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Potential Ocean Thermal Energy Conversion (OTEC) in Bali

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ABSTRACT: OTEC is a method for generating electricity which uses the temperature difference that exist between deep and shallow water with the minimal difference about 20°C. This paper aim to determine the potential and the provision of new and renewable energy in Indonesia.OTEC is very compatible build in Indonesian sea because Indonesia is placed in equator teritory, a lot of island, strain and many difference of topography especially in North Bali Sea. A calculation ocean thermal distribution in Indonesia for OTEC is doing with statistics from ocean thermal surface.The maximum efficiency of carnot engine (η_{max}) is obtained in the North Bali Sea by 0.788813. Figures are better than other regions in the Indonesia. OTEC power production is renewable energy that could be a solution to produce electricity, and also can produce fresh water and cold water for agricultural and cooling purposes especially in the tourist area like Bali.

Keywords: *OTEC, Bali, Temperature, Renewable Energy*

1. Introduction

Indonesia, which has the largest population of all ASEAN countries, will became a net oil import in the early 21st century. The Indonesia government has set up a long term energy plan aiming at energy diversification to reduce the country's dependence in oil. One of the renewable energy resources is the temperature gradient to exit in the sea, solar energy which creates this gradient and in particular Ocean Thermal Energy Conversion (OTEC).

OTEC uses the temperature difference that exists between deep and swallow water to run a heat engine. OTEC is an energy technology, which uses the ocean's natural temperature gradient to drive a turbine, which is connected to a generator.It is desirable that the temperature difference between the warm surface water and the cold deep water be at least 20°C (68°F).

North Bali Sea is area which excellent thermal potential of OTEC. North Bali Sea is a tropical climate and have surface water temperatures between 28°C - 31°C which has a very good resource and potentially significant in ocean thermal energy.

The sea area in Indonesia is ideal for OTEC power plant because the surface of sea water temperature is high and almost constant throughout the year. This paper aim to determine the potential and the provision of new and renewable energy in Indonesia.

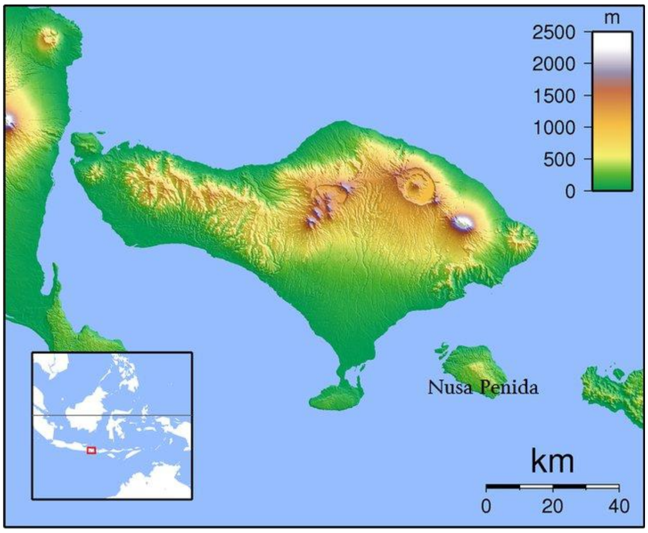

Fig. 1 Geographical location of Bali

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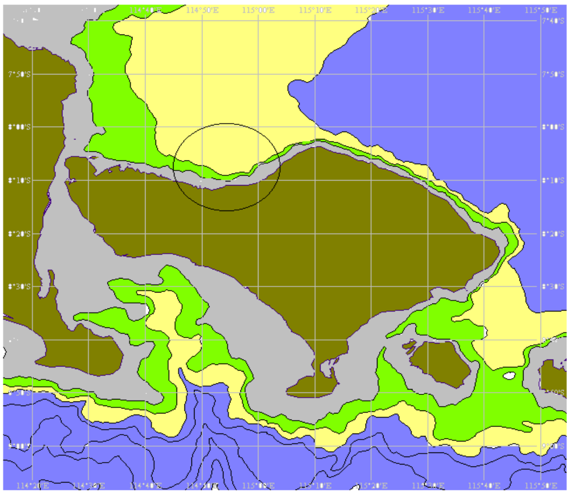

0 – 200 m | 200 – 500 m | 500 – 1,000 m | > 1,000 m

Depth in meter	Distance in meter
- 200	1,000
- 500	2,000
- 1,000	5,500

Fig. 2 Location map of OTEC in North Bali Sea

2. Material and Method

2.1 OTEC Power System

The OTEC system operates on a thermodynamic cycle, which uses the temperature differential between warm surface water (at 26°C or 79°F) and substantially colder water (at 4°C or 39°F) from the ocean depths. Apart from being able to use the differential to generate electricity, other useful by-products from the OTEC plant are fresh water, chilled water and nutrient-rich water. The system can be used in the OTEC are Open Cycle System and Closed cycle system.

2.1.1 Thermodynamics Basic Process for OTEC

OTEC systems rely on the basic relationship between pressure (P), temperature (T) and volume (V) of a fluid, which can be expressed by the following equation:

$$\frac{PV}{T} = a\ constan \qquad (1)$$

where pressure, temperature and the volume of a fluid can be closely controlled by manipulating the other two variables. Hence the differential in temperature of the fluid can be used to create an increase in pressure in another. The increase in pressure is utilised to generate mechanical work. There are basically three types of OTEC systems developed that can utilise sea water temperature differentials – they are: a closed-cycle, an open-cycle and a hybrid-cycle.

2.1.2 Closed-Cycle OTEC System

The closed-cycle system uses a working fluid, such as ammonia, pumped around a closed loop, which has three components: a pump, turbine and heat exchanger (evaporator and condenser).Warm seawater passing through the evaporator converting the ammonia[1] liquid ④ into high-pressure ammonia vapour ⑤. The high-pressure at ① vapour is then fed into an expander where it passes through and rotates a turbine connected to a generator. Low-pressure ammonia vapour leaving the turbine ② is passed through a condenser, where the cold seawater cools the ammonia, returning the ammonia back into a liquid ③.

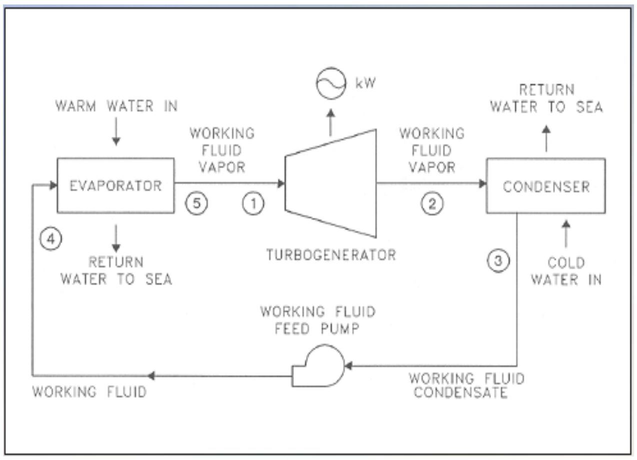

Fig. 3 Schematic of a closed-cycle OTEC system

Closed cyle is the process where heat use to evaporate the fluid on constant pressure in tank heater or evaporator which steam into the turbine and piston engine or expansion does work.The steam out enters into a container where the heat is transferred from the steam to coolant causing the steam is condensed into a liquid and the liquid is pumped back into the evaporator to complete the cycle.

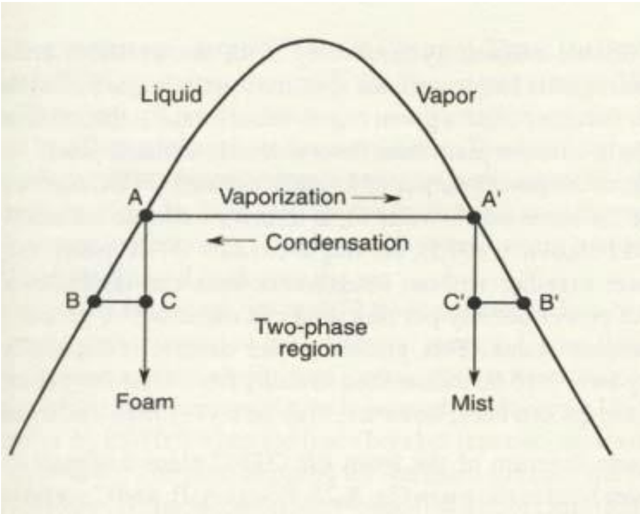

Fig. 4 Rankine cycle for OTEC system

2.1.2.1 General equation of closed-cycle OTEC plant

As referred to the T-s diagram in Fig. 5, pressure is assumed to be constant during heat addition to the evaporator, ($p1 = p4$) and heat extraction from the condenser ($p2 = p3$).

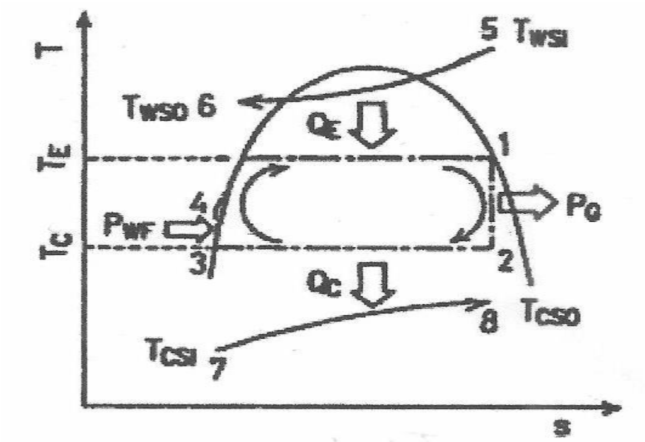

Fig. 5 T-s diagram of the closed Rankine Cycle

2.1.2.2 Net Power

The net power, P_{NET}, is given by:

$$P_{NET} = P_{TG} - (P_{WSW} + P_{CSW} + P_{WF}) \quad (2)$$

where:
P_{TG} = turbine generator power
P_{WSW} = warm sea water pumping power
P_{CSW} = the cold sea water pumping power
P_{WF} = the working fluid pumping power

2.1.2.3 Turbine Generator Power

The turbine generator power P_{TG} is given by:

$$P_{TG} = m_{WF} \,.\, \eta_T \,.\, \eta_G \,.\, (h_1 - h_2) \quad (3)$$

where :
m_{WF} = mass flow rated of working fluid
η_T = the turbine efficiency
η_G = the generator efficiency

Efficiency of turbine is given as:

$$\eta_T = \eta_m \,.\, \eta_e \quad (4)$$

where:
η_m = mechanical efficiency
η_T = theoretical efficiency

defined in reference as:

$$\eta_e = \frac{H_{ad} - \left(\Delta h_N + \Delta h_R + \Delta h_{Ex} + \Delta h_D + \Delta h_{WET}\right)}{H_{ad}} \quad (5)$$

where:
h_{AD} = adiabatic heat drop
Δh_N = kinetic energy loss in nozzle
Δh_R =rotor loss
Δh_{EX} =exhaust loss
ΔH_D =rotary disc loss due to disc fristion and windage
ΔW_{ET} = losses due to wetnees of steam

2.1.2.4 Cold Sea Water Pumping Power

The equation of cold sea water pumping power is given by:

$$P_{CSW} = m_{CSW} \,.\, v_{CSW} \,.\, \Delta P_{CSW} / \eta_{CSP} \quad \textbf{(6)}$$

where:
m_{CSW} = mass flow rate of cold sea water
v_{CSW} = specific volume of cold sea water
ΔP_{CSW} = total pressure difference of the cold sea water piping
η_{CSP} = cold sea water pump efficiency

2.1.2.5 Warm Sea Water Pumping Power

The warm sea water pumping power, P_{WSW} is given by:

$$P_{WSW} = m_{WSW} \,.\, v_{WSW} \,.\, \Delta P_{WSW} / \eta_{WSP} \quad \textbf{(7)}$$

m_{WSW} = mass flow rate of warm sea water
v_{WSW} = specific volume of the warm sea water
ΔP_{WSW} = total difference of the warm sea water piping
η_{WSP} = warm sea water pump efficiency

2.1.2.6 Working Fluid Pumping Power

The working fluid pumping power P_{WF} is given by:

$$P_{WF} = m_{WF} \,.\, v_{WF} \,.\, \Delta P_{WF} / \eta_{WF} \quad \textbf{(8)}$$

2.1.2.7 Heat Transfer Surface Area

Evaporator and condenser (Heat exchanger) are the most important component of an OTEC power plant. In 1975, the shell-and-tube type heat exchanger (evaporator, condenser) were selected. The overall heat transfer coefficient is 3300 kcal/m^2.h.OC. evaporator tube is the titanium and also condenser tube is the titanium.It was found by the cost estimation of the 1975 design that the total heat exchanger cost amounted to 45,7 % of the plant construction cost. Improvement of the heat exchanger should be the most important item OTEC plant development. T. Uehara of Saga University was proposed use of new plate-type heat exchanger, based advanced technology.

The total heat transfer surface area, A_T, is gives by:

$$A_T = A_{EV} + A_{CON} \quad \textbf{(9)}$$

where A_{EV} and A_{CON} are the heat transfer areas of the evaporator and condenser. In this paper, the shell and plate-type heat exchanger is used as the evaporator and condenser. The heat transfer surface area of evaporator, AEV, is given as:

$$A_{CON} = Q_{AE} / [\, U_{EV} \,.\, (LMTD)_{EV} \,] \quad \textbf{(10)}$$
$$= m_{wsw} \,.\, C_{p\ WSW} \,.\, (T_{WSW1} – T_{WSW0}) / [U_{EV}\,(LMTD)_{EV}]$$

where:
Q_{EV} = heat transfer rate of the evaporator
$(LMTD)_{EV}$ = logarithmic mean temperature difference of the evaporator
U_{EV} = overall heat transfer coefficient.

$$A_{CON} = Q_{CON} / [\, U_{CON} \,.\, (LMTD)_{CON} \,] \quad \textbf{(11)}$$
$$= m_{csw} \,.\, C_{p\ CSW} \,.\, (T_{CW0} – T_{CSW1}) / [U_{CON}\,(LMTD)_{CON}]$$

where:
Q_{CON} = transfer rate of the condenser
$(LMTD)_{CON}$ = logarithmic mean temperature difference of the condenser.
Q_{EV} and Q_{CON} = heat transfer rate of the evaporator and condenser

respectively, defined as:

$$Q_{EV} = m_{wsw} \,.\, (\, h_1 – h_4 \,) \quad \textbf{(12)}$$
$$Q_{CON} = m_{csw} \,.\, (\, h_2 – h_3 \,) \quad \textbf{(13)}$$

h1, *h4*, *h2* and *h3* are the enthalpy indicated by the four point in Figure 3.m_{WF} is the working fluid (ammonia) flow rate is given by:

$$m_{WF} = P_G / \ \eta_T \,.\, \eta_G \,(\, h_1 – h_2 \,) \quad \textbf{(14)}$$

Rankine cycle efficiency η_R and the net Rankine cycle efficiency η_{NET} are given by:

$$\eta_R \ = \ P_G / Q_E \quad \textbf{(15)}$$
$$\eta_{NET} = \ P_{NET} / Q_E \quad \textbf{(16)}$$

2.1.3 Open-Cycle OTEC System

The open-cycle system is generally similar to the closed-cycle system and uses the same basic components. The open-cycle system uses the warm seawater as the working fluid. The warm seawater passing through the evaporator ② is converted to steam ③, which drives the turbine/generator. After leaving the turbine ⑤, the steam is cooled by the cold seawater to form desalinated water. The desalinated water is pure fresh water for domestic and commercial use.

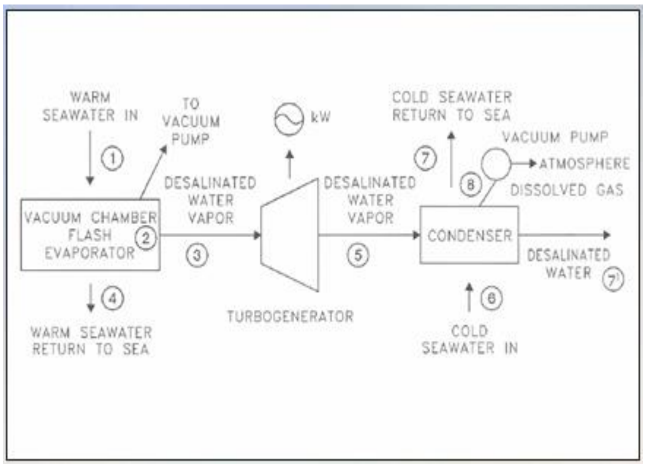

Fig. 6 Schematic of a open-cycle OTEC system

2.1.4 Hybrid OTEC System

The hybrid system uses parts of both open-cycle and closed-cycle systems to produce electricity and desalinated water. In this arrangement, electricity is generated in the closed cycle system and the warm and cold seawater discharges are passed through the flash evaporator and condenser of the open-cycle system to produce fresh water.

2.2 OTEC Efficiency

There is a theoretical limit, up to a maximum efficiency of an OTEC system by converting heat stored in the warm surface water of tropical oceans into mechanical work.

$$\eta_{max} = \frac{Tw - Tc}{Tw} \quad (17)$$

where:
η_{max} = maximum efficiency
Tw = absolute temperature from warm water
Tc = absolute temperature from cool water

For marine areas most suitable for OTEC operation, the average surface temperature of each annual is around 26.7°C to 29.4°C. Cold water at 4.4°C or below is available at a depth of 900 m. Therefore, the maximum efficiency of OTEC heat even without the inevitable reduction caused by friction and heat loss, can be achieved only at a very small rate of power production.
Efficiency is the ratio of energy or work in the system to the energy input into the system. Calculation method use to the equation relationship between sea surface temperature with depth, to compute the value of (b) as a function of the depth of the constants.

$$X_n = X_0 + BY \quad (18)$$

where:
X_n = Temperature at depth n
X_0 = Initial surface temperature
B = Constants of a function of depth
Y = depth

2.3 OTEC Plant Design and Location

The location of a commercial OTEC plant has to be in an environment that is stable enough for an efficient system operation. The temperature differential at the site has to be at least 20°C (68°F). Generally the natural ocean thermal gradient necessary for OTEC operation is found between latitudes 20 degrees north and 20 degrees south.

Land-based OTEC plants do not require a sophisticated mooring system, lengthy power cables and more extensive maintenance as required with open ocean environment. In addition, the land-based sites allow OTEC to be associated with industries such as agriculture and those needing cooling and desalinated water.

The offshore or floating OTEC plant is another option. There are a number of difficulties associated with such a facility as it is difficult to stabilise the platform. The need for lengthy cables to deliver power and extra transportation to access the plant are added expenses.The plant is also more susceptible to damage especially during storms.

3. Result and Discussion

Based on data,surface water in north Bali sea X0 =30.3°(From: Balai Riset dan Observasi Kelautan) and the calculated maximum depth is 600 meters.

Table 1
Calculation results of North Bali Sea

No	Depth	B	X0	Xn
1	0	0	30,3	30,3
2	100	-0,047	30,3	25,63
3	200	-0,068	30,3	16,74
4	300	-0,061	30,3	12,06
5	400	-0,054	30,3	8,78
6	500	-0,047	30,3	6,89
7	600	-0,04	30,3	6,4

From data, we get surface water temperature and deep water in north Bali sea with Tw = 30,30 and Tc = 6,40, so we can calculate efficiency from the equation of carnott efficiency so that **:**

Bali is a good regional for OTEC power plant because one of tourist areas. OTEC has important benefit other than power production, as by product of OTEC support chilled soil agriculture, aquaculture, fresh water, and OTEC power plant is not source of environmental pollution.

$$\eta_{max} = \frac{Tw - Tc}{Tw}$$

$$\eta_{max} = \frac{30{,}30 - 6{,}40}{30{,}30}$$

$$\eta_{max} = 0{,}788813$$

This is very good efficiency than other areas so that north sea of Bali is the most potential in the development of sea surface water temperatures for OTEC. If it take 100 KW for input power and carnot efficiency 0,788813 so net power become 78,8813 KW.
If Indonesian annual mean value of sea water temperature is taken, the data energy calculations, namely:

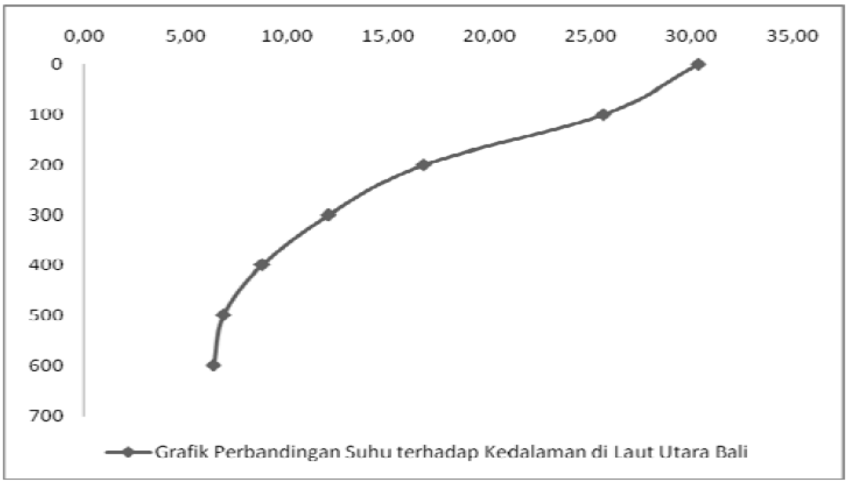

Fig. 7 Comparison of temperature against depth chart in north Bali sea

Table 2
Condition of Calculation Data of OTEC Plant Proposed

Generator Power	P_G	kW	120
Turbine efficiency	η_T	-	0.82
Generator efficiency	η_G	-	0.95
Warm sea water pump efficiency	η_{WSP}	-	0.80
Cold sea water pump efficiency	η_{CSP}	-	0.80
Working fluid pump efficiency	η_{WF}	-	0.75
Evaporator (plate-type heat exchanger) overall heat transfer coefficient T_{WSW1}-T_{EV}	U_{EV}	W/ m².K K	4000 4.0
Condenser (plate-type heat exchanger) overall heat transfer coefficient T_C-T_{WSW1}	U_{CON}	W/ m².K K	3500 4.0
Sea water temperature **(Annual mean value in Indonesia)** - Warm sea water temperature at depth 0 m - Cold sea water temperature at depth 1000 m		°C °C	26 5

Table 3
Calculation results of 125 kWe OTEC

Warm sea water inlet temperature	T_{WSNI}	(°C)	26.5
Warm sea water outlet temperature	T_{WSNO}	(°C)	23.0
Cold sea water inlet temperature	T_{CSWI}	(°C)	6.0
Cold sea water outlet temperature	T_{CSWO}	(°C)	8.0
Evaporation temperature	T_{EV}	(°C)	22.0
Condenser temperature	T_{CON}	(°C)	10.0
Net power	P_{NET}	(kW)	69.4
Warm sea water pumping power	P_{WSW}	(kW)	20.4
Cold sea water pumping power	P_{CSW}	(kW)	30.75
Working fluid pumping power	P_{WF}	(kW)	4.41
Warm sea water flow rate	m_{SWW}	Kg/s	325.25
Cold sea water flow rate	m_{CSW}	Kg/s	4920
Working fluid flow rate	m_{WF}	Kg/s	3467
Heat flow rate of evaporator	Q_{EV}	kW	4085.3
Heat flow rate of condenser	Q_{CON}	kW	4119.3
Logarithmic mean temperature differences	$LMTD_{EV}$	°C	4.37
Logarithmic mean temperature differences	$LMTD_{CON}$	°C	2.89
Heat transfer area of evaporator	A_{EV}	m²	236.0
Heat transfer area of condenser	A_{CON}	m²	407.0
Rankine cycle efficiency	η_R	%	3.1
Net Rankine cycle efficiency	η_{net}	%	2.0

OTEC power comparable with other power plants such as wave, hydro and diesel. However, it is important that all capital costs and on going maintenance/service costs are included so that the individual technologies are compared on a level playing field.

Table 4
Comparison of Unit Cost of OTEC with Conventional Energy Sources

	Plant capacity	Plant Life(Years)	Capacity Factor(%)	Annual Output(GWh)	Cost of Energy(US$/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

5. Conclusion

North Bali sea is ideal for OTEC power plant to generate electricity for small islands, because the sea areas in Indonesia have average monthly temperature difference between 28°C – 31°C and maximum carnott efficiency is 0,788813.

OTEC uses clean, abundant, renewable and natural resources to produce electricity. Research indicates that there are little or no adverse environmental effects from discharging the used OTEC water back to the ocean at prescribed depths.

As well as producing electricity, OTEC systems can produce fresh water and cold water for agricultural and cooling purposes. The use of OTEC also assists in reducing the dependence on fossil fuels to produce electricity. This is really important because Bali is a tourist area.

The OTEC technology is perhaps the promising solution to meeting some of the region's increasing energy requirements thus,reducing the need to import petroleum products. More comprehensive research and study needed to know the possibility location for OTEC to built and estimated cost.

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