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Suitable Site Selection for Ocean Thermal Energy Conversion (OTEC) systems – A case study for Pakistan

Selección de sitios adecuados para los sistemas de conversión de energía térmica oceánica (OTEC): un estudio de caso para Pakistán

Talha Bin Nadeem [1] | **Asad A. Naqvi** [1] | **Ahsan Ahmed**[1]

[1]Department of Mechanical Engineering, NED University of Engineering and Technology, Karachi, Pakistan.

Correspondence
Talha Bin Nadeem
Email: talhanadeem@neduet.edu.pk

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Abstract. In developing countries such as Pakistan, the issue of generating power is crucial. As conventional power sources (fossil fuels) are depleting at an alarming rate. An abundant amount of energy is generated by thermal power plants using fossil fuels as their primary energy resource for combustion. Hence extreme uses of fossil fuels are noticed, which is greatly responsible for damaging our environment. Oceans exists around 71% of the surface area of earth and it has enormous potential for electricity generation. This study focuses on site selection for harnessing ocean energy by utilizing Ocean Thermal Energy Conversion (OTEC) systems for coastal areas of Pakistan. In this study, four sites across the coastal region of Pakistan have been studied namely Karachi, Gwadar, Ormara and Pasni. Their theoretical maximum Carnot efficiencies have also been determined and Gwadar has been identified as the most suitable location for OTEC plant with the maximum theoretical efficiency of around 6.53%, 6.93% and 7.75% at the cold-water depths of 1000m, 1200m and 1500m, respectively..

Keywords: Renewable energy, Ocean energy, Ocean thermal energy conversion (OTEC), Temperature Gradient, Coastline of Pakistan.

Resumen

En países en desarrollo como Pakistán, el tema de la generación de energía es crucial. Como las fuentes de energía convencionales (combustibles fósiles) se están agotando a un ritmo alarmante. Las centrales térmicas generan una gran cantidad de energía utilizando combustibles fósiles como fuente primaria de energía para la combustión. De ahí que se noten usos extremos de combustibles fósiles, los cuales son en gran parte responsables de dañar nuestro medio ambiente. Los océanos existen alrededor del 71% de la superficie terrestre y tienen un enorme potencial para la generación de electricidad. Este estudio se centra en la selección de sitios para aprovechar la energía del océano mediante la utilización de sistemas de conversión de energía térmica oceánica (OTEC) para las zonas costeras de Pakistán. En este estudio, se estudiaron cuatro sitios en la región costera de Pakistán, a saber, Karachi, Gwadar, Ormara y Pasni. También se determinaron sus eficiencias máximas teóricas de Carnot y se identificó a Gwadar como la ubicación más adecuada para la planta OTEC con una eficiencia teórica máxima de alrededor del 6,53 %, 6,93 % y 7,75 % a profundidades de agua fría de 1000 m, 1200 m y 1500m respectivamente.

Palabras clave: Energía renovable, energía oceánica, conversión de energía térmica oceánica (OTEC), gradiente de temperatura, costa de Pakistán.

1 | INTRODUCTION

Pakistan is a developing country, and with huge growth in population in recent times, energy proficiency requirement is addressed for the country. With high energy demands and lower production of convenient energy power outages are a common issue in the country, The Gross Domestic Product (GDP) of the country has been affected by a 4% reduction [1]. Energy crisis has a great impact on the society and industrial sector which has resulted in closure of many industrial setups. Energy generation of Pakistan rely mostly on the fossil fuels. It can be clearly seen in Fig. 1.

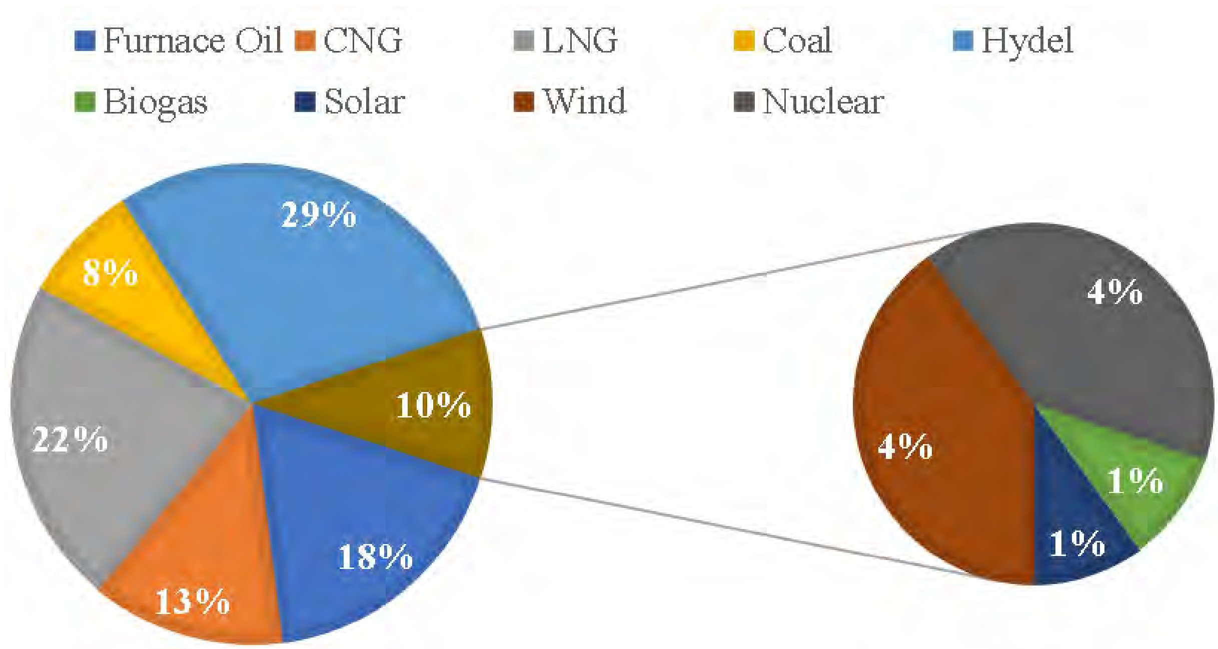

FIG. 1 Energy generation resources in used in Pakistan [2].

These numbers interpret that the Pakistan heavily rely on energy generation of fossil fuels. Liquefied Natural Gas (LNG), which gives 22% of energy to Pakistan, is mainly imported from other countries. Coal which is used in thermal power plants is about thousands of tonnes to generate electricity in one day hence one of the fastest depleting fuel sources. Hence, Pakistan needs to shifts its energy generation to alternative energy resources. Pakistan has four main renewable energy sources; wind, solar, hydro, and biomass. International Renewable Energy Agency (IRENA) has prepared in co-operation with the government, which provides a comprehensive analysis of the country's energy sector. Since Pakistan is going under rapid development therefore, energy and fuel demand is increasing rapidly as well [3, 4, 5]. The power shortfalls and outages occurring due to the rapid population increase and less consumption of traditional fuels topped with the weak governance and energy sector mismanagement has caused electricity supply to fall around 4500 MW short of electricity demand [6, 7, 8]. To overcome this shortfall, Pakistan needs to increase its electricity generation share of solar, wind, hydropower and biomass [9, 10]. However, Pakistan should also look for other alternative renewable energy resources such as harnessing ocean energy.

Ocean Thermal Energy Conversion (OTEC) is a technology for energy production by harnessing the thermal energy due to temperature differences between the ocean surface and deep ocean waters. Energy from the sun heats the surface water of the ocean. Since the ocean covers 71% of the earth's surface at which sun's energy falls giving a humungous amount of thermal energy to water surfaces. As the depth increases the intensity of the radiation decreases giving rise to temperature difference which OTEC take the advantage of to generate electricity. OTEC is a unique method to provide an uninterrupted power supply throughout the year as it does not require any energy storage systems. Pakistan has a coastline of around 1046 km and it offers a tremendous opportunity to harness ocean energy [11]. Pakistan has abundant pelagic energy and temperature profile for this technology to be used, with its win and win scenario preferable locations are close to the west coast near Karachi, Pasni, Gwadar, and Ormara where the required temperature difference of 20°C is achievable at depths of approximately 1000 to 1500 meters [1].

This study focuses on three main objectives (1) the overview of different classifications of OTEC technologies available for harnessing ocean thermal energy, (2) identification of such maximum Carnot efficiency potential of OTEC for coastal regions of Pakistan and (3) selection of site for application of OTEC plant for its extensive and detailed technical and economic analysis. None of the investigator has performed above mentioned three objectives in a single study for coastline of Pakistan.

1.1 | Types of OTEC

OTEC power generation is based on the Rankine cycle, which is similar to a nuclear power plant or natural gas/coal fired power plant where working fluid is boiled to vapours using a heat source such as nuclear reactor or boiler. OTEC has its own uniqueness. It harnesses the thermal energy of ocean which is due to the temperature difference between hot surface and cold depth water of ocean. This temperature range is around 20 to 25 °C. OTEC plants can be classified into three categories as shown in Fig. 2.

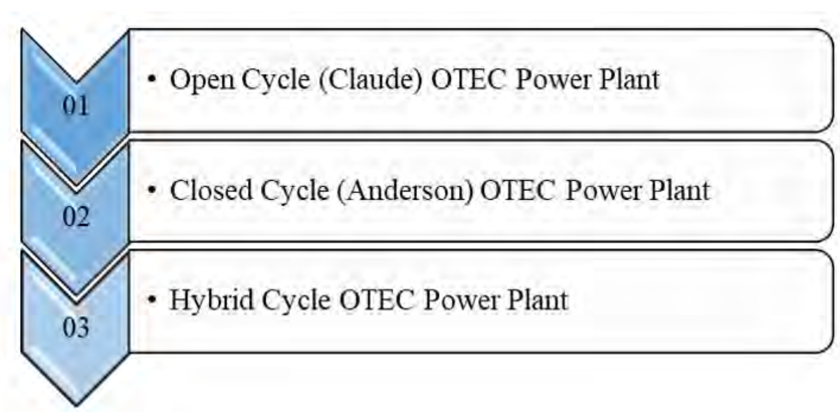

FIG. 2 Classifications of OTEC Power Plants.

1.1.1 | Open cycle (Claude) OTEC Power Plant

Warm surface water from tropical ocean surface is used in open-cycle OTEC to generate electricity. As it can be seen in Fig. 3, the warm surface water is passed through a low-pressure container i.e., evaporator converting it into flash steam. These vapours are directed at turbine inlet in which the expanding steam rotates the turbine. Turbine is coupled with an electric generator and electricity is generated. After passing through turbine, these vapours are condensed back in the liquid form with the aid of condenser by exposure to cold temperatures from deep ocean waters. This type of OTEC has the advantage of producing desalinized freshwater, as the condensed water is essentially freshwater which can be used as a by-product for drinking and irrigation purposes, the cold seawater which was pumped from down below can also be utilized for air conditioning purposes [12].

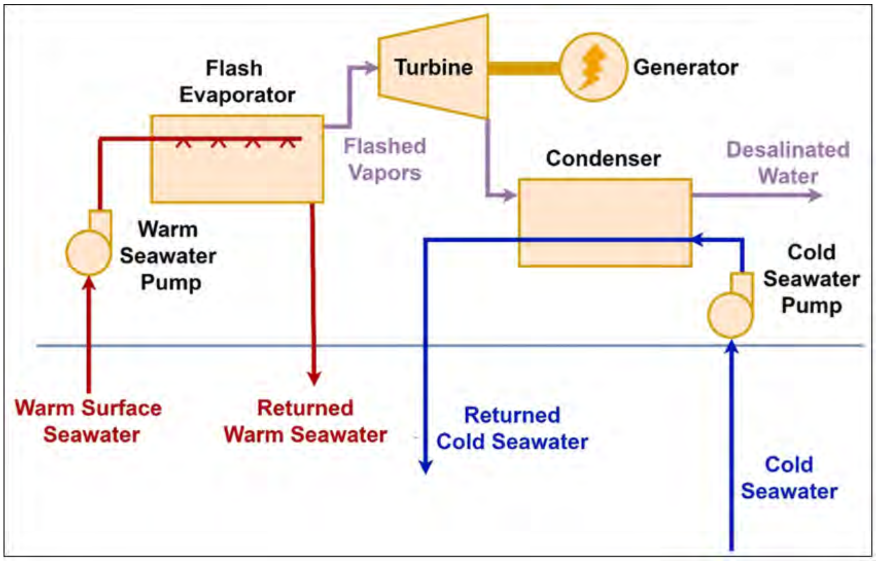

FIG. 3 Schematic of Open Cycle OTEC Power Plant.

1.1.2 | Closed cycle OTEC

Fluid with a low boiling point, such as ammonia refrigerants or polypropylene is used in the closed-cycle system for the rotation of turbine and generation of electricity. Low boiling point working fluid is vaporized in heat exchanger (evaporator) by using warm ocean surface water. The rest of the cycle is like an open cycle, as vapours turn the turbogenerator generating electricity and later get condensed in the condenser using deep cold water from the ocean. The smaller size of the turbine, duct, and heat exchanger in the closed cycle makes it more thermally efficient [13]. Fig. 4 represents a typical schematic of a Closed cycle OTEC power plant.

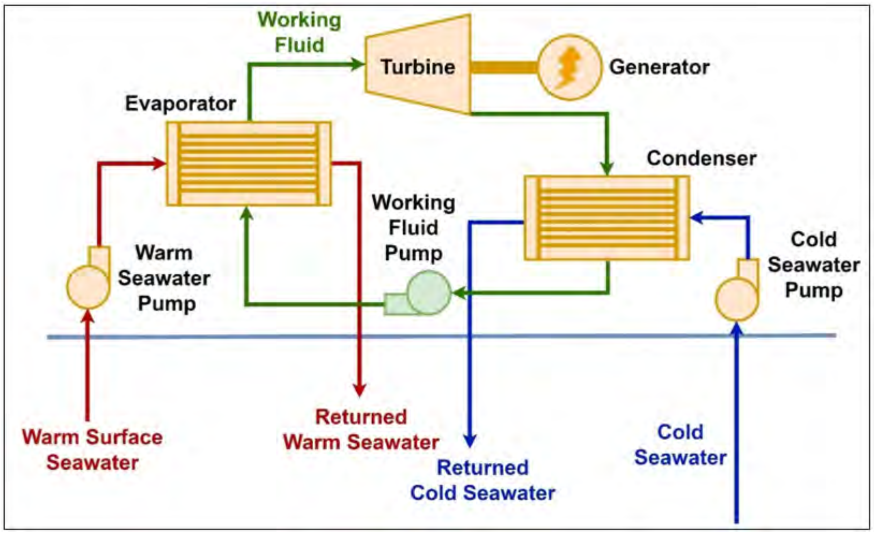

FIG. 4 Schematic of Closed Cycle OTEC Power Plant.

1.1.3 | Hybrid cycle OTEC

Hybrid Cycle OTEC combines the features of the closed and open cycle OTEC plants. In this classification of OTEC, water enters a vacuum chamber and is flash evaporated which is in correspondence to the open cycle. The steam vaporizes the ammonia working fluid of a closed-cycle loop on the other side of an ammonia evaporator. The vaporized working fluid then drives a turbine to produce electricity and is condensed in liquid phase by using cold depth water in condenser. However, the flashed hot ocean water vapours are condensed in ammonia evaporator and can be used for drinking purposes [14]. Fig. 5 represents a typical schematic of Hybrid cycle OTEC power plant.

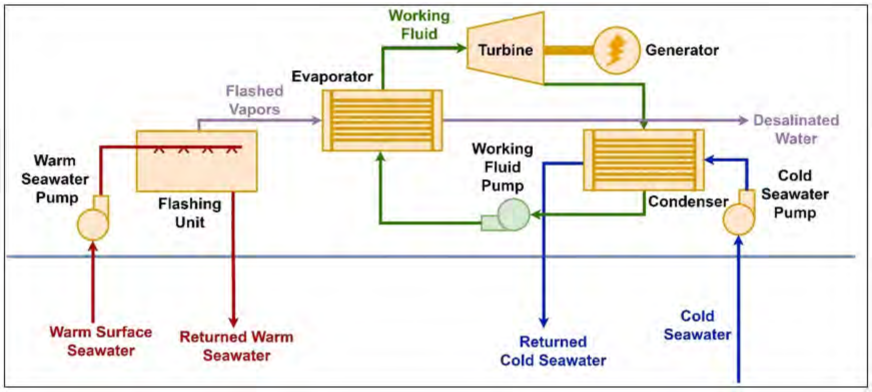

FIG. 5 Schematic of Hybrid Cycle OTEC Power Plant.

2 | SITE DESCRIPTION

Many different locations were shortlisted from Pakistan's Exclusive Economic Zone (EEZ). Pakistan has increased its continental shelf from 200 nautical miles to a maximum of 350 nautical miles, as shown in Fig. 6. Pakistan acquires more than 50,000 sq. km of maritime area. The outer limit of the extended shelf lies at 19° 10' 36.1" N, 62° 13' 25.6" E on Pak-Oman Boundary Line and 19° 15' 22.8" N & 63° 35' 21.6" E on the Pak-India boundary line. Based on factors involving the implementation of OTEC, the Coastlines of Pakistan were studied and the waters near various sites were chosen for the research mainly Karachi, Gwadar, Ormara, and Pasni. Analysis will be carried out to determine the most optimum and suitable location for the OTEC plant in terms of efficiency and potential aspect.

TABLE 1 Details of four studied coastal sites for OTEC application.

S. No.	Region	Coordinates	Distance from shoreline in km
1	Karachi	23.875° N 65.125° E	196
2	Gwadar	24.625° N 62.375° E	56
3	Ormara	24.375°N 64.625°E	104
4	Pasni	24.625° N 63.625° E	68

Ins this study, Ocean climatological mean field data was obtained from World Ocean Atlas 2013 (WOA13)

[15]. Which contains oceanographic data observed at different locations throughout the oceans to map and then interpolate to standard depths on 5°, 1°, and 1/4° girds for monthly, annual & seasonal assessment of temperature all around the world. In this study data on 1/4° grid was analysed for precise accurate measurement of temperatures at standard depths using open-source software Ocean Data View (ODV) [16] to obtain desired information for the depth-temperature relationship at various locations along the coastline of Pakistan. The data is obtained of such regions keeping in mind that the optimal temperature gradient should be about 20°C for the viable operation of the OTEC facility. Four locations have been selected across the coastline of Pakistan; Karachi, Gwadar, Ormara and Pasni. Table 1 consists of the coordinated for the selected coastal sites of Pakistan.

FIG. 6 Map showing EEZ and extended continental shelf of Pakistan [11].

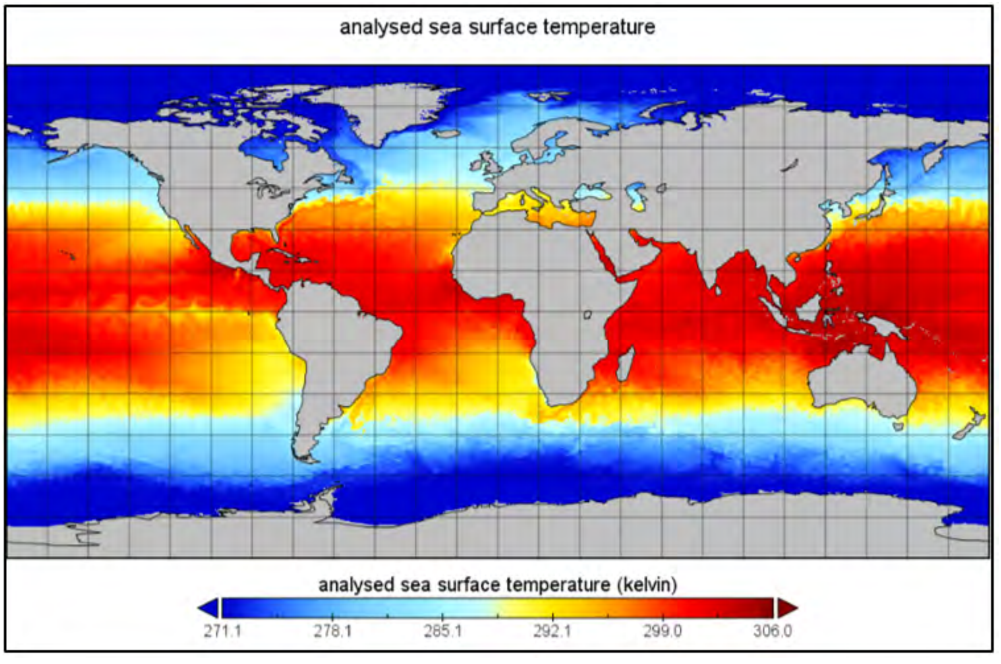

FIG. 7 World Ocean surface temperature distribution [17].

Ocean surface temperature is coastline of Pakistan are observed to be in higher side which results in significant temperature difference for operation of OTEC plants. Fig. 7 represents the world ocean surface temperature distribution and it is providing clear evidence that surface water temperatures of Pakistan's coastline are higher enough to operate OTEC plants. Fig. 8 represents the temperature difference ranges on world ocean map at the depth of 1000 m which indicates that the temperature difference in Pakistan coastline is lower than 20°C. Therefore, a detailed analysis is needed at different depths. This study will analyse OTEC potential at the depths of 1000, 1200 and 1500 m.

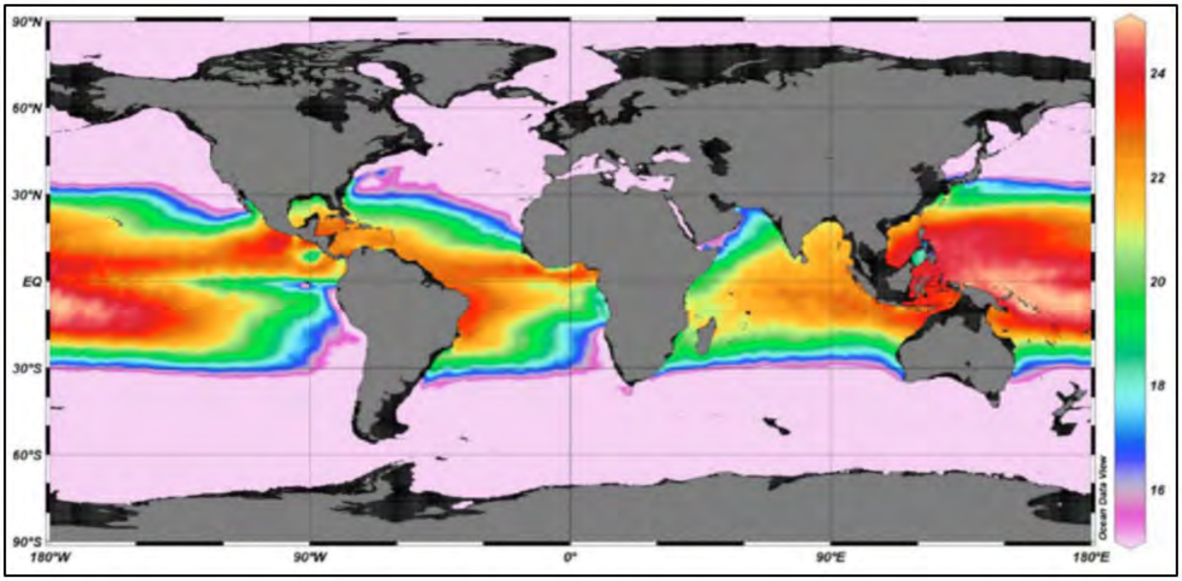

FIG. 8 Temperature difference by at depth of 1000m [18].

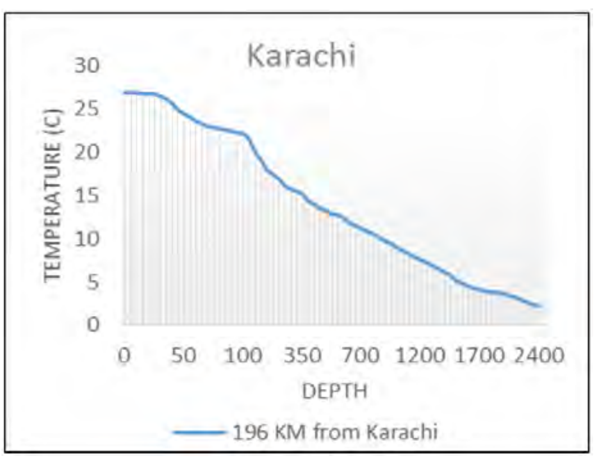

FIG. 9 Temperature-depth relationship at 196 km from Karachi [17].

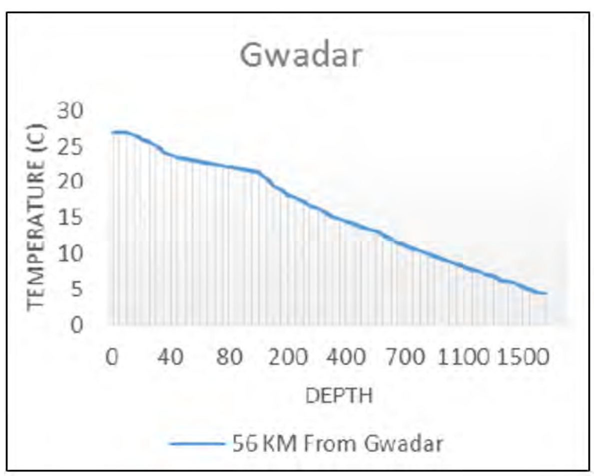

FIG. 10 Temperature-depth relationship at 56 km from Gwadar [17].

Karachi has ocean surface mean temperature around 23 to 25°C and the temperature decreases at the depth due to decrease in thermal radiation. Fig. 9 represents the temperature-depth relationship for ocean 196 km from shore of Karachi. Gwadar has ocean surface mean temperature around 26 to 28°C. Fig. 10 represents the temperature-depth relationship for ocean 56 km from shore of Gwadar. Ormara has ocean surface mean temperature around 25 to 27°C. Fig. 11 represents the temperature-depth relationship for ocean 104 km from shore of Ornara. Pasni has ocean surface mean temperature around 25 to 27°C. Fig. 12 represents the temperature-depth relationship for ocean 68 km from shore of Pasni [17].

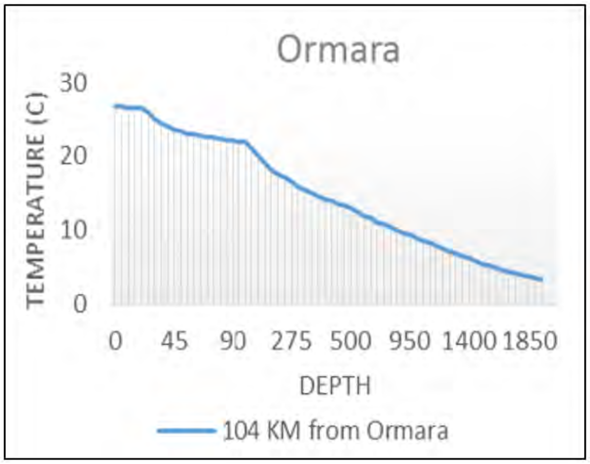

FIG. 11 Temperature-depth relationship at 104 km from Ormara [17].

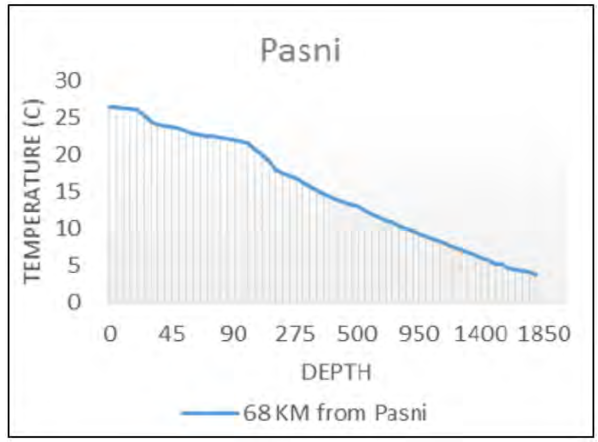

FIG. 12 Temperature-depth relationship at 68 km from Pasni [17].

3 | METHODOLOGY

The mean surface temperature of ocean water varies with the seasons. Therefore, a careful analysis must be carried out to observe these seasonal variations as well. Table 2 contains mean surface ocean water temperature for selected sites. Tables 3, 4 and 5 contains temperature at the depths of 1000, 1200 and 1500 m, respectively, in selected sites at all four seasons.

TABLE 2 Mean surface water temperatures of selected sites [17].

Surface Water Temperature in °C				
Seasons	Karachi (KHI)	Gwadar (GWD)	Ormara (ORM)	Pasni (PSN)
Summer	27.25	28.55	28.08	27.52
Spring	26.95	28.28	27.99	28.27
Fall	26.81	27.02	27.99	26.80
Winter	24.80	24.05	24.03	24.32

TABLE 3 Water temperatures of selected sites at depth of 1000 m [17].

Water Temperature in °C at depth of 1000 m				
Seasons	Karachi (KHI)	Gwadar (GWD)	Ormara (ORM)	Pasni (PSN)
Summer	9.12	8.86	8.80	8.98
Spring	8.86	8.89	8.78	9.17
Fall	8.80	8.82	8.92	8.83
Winter	8.90	8.91	8.96	9.06

3.1 | Maximum Theoretical Efficiency

Maximum theoretical efficiency of OTEC plant is called Carnot efficiency of OTEC. The Carnot efficiency of OTEC depends upon the two parameters: temperature of surface water (T_s) and temperature at of cooling water at certain depth (T_d).

$$\eta_{OTEC} = 1 - \frac{T_d}{T_s} \quad (1)$$

The temperature difference (ΔT) in OTEC plant is very small therefore, Carnot efficiencies of OTEC plants are very small. Typically, Carnot efficiency of OTEC plants vary in range of 6-9%. However, it is only Carnot efficiency, actual efficiencies are even less than the Carnot efficiencies. Actual efficiency of operating commercial OTEC plant varies from 2-4%. The thermodynamic efficiency of OTEC gives a negative impression about its commercialization. However, all this can be avoided as OTEC plants harness ocean thermal energy which is abundant and does not require any fossil fuel for operation.

TABLE 4 Water temperatures of selected sites at depth of 1200 m [17].

Water Temperature in °C at depth of 1200 m				
Seasons	Karachi (KHI)	Gwadar (GWD)	Ormara (ORM)	Pasni (PSN)
Summer	7.61	7.65	7.64	7.59
Spring	7.53	7.62	7.60	7.58
Fall	7.55	7.63	7.58	7.54
Winter	7.49	7.60	7.57	7.53

TABLE 5 Water temperatures of selected sites at depth of 1500 m [17].

Water Temperature in °C at depth of 1500 m				
Seasons	Karachi (KHI)	Gwadar (GWD)	Ormara (ORM)	Pasni (PSN)
Summer	5.02	5.19	5.10	5.20
Spring	5.00	5.08	4.80	5.10
Fall	4.98	5.42	5.43	5.51
Winter	4.97	5.42	5.47	5.51

4 | RESULTS AND ANALYSIS

With the aid of temperature-depth relationship curves and data given in Table 2-5, we can say that the selected sites have a considerable potential for installation of OTEC plants. Table 6 provides the temperature differences at different depths for selected locations at different seasons of year.

TABLE 6 Water temperatures of selected sites at depth of 1500 m [17].

	Temperature Difference (°C) at 1000 m				Temperature Difference (°C) at 1200 m				Temperature Difference (°C) at 1500 m			
	KHI	**GWD**	**ORM**	**PSN**	**KHI**	**GWD**	**ORM**	**PSN**	**KHI**	**GWD**	**ORM**	**PSN**
Summer	18.13	19.69	19.28	18.54	19.64	20.90	20.44	19.93	22.23	23.36	22.98	22.32
Spring	18.09	19.39	19.21	19.10	19.42	20.66	20.39	20.69	21.95	23.20	23.19	23.17
Fall	18.01	18.20	19.07	17.97	19.26	19.39	20.41	19.26	21.83	21.60	22.56	21.29
Winter	15.90	15.14	15.07	15.26	17.31	16.45	16.46	16.79	19.83	18.63	18.56	18.81

TABLE 7 Carnot efficiency at the depths of 1000, 1200 and 1500 m at selected sites.

	Carnot Efficiency (%) at 1000 m				Carnot Efficiency (%) at 1200 m				Carnot Efficiency (%) at 1500 m			
	KHI	**GWD**	**ORM**	**PSN**	**KHI**	**GWD**	**ORM**	**PSN**	**KHI**	**GWD**	**ORM**	**PSN**
Summer	6.04	6.53	6.40	6.17	6.54	6.93	6.79	6.63	7.40	7.75	7.63	7.43
Spring	6.03	6.44	6.38	6.34	6.47	6.86	6.77	6.87	7.32	7.70	7.70	7.69
Fall	6.01	6.07	6.34	5.99	6.42	6.46	6.78	6.42	7.28	7.20	7.50	7.10
Winter	5.34	5.10	5.07	5.13	5.81	5.54	5.54	5.65	6.66	6.27	6.25	6.33

Comparison of temperature differences for all the seasons can be seen in Figs. 13, 14, and 15 at the depth of 1000 m, 1200 m and 1500 m. It can be observed clearly that the temperature differences in Gwadar, Ormara and Pasni region are greater than Karachi for all seasons and all selected depths.

Based on the temperature differences determined in Table 6, Carnot efficiencies can be determined by using Eq. (1). Carnot efficiencies for the selected locations are mentioned in Table 7.

Seasonal changes in Carnot efficiencies of selected sites can be observed clearly in Table 7. The variations in Carnot efficiencies of OTEC plants in selected sites at depth of 1000 m, 1200 m, and 1500 m are presented in Figure 16, 17, and 18, respectively.

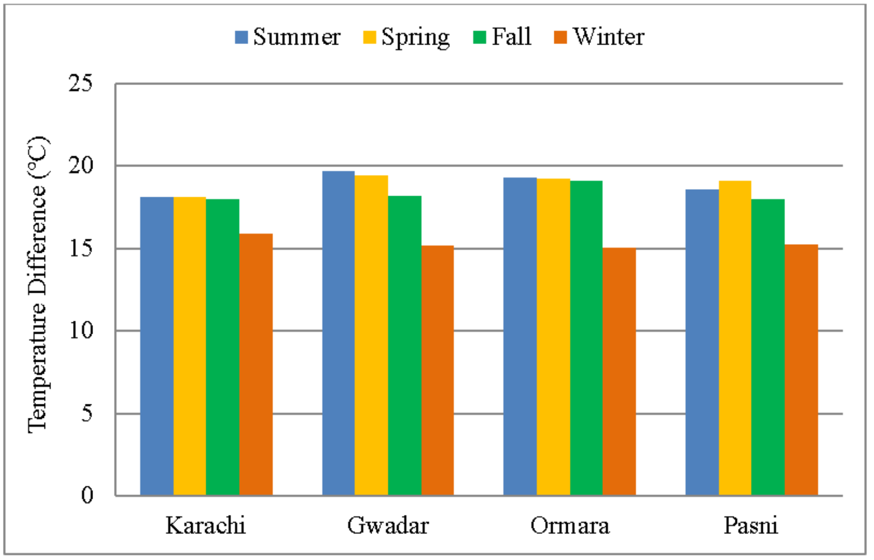

FIG. 13 Temperature Differences for selected sites in different seasons at 1000 m depth.

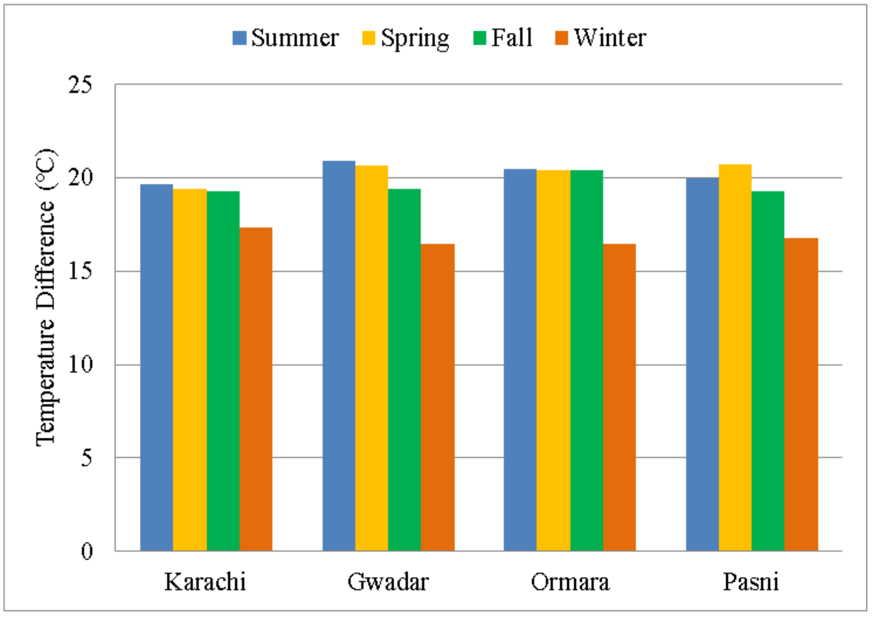

FIG. 14 Temperature Differences for selected sites in different seasons at 1200m depth.

From 16 to 18, it can be observed that Carnot efficiencies of OTEC in Gwadar region are in the range of

5.10 to 6.53% at 1000 m depth, 5.54 to 6.93% at depth of 1200 m, and 6.27 to 7.75% at the depth of 1500 m. Also, Carnot efficiencies of OTEC in Ormara region are in the range of 5.07 to 6.40% at depth of 1000 m, 5.54 to 6.79% at depth of 1200 m, and 6.25 to 7.70% at depth of 1500 m. However, Carnot efficiencies of OTEC in Pasni region are in the range of 5.13 to 6.17% at depth of 1000 m, 5.65 to 6.87% 1200 m, and 6.33 to 7.69% at depth of 1500 m. All of these variations is due to the seasonal climatic variations, which results in varying the temperature of ocean water both at surface and certain depths.

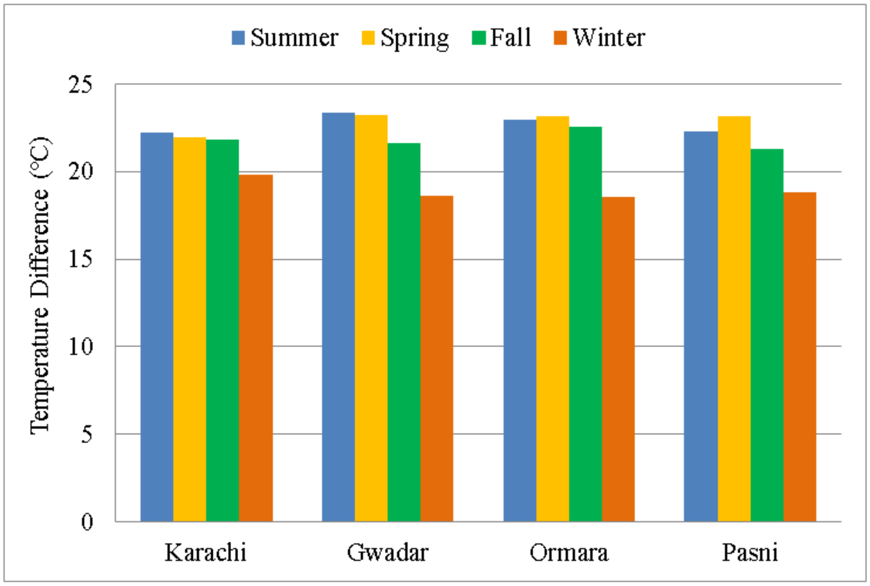

FIG. 15 Temperature Differences for selected sites in different seasons at 1500 m depth.

After this extensive analysis for several regions of Pakistan to identify the suitable location for OTEC plant application, it can be said that Gwadar region provides the best efficiencies among the selected regions at all the analysed ocean depths. This site is selected on the basis of not only the best Carnot efficiency of OTEC but also due to availability of sufficient temperature gradient and thirdly, it has the minimum distance from the coast of Pakistan as well.

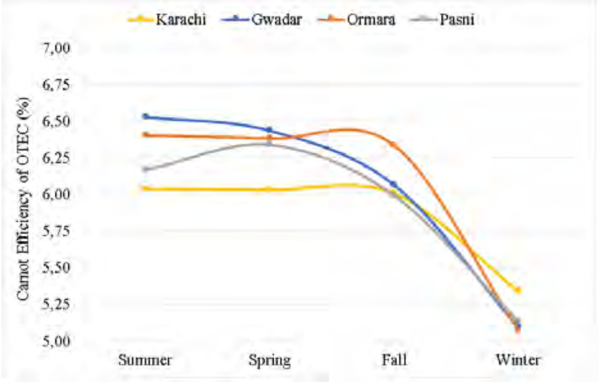

FIG. 16 Seasonal variations in Carnot efficiency of OTEC at 1000 m depth.

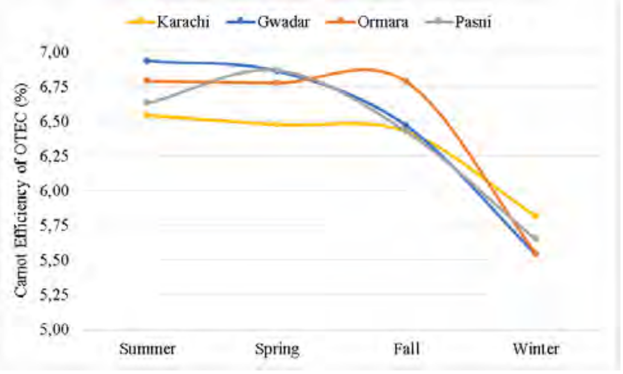

FIG. 17 Seasonal variations in Carnot efficiency of OTEC at 1200 m depth.

Since OTEC is still under research technology and it requires large capital investment because of its large infrastructure therefore, it is difficult to secure investment for such projects. Few studies have been carried out recent past for viability of OTEC plants but still there is very little information about the actual project cost is available. Majority of the studies which were previously carried out has been done between the ocean depth range of 600-1000 m and it has been found that the capital investment decreases with the increase in OTEC plant capacity size. OTEC plants can be categorized into three classifications on the basis of plant capacity. Table 8 provides details about the capital investment.

For application of OTEC plant it must be decided that which type of OTEC must be employed based on the local requirement. If only rural area electrification is an objective Close cycle OTEC plants must be installed. However, if aim is not only rural area electrification but also provision of drinking water so Open Cycle OTEC plants must be employed despite having lower efficiency than Closed cycle OTEC plants.

Since most suitable selected site of Gwadar is 56 km away from the shore therefore, a floating platform will be preferable. Such OTEC structures usually have enough weight which will keep it floating even in stormy days as well. These structures offer another advantage for manoeuvrability of platform is possible since the structure is not permanently anchored. Floating structures can be used for ocean depths of up to 3000 m.

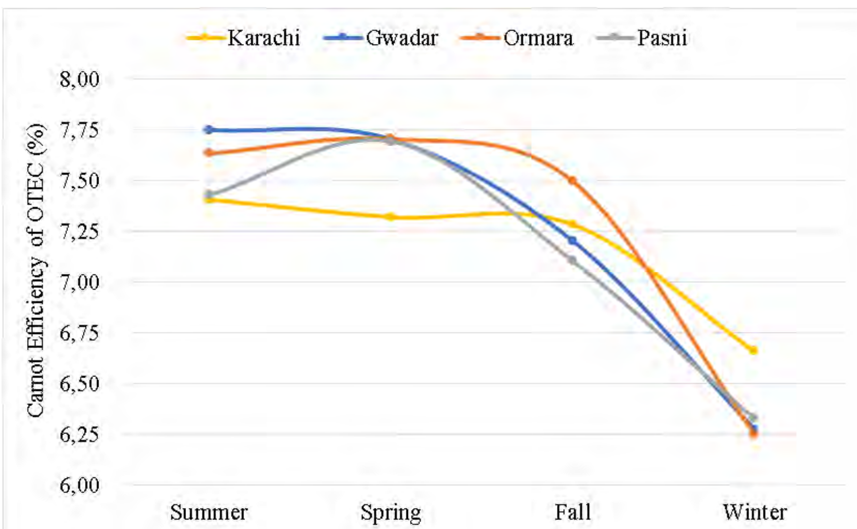

FIG. 18 Seasonal variations in Carnot efficiency of OTEC at 1500 m depth.

On the basis of above discussion, OTEC plants must be considered for electrification of selected site. It will operate steadily throughout the year with zero CO_2 emission and operating fuel cost.

TABLE 8 Estimated costs of different scale OTEC plants [11].

Classification	Capacity Range	Capital Investment in Million PKR/kW
Smaller Scale OTEC Plants	<10 MW	2.90 to 6.27
Larger Scale OTEC Plants with fixed structure Larger Scale OTEC Plants with floating structure	>10 MW	0.88 to 2.66 0.40 to 0.45

5 | CONCLUSIONS

Electricity shortfall in Pakistan has increasing trend and Pakistan must reduce the reliance of electricity from fossil fuels for sustainability. It is a known fact that Pakistan has huge potential for Solar and Wind energy. Gwadar region has been identified as the most suitable site for applications of OTEC plants.

Temperature differences for Gwadar region at depths of 1000 m, 1200m, and 1500m has been determined around 19.69°C, 20.90°C, and 23.36°C, respectively for summer season. Similarly, Carnot efficiencies of Gwadar region at depths of 1000 m, 1200m, and 1500m has been found 6.53%, 6.93%, and 7.75%, respectively. With the addition of another renewable energy resource, considerable electricity can be generated for national grid. It will also reduce the dependency from the fossil fuels which results in reduction CO_2 emissions as well. However, it is clear that the selected site has a highest potential for OTEC plant application but it does not indicate whether selected site will be economically feasible for OTEC application.

Extensive designing of OTEC plant and a detailed economic analysis must be carried out to evaluate its feasibility. This can be achieved by determining its Payback Period, Levelized Cost of Electricity (LCOE), Internal Rate of Return (IRR) and Net Present Value (NPV) for which identification of Capital Investment (CAPEX) for construction of OTEC plant, Operation and Maintenance (O & M) cost is necessary. Apart from generation of electricity, OTEC plants gives additional benefits such as provision of desalinated water for drinking and agricultural purpose. OTEC plants also support deep-water marine culture which is beneficial for fishing industry.

Declaration of Interest

The authors declare that there is no conflict of interest.

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