AREE Final Report- Sherwin Francis

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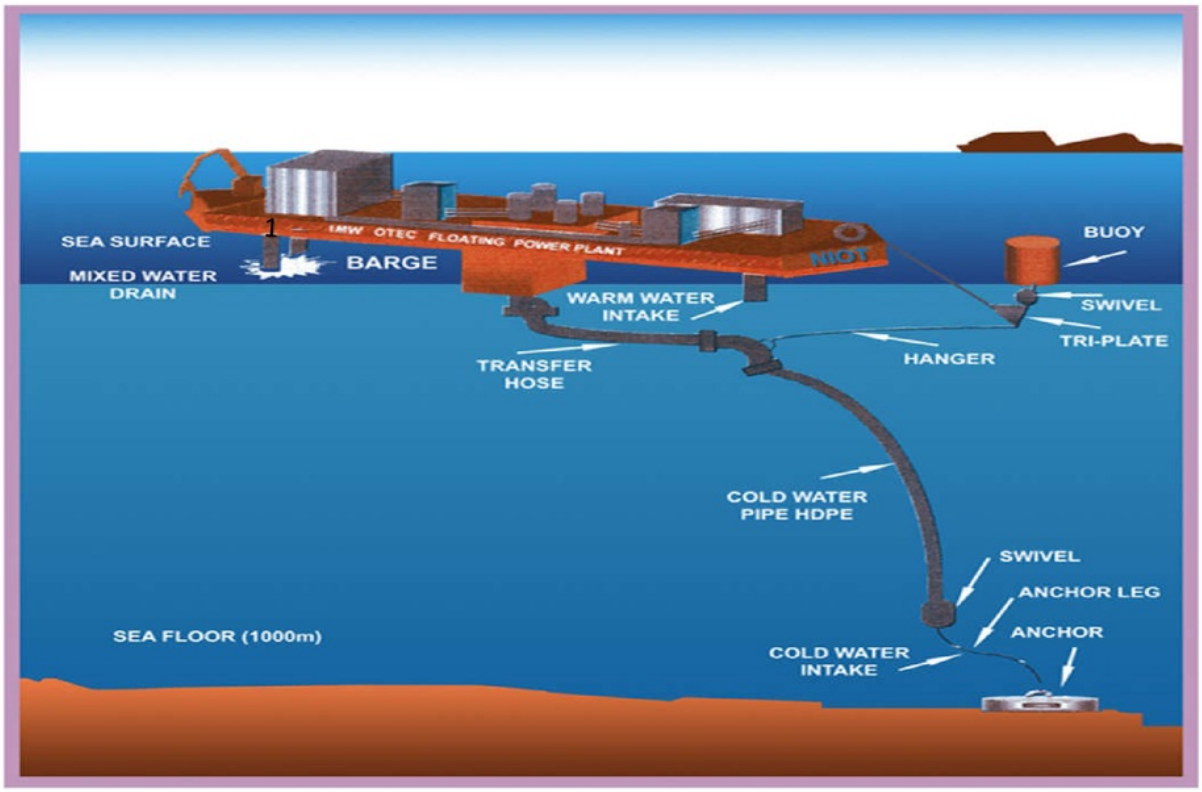
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Ocean Thermal Energy Conversion (OTEC) 100MW, for the energy and fresh water needs of an offshore oil platform.

Final Project Report

Heriot Watt University

Dubai, UAE



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Thursday, April 19, 2018

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Abstract

Ocean Thermal energy conversion (OTEC) work on the principle of conversion of solar thermal energy into electric energy. OTEC uses the ocean's natural thermal gradient to run heat engines and thereby generate electricity. The energy absorbed by the oceans from solar radiations is equivalent to the energy produced by 248 billion barrels of oil.

OTEC has a distinctive feature over other renewable energy sources, it not only produces electricity but can also be used as a source of other synergetic products.

This project aims to develop an Off-grid offshore 100MW hybrid cycle OTEC power plant to meet the energy and fresh water demands on an offshore oil platform, thus reducing the huge amounts of Fossil fuels which are used for energy generation.

An oil platform uses Approximately 192000 SCM (standard cubic meters) of natural gas per day for its energy requirements .(ONGC 2017)

Introduction

Ocean Thermal Energy Conversion (OTEC) uses the heat energy absorbed by the ocean from the sun's radiation. OTEC runs on the principle of Rankine cycle. OTEC technology being a very old concept is still being commercially for energy needs.

In the year 2001, the national Institute of Ocean Technology (NIOT) of India, and University of Saga from Japan, designed and developed a 1MW offshore floating OTEC power plant.

This plant, named as Sagar Shakti, was an inspiration for development and improvements of further such OTEC projects all over the world. (NIOT 2001)

The amount of solar thermal energy absorbed by the oceans on an annual basis is considered to be approximately 4000 times the amount of energy currently consumed by humans. This means that the OTEC plant which operates at an efficiency of only 3%,

would only requires less than 1% of the solar energy to satisfy the energy needs of the world. (Vega 2002)

Considering losses of 40% for parasitic losses, it is estimated that that India has a potential for development of 180,000MW OTEC Plants across the country. This confirms that there is scope for development of OTEC technology in India.(Ravindran 2001)

History of OTEC Plants

In 1881, a French physicist Mr. J. D'Arsonval, was the first to form a concept of utilizing the thermal gradient in the ocean to generate electricity. After two years, in 1883 Mr. De Laval, a Swedish Physicist developed the first thermal steam turbine. French scientist Mr. G. Claude developed an OTEC system working on open cycle but it was not successful. J. H. Anderson in the year 1964, developed a new OTEC plant which runs on a closed system, and was successful in overcoming the shortfalls of Claude's open cycle OTEC plant. The invention of Andersons OTEC plant was the stepping stone in development of OTEC technology across the world. Since then USA and Japan, carried out further research and developed new OTEC plants in rapid succession. In 1980s the Rankine cycle was improved and a new Kalina cycle was developed having higher efficiency. This Kalina cycle used a mixture of ammonia and water as the working fluid. This technology was further improved by a Japanese physicist Dr. H. Uehara in 1994, which has helped in commercial application of OTEC plants across the world. (KOBAYASHI 2015)

The Advancements in OTEC technology over the years have been shown in the Table 1

Table 1: Advancement in OTEC Technology

Year	Advancement
1881	J.D'Alsonval (France) presented the Idea of OTEC
1926	G.Claude (France) started experiments of OTEC
1933	G.Claude (France) constructed on board type OTEC 1982 Kyushu Electric Power Co. (Japan) succeeded to plant
1964	Anderson (USA) presented a proposal of Off-shore 1985 Saga Univ. completed 75kW experimental plant type OTEC
1970	New Energy Research Committee researched OTEC ammonia/water mixture technology (Japan)
1974	OTEC was researched as a part of Sunshine Project
1974	ERDA project started to research OTEC (USA)
1974	First OTEC conference was held (USA)
1977	Saga University (Japan) succeeded to generate 1kW
1979	Mini-OTEC generated 50kW (USA)
1980	Saga Univ. performed off-shore experiments at sea of Japan
1981	Tokyo Electric Power Co. (Japan) succeeded to generate 120kW on Nauru
1982	Kyushu Electric Power Co. (Japan) succeeded to generate 50kW at Tokunoshima Is
1985	Saga Univ. completed 75kW experimental plant
1985	Kalina (USA) invented a new cycle with ammonia/water mixture
1988	OTEC Association was established (Japan)
1989	Industrial and Technological Board succeeded to generate 3kW at Toyama Bay
1990	International OTEC Association (IOA) was established
1993	210kW open cycle OTEC was completed in Hawaii
2001	1MW closed cycle OTEC was constructed by NIOT (India)
2009-2013	Makai Ocean Engineering to complete the final design phase of a 10-MW

Classification of OTEC Plants

1. Depending on working cycle

- Open cycle

In an Open cycle system, the working fluid used is the sea water itself, this fluid is discarded after every cycle and not circulated in the system.

The open cycle consists of the following steps: (NREL 2018)

(i) Flash evaporation of the warm seawater.
(ii) Expansion of the vapor through a turbine to generate power;
(iii) Heat transfer to the cold seawater
(iv) Discharge of working fluid back into the ocean.

The Process flow diagram of an open cycle OTEC plant is shown in Figure 1

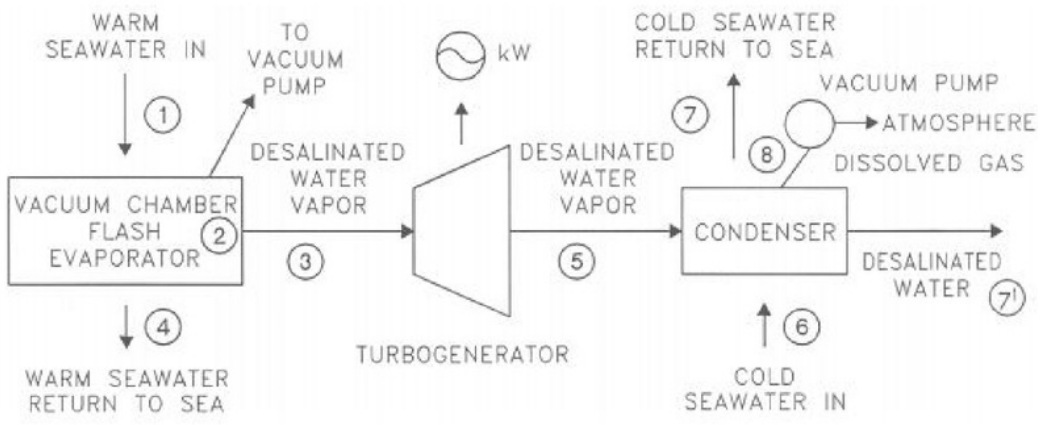


Figure 1: Open-Cycle OTEC Flow Diagram (NREL 2018)

- Closed cycle

In a closed cycle system, a different working fluid is used for the operation. Fluids having low boiling points are generally used for this system. The heat from warm sea water is used to boil the working fluid. The vapors from the evaporators are then used to drive the turbine, which is couples to the generators and thus produce electricity. The vapors from the turbines are then condensed in the condensers using the cold sea water and are reused in the system. Thus because the working fluid is circulated within the system, it is called a Closed system

Commonly used working fluid in this system is Ammonia. (KOBAYASHI 2015)

The Process flow diagram of a closed cycle OTEC plant is shown in Figure 2

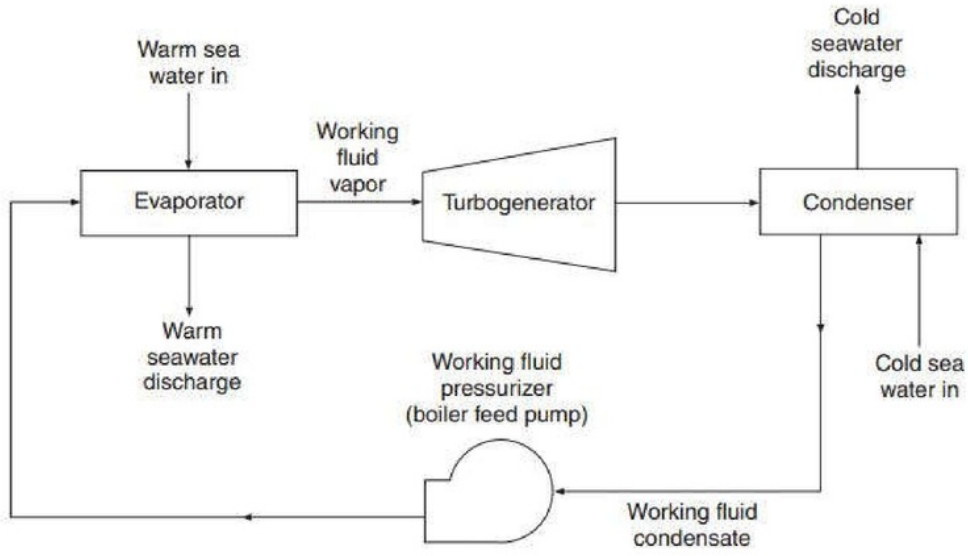


Figure 2: Closed cycle OTEC Plant Flow diagram (NREL 2018)

- Hybrid cycle

Hybrid OTEC power plants works on the principle of combination of open and closed cycle. This helps in the production of de-salinated water and also large capacity of electricity generation. This Hybrid cycle comprises of a closed cycle

OTEC system which can be used for electricity generation and a flash evaporation based desalination system which helps to produce de-salinated water from the plant. The main feature of this plant is that the production of water and electricity can be controlled independently.(Takahashi and Masutani 1997)

2. Depending on location

- Land based plants

  These types of OTEC plants are constructed on the land and the warm water and cold water are pumped into the plant through very long pipes from the ocean.

  These types of plants need less cabling and helps to reduce operation costs

  A typical floating type offshore OTEC plant is shown in figure 3

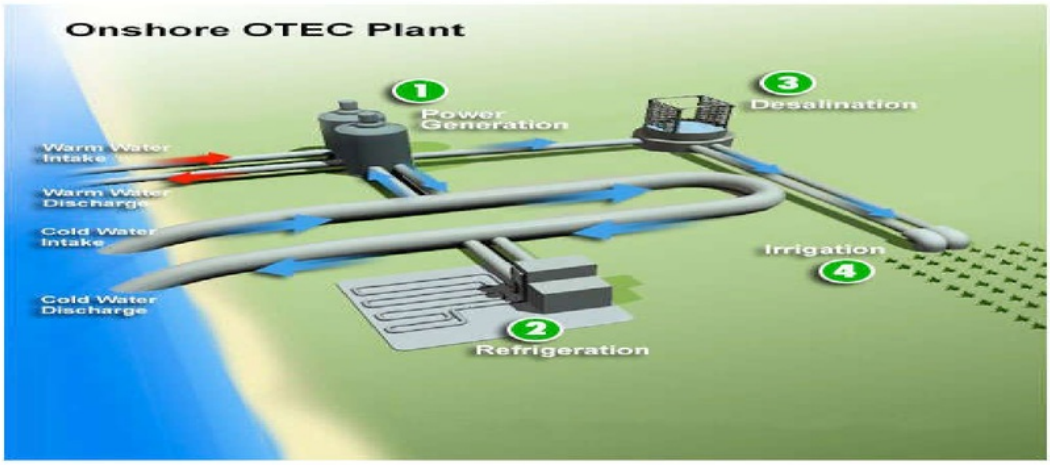


Figure 3: Land Based OTEC Plant (NREL 2018)

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- Floating plants

These types of OTEC plants are offshore and are mostly set up on a floating barge. These type of plants are closer to the cold water sources and thus reduces the cost of pumping water to long distance

A typical floating type offshore OTEC plant is shown in figure 4



Figure 4: Floating OTEC plant (NIOT 2001)

Project Details

An offshore floating OTEC plant has been selected for this project. This plant is housed on a 33,000-ton ship moored 100 nautical miles off the west coast of Mumbai (India). A **135 m** long **2.74m** outer diameter **fiber-reinforced-plastic** cold water pipe (CWP) is selected, as it is the largest diameter locally. This plant requires very huge flow rate of sea water through the system for the generation of the desired power output. (Kim et al. 2016)

OTEC requires huge investments for the development and construction of the power plants. The cost of electricity for a 10MW OTEC plant is estimated to be approximately $200/MWh whereas a 100MW plant will provide electricity at a cost of $100/MWh. (Vega 2002)

OTEC plants provide not only electricity but can even help to solve the 3 greatest global requirements , , i.e. Food, Water and Energy (KOBAYASHI 2015)

Figure 5 shows a 1MW OTEC power plant named Sagar Shakti, which is operational in India since the year 2000.



Figure 5: 1MW OTEC plant ,Sagar Shakti in India (NIOT 2001)

2

The Temperature gradient between the surface water and deep ocean water is the driving principle behind OTEC technology.

Fig 6 shows the exact variation in ocean temperatures with increasing ocean depths

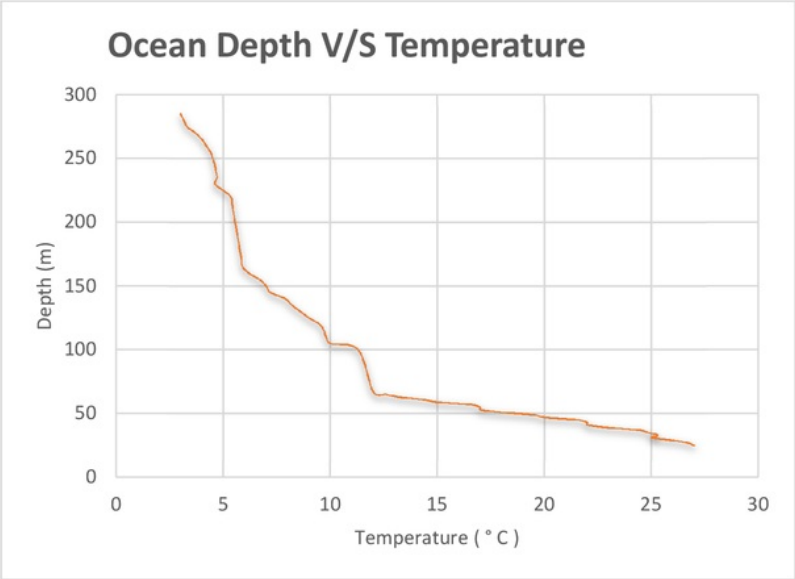


Figure 6: Temperature variation with depth

Figure 7 shows the various OTEC plants around the world which are in operation, under construction, Planned and proposed

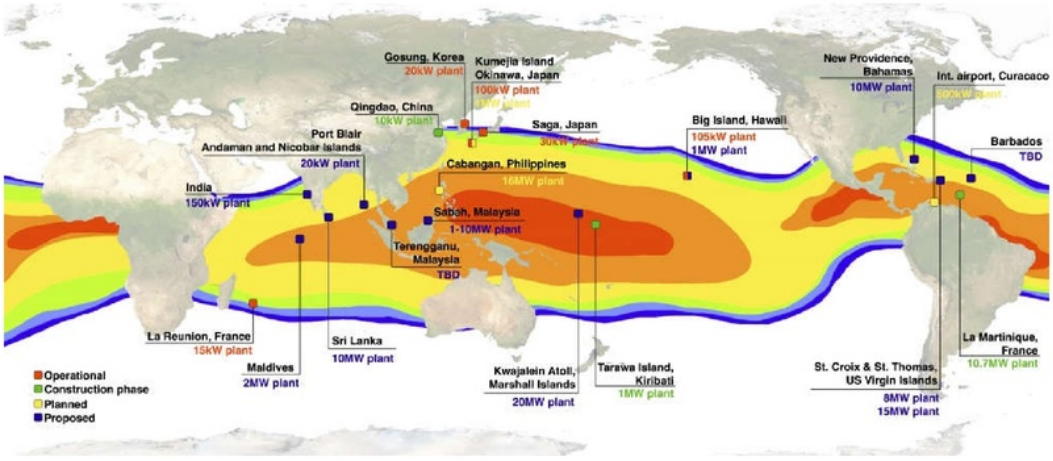


Figure 7: OTEC projects all over the world (Ravindran 2001)

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UEHARA CYCLE

Japanese physicist Dr. H. Uehara in the year 1994, developed an advanced OTEC cycle, which helped to improve the efficiency of the existing Rankine cycle from 3% to 5 %. The efficiency of any OTEC plant depends on the thermal gradient in the oceans temperatue.The development and working of Sagar Shakti, had pushed the world to make further improvements in OTEC technology and associated heat exchanger technologies.

The UEHARA cycles has higher efficiency due to the reduced load on the condenser by making use of a two phase separator before the turbine. This ensures that only dry vapor enters the turbine thereby increasing the energy produced and reducing the condenser load. (KOBAYASHI 2015)

Figure 8 and Figure 9 shows the Process flow diagram and the actual Uehara Plant respectively

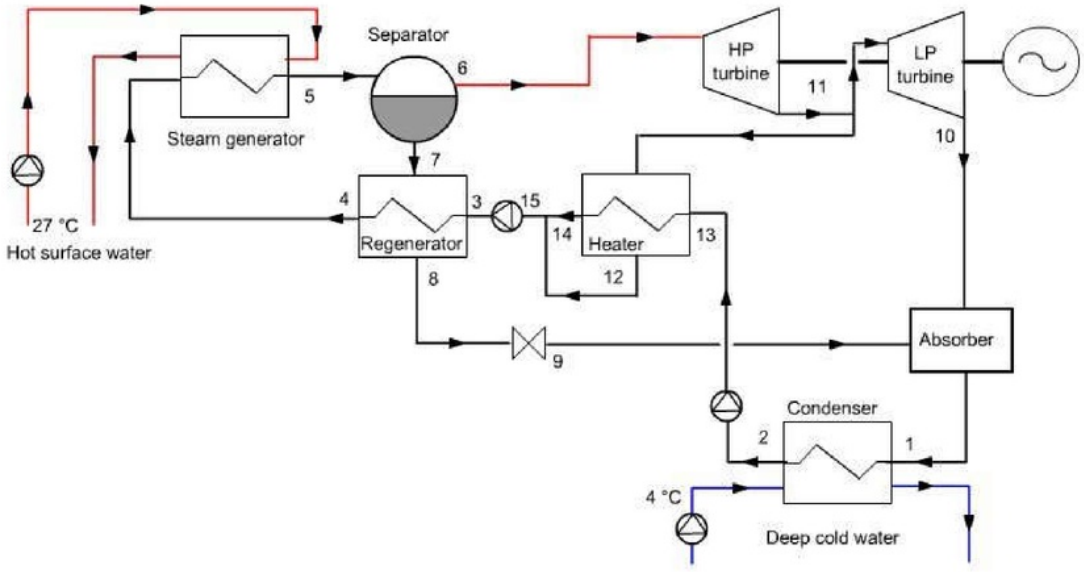


Figure 8:Schematic Flow diagram of Uehara cycle (KOBAYASHI 2015)

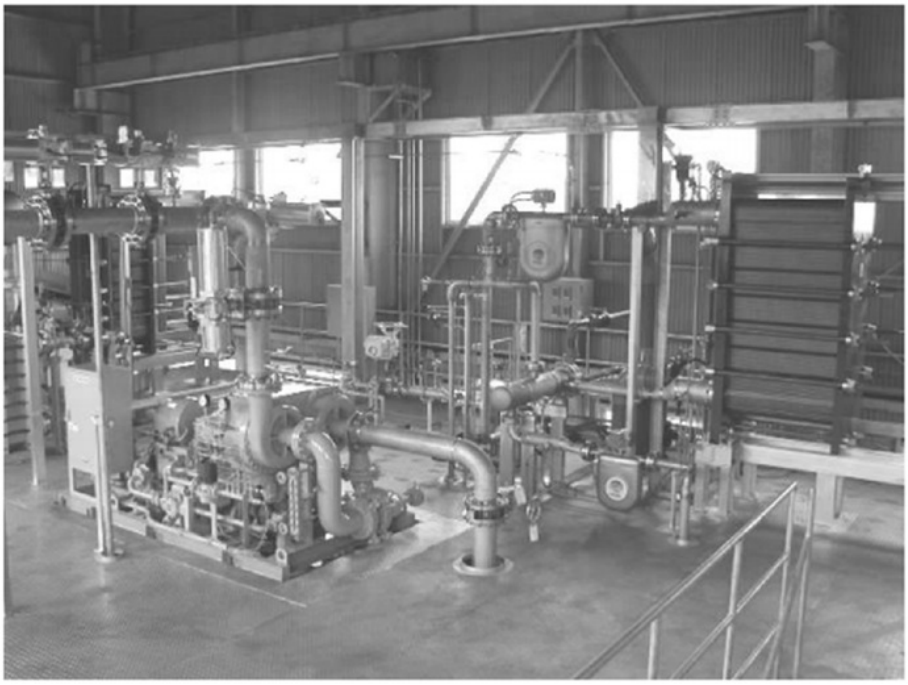


Figure 9:Actual Plant running on Uehara cycle (KOBAYASHI 2015)

Comparison of Required Seawater for a Uehara cycle and that for a conventional Rankine cycle is shown in Table 2. (KOBAYASHI 2015)

Gross output 100MW

Surface water temp. 27℃

Depth water temp. 4℃

Table 2: Comparison between Uehara cycle and Rankine Cycle

	Conventional Rankine	Advanced Uehara
Warm surface seawater	200 m3/s	110 m3/s
Cold Depth seawater	200 m3/s	120 m3/s

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Desalinated Water Production

Production of potable water from 100 MW OC-OTEC can be expected to be

P =0.005 * 400 * 24 * 3,600 m3/day, for round the clock plant operation = **172,800 m3/day** (KOBAYASHI 2015)

Demand data vs OTEC Plant deliverable

The power requirement for an offshore oil and gas platform varies from in between **890-1000MW** (ONGC 2017)

The power output of proposed 100MW OTEC plant is approximately **79-84MW**.

This means that that energy generated from the OTEC plant can be used to power all small equipment's like **illumination and HVAC system** (which contributes to around **8-9%** of the total energy requirements) (ONGC 2017)

The actual Ocean temperature data at the proposed Plant location has been requested from INCOIS (Govt of India), still awaiting approval.

The average warm water temperature is 27 °C and 4 °C for cold water.(Ravindran 2001)

Technical data

Most basically, the Rankine cycle consists of a heat exchanger, turbine, condenser, and pump.

The general processes are outlined as follows:

1-2: Isentropic expansion of the working fluid

2-3: Heat transfer from working fluid at constant Pressure

3-4: Isentropic compression in the pump

4-1: Heat transfer to working fluid at constant Pressure

The T-s Diagram of an OTEC plant running on conventional Rankine cycle is shown in Figure 10

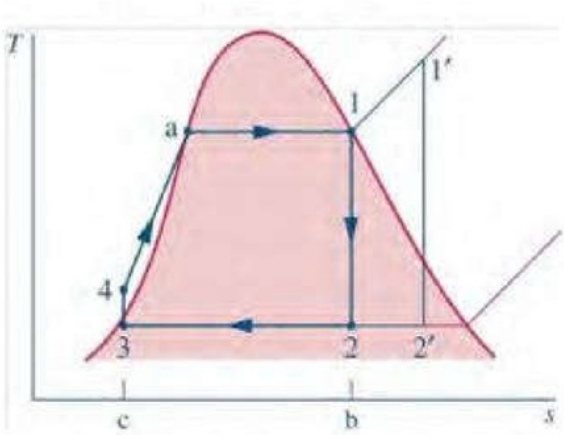


Figure 10: T-s Diagram of an ideal Rankine cycle

With the. Uehara cycle used in the OTEC Plant the existing Rankine cycle has been enhanced and the T-s Diagram of the new system is as shown in Figure 11

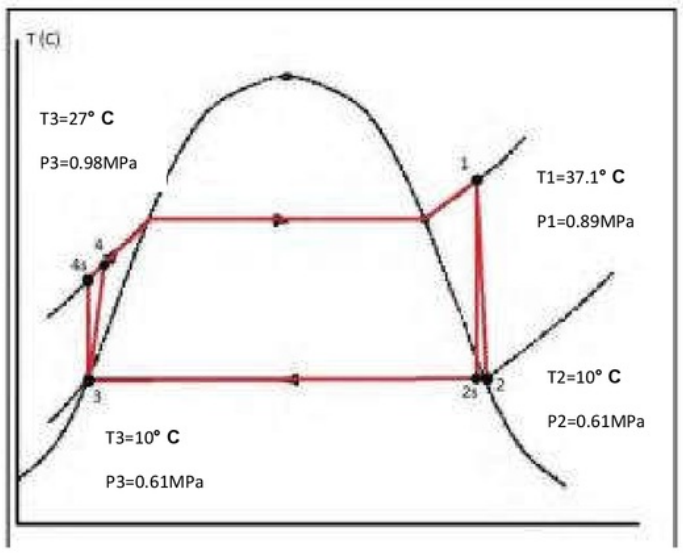


Figure 11:T-S Diagram of the improved cycle (KOBAYASHI 2015)

(Turbine efficiency = 0.8)
(Pump efficiency = 0.85)

STATE	T (° C)	p (Mpa)	s (KJ/Kg-K)	h (KJ/Kg)	Comments
1	37.11	0.9843	5.16	1500.78	(superheated vapor)
2	10	0.6159	5.2033	1451.78	(saturated vapor)
2s	10	0.6159	5.16	1439.39	
3	10	0.6159	0.8769	226.75	
4	(irrelevant)	0.9843	0.8769	227.34	(compressed liquid)
4s	(irrelevant)	0.9843	0.8769	227.445	(compressed liquid)

Wout, turbine = 49.0 kJ/kg
Win, NH3 pump = 0.69495 kJ/kg
Win, water pumps = 10.97 kJ/kg
Wnet = 37.34 kJ/kg
Qin = 1273.34 kJ/kg
efficiency = 2.93

The turbine efficiency and pump efficiencies were taken to be 80% and 85%, respectively.

The work output from the turbine was estimated to be 150MW in order to try to achieve a net output around 100MW

Finance

The approximate cost of electricity is estimated for Indian conditions for a range of 1 MW to 100 MW as shown in Table 3 *(Vega 2002)*

Table 3: 1 Cost of electricity from an OTEC plant (NIOT 2001)

Power Output Gross (MW)	1	25	50	100
Power Output Net (MW)	0.617	15.39	30.88	64.23
Heat exchanger cost (Mill.US$)	1.7	44.4	88.22	152.28
Cost of cold w. pipe (Mill.US$)	0.69	1.74	2.67	4.65
Cost of barge (Mill.US$)	0.69	2.33	4.65	9.3
Mooring cost (Mill.US$)	2.09	3.49	4.65	5.81
Turbine + Inst. Cost (Mill.US$)	1.16	17.44	34.48	69.76
Total cost (Mill.US$)	6.42	69.42	134.67	242.1
Cost of electricity (US$/kWh)	0.189	0.082	0.079	0.068

For small plants of 1 MW range the unit power generation cost is considerable compared to other conventional energy sources as shown in the Table 4 *(NIOT 2001)*

Table 4: Comparison of Unit Cost of OTEC with Conventional Energy Sources (NIOT 2001)

Source	Plant Capacity (MWe)	Plant life (years)	Capacity factor (%)	Annual output(GWh)	Cost of energy (USD/KWh)
Wave	1.5	40	68	9	0.062-0.072
Hydro	1.2	40	48	5	0.113
Diesel	0.9	20	64	5	0.126
OTEC	1.256	30	80	8.8	0.149

- Total capital cost- 240-250 Million USD
- LCOE- 0.068 $/KWh (approx.)
- Cost of water 0.015 $ / Lit
- Income from water- $2.59 Million/ day
- Payback period- 11-12yrs (inflation 10%)

Considering income from sale of fresh water, payback period will reduce to 6-7yrs

Environmental Impact Assessment

As during the operation of an OTEC plant there are huge discharge of water into the ocean, this can have huge impacts on the environment. There could be disturbance in the ocean's food web due to the circulation of cold, nutrient rich water to the surface. Organisms living underwater may also be sucked into the plant due to the huge suction of the pumps and may get caught in the filters. There may also be exposure to the working fluids which maybe corrosive in nature. These can be significant concerns. Large offshore plants can also disrupt fishing activities and the fishing habitats. There will be increase in fishes around the plant due to its nutrient rich waters around the plant.(Timothy 1995)

Ammonia which is the most commonly used working fluid is hazardous and is highly corrosive and flammable. If these working fluid is leaked into the atmosphere or into the ocean, it can cause irritation to eyes, skin, and may inhibit respiration. (Timothy 1995)

The chlorine which is used in heat exchangers, which are used to avoid marine growth, if leaked can be harmful to the marine life. (Sreebha and Padmalal 2011)

Due to the continuous circulation of warm and cold water around the plant, there are chances of mist formation around the plant over a period of time. This will affect the migratory birds. (Sreebha and Padmalal 2011)

Constraints

Microbial Fouling of Heat Exchanger Tubes

The seawater used in the heat exchangers are unfiltered, they contain all of the bacteria and other micro-organisms living naturally in the ocean. As seawater passes through the heat exchanger, some of these microorganisms can stick to the walls of the heat exchanger, forming a very thin layer between the heat exchanger surface and the seawater. (Soto and Vergara 2014)

This thin layer increases the thermal resistance between the seawater and the heat exchanger, making heat transfer more inefficient.

Fouling causes a decrease of 21% in the overall heat transfer co-efficient in the heat exchangers

Design constraints

- The major engineering and design challenges are given by the CWP (Cold water pipe) as these are long pipes and must withstand the strong underwater currents.
- The Floating plant can only operate under normal weather conditions, the barge will not be stable when wind speeds are more than 17-18knots and when the sea swells are more than 5mts.(ONGC 2017)
- These floating barges always need a standby Anchor handling vessel for emergency situations, this thereby increases the cost of operation.(ONGC 2017)
- Transportation of work personnel to the Plant site is costly as it is usually by helicopters.
- OTEC sites are not suitable all over the world, hence it must be designed specifically for each geographical region (International Renewable and Sustainable Energy 2013)

Conclusion

2

Considering all new achievements, we can easily predict the latest OTEC technology produce twice as much net power from the same heat source as the conventional OTEC

OTEC Plant shall not be only seen as a source of electricity generation by also provides other important resources as shown in Fig 12 (Vega 2002)

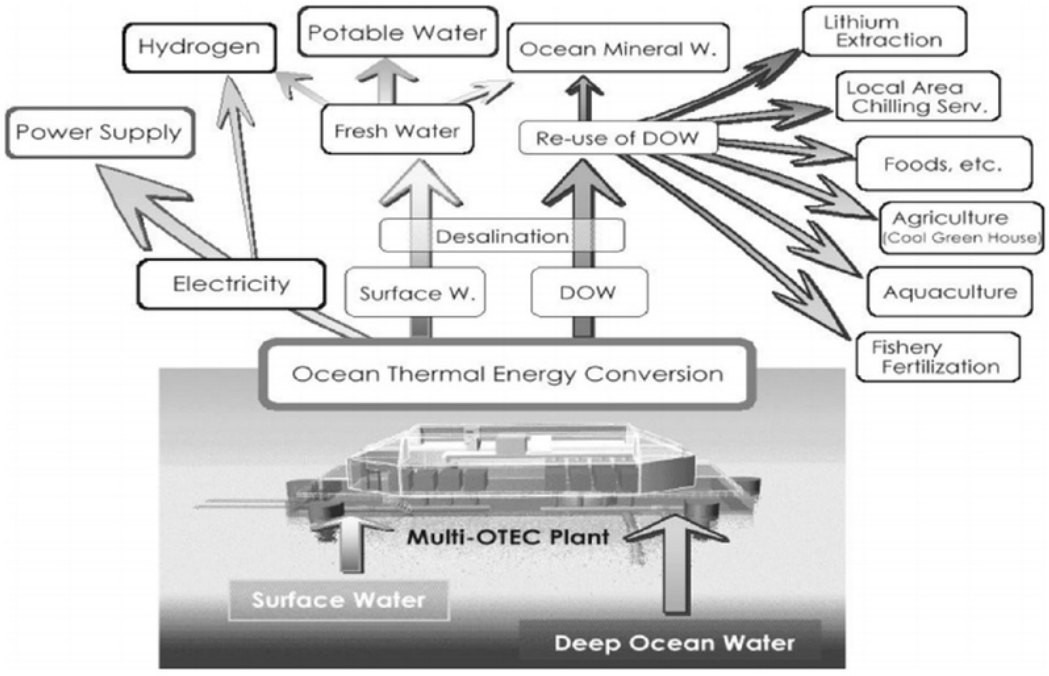


Figure 12:Future OTEC plants providing various deliverables (KOBAYASHI 2015)

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