Economic study on the construction of a 50 MW Ocean Thermal Energy Conversion (OTEC) facility in Banten Province, Indonesia

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Economic study on the construction of a 50 MW Ocean Thermal Energy Conversion (OTEC) facility in Banten Province, Indonesia

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Abstract. Electricity demand is increasing every year along with economic growth and population in Indonesia. Meanwhile, non-renewable fossil fuels are still the main source of electricity generation in Indonesia. Therefore, the development of an affordable and environmentally friendly renewable energy-based power plant is very necessary. Ocean thermal energy sources available in abundance and has great potential in meeting national energy needs. In this study, a design concept of the 50 MW Ocean Thermal Energy Conversion (OTEC) facility was developed for Banten Province. Capital costs and expenditures for OTEC facilities were identified based on location requirements. The cost analysis is then combined with the OTEC facility investment scheme to obtain the Levelized Cost of Energy (LCOE).

1. Introduction

Electricity demand is increasing along with population and economic growth in Indonesia. From 2009 to 2014, the state-owned electricity company (PLN) sales increased by an average of 7.8% per year. During this period, PLN also has an addition of around 3 million customers each year [1]. However, it turns out there are still many areas in Indonesia that are still without electricity. In 2014, the national electrification ratio was still around 84.35%. So that it still leaves around 40 million residents or around 10 million households which have not enjoyed electricity facilities. The lowest electrification ratio is in Papua with a ratio of 43.46% and followed by Eastern Nusa Tenggara (NTT) with a ratio of 58.91% [2].

Most power plants in Indonesia are still dominated by fossil fuel-driven that cannot be renewed. Fluctuating and increasing world oil prices due to reduced reserves also affect the prices of other fossil fuels, such as coal and gas. The production capacity of fuel oil and gas in Indonesia has not been able to meet national needs, so the import option is still continuously made. This causes the electricity production costs to swell, so that in the 2017 Draft State Budget (RAPBN), the government still had to issue an electricity subsidy of USD 3.138 billion.

Fossil fuel power plants also have negative effects on the environment. The result of combustion emits CO_2 gas which is the cause of global warming. In 2011 alone, CO_2 emissions due to energy utilization in the electricity sector reached 155.75 million tons [3]. Coal mining activities that are currently being carried out also damage forests. From several facts that exist in the condition of energy supply in Indonesia as above, it is considered necessary to develop new renewable energy sources that are cheap, easily accessible, and environmentally friendly.

At present, the Indonesian government has a very supportive policy in developing renewable energy. This is stated in Government Regulation No. 79 of 2014 concerning the National Energy Policy (KEN) which states that energy management is based on the principles of justice, sustainable and environmentally friendly to create energy independence and national energy security [4]. In the primary energy mix projection in KEN, the source of new and renewable energy (EBT) has increased from 11.6% in 2014 to 23% in the year 2015 [3].

One of the promising EBTs for energy security in Indonesia is marine energy. There are about five types of ocean energy that can be utilized, namely: 1) tides, 2) ocean currents, 3) ocean waves, 4) ocean heat, and 5) heat differences. Marine energy is very potential in Indonesia because about 70% of Indonesia's territory is the sea [5] and the islands are scattered and separated by the seas.

In this paper, the authors review more deeply the use of sea heat as a source of electrical energy or commonly called the Ocean Thermal Energy Conversion (OTEC). Ocean heat has the greatest energy potential in Indonesia compared to other types of marine energy. The Research and Development Agency of the Ministry of Energy and Mineral Resources (ESDM) and the Indonesian Ocean Energy Association (ASELI) in 2014 estimated the theoretical potential of ocean thermal energy at around 4.2 million MW [6], as shown in Table 1.

Table 1. Result of calculation of sea energy potential in Indonesia [6]

Energi Sources	Theoretical Potential (MW)	Technical Potential (MW)	Practical Potential (MW)
Ocean thermal	4,247,389	136,669	41,001
Ocean currents	287,822	71,955	17,989
Ocean waves	141,472	7,985	1,995
Total	4,676,683	216,609	60,985

2. Location of the Study

Site selection is done by considering bathymetry maps and electric power system maps in Banten Province [1]. The location resulting from the measurement is 11 km to the south of the coastline of Bayah District, Lebak Regency. This location is adjacent to the 150 kV substation in the same district.

Measurement of the average annual temperature (2007-2018) around the location of the OTEC facility was obtained from World Ocean Atlas 2018 [7] and then processed using Ocean Data View software. The average temperature for warm water sources at the surface (0-20 meters) is 28.6 °C and for cold water at depths (990-1,010 meters) is 6.2 °C. Visualization of temperature changes based on depth can be seen in Figure 1.

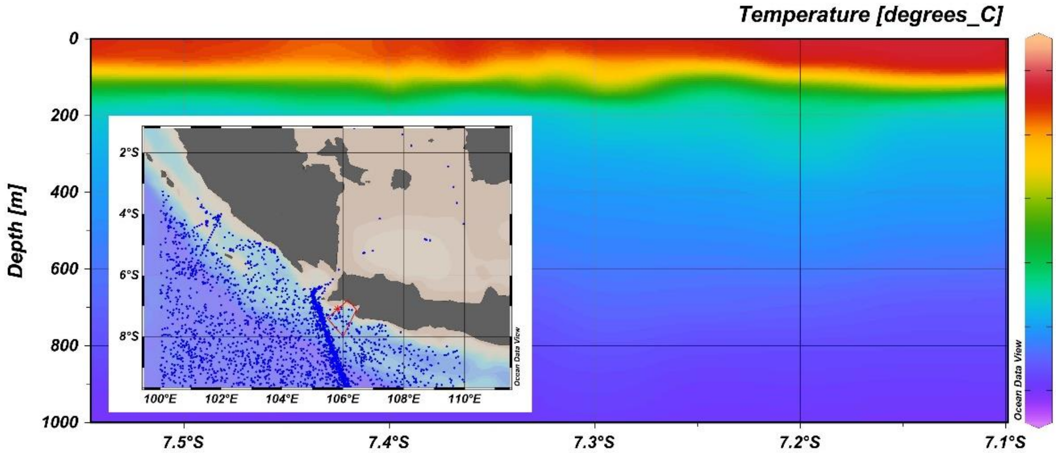

Figure 1. Temperature profile based on depths of 2007-2018 in South of Banten Province [7]

3. Design Concept

A simple diagram of a closed cycle OTEC system can be seen in Figure 2. The working fluid of ammonia in liquid form which has a low boiling point is evaporated by warm seawater from the surface (25-30 °C). The ammonia vapor then drives a turbine generator to produce electricity. Next, the ammonia vapor is cooled to return in liquid form with seawater from a depth of about 1,000 meters (5-7 °C). Liquid ammonia then returns to the cycle.

Nihous gives an overview of the difference in surface seawater temperature and depth of ΔT acting on the OTEC system, as depicted in Figure 3 [8]. With this temperature ladder, the gross power of the PG from the OTEC system can be described as in equation (1). The thermodynamic efficiency of the OTEC power cycle is $\varepsilon_{tg}\Delta T/2T$, where T is the sea surface temperature in K, and ε_{tg}, the efficiency of the turbine generator used in this study is 0.85. ρ is the average density of seawater, and c_p is the specific heat of seawater, about 4 kJ / kg K. Equation (1) as given by Nihous uses the design assumption of a seawater flow ratio γ representing Q_{cw}/Q_{cw} with a maximum value of 2.0. In this study, the value of γ used is 2.0 to minimize cold water flow from the depth. Estimated net power P_{net} is obtained by subtracting P_g with an average OTEC system requirement of 30% from the P_g described by Nihous in equation (2).

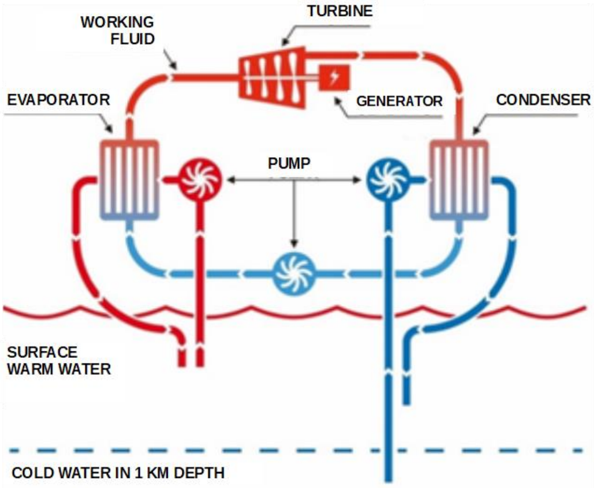

Figure 2. Process in a closed cycle OTEC system

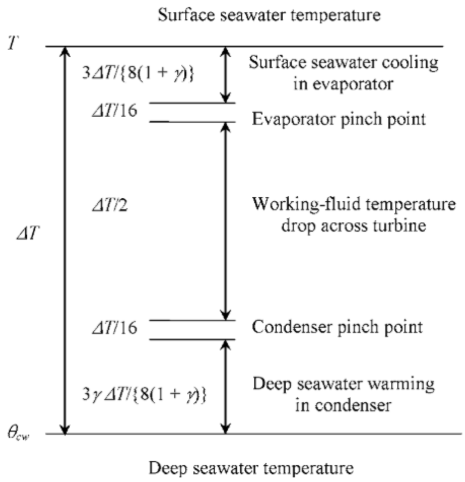

Figure 3. Illustration of OTEC temperature ladder [8]

Temperature data from the location of the study are then substituted into equations (1) and (2). To obtain the 50.4 MW gross power demand, the OTEC facility proposed to be 72 MW capacity. Meanwhile, the required seawater flow rate is 99.39 m^3/s for cold seawater and 198.79 m^3/s for warm seawater.

$$P_g = Q_{cw}\rho c_p \frac{3\gamma\Delta T}{8(1+\gamma)}\frac{\varepsilon_{tg}\Delta T}{2T} \tag{1}$$

$$P_{net} = \frac{Q_{cw}\rho c_p \varepsilon_{tg}}{8T}\left\{\frac{3\gamma\Delta T}{2(1+\gamma)}\Delta T^2 - 0{,}18\Delta T^2 - 0{,}12\left(\frac{\gamma}{2}\right)\Delta T^2\right\} \tag{2}$$

3.1 Heat Exchanger

The heat exchanger is a device used to transfer the heat in the OTEC system which is divided into two components, namely the evaporator and condenser. The heat exchanger design used in this study is a plate type, specifically designed for OTEC facilities by Xenesys Inc (XP Plate). The maximum dimensions of this XP Plate are 1 m × 1 m × 3 m with a surface area of 500 m^2 per unit. The heat load $\dot{Q}$ received by the heat exchanger is calculated using equation (1) by eliminating the thermodynamic efficiency of the system, which is 2282.06 MW for both the condenser and the evaporator, as expressed in equation (3).

$$\dot{Q} = Q_{cw}\rho c_p \frac{3\gamma\Delta T}{8(1+\gamma)} \tag{3}$$

To calculate the surface area of the heat exchanger used in this study, the general equation of heat flow through the dividing wall is given as follows [9]:

$$\dot{Q} = UA(T_1 - T_2) \tag{4}$$

Because heat is absorbed according to the flow of water through the surface of the heat exchanger, the water temperature at the outlet is lower than at the entrance of the heat exchanger. Therefore, the rate of heat transfer from water to ammonia will vary with the position of the heat exchanger. Therefore an appropriate average value must be used for calculations. If U does not depend on ΔT or the flow position in the heat exchanger, then:

$$\dot{Q} = \Delta T_m UA = \frac{UA(\Delta T_i - \Delta T_o)}{\ln(\Delta T_i / \Delta T_o)} \tag{5}$$

Using equation (5) the surface area of the heat exchanger can be obtained in detail as in Table 2. The number of heat exchangers needed in this design concept is 68 units for the evaporator and 114 units for the condenser. A comparison of net power with total area yields a total heat exchanger capacity in this study of 0.55 kW/m^2.

Table 2. Calculation of heat exchanger surface area

	Evaporator	Condenser
U	4520 W/m^2 C	4520 W/m^2 C
T_{a_i}	10.33 ℃	15.75 ℃
T_{a_o}	21.23 ℃	10.30 ℃
T_{w_i}	28.59 ℃	6.19 ℃
T_{w_o}	25.79 ℃	11.79 ℃
ΔT_m	14.97 ℃	8.76 ℃
A	33,719 m^2	57,645 m^2

3.2 Turbine Generator

In this design concept, the OTEC system is divided into four power generation modules. Each module has an average capacity of 18 MW which consists of one turbine generator and one submodule evaporator and conductor each. The dimensions required for turbine generators with capacities up to 20 MW are 12 m × 4 m × 5 m.

3.3 Water Ducting System

This system consists of pipes and pumps to meet the flow of warm and cold seawater for heat exchangers and make it possible to return water that has been used back to the sea. The design of the seawater pipe uses a sandwich fiber-reinforced-plastic (FRP) pipe consisting of two FRP sheets separated by layers of foam structure, as shown in Figure 4. The foam core which naturally floats is used as compensation for the weight of the FRP pipe in the design. FRP sandwich pipes are the main candidates used in OTEC cold water pipes due to their flexibility in material selection, ease of installation, corrosion resistance and relatively low prices [10].

The diameter of the water pipe is determined using an assumption of the flow velocity of 2.5 m/s for cold water pipes and 1.5 m/s for warm water pipes and output [9]. FRP layer thickness is calculated using the load collapse approach using equation (6) which is the total Δp of the pressure difference due to flow drag force, cold water and warm water pressure differences on the surface, dynamic flow loss, and other minor losses due to inlet filter and others which must also be considered [9]. The thickness of the pipe can then be calculated by entering the value Δp into equation (7). A summary of the seawater pipe design concepts obtained from the calculations can be seen in Table 3.

$$\Delta p = f\frac{L}{D}\rho\frac{{v_p}^2}{2g} + \int_0^L \frac{\rho_i(1-\rho_0)}{\rho_i}dy + \rho\frac{{v_p}^2}{2g} + \Delta p_{HX} + \Delta p_{misc} \tag{6}$$

$$\frac{t}{D} = \left[\left(p_o - p_i\right)\left(\frac{1 - v^2}{2E}\right)\right]^{0.333} \tag{7}$$

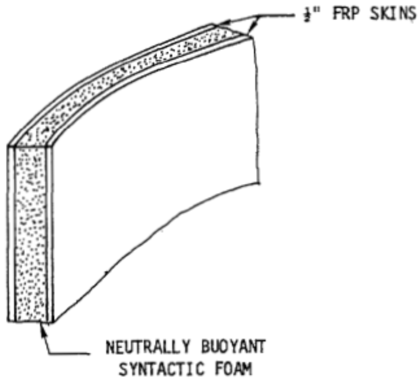

Figure 4. FRP sandwich wall construction [10]

Table 3. Dimensions of water flow systems

Pipe	Inside Diameter	Thickness		
		FRP	Foam	Total
Cold Seawater	7.1 m	3.3 cm	12.0 cm	18.5 cm
Warm Seawater	2 × 9.2 m	1.9 cm	6.8 cm	10.4 cm
Return Seawater	2 × 11.3 m	2.3 cm	8.4 cm	12.9 cm

3.4 Platform

From the design concepts of the previous OTEC facility section, one can get the layout and estimated dimensions of the platform needed to carry the whole system. The type of platform used in this study is a ship-shaped or monohull platform derived from considerations in Table 4 [11]. The general arrangement of the OTEC facilities in this study can be seen in Figures 5 and 6.

Table 4. Platform comparison for OTEC facilities [11]

Platform Type	Motion/Survivability Risk	Installation Difficulty	Price	Technical Readiness
Semi-submersible	Low	Medium	Medium	High
Spar	Low	High	Medium-High	Medium
Shipshape	Medium	Low	Low	High

3.5 Mooring and Submarine Cable Systems

Internal turret mooring systems are used in this design concept. The advantage of this system is that it can be installed permanently or not (dis-connectable) and can be applied to the field with moderate to extreme environmental conditions, and suitable for deep-water.

The underwater cable is assumed to have a length of 11 km to the coast. The outer diameter of the submarine cable is about 13 cm. Cable configuration consists of 3 core AC power cables and Ethylene Propylene Rubber (EPR) insulation with an operating voltage of 69 kV.

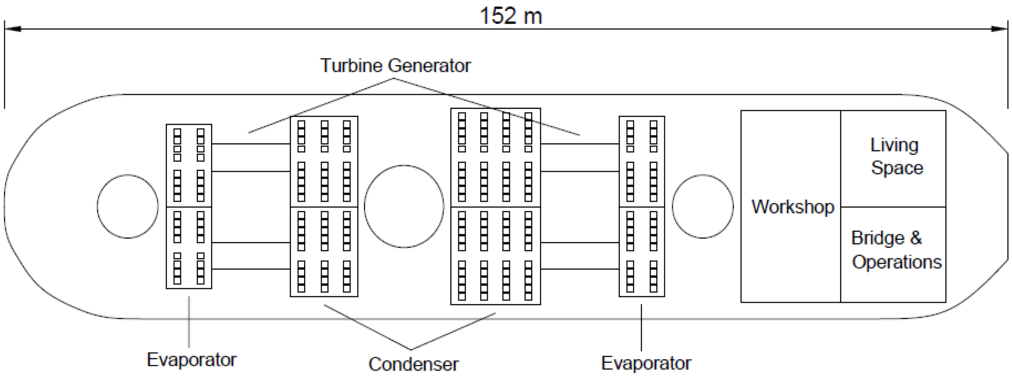

Figure 5. 50 MW OTEC facility: top view

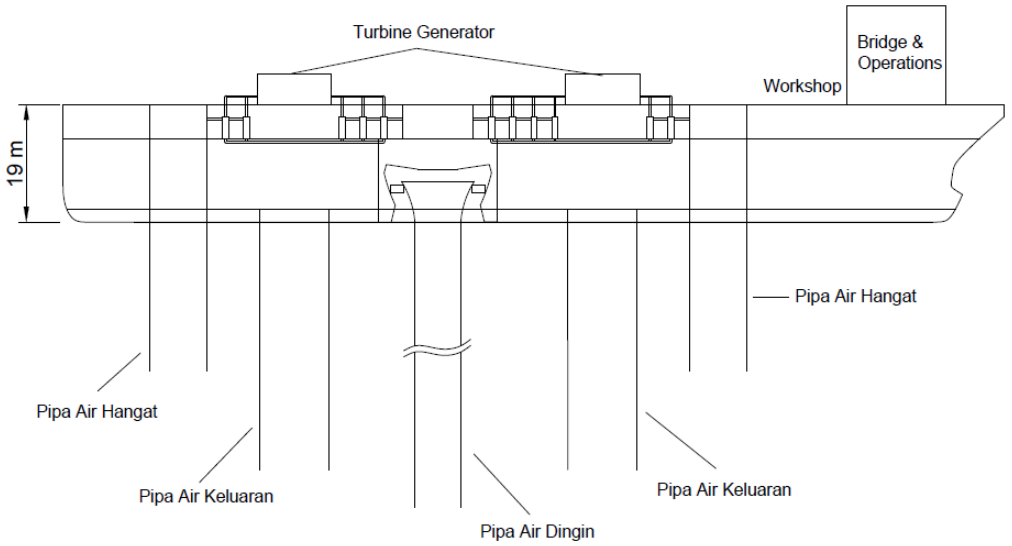

Figure 6. 50 MW OTEC facility: side view

4. Capital Costs

The capital costs of the OTEC facility are obtained from various sources and are processed in advance according to the design concepts in this study. The total capital cost of all OTEC facilities can be seen in Table 5, is USD 233,874,034.

Table 5. Capital Costs Estimates for 50 MW OTEC Facilities

Component	Cost	
Vessel [12]	USD	23,736,469
Mooring System [13]	USD	17,453,286
Submarine Power Cable 11 km [13]	USD	31,415,915
Seawater Pipes Installed [14]	USD	40,491,624
Seawater Pump Installed [14]	USD	16,057,023
Heat Exchangers [15]	USD	32,812,178
Turbine Generator [14]	USD	22,340,206
Electrical System/NH3/Control [14]	USD	20,943,944
Installation Mechanical and Electrical [14]	USD	28,623,389
All Components Total	USD	233,874,034

5. Expenses

Details of OTEC facility crews and salary levels per year can be seen in Table 6 [12]. Other expenses such as the cost of repairs and equipment for the first year of the OTEC facility amounting to about USD 275 thousands [15].

Table 6. OTEC Facility Crew and Salary Rate [12]

Position	Crew onboard	Rate Salary/Year	
Facilty Manager/Captain	1	USD	88,663
Ship Supervisor/Ship Engineer	2	USD	53,058
Facility Operator	3	USD	48,869
Maintenance and Repair Workers	3	USD	25,831
Sailors and Marine Oilers	2	USD	25,831
Chefs and Head Cooks	2	USD	32,812
	13	USD	275,064

6. Economic Analysis

The sum of capital costs and the level of expenditure is used to determine the level of electricity costs expressed in fixed annual costs. Annual electricity production can be calculated by equation (8). The OTEC facility in the design concept is assumed to experience downtime for 4 weeks per module per year, so the annual system availability is 92.3%. In contrast to other plants that have variable energy sources, the capacity of the OTEC facility is 100%. This is because the temperature of seawater both on the surface and the depth is relatively constant every year for 24 hours a day. The number 8760 is used as the reference of total hours to derive the electricity capacity every 1 year.

$$\text{Annual electricity production (kWh)} = P_{net}\,(\text{MW}) \times \text{Availability} \times \text{Capacity Factor} \times 8760 \quad (8)$$

To determine the level of levelized capital costs in a year, the capital costs of the study results are multiplied by the value of the Capital Recovery Factor (CRF) which can be obtained from equation (9). The interest rate I of 8% is taken for commercial loans. The age of the system N is defined as the length of time the debt agreement, in this study is assumed to be 15 years. The OTEC system itself is usually designed for 30 years of use.

$$CRF = \frac{I\times(1+I)^N}{(1+I)^N-1} \quad (9)$$

Levelized expenses cost are fixed amount that must be collected each year to cover all expenses that have been calculated with inflation rate IR. Levelized expenses cost is generated from the estimated expenses cost in the first year multiplied by Expenses Levelized Factor (ELF). Expenses Levelized Factor is calculated by multiplying the Present Worth Factor which can be calculated through equation (10) with the CRF. The final results of the economic analysis for this study in the form of a levelized cost of electricity are detailed as can be seen in Table 7.

$$PWF = \frac{(1+IR)}{(1-IR)} \cdot \frac{1-(1+IR)}{(1+I)^N} \quad (10)$$

Table 7. Economic Analysis of OTEC Facilities

Annual Electricity Production	USD	28,452	kWh
Levelized Capital Cost	USD	27,323,397	per year
Levelized Expenses Cost	USD	17,151,002	per year
Cost of Electricity (Capital Cost)	USD	0.067	/kWh
Cost of Electricity (Expenses)	USD	0.042	/kWh
Total Levelized Cost of Electricity	USD	0.109	/kWh

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7. Conclusions

Results of the analysis from this study yields the conclusions that can be drawn are as follows:

- The 50.4 MW net OTEC facility in this study uses four modules with a capacity of 18 MW each.
- The OTEC facility is supported by a ship-shaped platform sized length × breadth × depth of 152.0 m × 32.8 m × 19.0 m.
- The level of electricity costs generated for the 50.4 MW net OTEC facility in this study is USD. 0.109 /kWh for a loan interest rate of 8% and the assumed service life of 15 years.

Nomenclatures

Q_{cw} : OTEC cold deep seawater volume flow rate (m^3/s)
Q_{ww} : OTEC warm surface seawater volume flow rate (m^3/s)
ρ : seawater density (kg/m^3)
c_p : specific heat of seawater (kJ/kg K)
γ : ratio of OTEC seawater flow rates (Q_{ww}/Q_{cw})
ε_{tg} : turbogenerator efficiency
ΔT : temperature difference available for OTEC process (°K)
T : surface seawater temperature (°K)
$\dot{Q}$: heat transfer rate/heat load (MW)
U : specific heat transfer coefficient (kW/m^2 °C)
T_1 : first fluid temperature (°C)
T_2 : second fluid temperature (°C)
T_i : temperature difference on the inlet of heat exchanger (°C)
ΔT_o : temperature difference on the outlet of heat exchanger (°C)
T_m : logarithmic mean of temperature difference

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