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# A MACHINE LEARNING BASED ASSESSMENT OF OTEC POTENTIAL IN THE BAY OF BENGAL AND IT'S HARVESTING APPROACH

**A Thesis by**

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Submitted in Partial Fulfillment of the Requirements for the Degree of
**Bachelor of Science in Mechanical Engineering**

*Academic Year: 2020-21*

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## CERTIFICATE OF RESEARCH

*This thesis titled* ***"A MACHINE LEARNING BASED ASSESSMENT OF OTEC POTENTIAL IN THE BAY OF BENGAL AND IT'S HARVESTING APPROACH"*** *submitted by* ***ABIR RASHID (17001004)*** *and* ***TAHER HASAN NAKIB (170011005)*** *has been accepted as satisfactory in partial fulfillment of the requirement for the Degree of Bachelor of Science in Mechanical Engineering.*

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# DECLARATION

*I hereby declare that this thesis entitled "A MACHINE LEARNING BASED ASSESSMENT OF OTEC POTENTIAL IN THE BAY OF BENGAL AND IT'S HARVESTING APPROACH" is an authentic report of our study carried out as requirement for the award of degree B.Sc. (Mechanical Engineering) at Islamic University of Technology, Gazipur, Dhaka, under the supervision of Prof. Dr. Mohammad Ahsan Habib, Professor, MPE, IUT in the year 2022.*

*The matter embodied in this thesis has not been submitted in part or full to any other institute for award of any degree.*

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# ABSTRACT

Bangladesh has been steeply growing towards a concerning power demand. The coastal region and nearby islands surrounding the Bay of Bengal barely gets more than half of its required power through conventional power grid sources. This research attempts to look at the ocean thermal reserves of the Bay of Bengal and place a model 100 MW Net/150 MW gross OTEC power plant that could potentially alleviate the power shortage in the focused region. The potential sites were identified by analyzing big data obtained from HYCOM+NCODA using advanced data analytics. Placing the hypothetical plant, an estimated power output is calculated for different seasons. Cost estimations are found from an established model to provide an insight of the approximate levelized cost of electricity. A machine learning algorithm is trained to forecast the behavior of the temperature difference over the coming years to verify the consistency of the plant's power output during its lifetime. Findings reveal that the estimated power ranges between 133 MW to 158 MW net power throughout the year. Levelized cost of electricity ranges 0.164 to 0.605 $/kWh for its low-medium-high estimates. Time series forecasting of historical data provide a clear image of the temperature difference in the coming years, indicating satisfactory consistency in generated power throughout the plant's life. The work is novel as no prior work is noticeable in the OTEC field incorporates the use of modern data analytic tools or machine learning algorithms. Very few works in the field present optimum site selection as well as pertaining computations of the model plant's performance. Even further novelty of the work can be posited to no comprehensive OTEC based research can be seen based on the Bay of Bengal or Bangladesh. The findings present an attractive argument and show promise, however, practical implementation of such a large plant requires multiple rounds of trial and errors to minimize failure and cost overload. Future research could implement a physical scaled model of the plant to observe its harvested power and associated costs. With modern advances in technology and possible government sanctions, the prospect of looking into OTEC as a renewable and environment friendly power alternative takes immediate priority.

# Table of Contents

# LIST OF FIGURES

# LIST OF TABLES

# Nomenclature

| | |
|---|---|
| $A$ | Cold water pipe cross-sectional area |
| $C_{shb}$ | Cold water pipe static head bias correction |
| $D$ | Cold water pipe diameter |
| $f$ | Friction coefficient of cold water pipe |
| $g$ | Gravitational constant |
| $h_f$ | Head loss due to pipe friction |
| $L_{fixed}$ | Fixed OTEC power losses |
| $L_{pf}$ | Cold water pipe friction loss |
| $L_{pp}$ | Cold water pump power loss |
| $L_{sh}$ | Cold water pipe static head loss |
| $L_{ssh}$ | Simplified cold water static head loss |
| $L_{var}$ | Variable OTEC power losses associated with cold water pumping |
| $\dot{m}$ | Cold seawater mass flow rate |
| $P_{gross}$ | Gross OTEC power production |
| $P_{net}$ | Net OTEC power production |
| $Q$ | Volumetric transport of water |
| $Q_c$ | Volumetric transport of cold water |
| $R$ | Radius of Earth |
| $T$ | Water temperature |
| $T_d$ | Water temperature at the deep water intake depth |
| $T_s$ | Water temperature at the near surface cold water intake depth of 20 m |
| $V$ | Eastward component of the water velocity |
| $d$ | Depth below mean sea surface elevation |
| $\Delta T$ | Temperature difference between the warm and cold water resources |
| $\rho$ | Water density calculated as a function of temperature |
| $\rho_D$ | Density of seawater calculated using the cold deep water temperature |
| $\rho_f$ | Constant density value used for calculating head loss |
| $\rho_s$ | Density of seawater calculated using the warm near surface water temperature |
| $\eta$ | Seawater pump efficiency |
| $h$ | Minor head loss |
| $h_{intake}$ | Intake head loss |
| $CAPEX$ | Capital expenature |
| $OPEX$ | Operating expenses |
| $C_{heat\ ex}$ | Total heat exchanger cost |
| $C_{watersys}$ | Water system cost |
| $C_{turbogen}$ | Turbo generator cost |
| $C_{power}$ | Power cable cost |
| $C_{platform}$ | Platform making cost |

$C_{labor}$ Labor cost
$CRF$ Cost recovery factor
$CF$ Capacity factor
$LCOE$ Levelized cost of energy

## Chapter 1
# INTRODUCTION

The growing attention of the world towards converting the massive power demands of its population from traditional harmful fossil fuel based power sources to green and renewable means has been evidently notices for the past few decades. It has been one of the prime challenges of researchers and engineers to come up with efficient and competitive power generation that would ensure long term, sustainable, environment friendly power. The amount of works published and attempted to present various forms of renewable energy in the likes of solar, geothermal, hydroelectric, wind or even bio-mass has been astounding, and yet none have been able to successfully replace or compensate the magnitude or the efficiency of fossil based power generation. With technology growing faster than ever, it has become ever important to look into the possibilities of newer forms of renewable energy sources; to refine them and apply them into the world for human benefit. With the fossil fuel reserves slowly reaching its limit, it is safe to say that the future of power generation is quite clearly, all renewable. Keeping all this in mind, several international organizations and almost all the governments in the world has emphasized working on renewable energy technologies (RET).

The vast world of renewable energy and hundreds of bleeding edge technology to support these renewable energy sources still haven’t successfully replaced the use of fossil fuel power and the search for even more sources of renewable reservoirs remain. Since more than two-thirds of the earth’s mass is full of water, there is a huge opportunity to generate useful power from these sources. The concept of harnessing the ocean thermal energy was first put in place in the early 1880’s and since then several attempts have been made to refine the concept to an actual implantable technology for sustainable power generation. So far, only miniature model plants were employed to see the potential of this ocean water based power generation and the fact is, this technology requires more attention.

## 1.1 OTEC: What it is and its Prospect as a Renewable Power Generation Technology

The term 'OTEC' refers to Ocean Thermal Energy Conversion via running a Rankine Cycle that depends on the thermal gradient formed by the surface warm waters and deep cold waters of the ocean. Usually, the warm and cold water needs to have at least a difference in temperature around $20°C$ to start up a power cycle that will generate considerable electricity. However, there have been recent studies to operate such plants with shallower waters and less temperature differences. OTEC plants are known to operate at high capacities and hence can work in base load. Fig. 1.1 shows the OTEC resource potential distribution around the world [1]. The beauty of OTEC is that the reserves of ocean thermal energy is as vast as the oceans reach. This means that as long as we have ocean on earth, we should be able to harness power from it. Such propositions make OTEC plants so attractive.

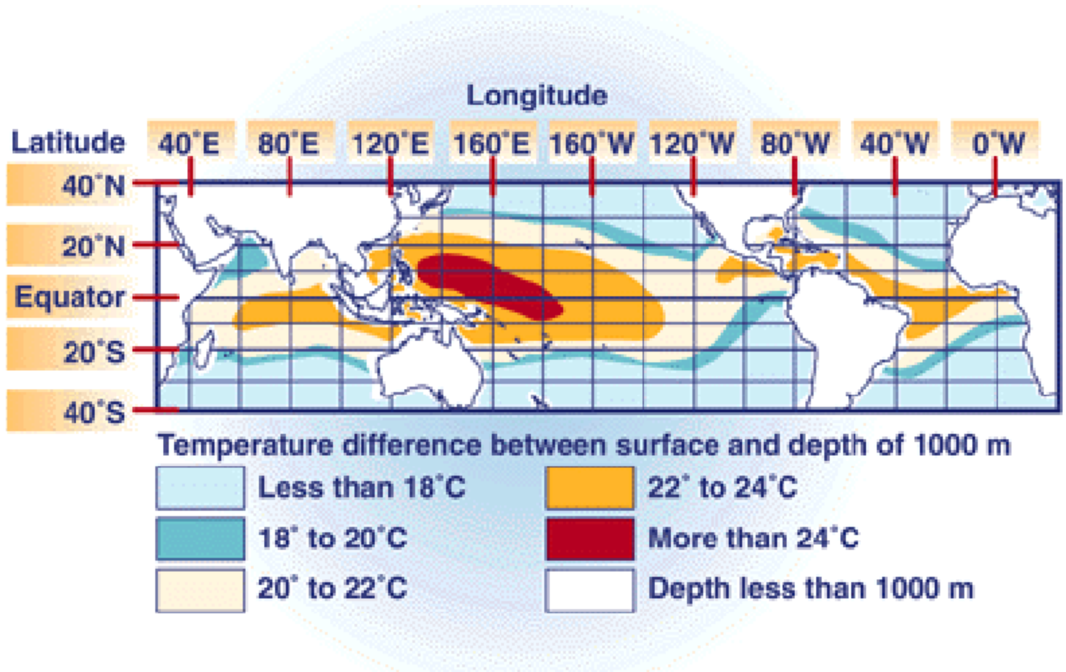



Fig. 1.1: OTEC resource potential around the world [1].

These plants don't vary vastly from the conventional layout of a thermal power plant. They require all the basic components like turbines, pumps, heat exchangers, condensers etc. The added components in this type of plant is the cold water cabling that have to be intricately made to reach the ocean bed and last a long period of time without natural damage. Other minor changes depend on the type of plant selected- whether it is a floating plant on the ocean bed or a land based plant on the coastline of the sea. The typical working fluids used in an OTEC plant can be Ammonia or R134a, while some new variations mention using other refrigerants and hydrocarbons to serve the purpose.

### 1.2 Types of OTEC plant:

Based on the type of power cycle used, OTEC plants are three types:

a) Closed Cycle
b) Open Cycle
c) Hybrid Cycle

#### 1.2.1 Closed Cycle

Closed cycles operate by using working fluids that have low boiling points, e.g. Ammonia that rotates the turbines to generate electricity. Heat exchangers are used to vaporize the fluid once it has been pumped into it. This vaporized fluid in turn makes the turbogenerators work. Cold deep

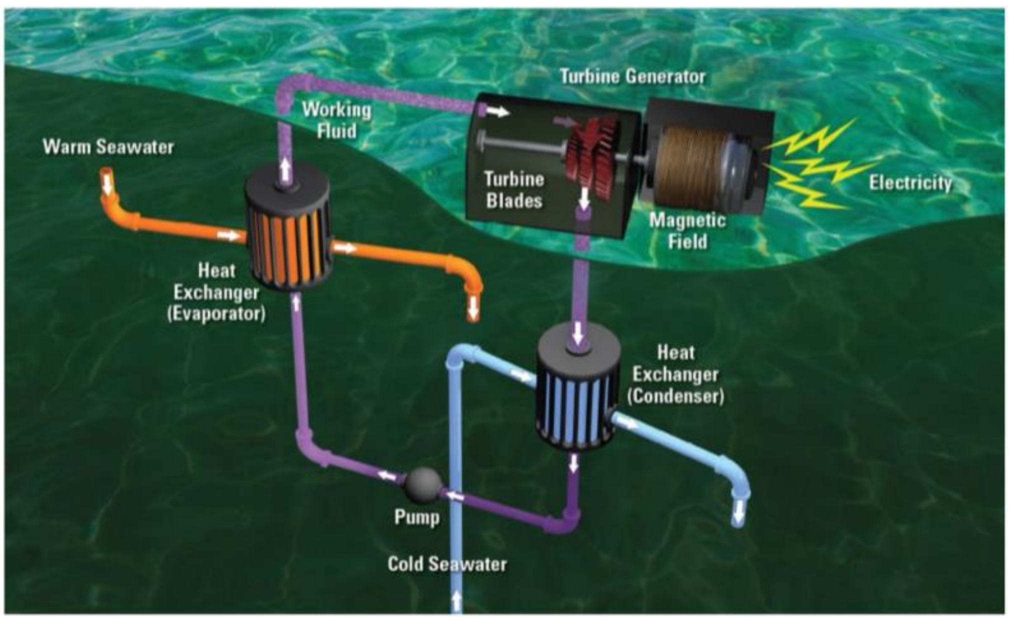


Fig. 1.2: Closed cycle OTEC [2]

ocean water is pumped up to condensate the ammonia that was previously steam via the heat exchanger. The liquid ammonia is once again pumped through the evaporator to follow the same procedure and generate electricity. Fig. 1.2 shows the basic cycle of the closed cycle OTEC plant in a simplified diagram.

### 1.2.2 Open Cycle

Open Cycle OTEC (Fig. 1.3) plants use the warm surface ocean water to drive the heat exchanger as its working fluid and generate power. This warm water is pumped into a vacuum chamber at low pressure, lowering the water's boiling point due to using vacuum to convert it into steam. This steam is in turn used to drive the LP turbine and produce electricity. The steam after use is

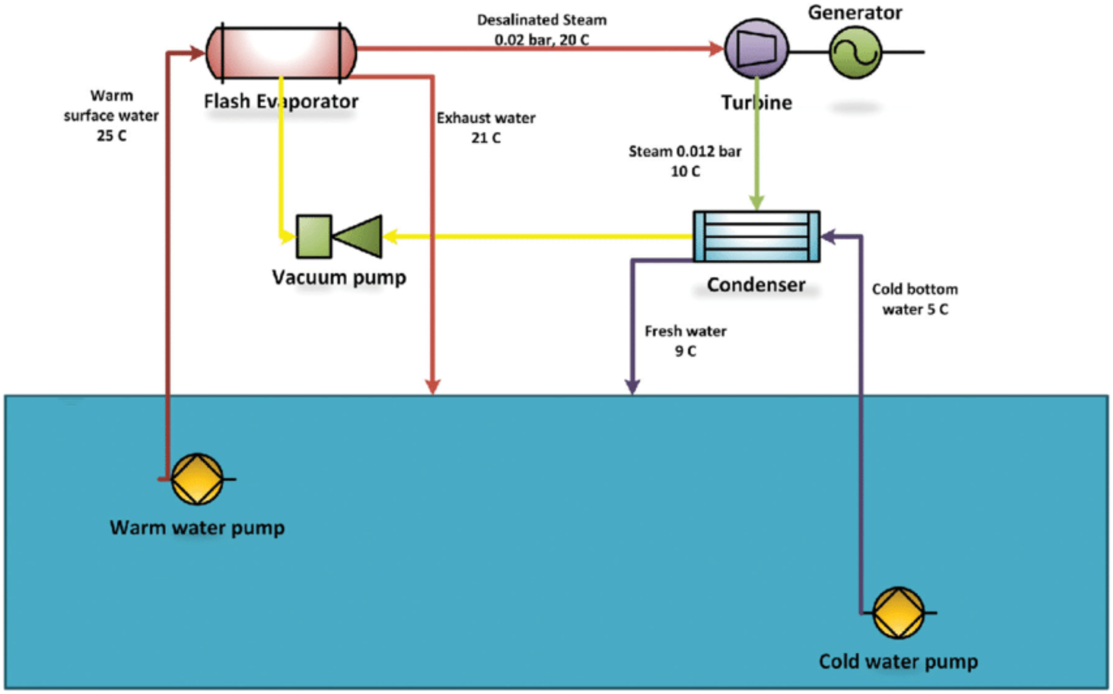


Fig. 1.3: Open Cycle OTEC plant [3].

condensed back to liquid courtesy of the condenser and placed back into the ocean. This method is completely environment friendly and does not affect the ocean. Desalination occurs simultaneously since the warm water is evaporated into steam in vacuum leaving pure fresh water which can be used further. This is a major bonus as it could help provide potable water to nearby communities, the likes of which cannot be seen in other fossil fuel run plants. However, a disadvantage that comes along such plants is that the vacuum chamber must be sealed at all times and any leakage of air into the chamber may cause severe damage to the plant, essentially rendering the functionality of the plant useless. Most modern designs of the OTEC plant take advantage of the hybrid layout of the plant cycle to utilize the benefits of both open and closed cycles simultaneously.

### 1.2.3 Hybrid Cycle

Hybrid Cycle OTEC plants combine the features of both open and closed cycles by using both warm ocean water and Ammonia to run the power cycle. In this cycle (Fig. 1.4), warm ocean water is turned to steam, much like the open cycle plant. The Ammonia is then mixed with this warm water steam and this mixture of working fluid drives the turbine, generating power. Steam of ammonia is then diverted from the mixture and re-condensed back into liquid ammonia using the cold deep ocean water, eventually placing it back in the closed cycle. Significant performance boost is observed in such OTEC plants due to the added effect of both types of cycles.

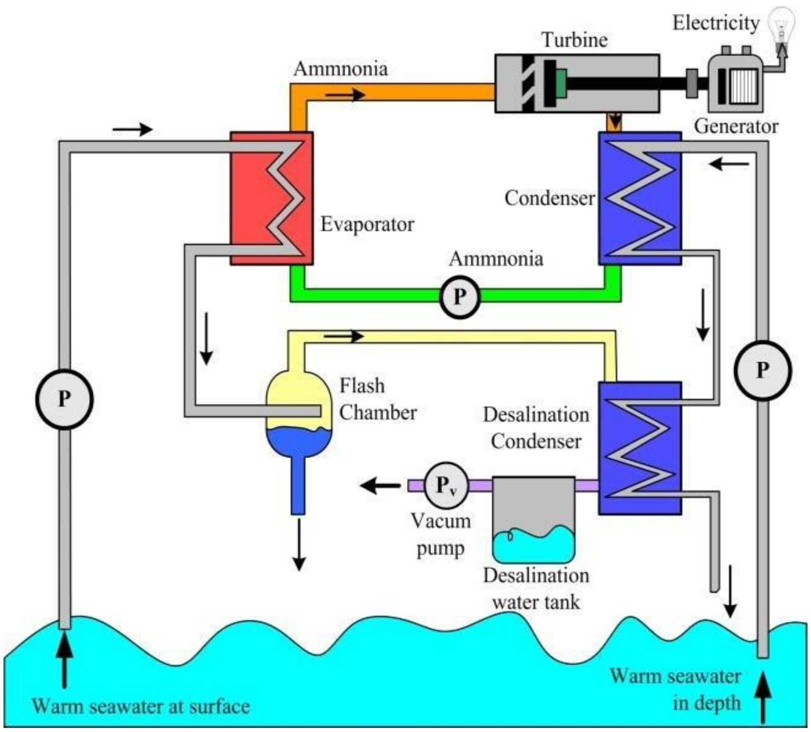


Fig. 1.4: Hybrid Cycle OTEC plant [4].

# Chapter 2
# LITERATURE REVIEW

## 2.1 Introduction

Nowadays widespread concern about global climate change, increasing rate of green-house gas emissions, fast depletion of ozone layer, various environmental hazards, limited storage and rising prices of fossil fuels have made people/researchers to shift their interest on cleaner renewable energy resources.

At present, among many more renewable energy sources, hydroelectric projects are the cheapest and the most efficient source; but oceanic wave energy could be a good competitive source to mitigate the increasing needs for cleaner energy.

Oceanic thermal energy has great potential in supplying the worldwide increasing demand for power. After the energy crisis in 1970s, ocean thermal energy rests among the several alternative forms of energy that attracts great attention but few people have heard of the capabilities of it. The inception of generating electricity utilizing thermal energy deposited between warm surface and cold ocean water was formed by a French physicist J. D'Arsonval in 1881[5]. Since then several advancements have taken place in this field and the imminence of OTEC plants turning into a sustainable renewable energy solution is right around the corner. . Following the trend, many efficient and effective modern design of OTEC power plants were patented in the past few decades. Some of them are now operational and supplying electricity commercially e.g. MAKAI's OTEC power plant in Hawaii [6]

Bangladesh too can utilize such ocean thermal energy technology to harness the energy of the waves in the Bay-of-Bengal to meet the demands of electricity in the coastal borders of the country. Under reasonable considerations, there is promise to construct a cost-effective and sustainable OTEC power plant to tackle exponentially rising power requirements.

## 2.2 Current Energy Scenario in Bangladesh

Immense population growth, unplanned urbanization as well as industrialization prompted energy consumption significantly Bangladesh. Initially, the energy consumption was 12.7 Mtoe in 2000 which increased almost twice and became 24.3 Mtoe in 2011 [7]. Final energy consumption climbed by more than 200 percent between 1992 and 2011. In 2011, however, per capita primary energy usage was 0.152 Mtoe. However, between 1980 and 2010, total primary energy use climbed by 2.59 percent each year [8]. The demand for energy in Bangladesh is expected to exceed 50,000 megawatts (MW) as the Bangladeshi government pursues a long-term goal of becoming a high-income country by 2041 [9]. Primary energy demand continues to rise sharply, and is currently met by depleting fossil fuel (nonrenewable energy) sources such as natural gas, coal, oil, and petroleum products [10].

However, biomass contributes significantly to overall primary energy supply. Around 65 percent of the country's population lives in rural regions, and 44 percent is poor, for whom biomass energy is utilized as a major energy source [11]. Natural gas is a popular local main energy source in Bangladesh, and it is widely utilized in power plants, fertilizer factories, industrial units, and, more recently, the transportation sector as compressed natural gas (CNG). Natural gas accounts for 73% of total energy consumption as a main energy source [8]. The projected electricity demand is expected to be 24,147 MW with a GDP growth rate of 7.4% by 2025 and by 2014, at a growth rate of 4.4%, the expected demand is set at 60,836 MW per year. As part of its long-term goal of becoming a high-income nation by 2041, Bangladesh changed its power system master plan in 2016 (PSMP- 2016) and forecasted its GDP growth rate appropriately [12].

Bangladesh's current electricity generating capacity is roughly 18,753 MW [13]. Electricity output in KWh per capita is predicted to be 433 kWh, which is still lower than in industrialized nations across the world. When compared to all other energy fuels, electricity generation in Bangladesh is heavily reliant on fossil fuels. Natural gas accounts for over 63 percent of total power generation, with the remainder coming from coal, liquid fuel (imported), and hydropower. Estimates projected that the country's supply of fossil fuels, a major source of power, will be exhausted within the following decade [14]–[16]. In an all-sector energy demand scenario, 5.6 BCF of natural gas will be required by 2025 [16]–[18]. The current natural gas resource is 11.77 trillion cubic feet (TCF), which is expected to decrease by 2019 [16], [17]. With this present consumption rate of fossil fuel, Bangladesh is anticipated to confront a severe energy problem during the next few decades.

As a result, Bangladesh must adopt a sustainable energy policy to meet the rapidly increasing demand for electrical energy. This sustainable energy program has the potential to lessen the current reliance on indigenous natural gas as well as other imported fuels such as coal, liquefied natural gas (LNG), and hydropower (imported from the neighbor country) [19].

## 2.3 Fossil Fuel Energy Mix in Bangladesh

### 2.3.1 Natural Gas

Natural gas is one of Bangladesh's most valuable indigenous natural resources, and it plays an important part in the country's economic progress. It accounts for 75% of primary commercial energy supply and 79% of power generating [8]. Natural gas accounts for 64% of total electrical generation in Bangladesh. However, the country's natural gas reserves in 26 gas fields total just 12.88 TCF, well short of the needed demand of around 4221 MMSCFD. According to sector-wise gas consumption, the great majority of natural gas, 64 percent, is utilized to generate electricity by power plants and captive power stations. Simultaneously, industries, domestic homes, fertilizer production, and compressed natural gas (CNG) consume around 16.13 percent, 14.63 percent, 5.44 percent, and 4.81 percent, respectively. Natural gas demand is expected to reach 5900 MMSCFD by 2041 [19]. As a result, there is a big disparity between natural gas demand and supply, and this need for natural gas is increasing dramatically due to Bangladesh's quickly rising industrial sector. Bangladesh is temporarily reliant on Liquefied Natural Gas imports to satisfy this requirement (LNG). The infrastructure development for LNG import and re-gasification facilities, as well as the pipeline linking to the present transmission and distribution network, is currently complete. Bangladesh expects to begin operations in 2018 at a rate of 500 MMSCFD, which corresponds to 18% of today's natural gas consumption. Despite developments, mono fuel reliance on natural gas is visible throughout the industry, which may represent a danger to future long-term energy sector planning and the country's sustainable growth.

### 2.3.2 Coal

Coal is the world's most abundant fossil fuel. Coal accounts for 3.25 percent of total electrical generation in Bangladesh. National coal policy is being developed, and realistic planning and allocation of national budget resources are intended to bring genuine growth in a sector that has traditionally been stalled owing to administrative and technological barriers [8]. So far, five coal seams have been identified in Bangladesh's northwestern region. Bangladesh, according to estimates, has 1117 million tons (MT) of coal deposits that might be extracted from five separate feasible places [15]. As a result, Bangladesh promotes a national and international coal exploration program throughout the country [14], [15]. Despite having a vast coal resource, the Barapukuria

Coal Mining facility is currently the sole coal extraction plant in Bangladesh that distributes coal fuels to various power generating units in the country. The commercial production of coal from the Barapukuria Coal Mine began in April 2003. This coal mine can now extract up to 4000–5000 metric tons per day [15]. This coal is largely used to fuel 250 MW coal power plants at the mine mouth, with the remainder being used in Bangladesh's brickfields and small-scale businesses.

### 2.3.3 Nuclear Power

The nuclear power plant has been acknowledged as a cost-effective technology that will play an important part in the economic volume of electricity generation to satisfy future energy demand and combat climate change challenges. In 2016, the global installed capacity of nuclear power plants reached 392 GW, and these nuclear power plants produced around 11% of global energy [20]. The nuclear power plant's key issue is its safety and radioactive waste management. Despite intense discussion over the safety of nuclear power plants across the country, it has become an unavoidable alternative for Bangladesh in order to meet the country's rapidly increasing energy demand and reduce its reliance on natural gas for electricity generation. At the moment, two units of a 1200 MW nuclear power station are being installed in Rooppur in accordance with International Atomic Energy Agency (IAEA) nuclear safety regulations. The commissioning of this nuclear power station was carried out by the Russian Rosatom State Atomic Energy Corporation. According to a feasibility assessment, the first unit of Bangladesh's Rooppur nuclear power plant (RNPP) might begin commercial operations in 2024 and the second unit in 2025. Furthermore, the government intends to raise the nuclear power reactor's generation capacity to 10,000 MW in the future [21].

## 2.4 Renewable Energy Resources and Their Prospects in Bangladesh

Renewable energy sources have long been considered as an alternative to fossil fuels for clean energy generation due to its capacity to emit zero pollution to the environment. Although green renewable energy sources have immense potential for long-term growth, converting energy from green energy sources into electricity poses significant obstacles. Because of its geographical location on the planet, Bangladesh offers significant potential for solar energy collecting when compared to all other renewable energy sources [22]. As a result, Bangladesh must adopt a sustainable energy policy to meet the rapidly increasing demand for electrical energy. This sustainable energy[23] policy has the potential to reduce the current reliance on indigenous natural gas as well as other imported fuels such as coal, liquefied natural gas (LNG), and hydropower (imported from a neighboring nation) [19].

### 2.4.1 Biomass

Agriculture residue, agricultural residue, rice husk, jute stick, wood, sugarcane bagasse, municipal garbage, and animal waste are just a few of the biomass resources available in Bangladesh. This energy is largely used in village areas for cooking and a few small enterprises. Bangladesh has 14 sugar mills, each with a raw material crushing capability of around 1400 tons per day. This amount of bagasse is sufficient to generate 178 MW of energy [24], [25]. In addition, rice husk has promising potential as a new biomass technology in the country's rice processing business. Rice mills may create three types of by-products: rice husk, rice bran, and broken rice, with relative percentages of 22.75, 8.25, and 5.0. Currently, 500 automatic and semi-automatic rice mills and 17,000 husking mills are in service, processing 30 million tons of paddy each year. Furthermore, one ton of rice paddy may yield around 227 kg of dry rice husk with a calorific value of 16.3 MJ/kg, which is enough to provide 300 kWh of electric energy. The BPDB estimates that the techno-economic potential of rice husk for generating electricity is roughly 275 MW . Furthermore, Bangladesh has a significant reserve of animals such as cattle, buffalos, sheep, and goats, with an estimated number of 24, 1.5, 3.4, 25.9, 275.2, and 54 million in fiscal year 2016–17 [24]. IDCOL has funded the construction of about 73,152 biogas plants that can produce gases ranging from 1.2 m3 to 25 m3 from animal dung through August 2018. IDCOL intends to construct over 150,000 biogas plants around the nation [26]. Furthermore, Bangladesh has a huge amount of municipal and industrial wastes such as plastic, paper, glass, metal, biodegradable waste, and so on [27], [28]. The BPDB intends to generate around 11 MW of electric power from these solid wastes as well [19].

### 2.4.2 Hydropower

Hydropower is often regarded as the most cost-effective and dependable renewable energy source for power generation in the world. At the moment, hydro fuel accounts for around 16.4 percent of total global power production. Annual rainfall in Bangladesh ranges from 1500 mm to 3000 mm in the west-central, northeast, and southeast regions, respectively [29]. Furthermore, Bangladesh is a riverine country, with the river carrying 140,000 cubic meters of water every second during the yearly monsoon season. During the dry season, however, this rate drops to 7000 cubic meters per second [30]. The country's typical landmass is flat, with 80 percent of its elevation less than 10 meters above sea level, excepting mountainous portions in the southeast and northeast. As a result, despite abundant water resources, the possibility to build huge hydropower facilities in Bangladesh is restricted. BPDB runs a 230 MW hydropower project at Kaptai, with the capacity of this plant potentially increasing to 330 MW in the future [13]. During the monsoon season, when the water flows downstream of the dam, the additional 100 MW of electricity will be generated. BPDB has investigated two potential hydropower generating sites on the Sangu and Matamuhuri rivers, with capacities of around 140 MW and 75 MW, respectively [19]. Furthermore, possible micro and mini-hydropower producing units at numerous potential sites around the country have the ability to generate up to 200 MW of electricity [31]. Furthermore, Bangladesh has an alternative option to discuss with neighboring countries about redistributing the hydro-based electricity network through regional grid interconnections for stable base load power supply, which could be the best solution to reduce the local energy crisis while improving environmental concerns.

### 2.4.3 Solar Energy

Despite being largely reliant on fossil-fuel-based electricity, there is an urgent need to explore for alternative green energy sources due to the grave implications of greenhouse gas emissions and a lack of sufficient reserves of fossil fuels/natural gas [32]. One possible alternative to fossil fuels is the collecting of solar energy, which has the potential to exceed the country's whole current energy consumption. Indeed, Bangladesh's geographical location offers a potential possibility to harness earth-abundant solar energy from the earth's surfaces. According to Bangladesh's average long-term sunlight statistics, the duration of bright sunshine hours varies from four to eleven hours per day throughout the year, excluding the rainy and winter seasons. The country's solar insolation ranges from 4 kWh/m2/day to 6 kWh/m2/day, with the highest value occurring during the summer season [18], [33]–[36]. With over 300 bright days each year, Bangladesh's geo-location permits it to collect approximately 250 trillion kWh of pure solar energy each year [37]. These findings, together with those of other research, imply that the possibilities for using solar energy in Bangladesh are significantly superior to those of other renewable energy sources [38]. Today, utilities in both the public and commercial sectors are developing large-scale grid-connected and off-grid-connected solar energy harvesting systems with capacities of up to 1 GW [39], [40]. The availability of land, energy regulation, and the incentive environment are major barriers to deploying large-scale solar PV modules in Bangladesh [26], [40]. Despite these obstacles, the first solar PV scheme in Bangladesh began in the Norshingdi area for rural electricity reasons, with financial backing from France. The government awarded funds to Infrastructure Development Company Limited (IDCOL) in 1997 to construct infrastructure for medium to large scale renewable energy enterprises [26]. IDCOL created the first Solar Home System (SHS) in Bangladesh in 2003, ensuring continuous off-grid power delivery to isolated populations in rural Bangladesh. Furthermore, IDCOL has established a scheme that will provide financing for more than six million SHSs by 2021, with around 5.2 million SHSs already successfully installed under this program [41]–[43]. These SHSs have now grown to be Bangladesh's greatest renewable energy scheme.

### 2.4.4 Wind Energy

Bangladesh's wind energy potential was investigated by the Sustainable and Renewable Energy Development Authority (SREDA) and the Bangladesh Meteorological Department (BMD). SREDA measured wind speed in 13 distinct places around the country, whereas BMD monitors wind speed in various towns and cities. In addition, the Bangladesh Centre for Advanced Studies (BCAS) examined the BMD wind statistics in order to assess the potential for wind energy in Bangladesh. The analysis of this wind statistics shows various possible wind energy harvesting sites in Bangladesh's coastal areas, including Patenga, Cox's Bazar, Sitakundu, Teknaf, Saint Martin's Island, Char Fashion, Kutubdia, and Kuakata. [44], [45]. Between March and October, the wind speed at these sites ranges from 4 to 7 meters per second above sea level (5–50 meters). During the summer and monsoon season, however, powerful wind gusts with speeds far over 35 m/s are possible. Except for these regions, Bangladesh's wind energy potential is quite restricted [23]. Until date, the offshore wind speed for wind energy harvesting has not been extensively recorded, although existing satellite data shows that offshore wind speeds are somewhat greater than coastal wind speeds. BPDB undertook a feasibility study in several sites around Bangladesh, estimating up to 667 MW of power output from wind energy sources [19]. BPDB has previously erected wind power plants with capacities of 900 kW and 1 MW at Muhuri Dam in Feni and

Kutubdia Island, respectively. On an IPP basis, another 50–200 MW wind power station is proposed for the Perky Brach region.

## 2.5 History of the OTEC field

OTEC has a longer history than most people realize. In 1881, D'Arsonval was the first to use the name "OTEC." He proposed using warm surface water from tropical oceans to evaporate pressurized ammonia via a heat exchanger, then using the vapor to power a turbine-generator. The ammonia vapor might then be re-condensed using cold water pumped from the deep ocean. Because the working fluid circulates in a closed loop, D'Arsonval's cycle is known as the OTEC closed cycle.

Closed cycle plants employ the Rankine power cycle, similar to a modern coal or natural gas fueled plant that uses carbon fuel to evaporate water. OTEC, like coal and gas plants, provides a reliable supply of base load electricity. Other working fluids mentioned besides ammonia include propane, different refrigerants, and ammonia-water combinations. Within the temperature range of tropical and subtropical ocean surface waters, all of these fluids have a low boiling point in common.

Several literary works have since taken place to move closer towards the practical implementation of OTEC plants in several oceanic regions of the world. second type of OTEC plant was proposed some decades later by D‘Arsonval‘s student, another Frenchman named Georges Claude [46]. Claude proposed and later constructed what came to be known as an open cycle OTEC plant, which uses the ocean water itself as the working fluid. Under Claude‘s operating scheme, warm water is flash-evaporated in a vacuum chamber and the resulting steam is used to drive the turbine generator directly. An important feature of the open cycle process is that the steam can then be condensed using cold, deep seawater. Once condensed, the desalinated water can be collected and represents a valuable supply of potable water.

In both plant types, after being used to condense the working fluid, the cold water may additionally be utilized for a wide array of related activities, such as air conditioning and aquaculture. Open cycle plants are currently limited in power production to about 2.5 MW[47], and so may find their best application in freshwater-poor island communities with low electricity needs. Other plant configurations that have been proposed include the hybrid cycle (a cross between open and closed cycle OTEC) and the mist-lift cycle. Unfortunately, Both of Claude‘s plants were destroyed by weather and waves before net power was produced [47].

After the second failed attempt by Claude in 1950s, also known as the Abidjan Project, no more attention was paid to OTEC for several years. In 1964, J. H. Anderson [5] and his junior conceived of a new closed cycle OTEC plant, which overcame the weak point of Claude's system. In his cycle he firstly solved the issues of excessive cost due to low pressure working fluid by using high density fluids, which boil easily under relatively low pressure. Secondly, warm sea-water raised at low pressure by previous method were hard to eliminate. These were solved by immersing the evaporator and condenser at the same pressure as the working fluid, restricting the release of the dissolved gases. The third problem posed due to the plant being on land and requiring long intake pipes was solved by locating the plant near the sea coast. This invention of Anderson's attracted considerable attention and created the opportunity for rekindling research concerning OTEC, which was solely carried on by Claude until that point.

After 1970's energy crisis, several OTEC based projects started to take shape and for the first time, it was legitimately acknowledged as a viable alternative energy source. In 1970, Japan established the Committee for a Comprehensive Survey of New Electric Power Generation. The group investigated numerous alternatives to thermal power generation, and OTEC was one of them.

Around 1972, universities and government research institutions began fundamental research on OTEC. Toden Sekkei (Tokyo Electric Power Services) established a proposal in 1971 to develop an OTEC plant in the Pacific island republic of Nauru, and in 1973 conducted an assessment of the selected site's geographical features, sea conditions, and temperature. Because the generated electricity was actually used for routine purposes, this was the world's first practical OTEC power plant.

In September 1975, the Institute for Comprehensive Electronic Technology built its first model system for a simple experiment, generating 100 watts of power. The Institute's system was a closed cycle that cycled up to 50 tons of temperature-controlled warm and cold water per hour and used 500 grams of fluorine (chlorofluorocarbon) as the working fluid. Although it only produced 50 watts of power when the temperature difference was 19 degrees Celsius, this was boosted to 600 watts when the temperature difference was 27 degrees Celsius. In 1977, the Institute for Comprehensive Electronic Technology completed its second model system for advanced study.

Saga University created five "Shiranui" models. Shiranui No. 1 was a tiny flask-based device that produced one watt of power. It was an open cycle, like Professor Claude's initial experimental model. The later ones were all closed cycle, with Nos. 3–5 producing 1,000–1,200 watts. In addition, the university built two experimental systems, Imari Nos. 1 and 2, on the shore of Imari city. Imari No. 2, constructed in 1980, is capable of generating 50 kilowatts and has been utilized for numerous trials as a real operational OTEC system.

Several small-scale OTEC initiatives were also carried out in America at the same period. While all previous experiments had been simple and straightforward, the "Mini-OTEC" experiment conducted off the coast of Hawaii Island by The Natural Energy Laboratory of Hawaii Authority (NELHA) from August to November 1979 aimed to generate surplus electric power above and beyond what was required to run the pumps and other components of the system. The Hawaii State Government carried out this experiment in collaboration with companies such as Lockheed Martin and the Dillingham Corporation. The experiment was successful in producing 53.6 kilowatts of power by pumping up 50 liters per second of cold water at a depth of 650 meters. The system consumed 35.1 kilowatts to power its own water pumps, resulting in a net output of 18.5 kilowatts. This equates to 34.5 percent of the generator's overall output. The Energy Research and Development Administration (ERDA) in the United States spearheaded efforts to create numerous types of evaporators and condensers, and put them all together for testing at the Argone National Institute. Furthermore, between April 1980 and November 1981, a series of experiments were conducted at the same site on Hawaii Island to test their performance at sea.

This experiment, known as OTEC-1, was carried out aboard a converted oil tanker (fig 2.1). Surface seawater was fed into the vessel from the stem, while cold water was pushed up from a depth of 686 meters via three intake pipes erected at midship. These pipes were 1.2 meters in diameter and 5 cm thick, and they were composed of polyethylene. They were sealed on both ends and dragged to the location by a ship, where they were sunk with weights at the end. However, no generator was installed in this experimental system; instead, researchers focused on the capabilities of evaporators and condensers, methods of connecting intake pipes, methods of removing marine creatures and other unwanted materials that clogged the system, and the effects of sea currents. Furthermore, the United States instituted a long-term plan leading up to the year 2000, in which the power industry achieves practical OTEC, national research and development for systems. It became evident from this project that OTEC technology could be associated with floating infrastructures, regardless of efficient power generation at the time. It was the inception of the concept of floating power plants that can generate power afloat.

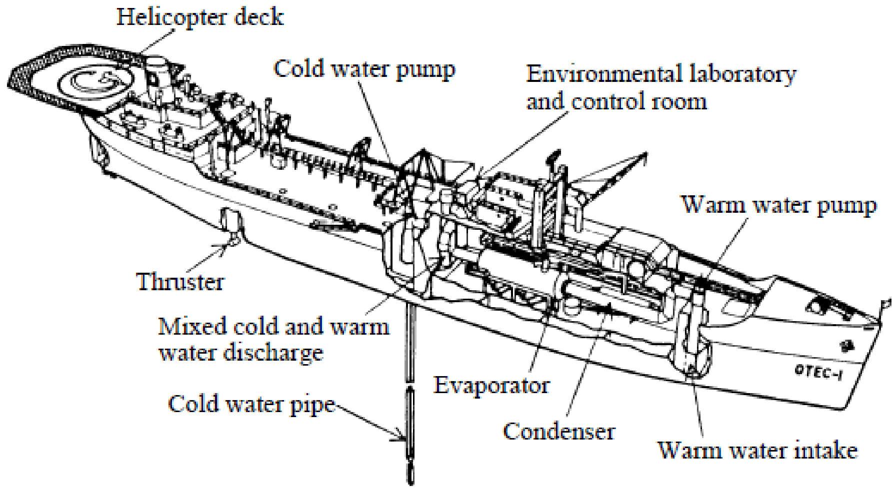



Fig 2.1: Converted tanker for OTEC-1 (no generator) [45]

The Mini-OTEC experiment in Hawaii was the first to create more power than was required to run the system, but it was only a modest quantity. The following tale is about the world's first occurrence of OTEC producing practically useful power. This occurred in the Republic of Nauru over the course of roughly a year. It was executed with the help of the Japanese government and in collaboration with the Toshiba Corporation and the Shimizu Corporation by Tokyo Electric Power Company and Toden Sekkei. A generator was built on land and was planned to produce 100 kilowatts of power using fluorine-22 as the working fluid. The inner diameter of the cold water intake pipe was 70 cm. Cold water was pushed up at a rate of 22 tons per minute from a depth of roughly 580 meters, 1250 meters off-coast, while surface water was pumped at a rate of 24 tons per minute from 150 meters off-coast. A total of 120 kilowatts of power were produced. About 90 kilowatts of this electricity was used within the facility, while the remainder was distributed to a nearby primary school and other locations on Nauru. On October 14, 1981, OTEC power was brought to that Nauru school for the first time [43]. Saga University (Japan) constructed 75 kW (1984) and 9 kW (1995) gross power closed-cycle Lab Models. Since 1998, the National Institute of Ocean Technology (NIOT), the Government of India, and Saga University in Japan have collaborated on the design, development, and demonstration of a 1 MW (gross) OTEC floating plant demonstration project off the Tuticorin coast of Tamil Nadu, which will be the world's first MW range plant. The unit, which is located 60 kilometers from Tuticorin, is installed on a 68.5-meter-long barge called the "Sagar Shakthi," which holds a Rankine Cycle-based power plant.

Moreover, a 210 kW (gross) open cycle shore-based OTEC plant facility off the island of Hawaii was developed, built, and successfully operated by NELHA (US) for the US Government for 6 years (1993-1998) with a net power generation of 100 kW.

On the drawing board at OTEC is a modest facility for the United States Navy installation on the British-occupied island of Diego Garcia in the Indian Ocean. OCEES International, Inc. is collaborating with the United States Navy on a design for a projected 13 MW OTEC plant that will replace the present power plant powered by diesel generators. This OTEC plant would also provide the base with 1.25 million gallons of drinkable water per day. A private American company has proposed constructing a 10 MW OTEC facility on Guam. The Alternative Energy Development team at Lockheed Martin is now in the final design phase of a 10 MW closed cycle OTEC prototype plant that will be operational in Hawaii by 2012-2013. In the near future, this technology will be expanded to 100 MW commercial systems.

Architect and engineer Dominic Michaelis, Alex Michaelis, and Trevor Cooper-Chadwick of Southampton University are working on a floating Hexagonal Energy Island near Hawaii Island that will gather energy from OTEC as well as winds, sea currents, waves, and the sun. The US government is funding and directing the Energy Island Project in Hawaii. Based on 2000 data, 52971 Energy Islands with a total area of 111 x 111 kilometers would be required to carry the whole global energy demand. Table 2.1 tabulates a timeline of the various historical projects that mark the progress of OTEC technology over the years. It is observed that the mid to late 20$^{th}$ century was the time when most of the relevant work was conducted on OTEC and eventually left out as a topic of interest due to insufficient technological support at the time. But with modern advances, new discussions on OTEC seems very much plausible.

Table 2.1: Historical Progression of OTEC technology [48]

| Year | Contribution | Year | Contribution |
|---|---|---|---|
| 1881 | J. D'Alsonval (France) Presented the idea of OTEC | 1981 | Tokyo Electric Power Co. (Japan) succeeded to generate 120kW on Nauru |
| 1926 | G. Claude (France) started experiments od OTEC | 1982 | Kyushu Electric Power Co. (Japan) succeeded to generate 50kW at Tokunoshima Island |
| 1933 | G. Claude (France) constructed on board type OTEC | 1985 | Saga University completed 75kW experimental plant |
| 1964 | Anderson (USA) presented a proposal od off-shore | 1985 | Kalina (USA) invented a new cycle with ammonia/water mixture |
| 1970 | New Energy Research Committee researched OTEC | 1988 | OTEC association was established (Japan) |
| 1974 | OTEC was researched as a part of Sunshine Project (Japan) | 1989 | Industrial and Technological Board succeeded to generate 3kW at Toyama Bay |
| 1974 | ERDA project started research on OTEC (USA) | 1990 | International OTEC Association (IOA) was established (Taiwan) |
| 1974 | First OTEC conference was held (USA) | 1993 | 210kW open cycle OTEC was completed in Hawaii |
| 1977 | Saga University (Japan) succeeded to generate 1kW of Power | 1994 | Uehara (Japan) invented an advanced thermal cycle |
| 1979 | Mini-OTEC generated 50kW (USA) | 2001 | 1 MW closed cycle OTEC was constructed by NIOT (India) |
| 1980 | Saga University performed off-shore experiments at the sea of Japan | 2002 | NIOT (India) performed 1 MW experiment |

Table 2.2 presents the various experimental plants that were attempted through the course of time. It is proven through several projects that a small scale plant is functional, while the possibility of a large scale plant is only dependent on time and investment.

Table 2.2: OTEC plants and experiments around the world [49]

| Location | Capacity | Remarks |
|---|---|---|
| Hawaii | 50 kW | Closed cycle, Lockheed Missile and Space Co., 1979. |
| Nauru, Japan | 120 kW | 1982, Tokyo Electric Power Company |
| Hawaii | 1 MW | Land based, open cycle, NELA and LLC, 1993 |
| Okinawa, Japan | 50 kW | Land based, 2013, Xenesys |
| Hawaii | 10 MW | Prototype plant, 2015, NELHA, DoE, Lockheed Martin Systems |
| Martinique | 10 MW | Floating plant, 2016, DCNS France |
| Southern China | 10 MW | 2017, designed to pave the way for small to large scale OTEC plants |

## 2.6 Contemporary Literary Works in the OTEC Field:

Following the ever-increasing emphasis of world leaders to find alternative solutions to power generation, a wide array of literary works have been published in recent years with the attempt to commercialize and generalize the use of ocean thermal energy in various parts of the world. Several works focus on the feasibility analysis in terms of power output, exergetic and economic considerations. Some others tried to optimize the various controllable parameters, like machinery performance, orientation of the components and working fluid variations.

Some of the old work in OTEC resource is conducted by Uehara et.al, who used the collected data from the extensive temperature readings of the sea surrounding the Philippine archipelago by the Hydrographic Department of the Japan Oceanographic Data Center. They subdivided the study region into several sites and analyzed the collected data that would allow the necessary water temperature difference. Further analysis of the bathymetry provided information of the weather conditions and sea nature such as current velocity and direction, wind speed, wind spectrum etc. Finally, they projected two models of OTEC plants- one 5 MWe gross power onshore type and the other 25 MWe gross power floating type. An optimization study of a 100 MWe power plant in Saga University was utilized to compute the essential parameters for the model plants. A cost estimation was presented for both types of plants and the onshore type 5 MWe plant was suggested to be economically and technologically feasible [50].

Nihous was among the first in his field to estimate the OTEC resources by conducting analysis on the Atlantic Ocean. He utilized an interhemispheric box model of the Atlantic thermohaline circulation (THC) is modified by replacing the tropical box with two vertically resolved sub-domains. His findings showed that under the specific conditions, steady-state OTEC net power production density would reach a maximum of about 80 kW/km2 (corresponding to 1.8TW) with a cold seawater flow per unit area of about 14 m/yr. It was concluded that the presented works here strongly hypothetical and only served to project the environmental effects like global warming on the OTEC resources in the studied location[51].

In a later work Nihous presented the mapping of OTEC resources around main Hawaiian island. The concept of identifying OTEC resources by simply utilizing the temperature difference between 20m and 1000m of the ocean water was formulated around several research works of this time. On Hawaii Island, they deployed cutting-edge equipment such as the HYCOM+NCODA 1/12° model, which allows them to follow changes on a daily basis across a large region. It was discovered that average OTEC temperature differences were continuously larger west of the islands by around 1 °C, although the amplitude of the annual cycle diminishes worldwide from north to south, as predicted. It was determined that a 1°C change in the resource would generally result in a 15% variance in net OTEC power production [52].

Rajagopalan et al. used an ocean general circulation model for the first time to analyze this (OGCM). In global (4°x4°) MITgcm simulations, large-scale OTEC processes were simulated by fluid sources and sinks of specified strength. Preliminary steady-state (timeasymptotic) results demonstrated parallels, but also major discrepancies, with previous one-dimensional (1-D) research. It was established that global OTEC resources are most likely constrained by OTEC flow impacts on the vertical oceanic thermal structure's stability. The substantial OTEC flow rates associated with maximum net power generation would result in a major boost to the oceanic thermohaline circulation (THC) [53].

The availability of OTEC resources around Colombia was assessed in a work published by Devis Morales et. al. They calculated the available thermal resources using monthly climatological temperature data from the World Ocean Atlas 2009 (WOA09). However, because the datasets lacked quantitative detail, they relied on bathymetric characteristics and high resolution oceanographic datasets. The targeted investigation was based on the General Bathymetric Chart of the Oceans (GEBCO), Colombian Navy seabed soundings, and temperature reanalysis data (GLORYS1V1) from MERCATOR-OCEAN. After careful consideration, San Andres Island was chosen as the best location for an OTEC system. Besides, the seasonal variability, seafloor features and social and economic effects of placing such a plant were discussed in their work. It was concluded that around 50% of the net power required by the San Andres Island could be met with a 10MW plant, which could be potentially cheaper that fossil fuel plants in future [54].

Doorga et al. created a model to calculate the temperature differential between deep (1000 m) and surface (20 m) ocean layers near Mauritius. An algorithmic technique was used to calculate the net power generated by a planned OTEC power plant using sea surface temperature satellite photos with a resolution of 1 km. The NOAA produced the comprehensive gridded bathymetry, known as the ETOPO1 dataset, with a resolution of 1 arc minute. By dividing the yearly data into four monsoonal time frames, the regional and temporal fluctuations of the net power generated were observed. The results revealed that the south-western area of Mauritius has considerable OTEC resources, with an annual mean daily net power generation capacity of roughly 95 MW, accounting for nearly 20% of the island's peak power consumption. The bathymetry of the southern region was also advantageous due to the availability of deep cold water less than 5 kilometers from the coastline. The 100MW net OTEC system's energy and exergy efficiencies were determined to be 1.9 and 22.8 percent, respectively [55].

A more recent study was conducted by Vanzwieten et al. to assess the ocean thermal energy potential around Florida and its surrounding regions. The OTEC resource was analyzed with the combination of a state-of-the-art ocean circulation model, the Hybrid Coordinate Ocean Model with Navy Coupled Ocean Data Assimilation (HYCOM+NCODA) with an accuracy of 1/25° resolution taken daily. A 100 MW net/ 150 MW gross model plant was theoretically placed in order to predict the attainable power values offshore Florida. The power predictions are then constrained by local cold deep sea water replenishment to provide an upper limit to the sustainable OTEC resource. Seasonal variations in power was assessed and mean annual power was compared to see the consistency of the results. The data source was validated further with in situ data to verify the reliability of the source. Graphical analysis of parameters like temperature difference and wind velocity was conducted. Results showed seasonal dependency with a maximum net power production potential of 152 MW in August and minimum of 78 MW in February, matching the seasonal trends of power demand in the region. A volumetric flow rate consumption of 0.01% was presented due to placing such a plant [56].

Garduno-Ruiz et al. undertook more work on the site selection criteria, proposing a preliminary selection approach to discover suitable places for OTEC deployment throughout the Mexican coastline. Time series analysis, geographical distribution via Geographic Information System (GIS), and Multi-Criteria Decision Analysis (MCDA) utilizing the Technique for Order Performance by Similarity to Ideal Solution were all part of the process (TOPSIS). Bathymetry was estimated for all coastal zones using the General Bathymetric Chart of the Oceans (GEBCO). The Deep Ocean Temperature (Td) at 1000 m deep was calculated using the World Ocean Atlas' monthly statistical mean (1955–2012). (WOA). The primary goal of this effort was to produce a preliminary list of ideal locations for the eventual deployment of an OTEC-50 MW (closed cycle) floating plant. The viability of such a plant was determined using a decision matrix. Environmental limits, societal needs, and electrical needs were all evaluated. A total of four potential sites were selected- Lazano Cardenas, Cozumel, Puerto Angel and Cabo San Lucas where there production capacity, economic, environmental, socio-economic criteria were analyzed [57].

Design of a 5MW OTEC plant was conceptually presented by Hamedi et.al. A 5MW closed cycle floating plant in Iran with an annual average temperature difference of 22°C was selected at a distance of 33 kilometers from Chabahar harbor. Deep seawater would be extracted from a depth of 1000 meters, yielding 3.52MW of net power. According to cost estimations, the plant's levelized cost of energy is roughly 0.117 $/kWh, which is an acceptable level when compared to other renewables. The proposed OTEC design described in this article reveals a thermal potential in the Oman Sea that might help satisfy Iran's southern coast's power requirement. However, the data source was not disclosed explicitly in their site selection [3].

Adiputra et al. proposed the design of a 100 MW OTEC plantship in Mentawai Island, Indonesia. The OTEC layout is configured utilizing the constraint fulfillment approach throughout the design phase, and the projected floating structure size is modified using Monte Carlo simulation. The goal of adopting this approach is to determine if a given plant size is acceptable, rejected, or even overdesigned depending on the limits. Variables in the design process include the cold and warm water transit velocities, the size of the plantship, and the proximity of the OTEC equipment to the seawater tank. On site experiments were conducted to measure the temperature profile of the selected sites. The seasonal variation in the warm surface temperature was observed, especially in the monsoon season. Design parameters of the heat exchangers, turbines, risers and pumps were discussed. Power output from such a converted OTEC plant were analyzed and some discussions were made on how to minimize cost and complication in the process. Optimization of the placement of components like the seawater tank and the heat exchanger were analyzed [45].

In a later collaborative work by Jia-Nihous, the impacts of OTEC effluent discharge on the physical features of the ocean environment on a Hawaiian island in the North Pacific Ocean

Their research included a near field mixing model that forecasts the near field dilution of effluent plumes and a high-resolution ocean circulation model that simulates effluent dispersion in the far field. Numerical experiments are carried out to investigate the parameters that impact wastewater dispersal. The results reveal that the presence of OTEC devices has no effect on the thermal resource over the study period, which runs from late spring to early fall, and that it remains above 20°C. In each experiment, the depth of neutral buoyancy (trap depth) for the OTEC effluent plumes was substantially below the discharge depth and remained quite steady over the summer months. Deeper trap depth results from deeper discharge depth and multiple devices. The physical environment changed little as a result of the presence of one OTEC device. Significant changes in flow and stratification are reported at 16-OTEC strength, while the physical environment would return to normal in about 2 weeks if OTEC activities were turned off [58].

## 2.7 Previous Work on OTEC in Bangladesh

Shifur Rahman [59] proposed the introduction of OTEC power plants in Bangladesh and tried to narrow down a few locations where there might be potential to place an OTEC plant, if such a project ever were to take place. Their works primarily focused on the theoretical possibilities of such a plant, as they mentioned various types of OTEC designs such as the open cycle, closed cycle and the hybrid cycle which could be used on such a plant. They tried to apply some idealistic conditions of such Rankine cycles to open the discussion on OTEC plants in general in Bangladesh. An estimation of efficiency was stated using the Carnot Cycle to give an idea of the type of output that can be obtained. As per the methodology used by them to obtain such potential sites was the temperature difference between surface and 1000m map from the works by L.A Vega, which show the Bay of Bengal region as a potential site for OTEC plants. The authors then estimated a few sites like Cox's bazar, Saint Martin Island, Kuakata, Patenga and Parki beach, Nijhum Island where such a plant may be effective to meet the growing demands of these coastal regions.

In a later work published by the same author, we see an effort to provide statistical data on Cox's bazar to demonstrate the population, area, demand and availability of electricity in Cox's Bazar. It was observed that for the 51,918 people, the demand of electricity was 45 MW, while only 9 MW was available through conventional lines. The rest were provided by fuel run generators. Hence, proving that Cox's Bazar could make use of such an OTEC plant as a green and alternative solution. A sample capital cost calculation was roughly estimated for a 50 MW OTEC plant. Unfortunately, the detailed description of such a plant and its viability in terms of concrete data analysis were beyond the scope of their study. Furthermore, no component description, detailed economic consideration or legal restrictions were discussed in the work. The assumption of Cox's bazar being a valid location for an OTEC plant was also not justified in their work. Effect of such a plant on the environment was not evaluated in detail to provide a solid argument for their case. Another work by Walid bin Habib [60] studies the electrification potential of remote and isolated tropical islands in Bangladesh using OTEC technology. Their work also proceeds in similar fashion to the previous work, identifying potential OTEC sites as per the temperature difference choropleth map of the world provided by L.A Vega. Likewise, the author demonstrates a few types of Rankine cycles that may be implemented in Bangladesh, but not going further into the technical details of such a plant. In their work, there is some indication of the environmental impact of such plant in terms of oil leakage and damage to the natural marine ecosystems, but further details are left out of the scope of their work.

As per their findings, a 'swatch of no ground' region near Khulna provides the nearest distance away from the shore where a feasible temperature difference can be obtained for power generation, and all other potential sites are more than 200 nautical miles from the coastal region of Bangladesh. Hence, arguing that this region would be the most economically viable zone for a commercial implementation of a power plant. However, their work too lacks constructive details of such an OTEC power plant, the involved costs and regulations from the government regarding such projects.

# Chapter 3
# METHODOLOGY

The purpose of this paper is to provide an assessment of the thermal reserves of the Bay of Bengal region, eventually identifying locations at which a potential 100 MW OTEC plant may be deployed the sea borders of Bangladesh suiting the required potential difference of approximately 20 degree Celsius. Afterwards, to determine the power output of the model power plant once deployed, its capital and operating cost estimates and Levelized cost of electricity (LCOE) and Emission of $CO_2$ due to the implementation of the plant. Afterwards, to utilize the powerful tools of machine learning to create a univariate model of the temperature difference against time and visualize the trend of temperature difference over the coming years once OTEC power plant is deployed.

The process of converting thermal energy in association with temperature gradient formed in the ocean to power, this idea that was first initiated over a century ago, is known as ocean thermal energy conversion (OTEC). [61] and [62], for example, review relevant technologies and conflicting theories (2003). Temperature declines with depth because the density of seawater has an inverse relationship with temperature, and ocean waters are layered in stable gradients except in deep convection containing highly localized zones. OTEC is feasible when the water on the surface has a higher temperature than the water at depth. Various attempts to implement this technology have been attempted throughout the years, but progress toward commercial-scale deployment has been difficult for a variety of reasons. As the recent importance on developing future renewable energy, a lot of attention in OTEC has resurfaced in the United States.

The availability of cold water (generally below 10°C) is an important component of ocean thermal resources, and as these waters can be utilized as a heat sink for air conditioning and forms of cooling purposes, a thorough study on the ocean on OTEC potential provides data on this resource. This paper also discusses these energy-saving resources.

## 3.1 Assessment of Technical, Theoretical and Practical Feasibility

For convenience of usage, the evaluation of the world's total OTEC resource can be classified in a number of groups in hierarchical order. At first, a theoretical analysis is done on the datasets to obtain necessary geophysical parameters for the process. The most basic of them is the temperature differential $T_D$ that is found between the warm surface water and cold deep water temperatures. Temperature difference of 20°C or more look to be a resource worth exploring with today's heat exchanger technology.

A previous study [51], [63] was published, and this research's theoretical assessment improves on that work. A second stage, called technical analysis, combines the dataset with other pertaining parameters in order to calculate the power generation potential. For OTEC technology, this necessitates the collection of additional geophysical data, including deep water depth (to find detrimental power losses due to pumping) and actual temperatures of cold and warm waters. A third stage, known as a practical analysis, considers aspects like sustainable conditions, excluding from protected areas, view-sheds and shipping lanes, and other social concerns that hamper the process of deployment. Global sustainable OTEC estimates range over three orders of magnitude, according to Nihous (2005). This research provides localized resource utilization on the basis of available deep water resource and published results by Nihous, however it ignores practical assessment considerations. The scope of this research, as a worldwide resource assessment, excludes those exceedingly heterogeneous and complicated aspects, and hence does not present a concrete "practical" assessment.

## 3.2 Ocean Data Source and Extraction

First, the project's resources prevent a precise focus that would be required for a site characterization. In any event, assessment of sites on a global scale would be a wastage of time and resources. It is possible to pick places of interest for OTEC improvement and facilitate required focus needed for a site characterization by starting with a resource evaluation. Moreover, there is just no universal oceanographic information that would aid for the development of detailed site attributes. It is feasible to select candidate sites for OTEC development based on the findings of the current resource assessment. Developers interested in a certain location would need to conduct a full site characterization to establish viability, cost drivers, and the best plant locations.

### 3.3 Criteria of Selection and Data Sources Available

Because there is a lack of "required and adequate" data for global-scale site characterization, applying those parameters to the resources classification task becomes a problem. There are various things to think about, each of which is covered in greater depth below:

- Observational data is ideal, but in the ocean, it is both less and inhomogeneous non space. While long-term climatologies are available (such as the one used by [51], their coarse resolution limits their application.
- In an era when global temperatures are trending increasing, the utility of long-term climatology for a contemporary evaluation and planning is being debated [53], [64].
- While global ocean temperature trends and changes are the primary geophysical data of relevance here, building the hierarchy of resource evaluations (particularly the practical assessment) necessitates knowledge of ocean currents, particularly at deep. For currents, observational databases are even less thorough than for temperatures.

Fundamentally, one of the most difficult aspects of the challenge at hand is converting natural resources – such as T of the water in the column to power potential. Estimates published [51] employed a simplified water column model of OTEC procedure and the water column interaction to reduce the widely discussed global potential of 10-20 terawatts (TWe) to a more reasonable number of roughly 5 TWe. The current study takes a unique strategy, which is detailed in Section 3, to estimate the potential OTEC resources using advanced satellite data and data analytics tools. However, first and foremost, it is required to comprehend the natural resource in question and to compile a dataset that can be translated (OTEEV Objective 1). As already stated, climatology is one method. Nihous used the National Oceanographic Data Center's (NODC) World Ocean Atlas 2005 [65] where he used 1000 m temperatures and 1° latitude-longitude datasets to create monthly maps, globally of T values sufficient to facilitate the OTEC procedure, thus finding the quantity of the oceanic resource.

This method increased the OTEC resource assessment, but the dataset's limitations (very coarse resolution and the relatively traditional usage of 1000-m temperatures for the cold source, TD, which removed prospective resources in shallower water) suggest that there is still more work to be done. [53] acknowledged this in a later study and turned to numerical model findings; his two-month localized daily resource maps based on high-resolution simulations are also available online.

The benefits of numerical model findings include consistent gridding, access to all state variables, and worldwide coverage. Naturally, because they are the outcomes of numerical model integrations, they are subject to the model's fidelity limits. These drawbacks can be overcome by using results from numerical integrations with data assimilation; that is, results from simulations in which global observational data is added in real (model) time to ensure that the findings are as close to the real ocean as feasible. Modeling in the form of interpolation is employed to grid the irregular observational data in datasets like the NODC WOA05 compilation used by Nihous, thus even those "observations" have undergone extensive computational processing.

The OTEEV Project would be ideal if there was a worldwide climatology of T and other quantities that could be included into the broader DoE resource database at high resolution. However, no such climatology exists, thus interpolating the NODC WOA 2005 dataset to a higher resolution is not justified. Furthermore, a climatology based solely on T would leave the issue of water-mass mobility unresolved. By their very nature, OTEC plants deplete both warm and cold water masses locally unless they are replenished by solar radiation and ocean circulation, respectively. This aspect of the ocean's climatology can be included in numerical simulations, and resource replenishment rates can be approximated.

The HYbrid Coordinate Ocean Model (HYCOM) [38], [66] is the most recent generation of atmosphere/ocean simulation tools in a family of numerical models that use density as the vertical coordinate. The HYCOM concept was initially presented by [67] after many years of work on a pure isopycnic-coordinate model (MICOM, the Miami Isopycnic Coordinate Model – [68], [69] and simplified attempts to overcoming MICOM's constraints [67].

The nature of the deep ocean's adiabatic flow field provides the basis for employing this approach to solving the equations of motion in finite-difference form. The seas conserve temperature and salinity, and thus density, below the surface photic zone and mixed layer, where mechanical mixing and thermodynamic processes can prevail. Potential-vorticity conserving layers — for which density is the "natural" coordinate system – accurately capture the dynamics. Because surface thermodynamic processes can change the density of upper-ocean seawater, a more traditional formulation (such as depth or pressure coordinates) is required there — hence the "hybrid coordinate" term.

Extensive research has concentrated on the issues of matching the two coordinate systems at their interface during the last 15 years, and the current formulation of HYCOM conserves key state variables and is numerically stable. The NRL simulations used in OTEEV employ the Navy Coupled Ocean Data Assimilation (NCODA – see [68] multivariate technique [69].

Wind stress and speed, heat fluxes (including evaporation), and precipitation are all included in the Navy's operational Naval Operational Global Atmospheric Prediction System [33], [70]. As the model advances in time, both the dynamics and thermodynamics of the model are realistically forced and guided toward the observations. All data relevant to OTEEV are included in the model outputs, which are interpolated using a physically and dynamically consistent interpolation approach to produce very high-resolution results. As a result, it provides a valuable platform for assembling the dataset needed to fine-tune the worldwide assessment of the OTEC resource [65].

The HYCOM+NCODA results, on the other hand, give full data coverage because they are derived from a worldwide, full-physics circulation model. Their fidelity is also quite strong because they contain global data assimilation, albeit some of the early HYCOM+NCODA simulations include a deep-water temperature bias. 3 While this effect is minor and limited to depths below 1000 m, using data that are free of this bias ensures that the TD values used in the study are as precise as feasible. As a result, the OTEEV study will be based on the findings of simulations 90.6 and 90.8, which are continuously updated and cover the period September 2008 to the present. As a result, the methodologies developed in this project can be simply utilized in the future to maintain a near-real-time OTEEV resource evaluation.

## 3.4 Characteristic Advantages using Data of HYCOM+NCODA

As previously stated, HYCOM has grown from a University of Miami-developed ocean circulation model to an international collaboration including a huge number of researchers. The community website [71] contains thorough documentation and user guides, as well as a bibliography, on the concept and its applications. The model's hybrid approach to the ocean's vertical structure allows it to calculate the impacts of both surface exchange processes and conservative advection in the oceanic subsurface to the best of its ability. HYCOM is the right vehicle for this resource evaluation since both of these effects on the oceanic temperature structure are significant for OTEC resources.

The following is the forecasting procedure. A ten-day model integration is computed each day [Day N], from Days N-4 to N+5, with Days N+1 to N+5 representing the prediction for that day and the rest a daily hindcast. The NCODA procedure is used to incorporate new observed data for Day N. The starting conditions for Day N-4 are derived from the previous day's outcomes for that same day, which contain data absorbed during four days of forecasting. Each integration's results are archived at 00:00 GMT (daily) and Day N-3 of the previous day are written over by Day N-4 of the Day N forecast run. Although the model's finite differencing uses a staggered grid, the archived data is re-mapped onto an un-staggered, depth-coordinate grid and stored as netCDF [72] files for user convenience.

The results for each day are divided into four files: temperature, salinity, two velocity results, and a file containing sea-surface height results. For this analysis, ten years (2012-2021) of such results were obtained in .csv format for data analysis, covering three difference seasons- summer, rainy and winter. Seasonal values were clustered together since the temperature for a particular season remains somewhat consistent. These consistent sets of data would be much easier to handle compared to significantly varying data over all seasons.

## 3.5 Generation of Datasets and Data Analysis

Processing for resource assessment for OTEC potential is simple given the later sections of this chapter. It is crucial to stress, however, that a completely theoretical evaluation is not conceivable. This is because determining meaningful values for T necessitates a criterion for determining temperature difference, which, in turn, necessitates knowledge of the technology in question. The earlier climatology-based study [51] used temperatures from 1000 m for the temperature differential, although the depth was chosen mainly at random. OTEC technology uses the Rankine cycle to generate electricity, and some energy is consumed in the process to power the OTEC plant. A portion of the electricity must be diverted to pump huge quantities of cold (heavy) water from a suitable depth. The deeper the water is, the colder it gets, because the ocean is stratified. However, in the upper regions of the water column, the temperature structure is more stratified (meaning the vertical temperature differential is bigger).

As a result, finding colder water to generate more power necessitates more pumping, and the cost-benefit trade-off between increased pumping and increased power generation must be considered when selecting a cold-water depth. The additional cost of long cold water pipes is added to this power trade-off, emphasizing the importance of finding the $T_D$ source as shallow as possible. To quantify the power trade-off, you'll need a model of the OTEC technology in question, which takes the evaluation from theoretical to technical. However, since such a model is required to estimate power levels in any case, it is appropriate to use it to create the T dataset.

The data extracted from HYCOM+ NCODA for the years 2013-2021 are not usable in their original forms. An extensive process of data analytics is required to receive useful information that is capable of giving out results that would help in selecting the right zone for placing an OTEC plant in the selected study region. The methodology of analyzing the data is presented below:

### 3.6 Data Selection Criteria and Collection

The data was downloaded in .csv format for every individual season- summer, rainy and winter of every year of the study period (2013-2021) from HYCOM+NCODA global 1/12° analysis. The selected dataset provides a versatile range of data for the entire co-ordinate system of the world, with a spacing of 0.08 degree for both latitude and longitude, up to 5500m from the surface. The frequency of data collected is also thorough as it collects data every hour. Other parameters available apart from temperature in the dataset were the water velocity in two direction components (eastward and northward) and salinity. The study region was set in between 5° N to 22°N longitude and 80°E to 95° E latitude. Since the theoretical works of OTEC resources states that an extractable form of energy can be obtained by the difference of temperature between 20m and 1000m depth of water, the study selects several fixed depths- 20m, 200m, 400m, 600m, 800m and 1000m for a comparative analysis and also as a means to verify the previously published theory. The stride for time was selected daily (1), while the strides for latitude and longitude were selected as 12.5. The seasons of the year were divided among the 12 months of a year as such-

Summer: 1st March to 30$^{th}$ June

Rainy: 1$^{st}$ July to 31$^{st}$ October

Winter: 1$^{st}$ November to 28$^{th}$ February (29$^{th}$ February for Leap years)

### 3.7 Data Processing using Python

After all the criteria were set, the datasets were compiled in .csv format to analyze them in python. The benefit of the .csv format is that it allows to compile the data in a dataframe, which is the standard for data analytics in python. The widely popular python module for data analytics, *Pandas* module was selected for this purpose. *Pandas* is a Python package that offers data structures that are rapid, adaptable, and expressive, making it easy and natural to deal with "relational" or "labeled" data. Its purpose is to provide a framework for conducting realistic, real-world data analysis in Python. It also wants to be the most powerful and versatile open source data analysis and manipulation tool accessible in any language. It is already well on its way to accomplishing its goal [73].

Pandas is a Python module that operates on top of NumPy and is widely used for data science and analytics. NumPy is a low-level data structure that allows you to work with multi-dimensional arrays and perform a variety of mathematical array operations. Pandas offers a more advanced user interface. It also includes robust time series capability and improved tabular data alignment. In Pandas, the dataframe is the most important data structure. As a 2-D data structure, it allows us to store and manipulate tabular data [74].

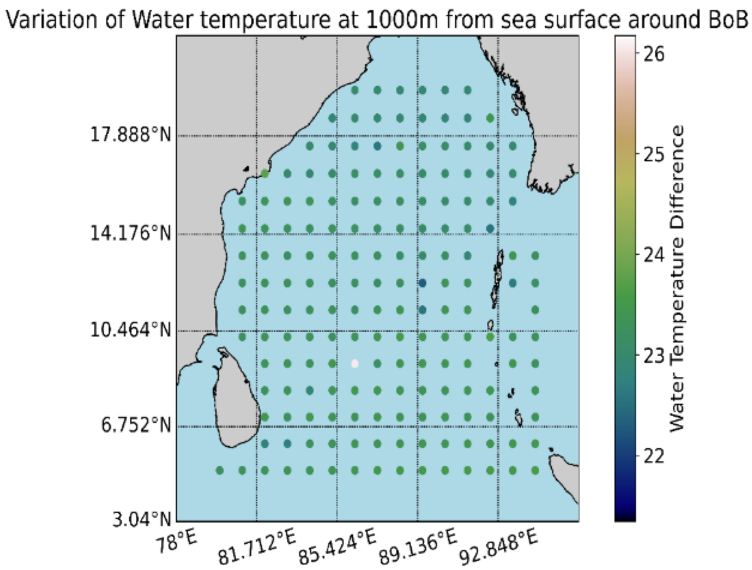
The collected dataset initially did not have the desired organization to conduct data analytical operations from the get go. They were compiled together by the *pd.merge* function and compiled into proper seasonal dataframe before conducting further analysis. A seasonal dataset for 20m ($T_s$) of a certain year was selected to conduct the required operation to get the average values. Consequently, the seasonal dataframe was rid of all invalid/ NaN values to filter out the unnecessary bulk of data and work with only valid information. The resultant dataframe was then grouped according to every combination of co-ordinate in the considered range and grouped using *pd.grouby* function. Once grouped, average values were extracted by using *pd.mean* function, eventually which leads to getting well defined temperature values for every single co-ordinate at the certain depth for the taken season. The same procedure is similarly repeated for the 1000m ($T_{1000m}$) dataframe for the same season and the difference between the corresponding coordinate temperatures is calculated to get the seasonal temperature difference at each co-ordinate. Similar operations were conducted for the same season for all the other years and eventually averaged to get the precise temperature difference for every coordinate for that certain season throughout all the years of the study period. Furthermore, the other seasonal datasets were repeated following the same procedure to get all the seasonal mean data for all the co-ordinates in the study region. This extensive process of repeated average is believed to hold very good precision to provide an excellent estimation of the actual temperature difference ($\Delta T$), eventually leading to an accurate estimation of the extractable power from the model power plant.

### 3.7.1 Selection of Appropriate Sites for a Model OTEC Plant

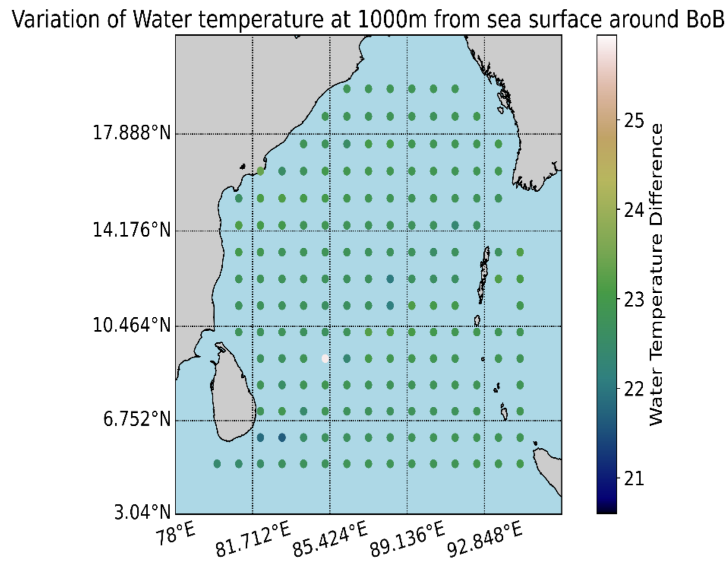
The dataframe obtained from previous analytics allows to plot the results in a color coded plot in the study region and identify potential sites of implementing the model OTEC plant. The *basemap* function [75] under *matplotlib* [76] library helps to make such plot with ease, showing an apparent gradient in the temperature difference values in a colorbar with the axes denoting the latitude and longitude. Three difference color bar plots were made for the three seasons- summer, rainy and winter respectively. Figure 3.1 demonstrates the seasonal temperature difference in the study region for (a) summer, (b) rainy season and (c) winter.

The intention behind these maps is to pin-point a location at which the OTEC potential seems the most attractive in terms of temperature difference as well as distance from shore. Projected results show consistency throughout all the considered seasons. As expected, summer season shows the highest temperature difference and winter projects the lowest temperature difference. It is worth noting however, that the lower $\Delta T$ values in winter is backed up by lesser load demand during winter season, compensating for the low power generation. The plotted maps show a higher potential of OTEC resources ranging from 17.5° N longitude and further beyond. The optimum locations must be selected based on sufficient temperature difference and proximity to the shore to reduce unnecessary cost burden.

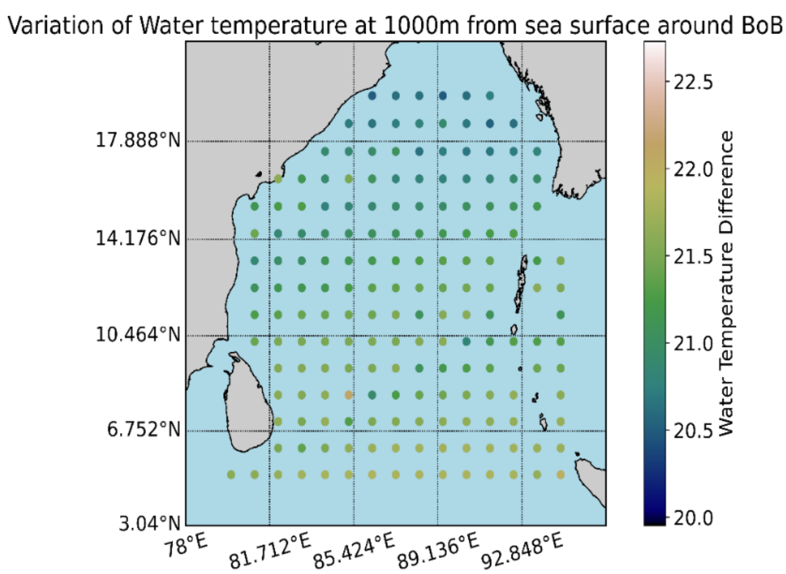
From the obtained results, it becomes clear that nearby shores of Bangladesh is not suitable for an OTEC plant as the plot suggests that there are no data points at those co-ordinates at 1000m. This can be reasoned with the fact that in the nearest coastal regions, there exists a range of shallow waters that do not go deeper than 400m, which is insufficient to extract the cold water temperature required for running an efficient power cycle. Hence, the co-ordinate having a temperature difference over 20°C from the shore of Bangladesh borders was observed to be 19.6N, 91.4E and its nearby regions. It is expected that placing the OTEC plant in this location should be able to provide power to the nearest islands, or the coastal border regions.




(a)




(b)

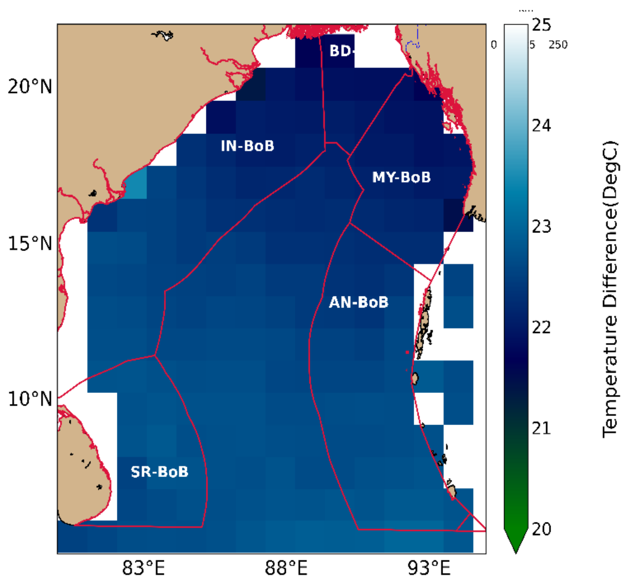



(c)

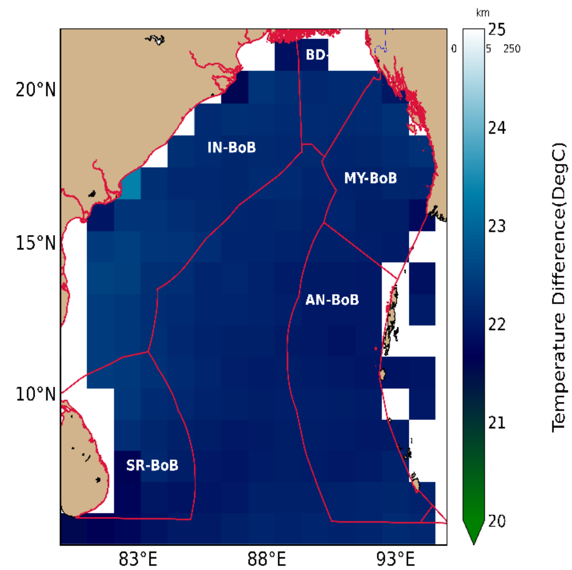
Fig 3.1: (a) Temperature difference in study region (summer) (b) Temperature difference in study region (rainy season) (c) Temperature difference in study region (winter).

### 3.7.2 Choropleth Plot of the Obtained Datasets

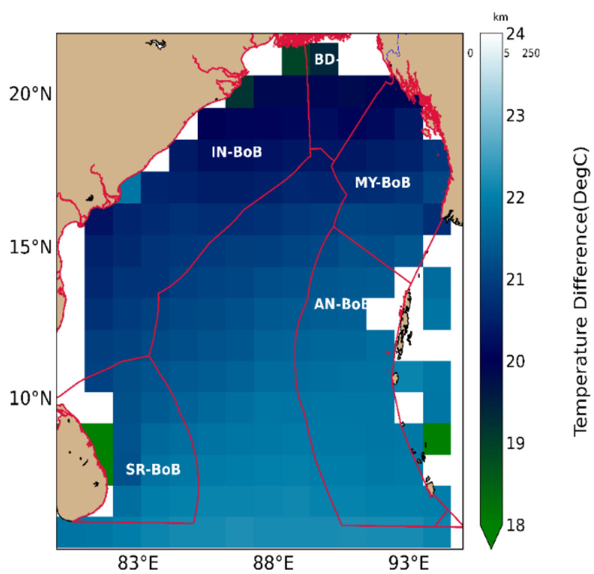
A Choropleth Map is a map composed of colored polygons. It is used to represent spatial variations of a quantity [77]. For even better clarity and ease of dividing zones of potential OTEC resources, choropleth plots were made available according to seasonal temperature difference values. It is observed that the results are consistent with the previously made colorbar plots. Choropleth plots provide a better visual aid in identifying zones and displays potential flaws in the dataset. Similar seasonal plots are shown for this case in figure 3.2, where (a) demonstrates potential zones as per the temperature difference of summer season. Figures 3.2 (b) and (c) shows similar color gradients for rainy season and winter respectively.




(a)




(b)

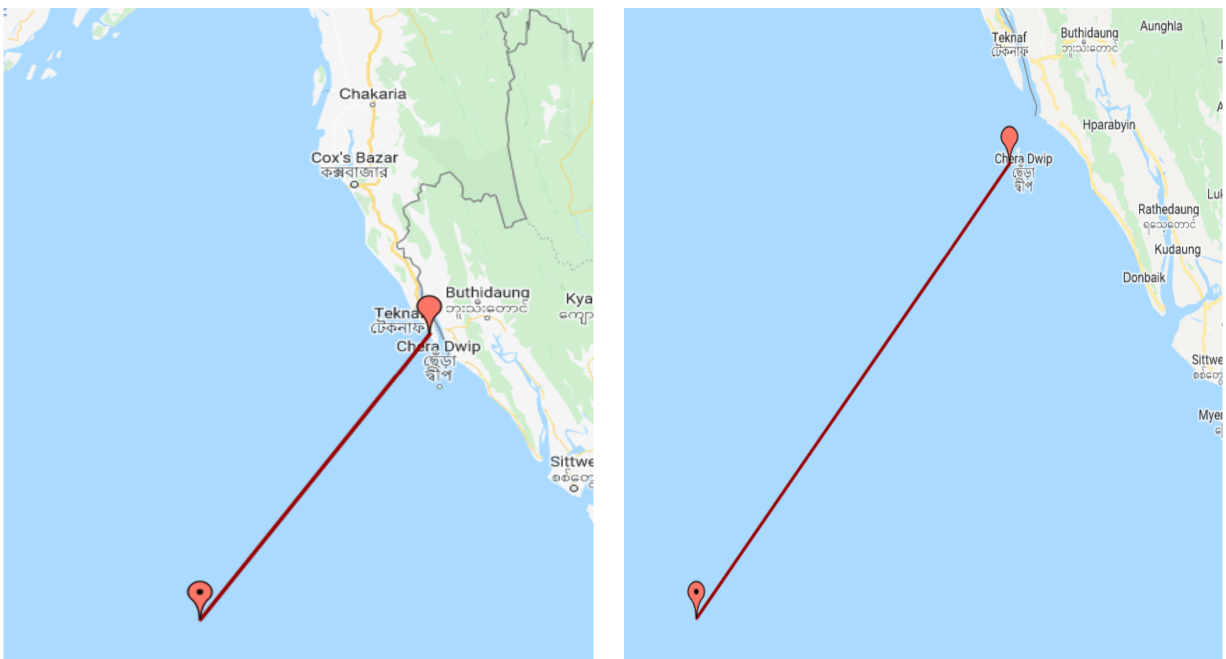



(c)

Fig 3.2: Seasonal Potential of OTEC resources (a) Summer, (b) Rainy and (c) Winter season.

### 3.7.3 Calculation of Nearest Distance from Shore

The selected co-ordinate is 19.6N, 91.4E as per the previous results of data analytics and graphical methods. It becomes necessary to then find the distance of this co-ordinate point from the nearest shore of Bangladesh. For this purpose, the Haversine distance must be calculated. The Haversine distance between two points on the spherical shaped earth is calculated using a unique formula that yields 'as-the-crow-flies' distance between the desired points. The nearest point on the shore is selected as 20.8N, 92.3E. Another point from which the shortest distance could be calculated is from the Saint Martin Islands (co-ordinate: 20.6N, 92.3E). The calculation was conducted in “Movable Type Scripts”, an open access software [78] . The results show that the Haversine distance from shore was 163.2 km and the distance from Saint Martin Islands was 145.6 km.




(a) (b)

Fig 3.3: Distance of selected with with a) Nearest shore Teknaf (163.2 km) and b) Saint Martin Islands (145.6 km)

# Chapter 4
# ENERGY EXTRACTION FROM MODEL OTEC PLANT

The net power production in an OTEC plant depends on various components. As such, an vitality extraction show was created beneath this venture to handle the accessible location particular sea characteristics that decide a plant's power generation capacity. The variables included within the demonstrate can be categorized into three bunches: gross power, cold water pipe (CWP) pumping cost, and all other pumping and transmission power costs. CWP pumping costs are also categorized into static and dynamic losses. Gross power calculation is carried out by establishing thermodynamic equations of a Rankine cycle. Pumping and transmission losses are also calculated from applied approach of pumping loss equations and assumptions conjugated with the OTEC plant [79].

## 4.1 Assumptions:

Certain parameters of the plant were beyond the scope of practical measurements. The assumed values considered are kept consistent with the assumptions made by Lockheed Martin Systems' work [2]. Table 4.1 demonstrates the various fluidic and machinery related parameters that have been considered to remain the same in this model plant.

Table 4.1: Assumptions considered for various parameters of power generation

| | |
|---|---|
| Surface water mass flow rate | 460000 kg/s |
| Cold water mass flow rate ($\dot{m}$) | 366000 kg/s |
| Condenser UA | 1350 MW/°C |
| Evaporator UA | 1410 MW/°C |
| SW pump efficiency ($\eta$) | 80% |
| Turbine expander efficiency | 86% |
| Ammonia pump efficiency | 75% |
| Generator efficiency | 97.5% |
| Friction factor ($f$) | 0.007933 |
| Pipe diameter ($D$) | 10 m |
| Pipe intake are (A) | 78.5 $m^2$ |

| | |
|---|---|
| Head loss water density ($\rho_f$) | 1025 kg/m$^3$ |
| Surface water depth | 20 m |
| Cold water depth | 1000 m |
| Piping Head | 5 m |

The OTEC plant demonstrate net power prediction at a particular area, given three inputs: surface temperature (°C), depth (m), and difference between surface water and cold ocean water temperature ($\Delta T$ in °C) at the given depth, compared to the surface temperature. The grid size is 1/12° latitude-longitude and the depth can stretch almost upto 5500 m, which is more than adequate as we only need to extend the depth upto 1000m [44].

In arrange to organize values to visualize the OTEC asset around the world, it is fundamental to set up expected pattern conditions based on a ostensible design. The pattern plan nitty gritty within the taking after table that has been optimized for conditions characteristic of the Hawai OTEC asset. As such, power output as calculated from the results of this project is not optimized for local conditions, but it helps to guide in order to select site.

The word UA refers to a heat exchanger performance metric that combines the total heat transfer coefficient (U-value) and heat exchange area (A). The comparative UA values are presented in the table in accordance with the thermodynamic model developed for the system by Makai Ocean Engineering.

## 4.2 Gross Power

$$P_{gross}(MW) = \frac{106.22 * \Delta T^2}{T_S - 0.25 * \Delta T + 273.15} \approx P_{gross}(MW) = 13.89\Delta T - 149.71 \tag{4.1}$$

The gross power appears to be exactly related to the temperature difference between the surface and cold water, $\Delta T = T_s - T_d$, where $T_s$ and $T_d$ are the temperatures (°C) of the surface (warm) and deep (cold) water, respectively. The equation was developed by determining the gross power output of 28 different places in the ocean and fitting an equation to those points in order to condense a multi-variable equation into a single-variable equation [80]. A 0 MW net power return is the highest net power return (as defined by a simplified OTEEV power formulation offered), was one of the 28 data points. at OCEANS '11 in Kona, HI6) and there are 26 intermediate points on the net power spectrum. [81].

### 4.3.1 Fixed Loss Factors

$$L_{Fixed}(MW) = 42.7 \qquad (4.2)$$

The total fixed loss factor $L_{Fixed}$ is calculated by adding the cold water intake power loss, condenser and distribution pumping loss, evaporator and distribution pumping loss, and ammonia pumping loss from the operation. These losses are each estimated in the below sections.

### 4.3.2 Cold Water Intake Power Loss

This fixed loss is calculated using water velocity and a known factor for a protruding pipe entrance, as assumed for the cold-water inlet.

Now, *Minor Head Loss* $(h) = \frac{CV^2}{2g}$, where $V = \frac{Q}{A} = \frac{4\,\dot{m}}{\pi\rho D^2}$

Here, C or the head loss co-efficient for protruding pipe entrance is 0.8 & the nominal sea water density ($\rho$) is around 1025 kg/m$^3$

Cold water pipe internal diameter is taken to be 10m. So, now,

$$V = \frac{4\,\dot{m}}{\pi\rho D^2} = \frac{4 \times 366000\,\frac{kg}{sec}}{\pi \times 1025\frac{kg}{m^3} \times (10m)^2} = 4.536\,\frac{m}{sec}$$

$$\textit{Intake Head Loss}\ (h_{intake}) = \frac{0.8 \times (4.456\,\frac{m}{sec})^2}{2 \times 9.81\,\frac{m}{sec^2}} = 0.843\text{m}$$

Here, *Cold Water Intake Power Loss = Pump Loss Factor * Intake Head Loss = 3.8 MW*

The Cold-Water Intake Power Loss has been recognized as a potential source of power loss reduction. To decrease losses, the entry might be rounded and shaped, which could be validated by model testing or computational fluid dynamics. However, because it is uncertain what filter components could be needed at the entry, the 0.8 coefficient for a typical protruding pipe entrance is utilized for this inquiry.

### 4.3.3 Condenser and Distribution Pumping Loss

This constant loss is calculated using anticipated losses in the condensers and distribution pipework. A head height of 5m was assumed. Parameters from the heat exchangers to the outlet are all factored into the 5m of head. When the Head Loss to Power Loss Factor is used, the overall loss is 22.4 MW.

Now, *Condenser & Distribution Pumping Loss = Pump Loss Factor * Assumed Design Head*

*= 4.488 MW/m * 5m = 22.4 MW*

### 4.3.4 Evaporator and Distribution Pumping Loss

This fixed loss is calculated using prior modeling and accompanying fixed assumptions for the nominal scenario of 100 MW net (150MW gross power). The same head loss would be about 2.5m [79]. The parameters and losses from the heat exchangers to the outlet are all accounted for by the 2.5m of head.

So, $Evaporator\ \&\ Distribution\ Pumping\ Loss = \frac{\dot{m}_{warm} g h_{warm}}{\eta}$

$$Warm\ Water\ Mass\ Flow\ Rate\ (\dot{m}_{warm}) = 460000\ \frac{kg}{sec}$$

As the warm water head loss ($h_{warm}$) and sea water pump efficiency ($\eta$) are taken 2.5m & 80% respectively, hence, Evaporator & Distribution Pumping Loss becomes 14.1 MW.

### 4.3.5 Ammonia Pumping Loss

This fixed loss is calculated using prior modeling and accompanying fixed assumptions for the nominal scenario of 100 MW net (150 MW gross power). This loss accounts for the expected liquid ammonia flow rate of 4060 kg/s.

$$Ammonia\ Pumping\ Loss = \frac{\dot{Q}_{NH_3} \Delta P_{NH_3}}{\eta_{NH_3}}$$

Here, $Ammonia\ Volumetric\ Flow\ Rate\ (\dot{Q}_{NH_3}) = \frac{\dot{m}_{NH_3}}{\rho_{NH_3}} = \frac{4060\ kg/sec}{625\ kg/m^3} = 6.496\ m^3/sec$

Here considered, $Ammonia\ Pressure\ Delta\ (\Delta P_{NH_3}) = 274\ kPa$

$Ammonia\ Pump\ Efficiency\ (\eta_{NH_3}) = 75\%$

Hence , Ammonia Pumping Loss comes to a total of 2.4 MW.

### 4.3.6 Variable Loss Factor

The summation of pipe friction and static head losses is the total variable loss factor $L_{Var}$, where d indicates the depth of the cold water in meters.

$$L_{Va}(MW) = 0.0038d + 4.488d \times (5.234 \times 10^{-10}d^3 - 1.378 \times 10^{-6}d^2 + 1.313 \times 10^{-3} d - 0.6541) \times \left(\frac{-0.00599T_S{}^2 + 0.031T_S + 1025}{-0{,}00599(T_S - \Delta T)^2 + 0.031(T_S - \Delta T) + 1025} - 1\right) \quad (4.3)$$

Cold water depth (d) is taken to be 1000m, which makes the variable loss factor the function of surface temperature ($T_s$) & temperature difference ($\Delta T$).

### 4.3.7 Cold Water Head Loss to Pumping Loss Factor

Using the pump power equation, it is possible to determine power loss in MW as a function of pump head in meters.

$$Pump\ Power\ (\dot{W}) = \frac{\dot{m}gh}{\eta} = Pump\ Loss\ Factor\ \times h$$

So, $Pump\ Loss\ Factor = \frac{\dot{m}g}{\eta}$

Putting the values from assumption table, the pump loss factor obtained is 4.488 MW/m.

### 4.3.8 Pipe Friction Loss

This variable loss is solely determined by the duration of the CWP. The factor is calculated using pipe wall friction estimates based on the smoothness of the pipe, pipe diameter, and water velocity. The velocity of the water flowing through the pipe influences the friction loss in the pipe. As a result, water velocity is a metric on which pipe friction loss is calculated. This calculation is also affected by pipe diameter and smoothness.

Now,

$$Pipe\ Friction\ Loss\ (L_{pf}) = \frac{h_f * \dot{m}g}{\eta} = \frac{f(\frac{\dot{m}}{\rho_f * A})^2 \dot{m}g}{2Dg\eta} = 0.0038d$$

Here, $Hydraulic\ Pipe\ Diameter\ (D) = 10m$

$$Pipe\ Velocity\ (V) = 4.546\ m/s$$

$$Colebrook\ Equation\ for\ Friction\ Factor\ (f) = 0.007933$$

As, d or cold-water depth is constant which is 1000m for our case, pipe friction will also be a constant value.

### 4.3.9 Static Head Loss

The right static head is determined by integrating the density difference between the cold water within the CWP and the warmer water on the outside of the pipe as a function of depth through the CWP depth (d). However, complete density depth profile information is not available at each site for use in this evaluation. Instead, the difference between average and surface water density may be utilized to create a highly precise approximation of the more proper integration approach. The error between static head obtained by the integration approach and static head produced by the approximation described here is only 0.05 percent at the most regularly occurring CWP depth of 1000m. Static head loss is computed on the basis of pump power loss ($L_{pp}$), simplified static head loss ($L_{ssh}$), static head bias correction ($C_{shb}$).

Now,

$$L_{pp} = \frac{\dot{m}gz}{\eta} = 4.488z \tag{4.4}$$

$$L_{ssh} = \frac{\rho_D - \rho_S}{\rho_D} = \left(\frac{-0.00599T_s^2 + 0.031T_s + 1025}{-0.00599(T_s - \Delta\mathrm{T})^2 + 0.031(T_s - \Delta T) + 1025} - 1\right) \tag{4.5}$$

$$C_{shb} = 5.234(10^{-10})z^3 - 1.378(10^{-6})z^2 + 1.313(10^{-3})z - 0.6541 \tag{4.6}$$

Hence, Static head loss can be represented as-

$$L_{sh} = \left(L_{pp} \times L_{ssh} \times C_{shb}\right)z \tag{4.7}$$

## 4.4 Final Equation and Calculation of Seasonal Power

The net power ($P_{net}$) calculation depends on three modules that are gross power ($P_{gross}$), fixed losses ($L_{fixed}$) and variable losses ($L_{variable}$).

So, $P_{net}(MW) = P_{gross} - L_{fixed} - L_{variable}$

$$= 13.891\Delta T - 149.71 - 42.7 - 0.0038d - 4.488d \times (5.234 \times 10^{-10}d^3 - 1.378 \times 10^{-6}d^2 + 1.313 \times 10^{-3}d - 0.6541) \times (\frac{-0.00599T_S{}^2 + 0.031T_S + 1025}{-0{,}00599(T_S - \Delta T)^2 + 0.031(T_S - \Delta T) + 1025} - 1) \tag{4.8}$$

Here, the net power is a function of surface temperature ($T_s$) and temperature difference (ΔT) as cold-water depth (d) = 1000m. Using equation 4.8, an average power over the seasons can be calculated.

**In Winter-**

For a temperature difference 20.390°C,

*Gross Power,* $P_{gross}$ *(MW) = 13.89(20.390) – 149.71 = 133.5071 MW*

$OTEC\ Net\ Power, P_{net}(MW)$ = *133.5071*− 42.7 -6.778

= **84.0291 MW**

**In Summer-**

For a temperature difference 22.195°C,

*Gross Power,* $P_{gross}$ *(MW) = 13.89(22.195) – 149.71 = 158.5786 MW*

$OTEC\ Net\ Power, P_{net}(MW)$ = *158.5786* − 42.7 – 7.229

= **108.6496 MW**

**In Rainy Season-**

For a temperature difference 22.105°C,

*Gross Power,* $P_{gross}$ *(MW) = 13.89(22.105) – 149.71 = 157.3285MW*

$OTEC\ Net\ Power, P_{net}(MW)$ = *157.3285* − 42.7 – 7.225

= **107.4035 MW**

Here, it is seen that both the rainy and summer season hold almost similar amount of power which is above 100 MW but it drops down in the winter season due to the lack of temperature.

## Chapter 5
# ECONOMIC FEASIBILITY ANALYSIS

### 5.1 Introduction

An OTEC plant's performance on the basis of design and operational parameters is useful, it does not determine the viability of such a plant as a source of power. When selecting whether or not to use one type of generating over another, economic feasibility of such a power generating plant is vital. Despite the fact that the concept has been validated through technical means, an actual full-scale OTEC plant is not fully functional yet due to extreme capital costs and doubts about economic feasibility, among other factors.

The primary variables of the economic model were constrained to predicted cost ranges on the basis of existing information from multiple papers[82]–[85], and using the consumer price index (CPI) was converted to 2018 dollars. These cost for different power plants and their related machines and equipment will be used in this analysis to establish a range of capital costs and Levelized Cost of Electricity (LCOE) for different operating conditions and plant designs. The determined obtained costs are not expected to be precisely accurate for OTEC electricity, but represent an outline which can potentially present a range of the actual cost.

### 5.2 Literature Review of the Economics of OTEC

Because of the scarcity of available cost data, incorporating economic variables into the performance model is a risky proposition. There hasn't been a commercial-scale OTEC plant built yet, other for a few sub-MW demonstration projects. Numerous design and feasibility studies have been carried out by businesses with competence in cost estimation for huge projects. These design studies are the foundation for the economic modeling section. In 1979, a 10 MW OTEC plant was issued to be proposed by the Department of Energy (DoE) that could be employed as a standalone plant or even a segment of a large arrangement.

In terms of price, the 10MW feasibility studies are the closest match for a 20MW facility. The costs after comparing to a 100 MW OTEC plant, the electrical cable work, the platform cost, and the cold and warm water pipes alongside other big expenses are like to be similar to a smaller plant as these costs are more or less uniform. Because the economic modeling was designed to provide a first-hand approximation, the expectation was that the 20 MW plant implemented would suffice for the purpose. The heat exchangers' costs were also scaled per-square-foot, while the turbogenerators, motors and pump’s costs were scaled identically on a per kW basis. The biggest cost variations between 10 and 20MW plants arise from this variation.

The 6$^{th}$ commencement of the OTEC Conference include several shorter versions of these approaches. The cost values following were used explicitly:

1. “Design of a 10MWe(net) OTEC Power Module using Vertical, Falling-Film Heat Exchangers" by Bakstad and Pearson[86]
2. “Design of a 0.2MWe (net), Plate-Type, OTEC Heat Exchanger Test Article and a 10MWe (net) Power Module" by Denton, Bakstad and McIlroy[82]
3. “System Design Considerations for a Floating OTEC Modular Experiment Platform" by George, James F.[84]
4. “Optimizing Plant Design for Minimum Cost per Kilowatt with Refrigerant-22 Working Fluid" by Olmstead, Mann and Yang[83]
5. “Conceptual Designs and Costs of OTEC 10 & 40 MW Spar Platforms" by Scott R.J. [85]

All the listed works were based on a 10 MW power plant that could be used as stand-alone plants or in combination with a larger plant. Both Bakstad and Denton’s proposed model had the economic information of the turbine/ generator, evaporator, condenser, power cycle and miscellaneous costs. However, neither of them explained the platform, mooring, power cabling, cold water pipe costs. The concept of using HX area (sqft) used to calculate a cost estimate is found useful in this calculation. George’s suggested model had the cold water pipes, platform, power cycle and water system costs. But his work lacks the electrical cabling costs. Model presented by Olmstead had HX information and turbogenerator costs. A collaboration with Sea Solar Power was noted, using similar heat exchanger design with R22 as working fluid. Finally, Scott’s model had electrical cabling, platform, cold water pipe, warm and cold water pump and similar related costs explained, but avoided enunciation regarding heat exchanger or turbogenerator costs. Neither did he mention electrical cabling costs.

The cost variables produced from these reports are applicable to a wide range of plant design options. Furthermore, because the subject of this thesis was a 100 MW plant, obtained data provide a reasonable place to start for study. All the values used were to estimate a magnitude approximation range instead of normalizing or averaging to present a base cost. Generators, pumps and turbines were standardized to a USD per kW standard to analyze the implications of different design configurations and operating parameters; heat exchanger expenses were also scaled to a USD per square feet value to analyze the impact of different operating and design conditions. The temperature of the cold water pipe, the platform, and the electrical cable system were expected to be constant. Based on the reports, a low-medium-high approximate can be obtained from Table 5.1 of each of the major economic variables.

Table 5.1: Range based cost estimates of primary cost variables[87]

| Capital Cost | Low | Medium | High |
|---|---|---|---|
| Heat Exchanger | 20 USD/sqft | 40 USD/sqft | 80 USD/sqft |
| Turbo-Generators | 700 USD/kW | 1000 USD/kW | 2000 USD/kW |
| Cold Water Pumps | 700 USD/kW | 1000 USD/kW | 2000 USD/kW |
| Warm Water Pumps | 700 USD/kW | 1000 USD/kW | 2000 USD/kW |
| Cold Water Pipe | 10,000,000 USD | 30,000,000 USD | 50,000,000 USD |
| Hull/ Platform | 30,000,000 USD | 90,000,000 USD | 150,000,000 USD |
| Power Cabling | 20,000,000 USD | 30,000,000 USD | 50,000,000 USD |
| Other Costs | 20% of Capital cost | 20% of Capital cost | 20% of Capital cost |

The kW value of power multiplied by the USD per kW cost parameter is unique to that variable. The power produced from the turbine, for example, is multiplied by the turbo-generator $/kW. The desired power of cold water pump is multiplied by the cold water pumps USD per kW value. The cost factors are not calculated in terms of dollars per net kilowatt-hour generated. An additional factor of 20% of the total computed capital cost will be applied to aid in account for these criteria would not include auxiliary equipment or installing fees. Though using such dated designs and data is not ideal, the underlying the core design of the primary components have remained more or less the same, particularly electric motors and pumps, so an order-of-magnitude estimate should suffice. The assumption of higher bounds for some fields would be offset by decreases in others is included in this rationale. The offshore oil business, and large scale offshore construction industry’s extension, were poorly established and developed when these evaluations were conducted. The aim of this analysis, yet again is to only estimate a range that would help evaluate prospective viability and the overall implications of individual components on total cost.

The reports get even more ambiguous when it comes to operations and maintenance expenditures; many of them don't give an estimate, except from possible heat exchanger cleaning or replacement. This research utilizes an annual operation and maintenance cost of 5 percent of the plant's capital expenditure for a conservative O&M estimate. The first OTEC plant is assumed to have a lifetime operation and maintenance expenses that are nearly similar to re-implementing the entire plant, and that this will be for a 20-year lifetime, which amounts to a 5 percent annual increase. While there is no specific mention of a 5% O&M expense in any documents, it appears to be a reasonable estimate. The labor cost estimate is also arbitrary, with this research assuming a salary and benefit budget of $1 million per year, which would cover 10 or more full-time employees. The assumed values here too are guessed to approximate, expecting an autonomous facility and others assuming dozens of full-time employees; the important task was to assume staff salaries in the million dollar range per year when computing the LCOE. Dr. Luis Vega, more recently in his work addresses economics of OTEC plants, both open and closed facilities in the context of prior OTEC ideas [88]. The Vegas 2010 report is an update of a 1992 research on OTEC economics. He also collated and adjusted various cost estimates from various sources to adjusted 2009 USD for plants ranging in size from 1.35 to 100 MW as part of the 2010 report.

## 5.3 Methodology of Economic Modelling

The funding and economic computation of power generation are complex, with a slew of external factors influencing the final cost of electricity. Only a simplified computation of the LCOE based on expected capital expenditures and annual O&M costs will be performed in this analysis. The LCOE is calculated by dividing the annualized capital expenses adding annual operational costs by the number of kWh of electricity produced by the plant in a year. The major parameters required to calculate the LCOE are capital expenditure (CAPEX), operating expenses (OPEX), and cost recovery factor (CRF) and capacity factor (CF). Capital expenditures refer to the high upfront costs of constructing a facility, such as materials, production, and installation of major plant components. CAPEX is defined as the sum of total heat exchanger costs ($C_{heat\ ex}$), the costs of cold water pipe and costs of warm and cold water pumps in summation (collectively $C_{watersys}$:), turbo-generator cost ($C_{turbogen}$), power cable cost ($C_{power}$), cost of platform making ($C_{platform}$).

In equations 5.1 to 5.4, the pump, turbo-generator and HX costs are observed to be functions of the pump power input requirement, and gross power producing capacity, and size of heat exchanger respectively. The prices of the platform, cold water pipe, and power cable are considered to be constant collective values. In order to provide accounts for the auxiliary equipment, contingent expenses, and costs that may not have been included in the specified numbers, constant K is multiplied with the sum.

$$CAPEX\ [USD] = K\ [C_{h\ eat\ ex.} + \sum C_{water\ sys.} + C_{turbogen.} + C_{platform} + C_{power}] \tag{5.1}$$

$$C_{heat\ ex.}\ [USD] = A_{total}\ [ft^2]\ x\ C_{hx\ \$\ per\ sqft.}\ [USD/sqft] \tag{5.2}$$

$$\sum C_{water\ sys.} = C_{cw\ pipe} + \sum \dot{W}_{cw\ \&\ hw\ pumps}\ x\ C_{pump\ \$\ per\ kW}\ [USD/kW] \tag{5.3}$$

$$C_{Turbogen}\ [USD] = \dot{W}_{gross}\ [kW]\ x\ C_{turbogen\ \$\ per\ kW}\ [USD/kW] \tag{5.4}$$

The same $C_{hx}$ \$ per sqft value for both the condenser and boiler is considered with the aim of simplicity. Similarly, the $C_{pump}$ \$ per kW for cold and warm water pump is considered to be the same. In case of availability of more specific and detailed information, the model is configured to handle individual values for these inputs. For the sake of this analysis, CAPEX refers to the plant's total up-front costs, which would be covered by a loan. By calculating CAPEX by the Cost Recovery Factor, annual loan payments for CAPEX can be determined. The Cost Recovery Factor (CRF) is the annual percentage of money that is paid over the entire loan period. CRF is determined by the loan's interest rate (or capital discount rate) and the loan period. In this calculation, the installments are paid annually at year end, as an assumption in this analysis. Equation 5.5 is used to calculate this component, where n is the number of years of loan and *i* is the rate of interest.

$$CRF = \frac{i\ x\ (1+i)^n}{(1+i)^n - 1} \tag{5.5}$$

The annual payment for capital expenditure loans is calculated by multiplying CAPEX by the CRF. This annualized payment represents the effective monthly cost of the upfront CAPEX costs;

the annualized cost is required for the LCOE calculation, which divides annual costs by annual power output.

The operational expenditures, or OPEX, are the other set of costs that go into the LCOE calculation. The OPEX is assumed to remain constant in this simplified LCOE calculation. Because repair and maintenance costs are likely to change from year to year, assuming a set OPEX is an idealization. Because there are no fuel expenses involved with operation, and the plant is planned to provide largely baseload power, O&M costs should be relatively constant throughout the year as the OTEC plant is setup and running for a few years. Using the O&M and labor methodologies and cost figures stated in the preceding section, the OPEX expenses are determined in equation (5.6).

$$OPEX\ [\$/\ year] = C_{labor}\ [USD/year] + C_{O\&M}\ [USD/year] \quad (5.6)$$

$$C_{labor} = 10\ [employees]\ x\ 50{,}000\ [USD\ per\ employee/year] = 500{,}000\ [USD/year] \quad (5.7)$$

$$C_{O\&M} = 0.05\ CAPEX\ [USD/year] \quad (5.8)$$

The capacity factor CF and $W_{electricty}$, which is simply the plant's net electrical power output, are the last components of the LCOE calculation. The fraction of the year at which power is produced at its expected output is measured in CF. The total amount of kilowatt hours (kWh) produced by the plant is calculated by multiplying $W_{electricty}$ and total hours in one year and the power generating fraction of the plant in that year. Hence, the denominator, as stated in equation 5.9, is this product. The LCOE is a method of calculating a power station's total annual cost per kWh produced, or, to put it another way, it is the lowest price at which the energy must be sold for the facility to break even for the year. Insurance, taxes, environmental costs, and other fees are not included in this simplified LCOE estimate.

$$LCOE\ [USD/kWh] = \frac{CAPEX\ [USD] x\ CRF\ [per\ year] + OPEX\ [USD\ per\ year]}{Welectricity\ [kW] x\ 8760\ [hr\ per\ year] x\ CF} \quad (5.9)$$

The LCOE allows comparisons to be made among the various conventional power plants and even the renewable energy sources as well between electricity prices in different markets. As a reminder, this is a simplified estimate that excludes many of the costs associated with generating plants.

Environmental regulatory fees, Taxes and a slew of other factors were left out. As a result, the predicted LCOE for the given CAPEX and OPEX inputs is deviated even lower than the LCOE. The Range of LCOE derived with the previous section's inputs is intended to provide a good order-of-magnitude estimate and also optimistic and conservative bounds on the estimate. The following section explains how to calculate these figures.

## 5.4 Comparison of the Calculated LCOE with Modern Technologies and Market

The ultimate purpose of the economic assessment was to produce a first-cut estimate of the cost of generating electricity with a pioneering OTEC plant with a capacity of around 20MW, in order to make a preliminary assessment of economic feasibility. The preceding section's economic equations were integrated into the plant's model, and the LCOE was determined for the range of CAPEX variables listed in Table 5.2. The reference case's plant design and operating data were employed as input variables for the economic analysis' thermal fluid systems model. Table 5.3 summarizes the key results that dictate the thermal power system costs.

An assumption was made to assess cold and warm water pumps to cost the same per kW of power consumption in this analysis, and the condenser and the boiler are similarly assumed to cost the same per square foot. This is merely a simplification made to make the calculative strain lesser, as actual costs will almost certainly vary, but pricing will most likely remain within the same range, so it is not unrealistic. The economic analysis model was done using the data from Table 5.3. The CAPEX, $/kW, and LCOE estimates based on the input design and economic data are summarized in Table 5.4. These figures are intended to represent a first-cut approximation, establishing the likely LCOE range for a typical first-generation OTEC plant.

Table 5.2: Calculated Primary Variable Outputs of the Economic Range Model

| **Gross Power (kW)** | **Net Power [kW]** | **Pump Power [kW]** | **Total HX Area [$ft^2$]** |
|---|---|---|---|
| 150,000 | 100,000 | 25,285 | 17,524,485 |

As seen from table 5.2, the gross power and net power assumed is considered to be 150 MW and 100 MW respectively. Calculation of pump power can be done by using parameters related to total gross power of the plant and rating of the pump and pump efficiency. Total heat exchanger area is calculated in square feet by interpolating plant power of various sizes. By using these parameters, it is possible to find out the several components that sum up to the capital expense of the plant's installation.

Table 5.3: Summarized calculated values of the Economic Model

| **Output variables of Economic Model (Units)** | **Output** |
|---|---|
| CAPEX (USD) | 684,600,000 |
| CAPEX per kW(USD per kW) | 6846 |
| OPEX(USD per kWh) | 34,230,000 |
| LCOE (USD per kWh) | 0.14 |
| LCOE (after inflation since 2012) (USD per kWh) | 0.182 |

The 'Low, Medium, and High estimates' are calculated using optimistic cost assumptions, roughly average cost estimates, and conservatively high cost estimates, respectively. The wide range is intended to establish a reliable upper and lower bound on the costs of a floating OTEC plant with a rated output of around 100MW. It's worth noting that a number of the costs are significantly non-linear and could give better results from scale economies.

The LCOE would most likely be around $0.1389 per kWh, according to the economic model's output. When we adjust for currency inflation since these estimates were made, we detect a 30 percent increase. The corrected LCOE value is $0.181 per kWh at the end. While the LCOE range is predicted to vary by nearly five times among the lowest and highest values, the economic input variable ranges are also expected to vary by that magnitude. For comparison, the LCOE of a hypothetical 100MW plant operating with the design inputs will be considered to be $0.18 per kWh.

Dr. Vega's 2010 study on the economics of OTEC was utilized as a starting point for calculating the model's LCOE. Langer, on the other hand, did a more recent analysis of numerous cost estimate works on OTEC. It included units ranging in capacity from 1.6 kW to 400 MW. There were specifics on the plant's location, CAPEX and OPEX expenditures, LCOE, and estimated plant life. In the table 5.5, a synopsis of a few of them have been provided:

Table 5.4: Comparison of Cost Estimates of Contemporary studies on OTEC [89]

| **Plant Size (MWe)** | **CAPEX (Million USD)** | **OPEX (% CAPEX)** | **LCOE ($/kWh)** | **Plant Type** | **Expected Life (years)** |
|---|---|---|---|---|---|
| 1.6 | 2.38 | 26 | 0.096 | N.A, CC | 25 |
| 2.35 | 37.78 | 3.3 | 0.269 | L,CC | 30 |
| 10 | 160.1 | 2-3 | 0.19 | F,CC | 30 |
| 20 | 144- 553.4 | 5.2-5.7 | .013-0.65 | F,CC | 20 |
| 50 | 110 | 1.4 | 0.04 | F, N.A | 30 |
| 75 | 600 | - | 0.15 | F,CC | 30 |
| 100 | 780 | 5 | 0.18 | F,CC | 20 |
| 100 | 795 | 2 | 0.11 | F,CC | 25 |

In addition, the Vega curve was used to fit these figures and generate a reasonable estimate of cost per kW for midrange plant sizes, which was represented in Equation (5.10) [88]. The nominal name-plate output power of the plant is P, and the installed capital cost per kW is CC.

$$CC\ [USD/\ kW] = 53{,}160 \times (P\ [MW])^{-0.418} \qquad (5.10)$$

Although the equation is essentially a curve fit to other estimated values, this comparison shows that the economic model generates an estimate that is consistent with other independent computations. Vega also calculated the LCOE depending on the capital costs. He used a combined labor and repair cost of somewhat more than 5%, as well as loan terms of 8% for 15 years and 4.25% for 20 years, the latter representing a government bond. Langer has recently replicated and improved the assessments similarly in his work.

The $0.18/kWh estimate from the economic models appears to be in accord with Vega's calculations. By fitting a comparable curve to the COE values, an LCOE of $0.178 per kWh was calculated. Obtaining a similar figure to Vega's estimate doesn’t quite cover the actual costs, however it most certainly does serve as a valuable benchmark to demonstrate a same range estimate that the model presents compare to that determined by separate studies. While economies of scale were not the focus of the economic research, they certainly play a role in OTEC power generation. Because larger OTEC facilities are more likely to adopt modular designs, the design costs per installed kW would be lower.

The cold water pipe would cost roughly the same despite having a wider diameter, mostly due to the designing, manufacturing, and deploying; the cost of cold water pipe for a 100MW plant may be twice in diameter compared to a 20MW plant, but it would produce five times the produced power. Similarly, the electrical cabling from the plant to the coast would need to be upgraded, as would the transformers, amplifiers, transformers, transmission lines etc. but the cost of construction for a 20 MW and a 100 MW cable would likely be comparable, lowering the overall cost per kW installed. Even more a significantly smaller plant, the cost of customized designs, manufacturing and installation of components would be similar due to the pioneer nature of the plant, but it the produced power would be significantly lesser, thereby increasing the cost even further.

Turbogenerators, pumps and heat exchangers seemingly would cost the same per kW and per sqft in either case (far larger or much lower than 20MW). Other expenses, on the other hand, are less size dependent, and has a tendency to produce non-linear USD per kW curve as costs vary from design criteria to selected material upto installation. Because the installed cost is the primary driver of the LCOE for OTEC plants, the LCOE trends in the same direction. Building larger plants enhances economies of scale, according to Vega's curve fit of estimates from prior OTEC feasibility studies [88]. On a USD per kWh basis, a larger OTEC plant, on the range of 50 to 100MW, naturally could take the benefit of having a better scale in economy, including factors like design, deployment, manufacturing etc, and may potentially be considerably more cost-competitive [88].

## 5.5 Comparison of LCOE with Contemporary Power Generation Technology

The following comparison was made with the expected LCOE for various power generation technologies in 2020, as determined by Langer in his review study utilizing a variety of current sources. Estimates made by the EIA in 2016 as part of the Annual Energy Outlook 2011 report an older source. The original numbers were modified from the EIA report's 2009 $/MWh to 2011 $/kWh. Furthermore, the EIA LCOE assumptions employed a lower interest rate (7.2%) and a longer loan term (30 years) than the LCOE calculations performed in this paper [90]. Langer, on the other hand, uses data that has been updated to the 2018 USD currency standard. His work provided an adjusted and original interest rate comparison between 10 MWe and 100 MWe OTEC plants to further have an overview regarding the taxation and tariffs related to such plants. Table

5.6 was prepared from the information as presented by Langer comparing all known LCOE values for different power generation technologies.

Because of the time it would take to create some of the potential projects they included in their research, such as large-scale concentrated solar PV and large scale wind energy run plants, the EIA report focused on 2016. Due to the planning, construction, and time of deployment of such plants, the 2016 estimate is useful because an OTEC facility would also take around half a decade at least to construct and install successfully such a plant. The EIA estimates are for constructing a new plant utilizing the technology mentioned, as well as the regional correction factors and capacity factors mentioned in the 2011 report's reference listing [90]. It's vital to keep in mind that these figures apply to the United States, not to isolated little island settlements. Regardless, they help to put the predicted OTEC LCOE into perspective.

Table 5.5: Comparison with other power generation technologies [91]

| **Power Generation Technology** | **LCOE (2018 USD/ kWh)** |
|---|---|
| 10 MWe OTEC | 0.20-0.67 |
| 20 MWe OTEC | 0.13-0.65 |
| 100 MWe OTEC (original interest rate) | 0.03-0.22 |
| 100 MWe OTEC (adjusted interest rate) | 0.04-0.29 |
| Solar PV | 0.04-0.046 |
| Wind | 0.029-0.056 |
| Gas Peaking | 0.152-0.206 |
| Nuclear | 0.112-0.189 |
| Coal | 0.06-0.143 |
| Gas Combined Cycle | 0.041-0.074 |

In comparison to all of the traditional power generation technologies like the coal and natural gas plants, the OTEC LCOE would not be a viable option, according to EIA estimates. However, these figures suggest that OTEC could provide competitive prices against solar thermal generating, as well as offshore wind and solar PV. The levelized cost of electricity as calculated by the EIA does not account for the cost of firming of renewable sources, indicating that the overall LCOE could actually be greater for them. It's worth noting that the EIA does not even mention OTEC plants in its report. Possible explanations for this could be the lack of actual running plants that are commercially producing power as well as the location specific characteristic of such plants.

## 5.6 Comparison of Retail Cost of Electricity in Various Islands around the World

The final comparison would be made by observing the data of available energy tariffs in several island regions. The retail electric rate includes the LCOE, taxes that may have been excluded in previous calculations and side benefits that may have been guaranteed beyond the marginal costs. As a result, the retail rate establishes the upper limit for LCOEs that could be feasible economically in the market. If a plant fails to produce electricity at a cost lower than retail, it fail to provide benefits without some form of financial assistance, such as a renewable energy production credit. Table 5.6 shows the electric rates and notable points on the process these sources are generated for numerous islands.

The retail power rates in Table 5.6 provide a better indication of OTEC's possible economic sustainability for some island settlements, particularly those in smaller and more isolated areas. Although an LCOE of roughly $0.20 to $0.25/kWh falls within the model's expected cost per unit electricity generated, it is still a rough estimate of real expenses. This analysis alone is not sufficient to provide insurance that an OTEC plant of 100 MWe becomes viable for the islands in which the unit cost of accessible electricity is higher. It is merely a future possibility considering that the technologies concerning OTEC plants become more efficient and usable. Besides, as suggested by Vega, improvements through economies of scale, a larger OTEC plant would mean better cost per unit power produced ratio, would have several added benefits, and could provide much better prices on a USD per kW basis for these power deprived islands. If under such conditions, an OTEC plant were to be placed in Bangladesh, more specifically in the Saint Martin Islands, there remains a good promise of alleviating the power requirements of the population. This may reduce the usage of the diesel run generators and aid in saving otherwise very high costs in fuel purchases. Environmentally, the plant would be beneficial as well.

Table 5.6: Comparison of current retail costs of various islands across the world.

| Island(s) | Retail LCOE | Notes |
|---|---|---|
| Hawaii | 0.25 $/kWh | Approximately 80 percent power generated via petroleum-based plants. [90]. |
| Puerto Rico | 0.22 $/kWh | More than 90% of the demand is met by oil, coal and natural gas power. |
| Fiji | 0.34 $/kWh | Peak load of 138 MW. Mainly diesel fired but recently implemented 10 MW wind and 40 MW hydro power plants. [92]. |
| Sumba Islands, Indonesia | 0.039 $/kWh | 37 kW hydro power mini grid. Rest is comes from fossil fuel sources [93] |
| Pangan an Islands, Philippines | 0.7 $/kWh(donated)<br>1.45 $/kWh (not donated) | Mini grid and private diesel generators. Average households use less than 6 kWh electricity per month [94] |
| Bulon Don Islands, Thailand | 12.8-63.4 $/kWh | SHS and private diesel generators |
| Terumbu Layang, Malaysia | N.A | 150 kW Wind Turbine [95] |
| Saint Martin Islands, Bangladesh | 0.58 $/kWh | Grid lines and private diesel generators. Massive shortage of power supply to meet demand. No feasible alternate power generation implemented [31]. |

A notable observation is the data received from Saint Martin Islands, Bangladesh. It is seen that only 63% of the consumer load is sufficed with traditional feed lines of electricity. The rest is compensated privately using diesel fuel run generators which in most cases become a luxury most cannot afford. Moreover, the common masses don’t have access to such alternative power sources and almost no efforts have been made to implement a renewable power generation method that would be long term. Solar PV cells established on rooftops do play somewhat role in keeping some homes lit but often fail to remain consistent due to poor quality panel provided to the poor communities. For an island like Saint Martin's the retail LCOE becomes $0.58, which is significantly higher than the cost as calculated from this work. If implemented correctly, the thermal output from the 100 MWe net OTEC plant could bear fruitful results for the people of Saint Martin by providing uninterrupted green energy in the long term.

## 5.7 Conclusion

Rather than estimating a price, the economic modeling was used to establish a best-guess range of estimate for the levelized cost of electricity. The determined LCOE was $0.18 per kWh, which is an average estimate of educated assumptions. The calculated results were based on values from prior feasibility studies of plants of similar size. This was in line with a more recent feasibility assessment by Luis Vega, in which he collated cost estimates for numerous plants in order to calculate LCOE values.

Comparing the model OTEC's output LCOE with the estimated LCOE for various common generation technologies as estimated by Langer and EIA, showed that a 100MW OTEC would most likely be a cost effective option for a country like Bangladesh as the price paid by the people of coastal regions and islands is inexorably high. Despite the presence of solar PV cells planted in several homes, which is economically cheaper than ocean thermal energy production, it fails to provide a long term solution and lacks the potential that an OTEC plant can hold. Besides, conventional technologies and even solar energy technologies are quite saturated at this point and there is very less room for improvement in terms of the cost effectiveness as seen in recent times. On the other hand, OTEC is yet to meet its most effective form. Because any plant created would become a first generation pioneer plant, and manufacturing and installation would be a highly tailored and engineered process, the early iterations of OTEC would be considered pioneer ventures of their kind. But with gradual improvement and availability due to demand of these technology, it is a likely scenario that the overall cost of establishing an OTEC plant could potentially decrease over time.

Finally, the economic model's predictions were compared to retail energy rates on Hawaii, Puerto Rico, Fiji, Sumba Islands, Terembu Layang, Pangan a Islands, Bulon Don Islands, and Saint Martin Islands. The larger islands, such as Hawaii and Puerto Rico, have far larger populations and much higher power demand, allowing for larger, more economically efficient power plants to be built. Fiji, the Panganan Islands, and the Saint Martin Islands are small island communities with 50% of their population reliant on small-scale diesel generation. . Their power prices are influenced not just by the high cost of the fuel, but also by the added expenditures of transporting it to the island. For electrical generation, all of the Island settlements rely heavily on diesel or petroleum, exposing them not only to high pricing but also to considerable price volatility. Because of these qualities, OTEC is a particularly intriguing prospective source of electricity, as it has the potential to easily replace a considerable percentage of the diesel generation currently utilized for baseload power. Besides, economy of scale would come into play as there would remain a huge surplus amount of power generated from the 100 MW OTEC plant after meeting the needs of Saint Martin Islands.

# Chapter 6
# FORECAST USING MACHINE LEARNING

## 6.1. Introduction

Time series forecasting is a strategy that uses previous data as inputs to produce well-informed predictions about the direction of future trends. The technique aggregates and analyzes historical data to uncover patterns, which are then used to forecast future trends and changes. This type of forecasting can reveal which events are more likely — or less likely — to occur than others. The more complete the data, the more accurate the forecasts are likely to be. Time series analysis entails creating models in order to acquire a better understanding of the data and the underlying causes. The "why" behind the observed outcomes can be discovered through analysis. The next step in forecasting is deciding what to do with that information and the predictable extrapolations of what might happen in the future. . The "why" behind the observed outcomes can be discovered through analysis. The next step in forecasting is deciding what to do with that information and predicting through extrapolation the occurrence of future events.

Forecasting is useful in a wide number of sectors. Weather forecasting, climate forecasting, economic forecasting, healthcare forecasting, finance forecasting, engineering forecasting, retail forecasting, business forecasting, environmental forecasting, social forecasting, and many more practical applications are just a few examples. Essentially, the sequence of such forecasting centers on manipulating gathered data through time series analysis methods, followed by modeling, forecasting, and prediction. Some technologies, such as augmented analytics, can even choose predicting from a list of statistical algorithms based on which provides the most certainty.

When dealing with the unforeseen and unknown, there are bounds to be overcome. Time series forecasting isn't perfect, and it's not appropriate or beneficial in every circumstance. Because there are no clear guidelines for when to use forecasting and when not to, it is up to analysts and data teams to understand the constraints of analysis and what their models can handle. Not every model will fit every set of data or provide an answer to every inquiry. The performance of a time series forecasting model defines its capacity to predict the future. This usually comes at the price of being able to explain why a certain forecast was made, confidence intervals, and even a better understanding of the underlying reasons of the problem [96].

## 6.2 Forecasting Considerations

### 6.2.1 Size of Data

The amount of data accessible is the first thing to consider—the more points of observation available, the better the comprehension of trends. This is true for all types of research, including predicting utilizing time series analysis. Forecasting, on the other hand, is heavily reliant on data, sometimes much more than other evaluations. It is based on past and present data. As a result, the less evidence there is to extrapolate, the less accurate the forecasting becomes [97].

### 6.2.2. Time Horizons

The time frame of the forecast is also essential. A time horizon is a fixed point in time at which a process (such as prediction) concludes. A shorter time horizon with fewer variables is easier to predict than a longer time horizon with more variables. The variables will be more unpredictable the further back in time the model is set to learn from. Alternatively, if the time horizons are changed appropriately, having fewer data can sometimes still work with forecasting. It is feasible to construct short-term projections in the absence of long-term recorded data by combining a large volume of short-term data.

### 6.2.3 Dynamic and Static States

The state of your forecasting and data matters as much as the time frame in which it is used. If the forecast is static, it is set in stone and will not change over time. As a result, it is critical to ensure that the data is sufficient for a projection. Dynamic forecasts, on the other hand, can be revised as new information becomes available. This means that fewer data may be available at the time of forecasting, but that as data for future dates becomes available, more accurate predictions can be generated.

### 6.2.4 Data Quality

The best analysis is only useful if the data is of usable quality, as it always is with analysis. Data that is unclean, poorly handled, overly processed, or improperly obtained might bias results and lead to drastically erroneous estimates. The standard data quality guidelines apply here:

- Ensure that the data is complete,
- Filter duplicate or redundant data,
- Data collection was timely and consistent,
- Standard formatting of datasets,
- Provide accurate measurements of desired quantities,
- Gives uniform results through several sets of data.

When working with time series data, it's even more critical that the data was obtained at regular intervals during the time period being studied. This takes into account data trends, cyclic behavior, and seasonality. It can also assist determine whether an outlier is genuinely an anomaly or part of a bigger cycle. Gaps in data can obscure cycles or seasonal fluctuation, skewing the forecast.

## 6.3 Machine Learning for Time series forecasting

Since the introduction of powerful data processing-boosting technologies like machine learning, data forecasting has come a long way. Seasonality, trends, cycles, irregular components, and other time-dependent components can now be considered by ML-based predictive models to improve the precision of data-driven predictions and forecasts. This is known as machine learning forecasting, and it may be used in a variety of commercial situations, such as recruiting forecasting, demand and sales forecasting, weather forecasting, goods consumption forecasting, predictive planning and maintenance, and so on.

The specialized models are used to evaluate, characterize, and interpret the acquired time-series data, as well as make assumptions based on shifts and odds in the data. Switching trends, seasonal surges in demand, some recurrent changes or non-systematic alterations in regular patterns, and so on are examples of these shifts and odds. All previously, recently, and currently acquired data is utilized as input for time series forecasting, which uses complex math-driven algorithms to estimate future trends, seasonal variations, irregularities, and other factors. In the long term, time series forecasting gets faster, more exact, and more efficient thanks to machine learning. ML has been shown to improve the processing of both structured and unstructured data flows, capturing correct patterns within massive amounts of data quickly [98].

It's safe to say that time series machine learning techniques outperform the traditional method to time series forecasting. As a result, traditional approaches can only process demand data that has already been collected and is easily available. As a result, machine learning autonomously defines points of interest in an infinite flow of data, aligning them with customer data insights and conducting what-if analysis. As a result, particularly effective approaches to generating demand in the commercial sector, for example, emerge.

## 6.4 Different Models of Time-Series Forecasting:

### 6.4.1 Recurrent Neural Network (RNN)

RNNs go through a time series step by step, keeping an internal state from one step to the next. In this case, neural networks are ideal since they can learn the time dependence from the given data. Taking input sequences into account from a temporal perspective also offers up possibilities for more precise predictions. The method, however, is regarded a relic since "education" of neural networks can take a long period. *Recurrent* indicates that the current time step's output becomes the next time step's input. The model analyzes not just the current input, but also what it knows about the previous elements at each element of the sequence. As input, the RNN model effectively preserves a memory sequence. This memory enables the network to learn long-term relationships in a sequence, allowing it to anticipate the next word in a sentence, an emotion categorization, or the next temperature measurement while considering the full context [99].

### 6.4.2 ARIMA model

As mentioned in the above section, it is a combination of three different models itself, AR, MA and I [100], where

- "AR" represents the developing variable of interest when it is regressed on its own past values.,
- "MA" denotes that the regression error is a linear combination of error term values that occurred at various points in time previously, and
- The letter "I" indicates that the data values are replaced by the difference between their values and the preceding values.

"ARIMA" aims to fit the data into the model as a whole, and ARIMA is also dependent on the accuracy over a wide range of time series.

### 6.4.3 Long Short-Term Memory (LSTM) Model

LSTM models are comparable to RNN models, however instead of learning the temporal dynamics of sequential data, LSTM can also tackle the problem of vanishing and exploding gradients [101]. As a result, large multivariate data sequences can be effectively modeled, and the necessity for pre-defined time slots can be eliminated (which solves many tasks that feed-forward networks cannot solve). However, the disadvantage of excessively time-consuming supervised learning remains.

Because significant occurrences in a time series may have unpredictable delays, LSTM networks are well-suited to classifying, analyzing, and generating predictions based on time series data. LSTMs were developed to address the issue of vanishing gradients that can arise when standard RNNs are trained.

### 6.4.4 Prophet Model

The ARIMA, Auto-ARIMA, LSTM, RNN models require the data to be fed and with certain tweaking and fine-tuning they help us to make predictions. But the Facebook prophet model can perform the fine tuning by itself and has the capability of handling stationarity within the data and also seasonality related components [102]. All the previously faced troubles of seasonality affecting the training of the model has been eradicated by prophet model. There is also a provision to perform cross-validation with the help of the Prophet library which helps in increasing the accuracy of predictions [103].

Lorenzo Menculini and his colleagues examined the performance of AutoRegressive Integrated Moving Average (ARIMA) and Prophet in a recent study. According to the research, Prophet's performance is significantly worse than ARIMA's. Furthermore, when compared to the no-change forecasting model, Prophet did not produce any overall improvement. The investigation also revealed that Prophet was the worst performer in terms of forecasts, even when it used more data for the fit than other models. The problem with Facebook Prophet is that it doesn't seek for unintentional connections between the past and the future. It simply uses a linear logistic curve component for the external regressor to select the best curve to suit the data. Another criticism made against Prophet is that its assumptions are often too simplified and weak.

### 6.4.5 Neural basis expansion analysis for interpretable time series (N-BEATS) Model

NBEATS is a fascinating method of using deep learning to analyze time series data since it creates a time-series-specific architecture. Fig. 6.1 demonstrates the operating architecture of the NBEATS model in a block diagram. In a single pass, it takes a whole window of past values and computes numerous predicted time-points values. It accomplishes this by employing a large number of fully connected layers [104]. It is made up of several blocks that are linked with each other: the first attempts to model the past and future data as accurately as possible, the second tries to model only the residual error of the previous block's past reconstruction (and also updates the data to be forecasted using information of this error) and as such. The forecast is the prediction made using the sum of numerous blocks, where the first block’s job is to catch the main trend, the second’s specialty lies on small errors and other blocks similarly have their own function. This residual architecture also applies the ensembling or boosting techniques as used in classic versions of machine learning: the sum of predictions made from numerous blocks of information and commands, where the first block captures the primary trends, the second block mainly attempts to minimize small errors etc. Some specific trend and frequency blocks, which learn parameters of supplied functions, such as polynomial trends and sinus/cosinus with multiple frequencies, can also be employed.

This type of architecture operates differently from conventional recurrent networks and offers several key advantages, namely:

- **Trains Faster**: Since the operations are parallelized, the training is done much quicker in comparison to other recurrent networks.
- **Networks are light**: NBEATS blocks are far more programmable, resulting in lighter networks that are ideal for solving tiny problems or running on embedded devices.
- **Forecasting and Backcasting is totally configurable**: NBEATS may foresee arbitrarily in the future and employ arbitrarily long sequences in the past. Depending on the situation, this is customized once for each model.

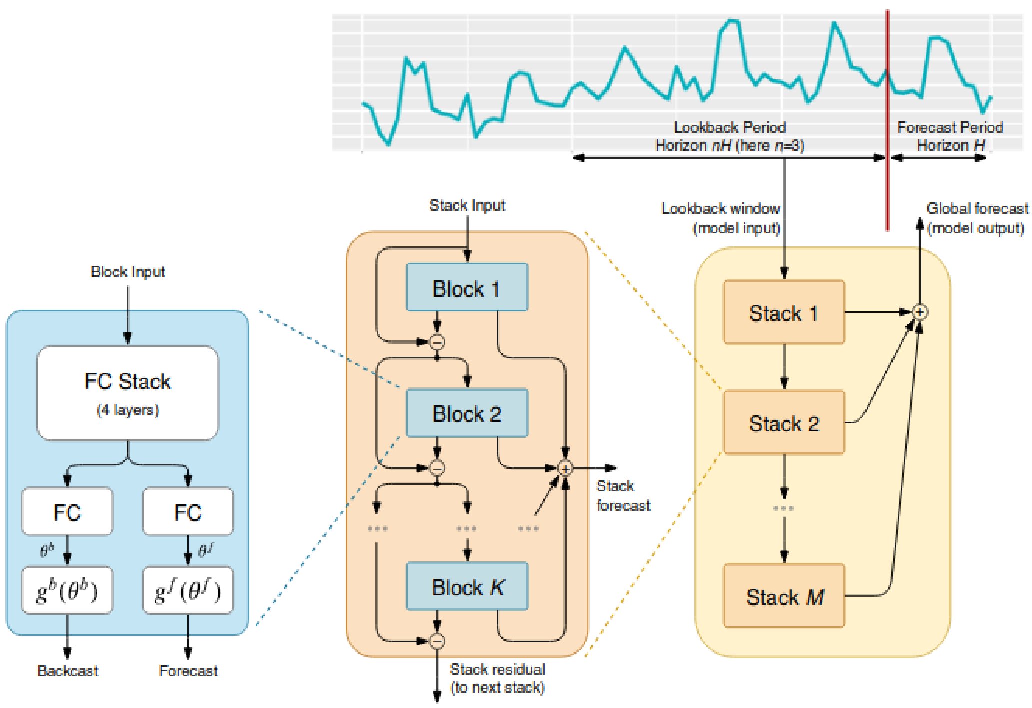



Fig. 6.1: Operating Architecture of the NBEATS model [104]

## 6.5 Forecasting using DARTS:

**Darts** is a Python package that allows you to easily manipulate and forecast time data. It includes a wide range of models, ranging from classics like ARIMA to deep neural networks. The models can all be used in the same way as scikit-fit learn's () and predict () algorithms. Backtesting models and combining the predictions of several models and external regressors are also simple using the library [105]. Fig. 6.2 shows the process flow diagram of the Darts library, where data uploading, data processing, evaluation and forecasting steps have been presented.. Both univariate and multivariate time series and models are supported by Darts. Models based on machine learning can be trained on numerous time series, and some of them can make probabilistic predictions.

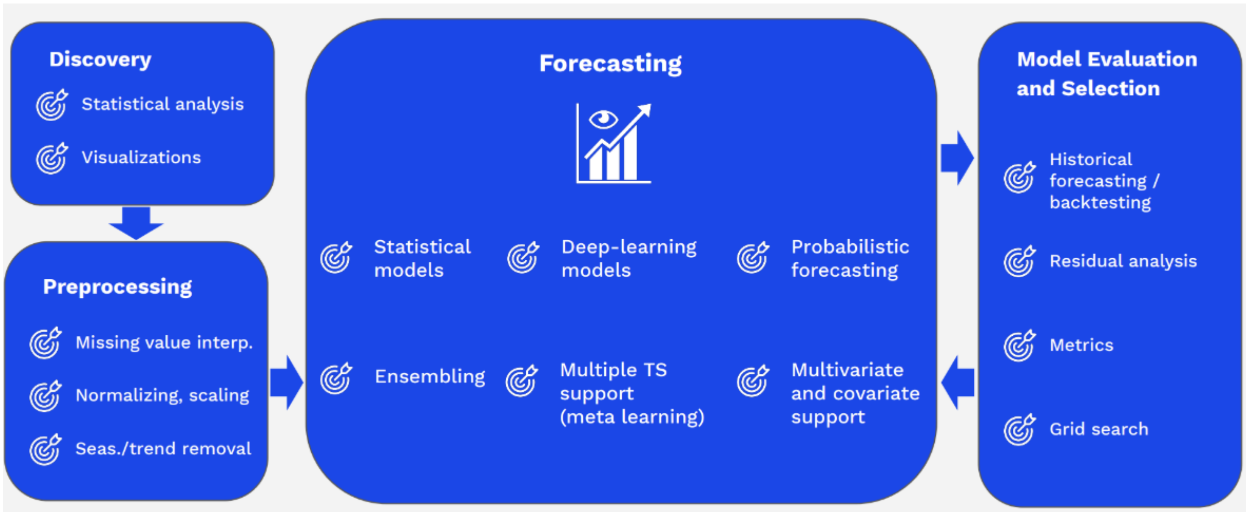



Fig. 6.2: Process Flow Diagram of Time Series Forecast in Darts [105]

### 6.6 Forecasting Results

The objective of the time series forecasting was to observe the long term behavior and predict the consistency of future power output based on the long term temperature data under the study. Hence, the dataset was generated for the considered co-ordinate point (19.6° $N$ longitude, 91.4°$E$ latitude). An NBEATS model was made to fit and train a dataset of daily temperature difference (20m and 1000m depth) between the years 2012-2021. The raw data had irregular seasonality and required conditioning. Hence, the daily data was then grouped to every month and was averaged to get a cleaner, more predictable pattern using *pd.resample* function of the *pandas* library. In order to fit into the forecasting model, the dataset was initially converted to *TimeSeries* format. The *TimeSeries* was then scaled to a standard range of values between 0 and 1 for the model to operate on. Resulting output was plotted using *matplotlib* functions such as *plot ()* to better visualize the distribution of datasets throughout the course of time.

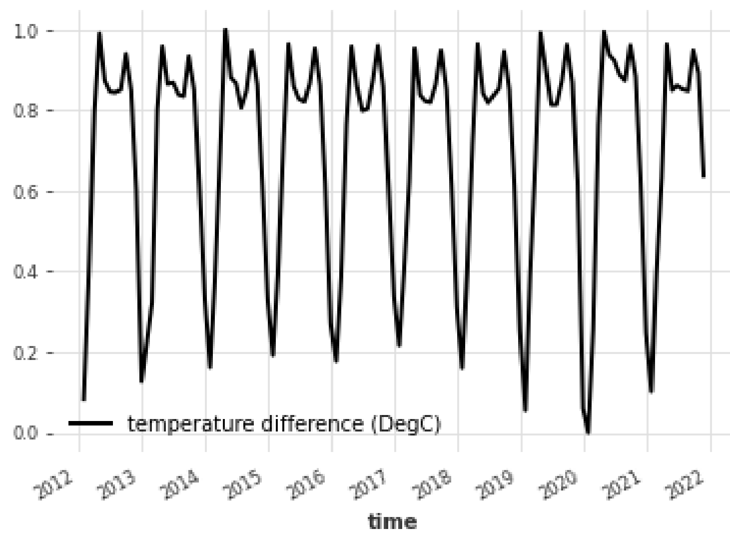



Fig. 6.3: Scaled plot of the temperature difference against time

As displayed by fig. 6.3, distinct annual behavior was spotted for the time series dataset and such patterns are exactly what makes the forecast predictable and produces excellent results. It is worth mentioning that a ML based forecasting is only a tool to project regular behavior and in no way represents the actual outcome. There could be various deciding factors which may affect the ocean temperature at a certain point of time i.e. disasters like cyclone or tsunami, global warming or high floods. Keeping exceptional tragedies aside, this model is expected to generate a future behavior that potentially expresses the stability of the ocean waters as a whole in the event of long term use of the proposed OTEC plant.

After plotting the scaled values of temperature difference over time, the next focus was to train the model. The model was trained to train 12 months of data using test dataset to be the rest data apart from the 12 months to be validated. Thus, 108 months were tested and 12 months were trained to generate the desired outcome. The trained model then generated positive results, approximating the accuracy of forecast to 5.05% MAPE (mean average percentage error). As visualized by fig. 6.4, the dataset in black stands for the historical data from previous records of temperature difference, whereas the blue line over the black line at the tail end represents the accuracy of the trained model with the actual dataset, validating the precision in the machine learning model.

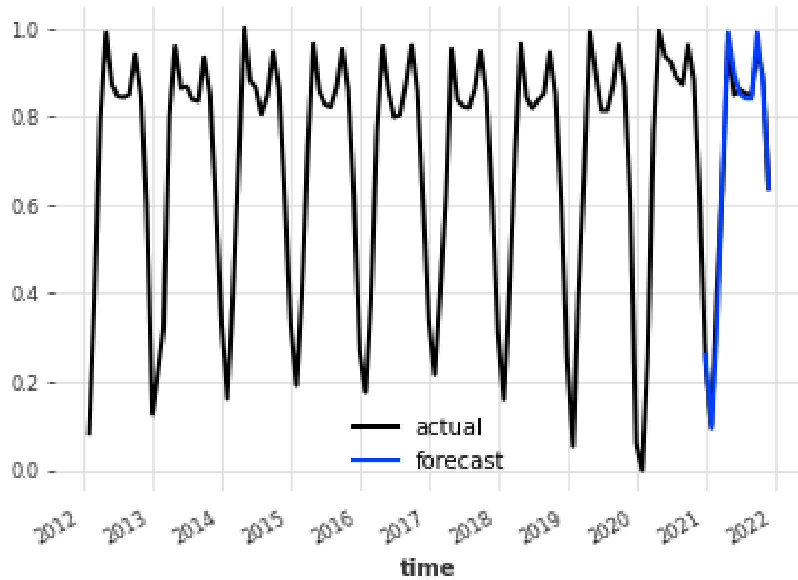



Fig. 6.4: Validation of 12 months of data using the rest as training sets (MAPE 5.05%)

After satisfactory validation of the model, it was then used to forecast a future trend for the next 10 years. The results were equally satisfactory as this forecasted dataset also carried the same MAPE of 5.05%. The projected temperature difference for the coming 10 years is displayed in the fig. 6.5, where the black lines represent historical data of temperature difference plot against time, and the blue lines represent the forecasted values of the temperature difference for the future 10 years of the plant's life. The forecasting results show satisfactory consistency as the mean average percentage error is only above five percent and seems to maintain consistency with historical records of previous data. As no unpredictability is noticed in the forecasted results, it appears that the installation of the plant should be safe enough to generate power through its lifetime. The novelty of these findings is that no previous work in this field has attempted to forecast the temperature difference values to verify the variations in temperature in coming years. The trained model presented demonstrates long term behavior and could easily be used to predict further years of the plant to get a somewhat view of the power output to be expected from the plant.

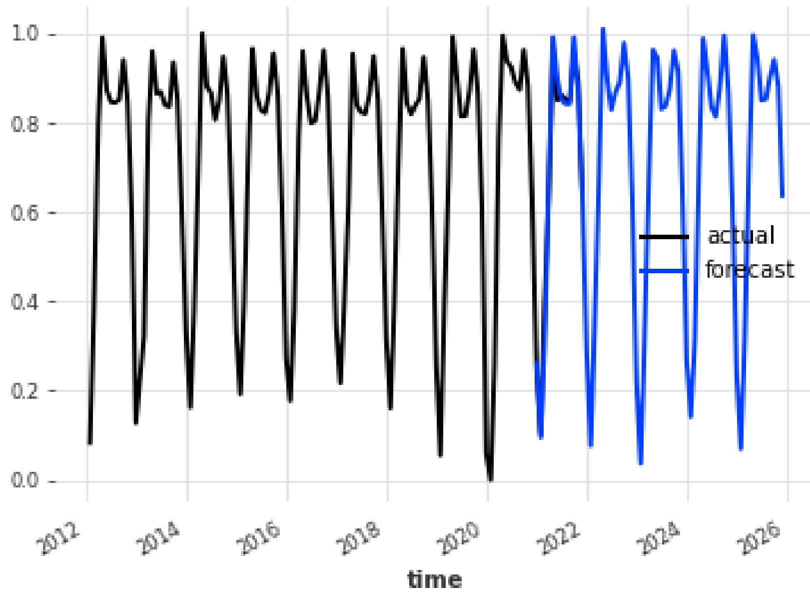



Fig 6.5: Forecasted temperature difference (blue) over 10 years' time (MAPE 5.05%)

Since the results of the forecasted temperature difference shows a reliable consistency of the ocean water temperature in the coming decade, the OTEC plant is set to generate roughly the same amount of output throughout its lifetime. It must be borne in mind that such forecasting is only a projection of the future outputs and does not guarantee the future, as there can be several sources of uncertainty involved. There is a scope of further work to be conducted by validating the results obtained here with other models of machine learning and deep learning, which would encompass more uncertainties and represent an even precise forecast. However, the presented data should suffice as the added uncertainties only appear to be temporary, meaning that they should not affect the long term behavior of the ocean water temperature. Hence, due to the presented forecast, the implementation of an OTEC plant as a renewable power generation source in the coastal region of Bangladesh seems more plausible a case.

# Chapter 7
# FUTURE SCOPE OF WORK

## 7.1 Reducing Cost through Learning Effects

Most economic analyses of OTEC plants tend to exclude the effects of learning effects apart from a few exceptions. A possibility of 30% reduction of modern times' capital costs can be expected to lessen through the benefits of learning effects at the rate of 7% [88], [106]. As per the statements by Vega [88], [107] and Martel et. al. [106] the scope of learning effects is finite as it converges to an asymptote eventually after four or five times the installation power output is doubled. This limitation can be countered by the maturity in modern technology, especially in components like power cables, turbines and heat exchangers, all of which are now upgraded from modern ship construction and utility engineering [89]. Potential ways to make a step in the right direction could come from reducing knowledge gaps within the OTEC literature, realistic system and component costs, reduction of operational uncertainty, implementation of learning effects and technological learning in the OTEC field.

## 7.2 Co-generation Projects alongside OTEC

There are several projects which can be run alongside OTEC plants which can benefit the community. The exit water from the OTEC plants can be used as a desalination unit in which can supply fresh water to the community, which can many times be a scarcity for people living in islands and coastal regions. According to Kobayashi et. al. the capacity of distilled water obtained per day from a 1 MW OTEC plant can be 10,000 $m^3$/day and for a 100 MW plant, the volume can be 1,000,000 $m^3$/day [5]. This fresh water can in turn be used in the production of hydrogen in the same plant system. With the rising trend of the world moving towards hydrogen fuel, the emergence of such a system may be imminent. Estimated amount of hydrogen produced approximates to 1.2 kg/hour from a 100 kW OTEC plant and even higher from large scaled plants [108]. Air conditioning is another benefit that can be added to the list of co-generation projects. In the experimental OTEC plant by NELHA, they utilized the cold seawater and passing it through the heat exchanger achieved air conditioning in their office and surrounding buildings [109].

Similar air conditioning systems can be implemented in various forms in much bigger scale to derive benefits from them.

### 7.3 Aquaculture and Mariculture

OTEC plants are completely zero emission power generation sources which even aids in creating suitable environment for certain kinds of aquaculture and mariculture. The deep ocean water (DOW) extracted from such plants not only are beneficial for certain kinds of plants and fishes but also effective in maintaining the richness of the ocean water. Experimental culture of Nori seaweed (*Porphyra Tenera*) have been conducted alongside OTEC plants [110]. The extracted samples after 39 days appeared to have high nitrogen and phosphorus contents in comparison to common Nori found in Japan. The deep ocean water extracted from the exhaust of OTEC plants is again beneficial for mariculture of certain types of fish. In a collaborative OTEC

DOWA (Deep Ocean Water Agriculture) in the mainland China-Taiwan, the prospect of such a maritime project have been analyzed [48]. An open cycle OTEC plant was proposed to help meet the electricity and freshwater demands of the fishing and transport industries. Construction of a wave driven upwelling was proposed to improve the maritime culture in the ocean regions using nutrient rich DOW.

# Chapter 8
# CONCLUSION

With the growing energy crisis in the world and technology advancing faster every day, it is essential to look past the realm of fossil fuel power and consider renewable sources more strongly than ever. For a country like Bangladesh, an OTEC plant could be highly suitable to alleviate the demands of islands like Saint Martin and the coastal regions as a whole. With the right technology and the mindset to bear the initial cost in exchange of clean, continuous power, it is hard to find a better starting point than OTEC. To add on, the byproducts of OTEC plants could be used to create potable fresh water, as the plant cycle desalinates the ocean water, leaving usable and safe water for use. Another set of benefits could come by generating hydrogen side by side with electricity could add to the list of benefits. Other forms of secondary production could be aquaculture, fertilizer production, air conditioning and lithium extraction. All of these secondary projects could make the deal of using OTEC plants even more attractive. The primary findings of this thesis can be summarized into the following points:

- Identifying the Bay of Bengal as a potential OTEC resource site.
- Selecting appropriate zones in the study region in which an OTEC plant can be placed using advanced Python based Data Analysis tools.
- Proposing a model 100 MW net OTEC plant that could be implemented in the selected sites and observing the power output over different seasons.
- Calculating an estimated range of cost values for the model plant, starting from capital expenses to levelized cost of per unit electricity production.
- Evaluating emissions of various compounds due to operating the model OTEC plant.
- Forecasting the data to project the future temperature behavior of the ocean waters using powerful Machine Learning tools. Findings reveal that temperature difference consistent enough to obtain desired power through the life of the plant.

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