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Site Determination for OTEC Turbine Installation of 100 MW Capacity in North Bali Waters

Penentuan Lokasi Turbin OTEC dengan Kapasitas 100 MW di Perairan Bali Utara

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ABSTRACT: This research was conducted to investigate a suitable location for the OTEC (Ocean Thermal Energy Conversion) pilot plant in North Bali. The investigation was done by calculating the theoretical potential of electric power output using the method of Uehara and Ikegami (1990) for closed cycle OTEC. OTEC power plants require a temperature difference between surface and bottom water layers at least 20°C. Temperature data were obtained from the HYCOM temperature model for a period of 9 years (2008 - 2017) at 4 points which were verified with field data taken in 2017 using KR Geomarin III. The results of field measurements show that the sea surface temperature (SST) in the study area ranges from 28 to 31°C while at depth of 800 m 5.75°C. ΔT values range from 22 to 25°C. Verification of modelling temperature and measurement temperature shows that the modeling results resemble the temperature of North Bali Waters. Analyses results for the four points showed that B-11, located in the Tedjakula area, has the largest electrical power output (71,109 MW). Thus, point B-11 is the best location for development of OTEC pilot plant in North Bali Waters.

Keywords: sea water temperature, net power, OTEC closed cycle, North Bali

ABSTRAK: *Penelitian ini dilakukan untuk menentukan lokasi yang layak untuk pilot plant OTEC (Ocean Thermal Energy Conversion) di perairan Bali Utara. Penentuan dilakukan dengan menghitung potensi teoritis output daya listrik menggunakan metoda Uehara dan Ikegami (1990) untuk OTEC siklus tertutup. Pembangkit listrik OTEC membutuhkan perbedaan suhu antara lapisan permukaan dan lapisan dalam sebesar 20°C atau lebih. Data suhu didapatkan dari model suhu HYCOM untuk jangka waktu 9 tahun (2008 – 2017) pada 4 titik yang diverifikasi dengan data lapangan yang diambil pada tahun 2017 dengan menggunakan KR Geomarin III. Hasil pengukuran lapangan menunjukaan bahwa suhu permukaan laut (SPL) daerah penelitian berkisar 28-31°C dan suhu air pada kedalaman 800 m adalah 5,75°C. Nilai ΔT berkisar 22-25°C. Verifikasi suhu hasil pemodelan dengan suhu hasil pengukuran menunjukkan bahwa suhu hasil pemodelan dapat mewakili suhu perairan Bali Utara. Hasil analisis yang dilakukan pada 4 titik menunjukkan bahwa titik B-11 yang terletak di daerah Tedjakula memberikan output daya listrik terbesar (71,109 MW). Titik B-11 merupakan lokasi terbaik untuk pengembangan pilot plant OTEC di perairan Bali Utara.*

Kata kunci: *suhu air laut, daya listrik, OTEC siklus tertutup, Bali Utara*

INTRODUCTION

As the sole energy provider in Indonesia, the National Electrical Company, or PLN, is required by law to suppy electricity all over Indonesia. In doing so, PLN faces various challenges, such as increasing electrification ratio and meet the increasing number of registered customers. In 2019 press release, PLN claimed to have increased electrification ratio to 98.81% in June, 2019, surpassing the value at the end of 2018, which is 98.3% (Abdullah, 2019). PLN also said to have rose energy supply by 3.82 million customers, from 69.7 million in June 2018 to 73.62 million in June 2019 (Abdullah, 2019). One of the problems that are faced by PLN is the economic lifetime of power generator and the fuel for the generator. Keeping in mind that Indonesia is an archipelago that prohibits simple and efficient distribution of fossil fuel, it is imperative to explore power generator that is fueled by alternative energy such as solar, wind and ocean energy, particularly considering the energy output varies depending on the type of energy source (Ilahude *et al.*, 2017). The application of development of alternative power plant is part of the policy of the Ministry of Energy and Mineral Resources (MEMR) to decrease carbon dioxide emission.

The geographical arrangement of Indonesia offers great potential of renewable energy, particularly solar and ocean energy, considering that it comprises of large and small islands that straddle the Indian and Pacific Oceans in the equator. Solar panel have been used as power generator in some areas, such as Rote Island, while ocean energy has yet to be tapped as alternative source. Ocean energy that can be used include waves, current, tidal and ocean thermal energy (Bassam *et al.*, 2013).Some energy experts believe that optimizing the utilization of ocean thermal energy (OTEC) could produced billion watts of electrical power (Vega, 1992; Bassam *et al.*, 2013; Syamsuddin *et al.*, 2015).

Ocean Thermal Energy Conversion

Ocean thermal energy conversion or OTEC is one of the solutions in developing the potential of ocean energy that use temperature difference between the sea surface and the deep ocean to operate a generator to produce electrical energy (Syamsuddin *et al.*, 2015; Koto, 2016). Ocean thermal energy utilizes the difference in temperature, ΔT, between the warm (Tw ~22°C to 29°C) tropical surface waters, and the cold (Tc ~4°C to 5°C) deep ocean waters (Vega, 1992). Temperature difference between surface water and deep ocean water that is needed for OTEC is at least 20°C (Vega, 1992).

The surface waters that comprises the upper part of water column is also kown as mixed layer, within which salinity, temperature, and density are almost vertically uniform as process interacts with upper ocean dynamics (Montegut *et al.*, 2004).The mixed layer entrains heat from solar radiation. Solar penetration in the tropical region mostly reaches less than 50 m, but it can extend to greater than 100 m outside the tropics (Ohlmann *et al.*, 1996).

The difference in temperature and pressure can be converted to move turbine to produce electricity by applying Rankine cycle (Uehara *et al.*, 1988). Due to its relatively small seasonal difference in sea surface temperature, energy derived from ocean heat is very suitable to be developed in tropical regions such as Indonesia. If this can be done effectively and on a large scale, OTEC is able to provide renewable energy sources needed to cover various energy demands (Finney, 2008; Syamsuddin *et al.,* 2015).

As a part of Indo-Pacific wam pool, Indonesian waters play important role in the heat transfer from Pacific to Indian Oceans (Sprintall *et al.,* 2014). The average sea surface temperature (SST) of Indonesian Seas is 28ºC and it is relatively stable throughout the day (Deckker, 2016). A study by Martono (2016) showed slight seasonal SST variation in the central part of Indonesia waters: warmer SST (<29.8°C) during west season and cooler SST (~26°C) east season **(Figure 1).**

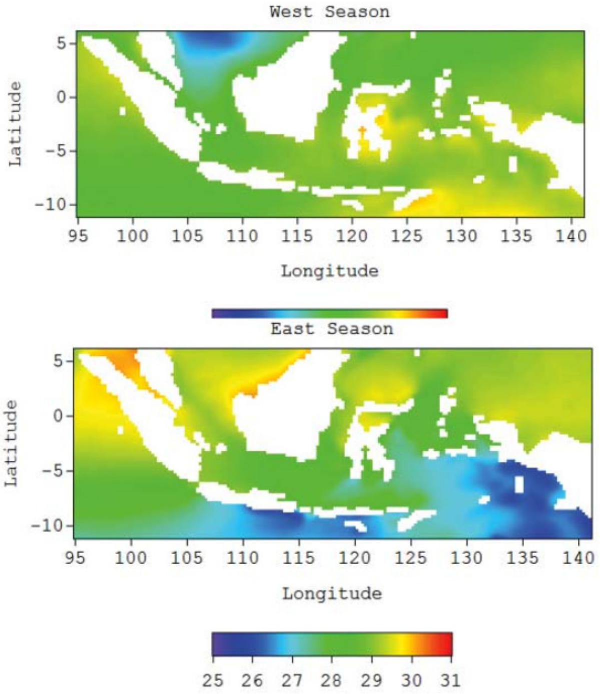


Figure 1. Seasonal pattern of sea surface temperature in Indonesian waters tended to show a rising trend (Martono, 2016).

The global ocean current transports ice-cold water from the polar region to the equator that resulted in cool water temperature of 3-9 C at depths of 500-1000 m (Uehara *et al.*, 1988). Thus, annual temperature difference between sea surface and subsurface layer in Indonesia is between 20ºC and 24ºC (Uehara *et al.*, 1988).

Previous study showed that temperature difference (ΔT) between sea surface and subsurface layer from less than 1000 m water depth in the eastern Indonesia is larger than western Indonesia, including North Bali waters (Ilahude *et al.*, 2017). Utilization of OTEC has higher economic value with positive impact on local community due to other uses of OTEC such as potential demand by industry *e.g.* pure water, food, irrigation, chemical, air conditioning and refrigeration, aquaculture, mariculture, or coldwater agriculture (Vega, 1992; Finney, 2008). The concept of OTEC is still new in Indonesia even though Hawaii has developed it since 1974 (Vyawahare, 2015).

As a marine research institute under the MEMR, Marine Geological Institute has conducted eleven (11) studies on OTEC potential within the Indonesian Seas. The results of the study were then reviewed in collaboration with Saga University, Japan. The review concluded that the best location to develop an OTEC pilot plant in Indonesia is North Bali waters (Ilahude *et al.*, 2017).

The research location is at coordinates 114°40'-115°45' E and 07°50'- 8° 22.50' S (Figure 2). North Bali water is considered as a potential area for OTEC development due to the following reasons: energy demand, bathymetry condition, distance from populated area, the depth of cold water, and the existing electricity grid in the region. This study is aimed to simulate net power potential and cycle efficiency of four sites off North Bali waters. The sites were selected based on their proximity to the island.

Figure 2. Location of potential OTEC studies in northern Bali waters

PHYSICAL CONDITION OF NORTH BALI WATERS

At present, the electricity supply in Bali reaches 1,100 megawatts (MW) with normal usage of 900 MW. Under normal conditions, the supply is sufficient to fulfill energy consumption. However, the condition of electric power infrastructure might decrease the supply (https://radarbali.jawapos.com/read). Considering Bali is one of the most popular destinations in Indonesia, it is imperative to provide alternative electrical source to overcome the possibility of power outage in the island.

The proposed OTEC pilot plant location is within Singaraja Regency that is one of tourist destination. An OTEC pilot plant requires that the environmental and engineering categories considered from mitigating or reducing potential environmental impacts (Sullivan *et al.,* 1981) *e.g.* low level of sedimentation, household wastes, and seabed morphology in forming a basin. The water quality, bathymetry and distance of the basin satisfy the requirement for OTEC power plant. The bathymetry of North Bali forms narrow coastal platforms with water depth of 200 m, that gradually dipping north and eastward to reach 1500 m (McCaffrey *et al.*, 1987).

There are three types of OTEC systems: open cycles, closed cycles, and hybrid cycles (Uehara and Ikegami, 1990; Avery and Wu, 1994; Finney, 2008; Adiputra *et al.*, 2019) that have been developed. Among the three types, the closed cycle has been studied extensively due to its smaller size and ability to improve the efficiency of electrical energy produced by generators (Masutani and Takahashi, 2001) and is considered the best type that can be developed in Indonesia. This closed cycle system will repeat continuously with the same working fluid acting on closed flow **(Figure 3).** The working fluid used in this system must work in a relatively small range of temperature differences. Ammonia is chosen as a working fluid because it has a lower boiling point than water (Avery and Wu, 1994; Masutani and Takahashi, 2001; Finney, 2008).

In this closed cycle OTEC system, heat from the surface is channeled to a heat exchanger and in the evaporator to produce saturated steam from the working fluid. The vapor will spread to a lower pressure chamber through the turbine and at this stage electricity will be generated. Heat is flowed from the working fluid vapor (ammonia) to cold sea water in the condenser, and the condensed working fluid is pumped back to repeat the cycle continually (Masutani and Takahashi, 2001). Ammonia will change into high pressure steam and flow into the turbine to turn the turbine.

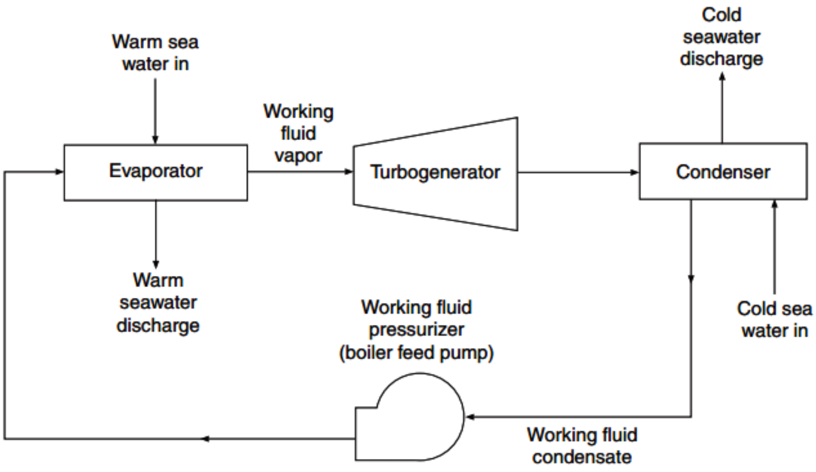


Figure 3. Simplified diagram of closed cycle OTEC system (Masutani and Takahashi, 2001.

METHOD

This study comprises of fieldwork to obtain sea surface and subsurface temperatures in the study area; modeling of annual temperatures of the two layers; and theoretically calculate the net power output of closed-cycle the OTEC system for North Bali waters and selected the most suitable site for OTEC pilot plant. Fieldwork was conducted in 2017 on board Geomarin III. Temperature data was acquired by CTD SBE 19Plus V2, with 4Hz frequency rate. Pre-processing CTD data was conducted by SBE Data Processing to convert, align and filter the data.

Nine year annual temperature model was obtained from HYCOM and verified by measured temperature. The temperature model was applied to the formulation of Uehara and Ikegami (1990) to calculate the theoretical potential of OTEC power. The formula used is presented in Table 1.

Temperature data obained in this study were substituted by including the effects of turbine efficiency, warm and cold sea water pump power and pipe surface area of the equation presented in Table 1. With the value of the components present in the OTEC system, calculations are performed at several points using data models to calculate the net power generated by the OTEC system. The results of this analysis will help determine the location of the OTEC system installation.

Table 1. Formulas that are used in the simulation of OTEC system power output following Uehara and Ikegami (1999).

Equation	Difference in Pressure of Warm Water, Cold Water and Working Fluid
$P_W = \frac{m_W \; \Delta H_W \; g}{\eta_W}$	$\Delta H_W = f\left(\frac{V^2}{2g}\right)\left(\frac{L}{D}\right)$
$P_C = \frac{m_C \; \Delta H_C \; g}{\eta_C}$	$\Delta H_C = f\left(\frac{V^2}{2g}\right)\left(\frac{L}{D}\right)$
$P_W = \frac{m_W \; \Delta H_W \; g}{\eta_W}$	$\Delta H_W = f\left(\frac{V^2}{2g}\right)\left(\frac{L}{D}\right)$
$P_G = m_W \; \eta_T \eta_G (\Delta \quad)$	$\Delta H_W = f\left(\frac{V^2}{2g}\right)\left(\frac{L}{D}\right)$

Where:

P_N	: Net power (*MW*)	m_W	: Mass flow rate of working fluid	= 383 t/s
P_G	: Turbine generator power (*MW*)	η_W	: Warm water pump efficiency	= 0.75
P_W	: Warm water pump efficiency (*MW*)	η_C	: Cold water pump efficiency	= 0.85
P_C	: Cold sea water pump power (*MW*)	η_W	: Efficiency of working fluid pump	= 0.75
P_W	: Working fluid pump power (*MW*)	η_T	: Turbine pump efficiency	= 0.85
		η_G	: Generator pump efficiency	= 0.75
ΔH_W	: Total pressure different at warm water pipe	m_W	: Warm sea water mass rate	= 383 t/s
ΔH_C	: Total pressure difference at cold water pipe	m_C	: Mass sea water flow rate	= 327 t/s
ΔH_W	: Total pressure difference of the working fluid pipe	L	: Length of pipe	= 800 m
g	: Acceleration due to gravity = 9.81 m/s^2	D	: Pipe diameter	= 11.2 m
		V	: Speed of warm water flow	= 3.81 m/s

Net power is obtained by reducing the power output of turbine generator with the power used for the performance of warm water pumps, cold water pumps, and working fluid pumps. The net electrical power equation used is as follows:

$$P_N = P_G - (P_{WS} + P_{CS} + P_{WF})$$

RESULTS

HYCOM temperature model

This step utilizes 9 years model of daily temperature of North Bali water for the period of October 2008 to June 2017 downloaded from the following website: http://ncss.hycom.org/thredds/catalog.html. Daily temperature was obtained from six (6) sites (**Figure 4**). Data resolution is 1/12°with water depth ranges from 0 to 1500 m. The modeling result is then verified with data from CTD measurements conducted by Ilahude *et al.* (2017) from four sites **(Figure 5**). Data verification is carried out to determine the accuracy and error value of the prediction data. The error value of the model data was calculated using the Root Mean Square Error (RMSE) to evaluate the accuracy of the forecast results of a model.

Table 2. Sample points of daily temperature data that is obained from HYCOM.

No.	Location	Latitude (S)	Longitude (E)
1.	H-1	8°12’36”	115°40’48”
2.	H-2	8°7’48”	115°36’0”
3.	H-3	8°3’0”	115°31’12”
4.	H-4	8°3’0”	115°26’24”
5	H-5	7°58’12”	115°21’36”
6.	H-6	7°58’12”	115°16’48”

Table 3. Site locations of CTD data acquisition from North Bali (Ilahude *et al.*, 2017).

No.	Location	Latitude (S)	Longitude (E)
1.	B-10	8°11’39”	115°34’35”
2.	B-11	8°5’59”	115°22’25”
3.	B-16	8°3’12”	115°17’50”
4.	B-17	8°1’27”	115°11’15”

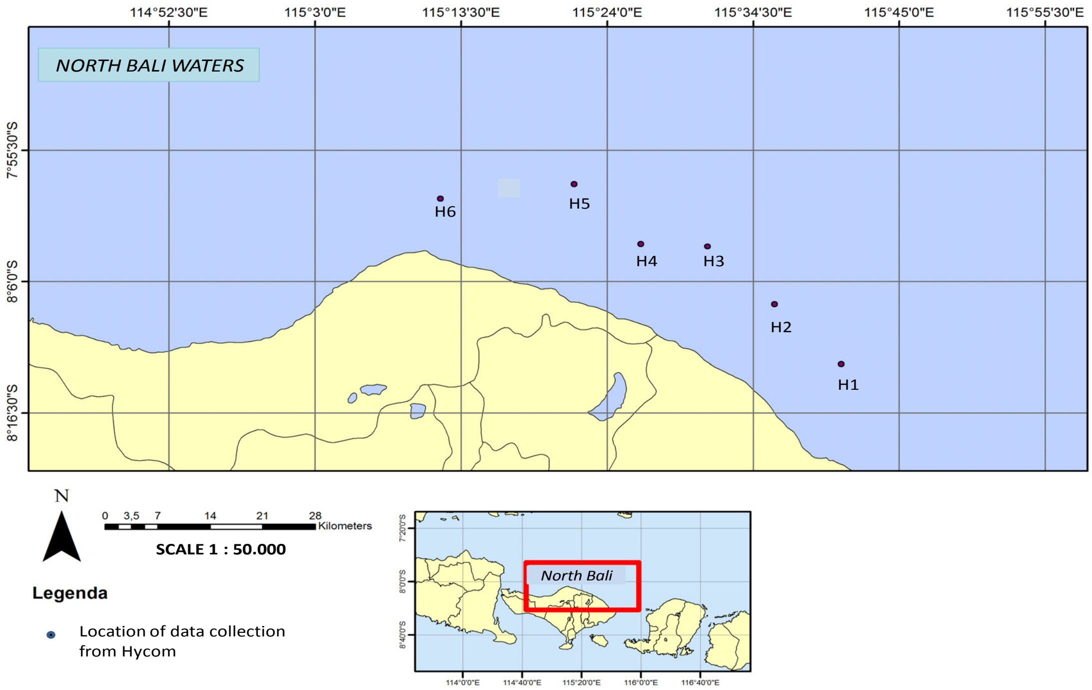


Figure 4. Sample points of temperature data acquisition taken from HYCOM.

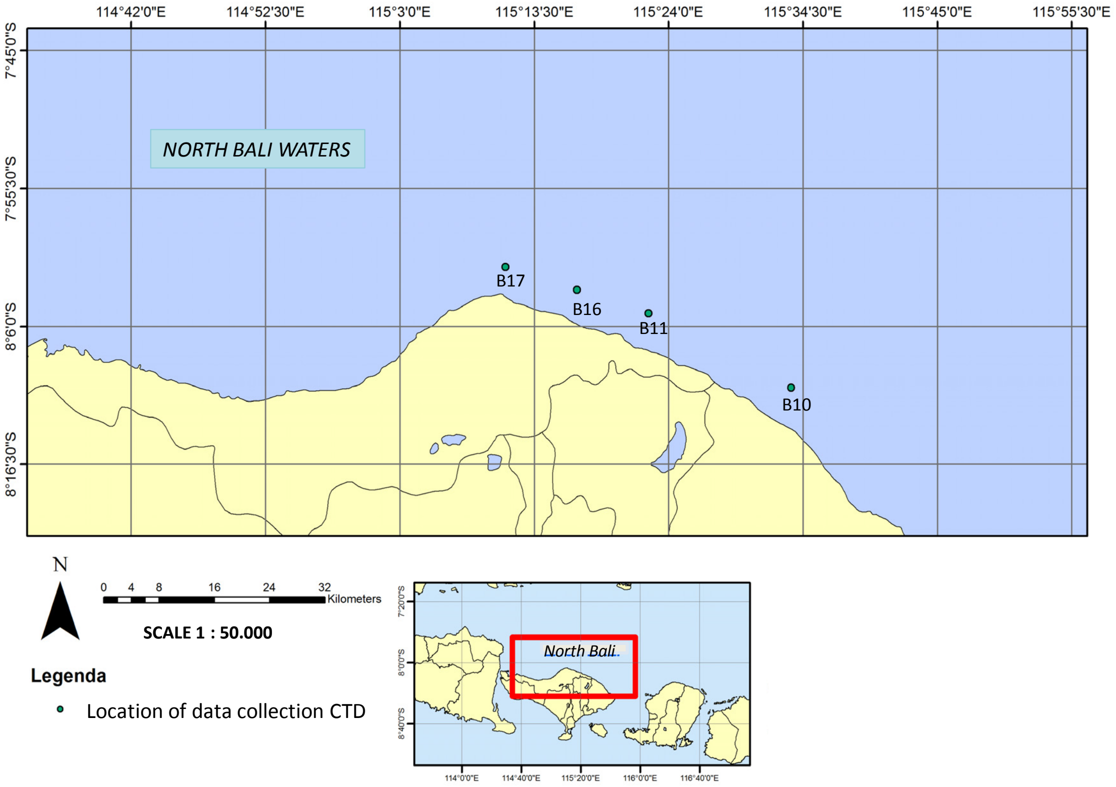


Figure 5. Site locations of CTD data acquisition by MGI (Ilahude *et al.,* 2017).

Verification of HYCOM and CTD Temperature Data

The accuracy of HYCOM data is verified by comparing vertical temperature distribution between HYCOM and CTD (Figure 6). The calculation of bias value and Root Square Mean Error (RMSE) between HYCOM and CTD showed average values of 0.0362 and 0.7934.

The distribution of temperature values to the depths (Figure 6) and the relationship between HYCOM and CTD (Figure 7) show reasonably good results that indicate the HYCOM data can be considered to represent measured temperature of North Bali waters. CTD data shows that temperature decreases dramatically at depths between 100-300 m (Figure 7) and forms what is known as thermocline layer (Bereau 1992). Sea water temperature shows no significant change at 500-800 m water depth that is known as deep layer. Deep water layer shows no seasonal change because it is formed by cold polar water mass that flows into the equatorial region (Gross, 1995).

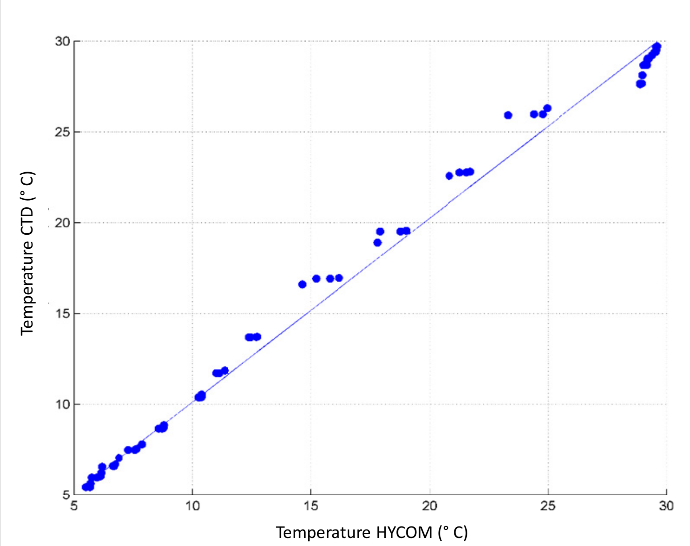
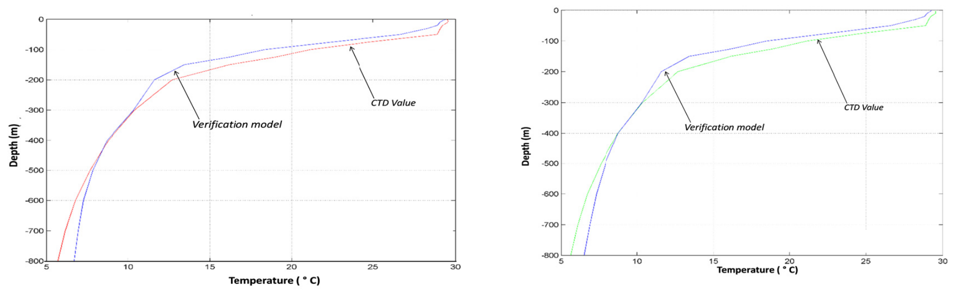


Figure 6. Distribution of temperature values obtained from HYCOM and CTD.

The results show that North Bali SST ranges between 28-31^{o}C, while the temperature at 800 m is 5.75^{o}C (Ilahude, 2015). Temperature difference (ΔT) of the study area ranges between 22^{o}C and 25^{o}C.

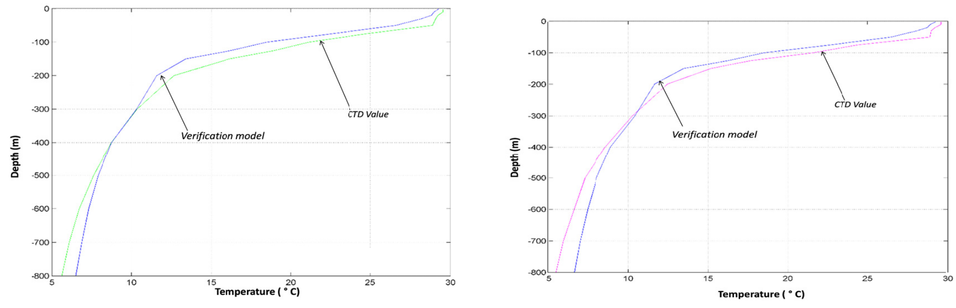
OTEC Net Power Potential and Cycle Efficiency

Calculation of potential net power in the study area is conducting using the formulations in Table 1. The net power value obtained is based on temperature difference (ΔT) between sea surface at 10 m and cold water at 800 m. The calculation results are presented in Table 4.



a. Verification at location B-10

b. Verification at location B-11



c. Verification at location B-16

d. Verification at location B-17

Figure 7. Verification of temperature values obtained from HYCOM to CTD.

Table 4. Annual ΔT and potential net power calculated for North Bali waters.

Location	ΔT (°C)	Potential Net Power (MW)		
		Average	Min	Max
B-10	23.143	70.425	69.942	71.004
B-11	23.327	70.5	70.002	71.109
B-16	23.054	70.387	69.929	70.975
B-17	23.073	70.388	69.931	71.042

The results of OTEC net power calculation in 4 locations (Table 4) show that the maximum potential net power of 71.109 MW is located at site B-11, off Tedjakula, Buleleng Regency. The highest net power occurred in 2010 and the lowest in 2015 (Figure 8).

The changes in ΔT will affect the OTEC net power potential. Figure 8 shows temporal decline of annual net power potential within the period of 9 years (2008 to 2017). Peak net power was reached in 2010 and drastically decreased in 2011. Net power continued to decline until it reached minimum value in 2015 before increasing in 2016.

We also calculated monthly net power potential to observe monthly fluctuation as well as identify the months when maximum and minimum net power potential were reached. Monthly net power potential was observed in April with an average net power of 70.8 MW and the lowest occurred in August with an average net power of 69.99 MW (Figure 9). Figure 9 shows monthly fluctuation of net power potential for the period between 2008 and 2017. The fluctuation is related to temperature variability that is infuenced by monsoon. Thus, net power potential of North Bali waters reflects seasonal trends.

Rankine Cycle

The Rankine Cycle used in this OTEC system simulation is a thermodynamic cycle that converts heat energy into motion energy. The Rankine cycle is built consisting of 4 basic components, namely pumps, evaporators, condensers, and turbogenerators (Multon, 2012). The Rankine cycle process that occurs results in the efficiency of the Rankine cycle. The efficiency of the Rankine cycle is obtained from a comparison between the amount of power used to operate the OTEC system and the heat flow rate on the evaporator (QE) (Yamada *et al*, 2009). The results of annual Rankine (ηRan) cycle efficiency calculations are presented in Table 5.

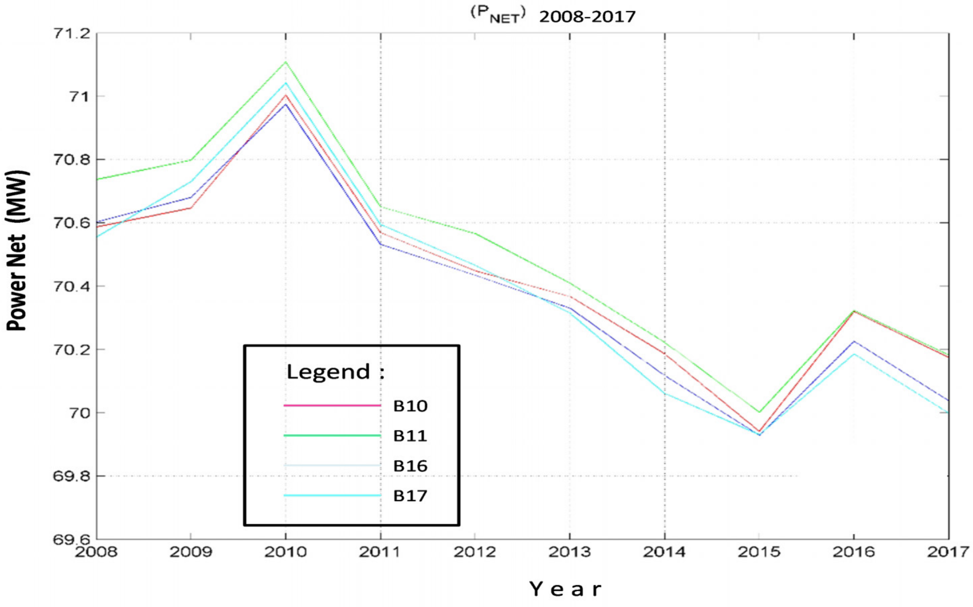


Figure 8. Average annual net power potential between the period of 2008 to 2017.

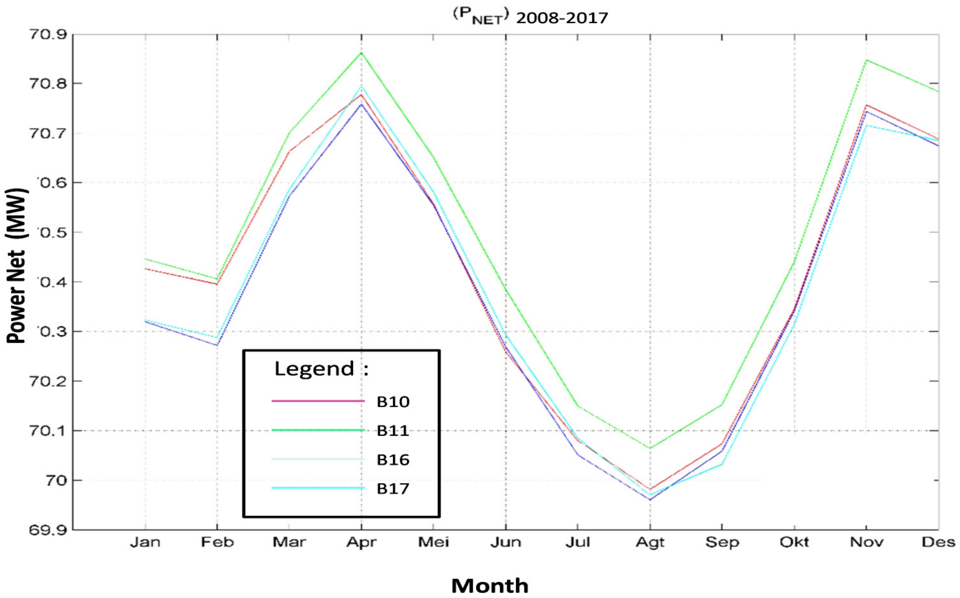


Figure 9. Monthly average of net power potential between the period of 2008 to 2017

Table 5. Annual average of Rankine Cycle Efficiency in the study area.

Location	Average Net Power (MW)	Efficiency		
		Average	Minimum	Maximum
B-10	70.425	0.38897	0.36927	0.41176
B-11	70.5	0.39207	0.37166	0.41598
B-16	70.387	0.38756	0.36874	0.41061
B-17	70.388	0.38761	0.36884	0.41330

Based on the OTEC net power calculation that is presented in Table 5, the maximum cycle efficiency is 0.41598. The highest efficiency occurred in 2010 and the lowest in 2015 (Figure 10). Complete result of simulation parameters along with net power and cycle efficiency is presented in Table 6.

Rankine cycle efficiency shows similar pattern to net power (Figure 10) with peak efficiency at 2010 and lowest value at 2015. This trend exhibits the direct proportional 10 realtionship of net power to cycle efficiency. Monthly Rankin efficiency was also calculated to understand intra-annual fluctuation. Cycle efficiency reached maximum value at 2010 followed steady decline until it reached minimum value at 2015 (Figure 11). The comparable pattern of cycle efficiency to net power reflects their direct proportional relationship.

Figure 12 shows the linear relationship between net power and efficiency of the Rankine cycle of an OTEC generator. Thus, to produce maximum electric power of 71.109 MW, the efficiency of the Rankine cycle needs to reach maximum value of 0.41598 or 41,598%. The efficiency of Rankine cycle reflects the efficiency of OTEC generator in releasing power to pump warm sea water (PWS), cold sea water (PCS), and working fluid (PWF). Thus, to obtain greater net power, the pump power must also be greater and this will increase the efficiency of the Rankine cycle.

CONCLUSION

We conducted simulation of OTEC net power potential of four site location in North Bali waters by applying Uehara and Ikegami (1990) method to select suitable site for OTEC development. This study used 9 year temperature difference obtained from HYCOM and verified by field measurements of Ilahude *et al.* (2016). The results of the study are:

- The SST of North Bali ranges between 28-31°C and temperature is relatively stable at 800 m at

Table 6. The result of net power and cycle efficiency calculation based on Uehara and Ikegami experiments

Point of Study	**Overall Heat Transfer Coefficient (x10^{3}W/m^2 K)**		**Seawater Mass Flow Rate Seawater Mass Flow Rate (t/s)**		**Heat Transfer Area (x10^5 m^2)**	**Net Power (MW)**	**Cycle Efficiency**
	U_E	**U_C**	**m_{WS}**	**m_{CS}**			
1	5.2274	4.7167	204.255	216.479	2.61439	70.425	0.389
2	5.2876	4.7341	198.242	212.793	2.50295	70.500	0.3921
3	5.2003	4.7088	206.969	218.142	2.67037	70.387	0.38756
4	5.2011	4.709	206.886	218.092	2.66834	70.388	0.38761

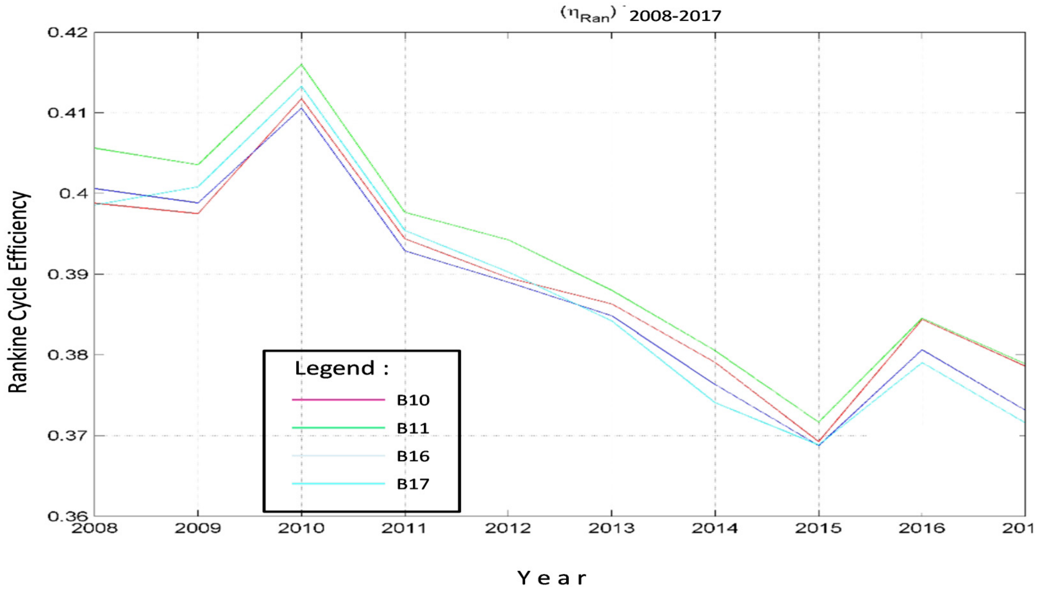


Figure 10. Annual average of Rankin cycle efficiency for the period of 2008 to 2017

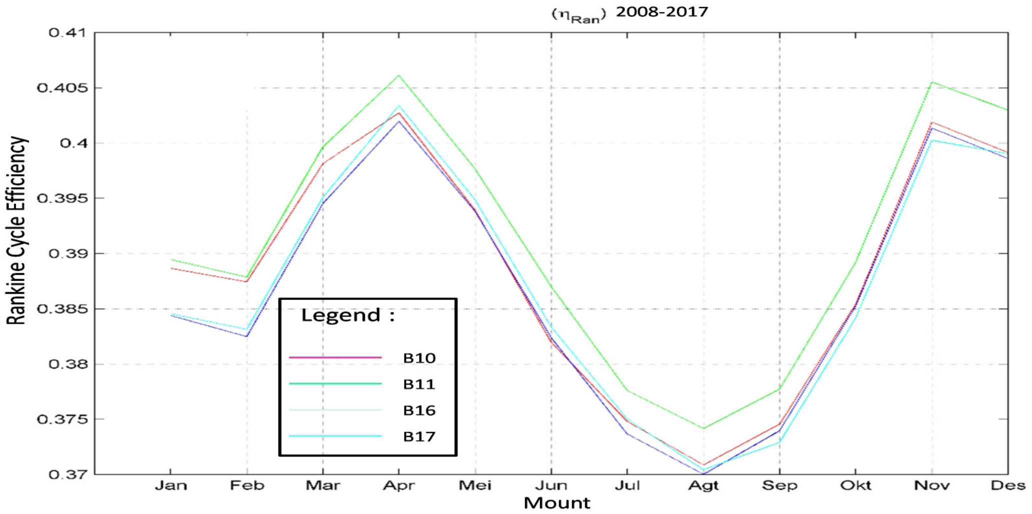


Figure 11. Monthly average of Rankin cycle efficiency for the period of 2008 to 2017

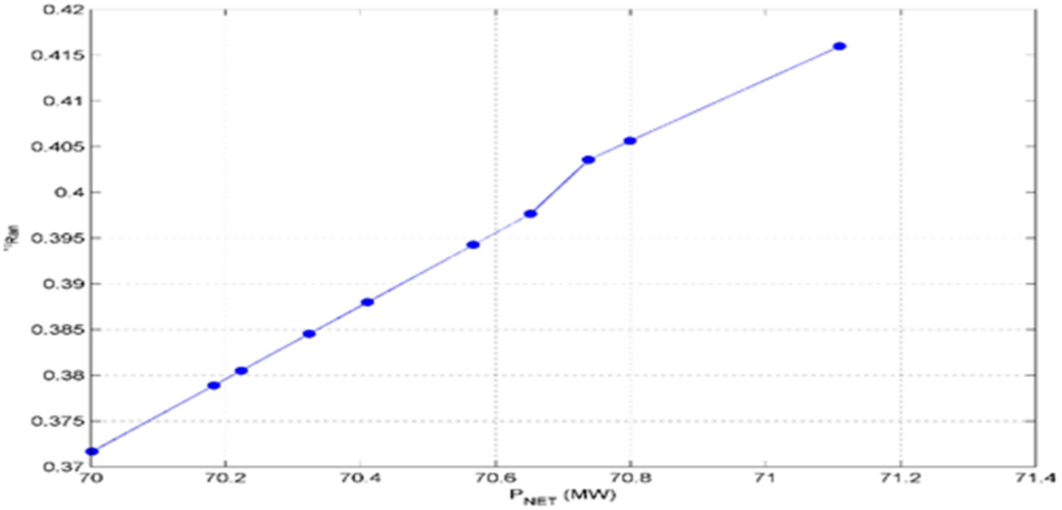


Figure 12. Relationship between Clean Electric Power (P_{NET}) and Cycle Efficiency (ηRan)

5.75°C. The ΔT ranges between 22°C and 25°C. Verification of temperature model with measured temperature shows that temperature model can represent North Bali waters temperature.

- Among four sites that have been studied, site B-11 (Tedjakula, Buleleng Regency) yields maximum net power (71.109 MW). This result indicate that B-11 the best candidate for OTEC pilot plant development.

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