate whether an OTEC plant in Pakistan will be economically viable. A thorough cost analysis is therefore needed. This can be made possible through an extensive design of an OTEC plant which can assist in evaluating levelized cost of electricity (LCOE) along with the capital expenditure required for its construction and operating expenditure for its maintenance.

5. References

- [1] A. Symington, "Pakistan's Energy Shortage: Lights Out," *The economist*, 2016.
- [2] K. Harijan, "Renewable Energy for Managing Energy Crisis in Pakistan," in Conference: Wireless Networks, Information Processing and Systems, International Multi Topic Conference, IMTIC 2008, Jamshoro, Pakistan, 2008.
- [3] H. Muzamil, "Pakistan's Energy Mix: Power and Politics," *Dawn*, 2015.
- [4] M. Betchel and E. Netz, "OTEC - Ocean Thermal Energy Conversion," [Online].
- [5] G. C. Nihous, "An Order-of-Magnitude Estimate of Ocean Thermal Energy Conversion Resources," *Journal of Energy Resources Technology*, vol. 127, no. 4, pp. 328-333, 2005.
- [6] C. Woodford, "OTEC (ocean thermal energy conversion)," 2017. [Online].
- [7] S. M. Masutani and P. K. Takahashi, *OCEAN THERMAL ENERGY CONVERSION*, New York: Wiley, 1996.
- [8] W. H. Avery and C. Wu, "Renewable Energy from the Ocean," in *International Journal of Hydrogen energy*, New York, Johns Hopkins University Applied Physics Laboratories Series in Science and Engineering, 1994.
- [9] G. C. Nihous, M. A. Syed, L. A. Vega, "Conceptual design of an open cycle OTEC plant for the production of electricity and fresh water in a Pacific Island," In proceedings of First International Conference on Ocean Energy Recovery ICOER, American Society of Civil Engineers, 1989.
- [10] World Ocean Atlas, "World Ocean Atlas 2013 Figures, version 2," National Center for Environmental Information, [Online]. Available: <https://www.nodc.noaa.gov/cgi-bin/OC5/woa13fv2/woa13fv2.pl?parameter=t>. [Accessed 14 Oct 2017].
- [11] World Ocean Atlas, "WOA 2013 V2 Data Access," National Centers for Environmental Information, [Online]. Available: <https://www.nodc.noaa.gov/cgi-bin/OC5/woa13/woa13.pl>. [Accessed 14 Oct 2017].