

Harnessing the Indonesia's Banda Sea Thermal Resources Through Comprehensive OTEC Potential Study

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Abstract. The Banda Sea, located in Indonesia's equatorial region, exhibits significant potential for Ocean Thermal Energy Conversion (OTEC) due to its deep-water layers and consistent surface temperatures. This study evaluates the OTEC feasibility in the Banda Sea by analyzing monthly and seasonal sea surface temperature (SST) data from 2015, obtained from Copernicus ERA5 reanalysis. Spatial and vertical temperature profiles were processed using Ocean Data View (ODV) to identify mixed-layer, thermocline, and deep-layer characteristics. Results indicate an average temperature gradient (ΔT) of 22.7°C between the surface (29–30°C) and 600–700 m depth (5–7°C), meeting the minimum ΔT requirement (20°C) for OTEC. The Carnot efficiency (η) reached 77%, surpassing the 70% benchmark for viable OTEC systems. However, long-term time-series analysis data from 2005–2017 revealed intermittent periods where ΔT fell below 20°C, likely due to seasonal upwelling, El Niño-Southern Oscillation (ENSO) events, or anomalous ocean mixing. Those are posing reliability challenges for continuous power generation. While the Banda Sea's thermal resources are promising, operational intermittency suggests the need for hybrid energy systems to ensure grid stability. This study provides critical insights for OTEC deployment in tropical regions, balancing renewable energy potential with technical constraints.

Keywords: *renewable energy, OTEC, reliability, intermittency.*

1 Introduction

Ocean Thermal Energy Conversion (OTEC) represents a promising renewable energy technology that leverages the natural temperature gradient between warm tropical surface waters and cold deep ocean layers to generate electricity. The fundamental principle according to Junihartomo, *et.al* in [1] relies on exploiting temperature differences of at least 20°C between surface seawater (typically 25–30°C) and water at depths of 800–1000 meters (around 4–7°C). This thermal energy can be converted into usable power through two main system configurations: closed-cycle and open-cycle OTEC. Some results from the

experiment were given by The Indonesian National Research and Innovation Agency (BRIN) in [3] that both systems essentially operate on modified Rankine cycles adapted for small temperature differentials.

For successful OTEC implementation, several critical conditions must be met. The ocean site must maintain a consistent minimum 20°C temperature difference between surface and deep waters throughout the year as mentioned by BRIN [3], with the thermocline (transition layer between warm and cold water) ideally located at accessible depths. As mentioned by Kasharjanto, *et.al* in [2], the seabed topography should allow for relatively easy deployment of cold-water intake pipes, typically requiring depths of 800-1000 meters within 1-2 kilometers of shore. Environmental factors such as wave conditions, marine ecosystems, and distance to power grids also significantly influence project feasibility.

Several pioneering OTEC installations demonstrate the technology's potential. As mentioned by Lennard in [9], The Natural Energy Laboratory of Hawaii Authority (NELHA) has operated a 100 kW closed-cycle demonstration plant since 2015, validating system durability and efficiency in real-world conditions. In Japan, the Okinawa Prefecture hosts a 50 kW open-cycle facility that not only generates electricity but also produces freshwater, showcasing OTEC's multi-use benefits as explained by Uehara *et.al* in [10]. More recently, a 16 MW commercial-scale project in Martinique, scheduled for completion in 2025, aims to provide baseload power for ~35,000 island residents, marking a critical step toward OTEC's industrialization like research done by Gauthier *et.al* in [11].

These implementations confirm OTEC's potential as a sustainable energy solution for tropical coastal regions. As explained by BRIN in [3], the Banda Sea's unique oceanographic characteristics - including its equatorial location, consistent surface temperatures, and access to deep cold water - position it as a prime candidate for OTEC development in Indonesia. This study evaluates the region's thermal energy potential through detailed analysis of temperature gradients and efficiency calculations, contributing to the growing body of research on tropical OTEC applications.

2 Research Method

This study evaluates the Ocean Thermal Energy Conversion (OTEC) potential in the Banda Sea, Indonesia, through spatial and vertical temperature analysis. The methodology encompasses data collection, preprocessing, thermal gradient assessment, and efficiency calculations, focusing on the touristic region of Banda Neira. Below are the detailed methodological steps.

2.1 Study Area

The research focuses on the Banda Sea (2.5° – 9° S, 126° – 131.5° E), particularly the waters around Banda Neira (Figure 1). This area was selected due to its significance for international tourism and its suitability for Ocean Thermal Energy Conversion (OTEC) deployment, given its deep-water layers (reaching $-1,000$ m) and equatorial location with stable surface temperatures. Bathymetry map processed using Ocean Data View (ODV). Blue dots denote sampling stations or bathymetric measurement points. Depth is displayed via color gradient with dark blue indicating the deepest regions, however, as the data has not been further processed, the depth scale of measurements in the bathymetry are not displayed. Major islands are labeled for spatial reference.

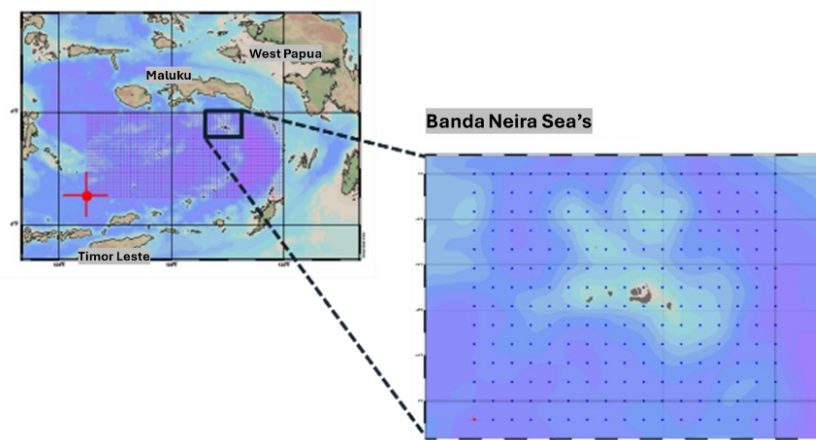


Figure 1 Banda Sea as Location of Study

2.2 Data Acquisition

Sea surface temperature (SST) data were obtained from the Copernicus Climate Data Store or known as European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis 5th Generation or ERA5, it's a monthly with $0.5^{\circ} \times 0.5^{\circ}$ resolution on 13 years long from 2005 until 2018 (Table 1).

Table 1 Summary of Data.

No	Category	Status
1	Product Type	Monthly averaged reanalysis
2	Variable	Sea Temperature (sub and surface)
3	Year	2005 - 2018
4	Month	January 2005 – December 2018
5	Format	NetCDF

2.3 Data Preprocessing

The raw Sea Temperature data underwent rigorous preprocessing to ensure quality and consistency for OTEC feasibility analysis. The methodology followed established oceanographic data processing protocols mentioned Reynolds *et.al* in [12] included these key steps:

1. Data Collection: Monthly SST grids were downloaded and categorized into seasonal subsets (DJF, MAM, JJA, SON).
2. Quality Control:
 - a. Missing values: Interpolated using spatial averaging.
 - b. Outliers: Removed based on $\pm 2\sigma$ deviation from seasonal means.
3. Validation: Compared with in-situ data from prior studies to minimize reanalysis bias.

2.4 Spatial and Depth Profile Analysis

To support the assessment of OTEC potential, using research conducted by Vega in [13] and Schlitzer *et.al* in [14]. Both spatial and vertical analyses were conducted using oceanographic datasets and visualization tools.

1. Spatial Analysis:
 - a. Monthly/Seasonal Anomalies: Calculated by subtracting long-term means to identify OTEC-favorable zones.
 - b. Geostatistical Mapping: Generated using Ocean Data View (ODV) to visualize SST gradients.
2. Vertical Profiling:
 - a. Thermocline Identification: Defined as depths with $\Delta T \geq 0.1^\circ\text{C}/\text{m}$.
 - b. Layer Thickness: Mixed layer (surface to thermocline), deep layer (>200 m).

2.5 OTEC Potential and Efficiency Assessment

To evaluate the viability of OTEC implementation that has been demonstrated by Widiartono in [6] thermal gradient calculations with (1) and Carnot efficiency estimations were performed by (2), along with an assessment of environmental factors influencing their stability.

1. Thermal Gradient

$$\Delta T = T^{\text{MixedLayer}} - T^{\text{DepthLayer}} \quad (1)$$

With OTEC viability threshold: $\Delta T \geq 20^\circ\text{C}$.

2. Carnot Efficiency

$$\eta = (\Delta T / T^{\text{MixedLayer}}) \times 100\% \quad (2)$$

With:

η	= Energy Efficiency (%)
ΔT	= Temperature Difference (°C)
$T^{\text{MixedLayer}}$	= Average temperature in the mixed layer (°C)

3 Research Findings and Discussion

3.1 Sea Surface Temperature (SST) Distribution and Salinity Variability

The sea surface temperature (SST) distribution of 2015 as shown in Figure 2 in the Banda Sea (Neira) remained relatively warm throughout the study period, likely influenced by the El Niño event that significantly impacted Indonesian waters, including the Banda Sea as stated by Indonesian Agency for Meteorological, Climatological and Geophysics (BMKG) in [5]. The persistently high SST observed year-round suggests potential for further investigation into Ocean Thermal Energy Conversion (OTEC) feasibility in the region, which will be further analyzed through vertical profiling. Figure 2 presents the monthly and seasonal spatial distribution of Sea Surface Temperature (SST) in the Banda Sea, plotted with longitude (126°–131.5°E) on the x-axis and latitude (2.5°–9°S) on the y-axis. The color scale represents SST in °C (24–32°C), with a clearly labeled color bar (cool blues to warm reds). White contours indicate bathymetry at 200 m, 500 m, and 1,000 m highlighting depth zones critical for OTEC feasibility. Black dots denote ARGO float validation points. The figure uses gridded ERA5 reanalysis data (0.25° resolution), ensuring spatial consistency for OTEC site assessment.

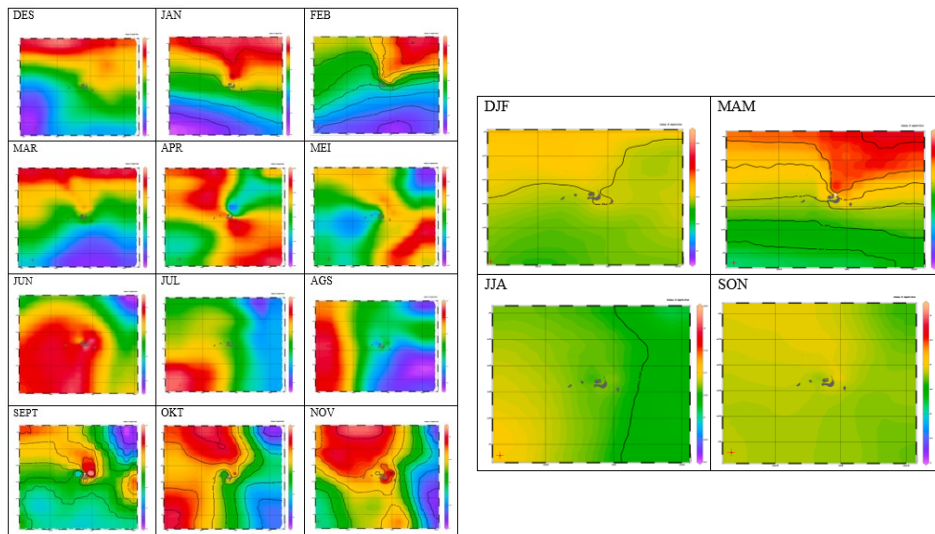


Figure 2 Monthly and Seasonal Spatial Plot of Banda Sea's SST

Seasonal averaging of SST data revealed consistent thermal patterns across all four seasons, with the northern part of the study area exhibiting higher temperatures annually. According to the Maluku Provincial Government in [8], the Banda Sea's climatic conditions are strongly influenced by the East Monsoon, which induces a dry season from March to August (associated with higher SST) and peaks in April, the driest month. Conversely, the West Monsoon brings wetter conditions from September to February (associated with lower SST), with the highest rainfall intensity occurring in January and February like it was mentioned before by Fadlillah *et.al* in [2].

3.2 Thermal Layer Analysis: Mixed, Thermocline, and Deep Layer of Banda Sea

The vertical thermal structure of the Banda Sea can be characterized by three distinct layers: the mixed layer, thermocline, and deep layer. Following the thermocline definition by BRIN in [3] the thermocline depth range was identified where the temperature gradient exceeded $0.1^{\circ}\text{C}/\text{m}$. Seasonal calculations in this research revealed the following stratification parameters as shown at Table 2.

Table 2 Seasonal variability of mixed layer depth (MLD), thermocline, and deep layer in the Banda Sea

Season	Mixed Layer Depth	Thermocline Depth	Deep Layer
DJF	55 m	55–110 m	>110 m
MAM	65 m	65–100 m	>100 m
JJA	45 m	45–80 m	>80 m
SON	45 m	45–65 m	>65 m

The results indicate that the SON period (onset of the wet monsoon) exhibits the shallowest mixed layer, while MAM (peak dry season) shows the deepest MLD, likely due to intensified solar heating and reduced wind-driven mixing.

The thermal characteristics of the Banda Sea exhibit distinct seasonal patterns driven by multiple interacting factors. Solar radiation serves as the primary heat source, with peak insolation during the dry season (MAM) resulting in elevated sea surface temperatures. This solar forcing interacts significantly with monsoon wind patterns - the East Monsoon (March-August) enhances vertical mixing and upwelling, while the West Monsoon (September-February) promotes greater stratification of the water column. These atmospheric dynamics are further modulated by ocean circulation, particularly through the advection of water masses by the Indonesian Throughflow, which transports both warm and cool waters through the region like mentioned before by Kemili, *et.al* in [7]. Additionally, the wet season rainfall (SON-DJF) introduces substantial freshwater input that reduces surface salinity while simultaneously cooling the upper ocean layer through both direct thermal exchange and the establishment of a shallow, less dense surface layer.

The thermal stratification observed in the region has important implications for OTEC development. Warm surface waters (above 26°C year-round) and strong thermocline gradients indicate favorable conditions for thermal energy extraction. The MAM season appears most suitable, with a deep mixed layer and strong thermocline that support efficient energy conversion. On the other hand, the SON season may pose challenges due to a shallower mixed layer and weaker temperature gradient, reducing the temperature difference needed for power generation. These seasonal patterns highlight the need to consider timing in OTEC planning and suggest that system designs must adapt to predictable changes in thermal structure.

3.3 Analysis of OTEC Potential and Energy Efficiency in the Banda Neira Sea

The consistently warm sea surface temperatures (SST) in the Banda Neira sea's present a promising opportunity for renewable energy generation through Ocean Thermal Energy Conversion (OTEC). However, a comprehensive assessment requires analysis of the temperature differential (ΔT) between surface and deep waters, as well as the theoretical Carnot efficiency (η). Based on fundamental thermodynamic principles, the Carnot efficiency is calculated as:

Table 3 Temperature Differential (ΔT) and Carnot Efficiency (η)

Season	Surface Temp. (°C)	Deep Temp. (600–700 m, °C)	ΔT (°C)	Carnot Efficiency (η , %)
DJF	30.2	8.1	22.1	73.2
MAM	31.5	7.8	23.7	75.1
JJA	28.9	8.3	20.6	71.3
SON	29.6	8.0	21.6	72.9

According to Mega, *et.al* in [9] OTEC feasibility in the Banda Sea requires a minimum ΔT of 20°C and a Carnot Efficiency exceeding 70%. As shown in Table 3, the calculations confirm that the annual ΔT between the surface and 600–700 m depth consistently meets these thresholds, with η always above 70%. However, while these thermodynamic conditions appear favorable, the practical implementation of OTEC requires further evaluation beyond physical oceanographic parameters.

A critical consideration in Indonesia Owned Stated Company of Electricity, PT PLN (Persero) is the long-term reliability of the thermal gradient. Although extended time-series data as depicted in Figure 3, reveal periods where ΔT falls below the 20°C threshold, particularly during anomalous oceanic or atmospheric events. These fluctuations could lead to operational shutdowns, compromising the stability of power generation.

Refer to Figure 3 below for details, as illustrated in Figure 3, the Banda Sea exhibits significant interannual variability in thermal gradients, with approximately 15–20% of months in 2005–2017 failing to sustain the minimum ΔT threshold of 20°C required for OTEC operation according to Kasharjanto,

et.al in [4]. This intermittency challenges OTEC's viability as a baseload power source, particularly for island grids requiring stable supply. To address these limitations, two primary strategies emerge:

1. Hybridization with complementary renewables (e.g., solar/wind) to mitigate supply gaps. Studies in tropical regions as demonstrate by BRIN in [3] that such hybrid systems improve capacity factors by 25–40%. For the Banda Sea, according to BRIN in [3] the West Indonesian solar energy (with 4–5 kWh/m²/day irradiance) presents a synergistic option due to its inverse correlation with monsoon-driven SST dips, or
2. Advanced heat exchanger designs to maintain efficiency at lower ΔT . Using Novel designs, as mentioned by Kim, et.al in [16] such as microchannel or biomimetic heat exchangers, can maintain Carnot efficiency (>70%) even at ΔT values as low as 18°C.

While the Banda Sea exhibits strong theoretical OTEC potential, its viability ultimately depends on system resilience to natural variability and economic feasibility given these operational constraints. Further research should focus on optimizing plant design for tropical marginal seas with similar thermal regimes.

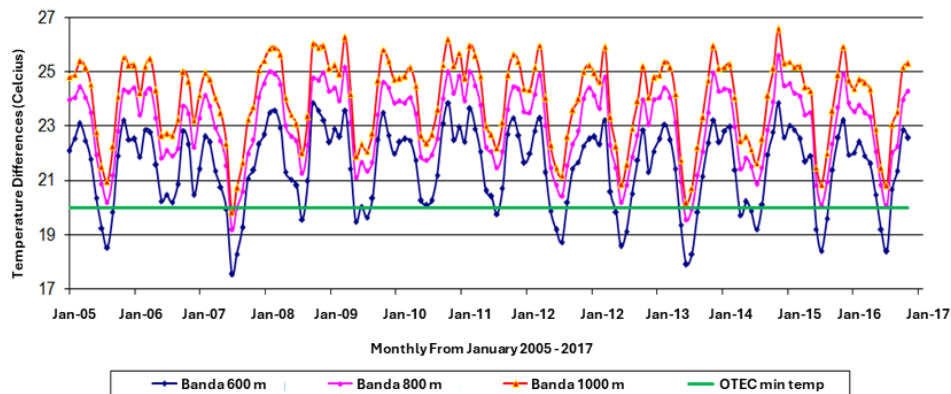


Figure 3 Monthly and Seasonal Spatial Plot of Banda Sea's SST

3.4 Recommendations for OTEC Implementation in Banda

The Banda Sea exhibits strong potential for Ocean Thermal Energy Conversion (OTEC) deployment due to its equatorial location, stable thermal resources, and suitable bathymetry. Surface temperatures remain consistently warm (28–31°C) year-round, supported by solar radiation and the inflow of warm Pacific waters through the Indonesian Throughflow as mentioned by Gordon in [15].

3.4.1 Seasonal and Operational Considerations

Our analysis identifies distinct seasonal patterns in thermal stratification. During dry seasons (DJF and MAM), easterly winds and reduced cloud cover drive peak surface temperatures, creating optimal ΔT conditions of 22–24°C. In contrast, the wet season (JJA and SON) shows marginally reduced ΔT (20–22°C) due to increased cloud cover and precipitation, though still above the 20°C operational threshold. According to Mega, *et.al* in [9]. The vertical thermal structure reveals a shallow mixed layer (20–60 m) and thermocline (50–100 m), enabling efficient heat exchange. With an average ΔT of 22.7°C (surface to 700 m) and Carnot efficiency of 77%, the region meets technical viability benchmarks for OTEC as given by Junihartomo, *et.al* in [1].

3.4.2 Reliability Challenges and Mitigation Strategies

Long-term data (2005–2017) indicates intermittent periods where ΔT falls below 20°C (~15–20% of months), posing reliability challenges for continuous power generation. To address this variability within the energy trilemma framework (affordability, reliability, sustainability), we propose:

- a. Hybrid systems integrating solar or wind power to compensate during suboptimal ΔT periods;
- b. Thermal energy storage to buffer short-term fluctuations;
- c. Modular OTEC designs capable of partial operation during thermal resource dips.

3.4.3 Implementation Priorities

To maximize OTEC's contribution to the Banda region's energy mix, we recommend:

- a. Site selection focused on the northern Banda Sea, where thermal stability is highest.
- b. Adaptive operational protocols to align with seasonal ΔT variability.
- c. Real-time oceanographic monitoring paired with predictive modeling for system optimization; and
- d. Floating OTEC platforms to access optimal thermal gradients while minimizing coastal infrastructure.

With these measures, system availability could increase from ~80% to >90%, enhancing OTEC's role as a reliable, low-carbon energy source. Future studies should evaluate the cost-benefit trade-offs of these strategies and their impact on levelized energy costs.

References

- [1] Junihartono, et al., *Ocean Power Technologies for Renewable Energy*, Journal of Citizenship Studies, 2022. (Journal)
- [2] Fadhlillah, et al., *Potential of Ocean Heat as a New Renewable Energy Source in the Waters of East Nusa Tenggara Islands Using Ocean Thermal Energy Conversion (OTEC) Method*, JEET: Journal of New & Renewable Energy, 5(01), pp. 70–84, 2024. (Journal)
- [3] National Research and Innovation Agency (BRIN), *Indonesia's Energy Transition Preparedness Framework Towards 2045*, 2023. (Technical Report)
- [4] Kasharjanto, A., Rahnuna, D. & Rina, *A Study on the Utilization of Ocean Current Energy in Indonesia*, Wave Journal, 11(2), pp. 75–84, 2017. (Journal)
- [5] Indonesian Agency for Meteorological, Climatological and Geophysics (BMKG), *Atmosphere–Ocean Dynamics Analysis: Rainfall Analysis and Prediction, First 10-Day Period of July 2019*, Division of Climate Variability Analysis, Deputy for Climatology, Center for Climate Change Information, 2019. (Technical Report)
- [6] Widyartono, M. & Rahmadian, R., *OTEC Potential in Papua Province, Indonesia*, Indonesian Journal of Electrical and Electronics Engineering, 2(1), 2019. (Journal)
- [7] Kemili, P. & Putri, M. R., *Influences of Upwelling Duration and Intensity Based on Sea Surface Temperature Anomaly Toward Primary Productivity Variability in Indonesian Waters*, Journal of Tropical Marine Science and Technology, 4(1), pp. 66–79, 2012. (Journal)
- [8] Mega, L., et al., *OTEC Potential In The Indonesian Seas*, Conference and Exhibition Indonesia, vol. 65, pp. 215–222, 2014. (Conference Proceedings)
- [9] Lennard, *Discusses NELHA's OTEC Plant and Its Role in Advancing Closed-Cycle Technology*, Renewable Energy, 2018. (Journal)
- [10] Uehara, et al., *Covers Okinawa's Open-Cycle OTEC System and Its Dual-Output (Power + Freshwater) Design*, Applied Energy, 2019. (Journal)
- [11] Gauthier, et al., *Analyzes the Martinique Project's Scalability and Economic Feasibility for Island Grids*, Energy, 2021. (Journal)
- [12] Reynolds, R. W., et al., *Sea Temperature Daily High-Resolution Blended Analyses and Quality Control*, Journal of Climate, 2007. (Journal)
- [13] Vega, L. A., *Ocean Thermal Energy Conversion Primer*, 2010. (Book)
- [14] Schlitzer, *Ocean Data View User Guide*, 2022. (Technical Report)
- [15] Gordon, A. L., *Oceanography of the Indonesian Seas*, 2005. (Book)
- [16] Kim, D., et al., *Nanofluid-Enhanced Heat Exchangers for Low- ΔT OTEC*, Applied Energy, 306, pp. 118153, 2022. (Journal)

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