

Assessment of Ocean Thermal Energy Conversion Potential in Cenderawasih Bay, Papua, Indonesia: Energy Performance, Techno-Economic Feasibility, and Environmental Considerations

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Article Info

Article history:

Received Aug 29th, 2026

Revised Sept 26th, 2026

Accepted Oct 5th, 2026

Keyword:

Ocean Thermal Energy Conversion; Cenderawasih Bay; renewable energy; thermal efficiency; electrical power generation; environmental impact

ABSTRACT

This study evaluated the potential of Ocean Thermal Energy Conversion as a renewable electricity source in Cenderawasih Bay, Papua, Indonesia. Ocean temperature data from the World Ocean Atlas for 1955-2018 at station 21576 were analyzed to characterize the surface and deep-water thermal conditions and to assess the performance of an open-cycle Ocean Thermal Energy Conversion system. The assessment covered thermodynamic efficiency, electrical power generation, production cost, freshwater production, and potential environmental impacts. The annual mean sea-surface temperature was 29.28 °C, while the temperature at a depth of 500 m was 8.19 °C, corresponding to an average Carnot efficiency of 6.98%. The estimated electrical power output reached 7,750 kW, with a projected electricity generation cost of Rp539.448 kWh⁻¹. The system was also estimated to produce approximately 22,622 L of freshwater per day. Nutrient-rich seawater discharge may increase the risk of harmful algal blooms and therefore warrants environmental monitoring. Overall, Cenderawasih Bay showed considerable potential for Ocean Thermal Energy Conversion development, although technical, economic, and environmental aspects required further assessment.



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INTRODUCTION

The growing demand for reliable and sustainable electricity has increased interest in renewable energy sources, particularly for remote and island communities where access to centralized electricity infrastructure remains limited. This challenge is particularly relevant to Papua, where geographical isolation increases the need for locally available energy resources. Ocean Thermal Energy Conversion (OTEC) is one potential option because it uses the temperature difference between warm surface seawater and cold deep seawater to generate electricity. Tropical regions are particularly suitable because they provide relatively warm surface water and accessible deep-water thermal gradients (Chen & Huo, 2023; Herrera et al., 2021; Nithesh & Chatterjee, 2016). Despite this advantage, the relatively low thermodynamic efficiency and high capital cost of OTEC remain important barriers to wider deployment (Aresti et al., 2023; Gao et al., 2025; Xiao et al., 2024).

OTEC performance depends strongly on the available temperature gradient and the configuration of the energy-conversion system. Previous studies have examined turbine performance, hydrodynamic problems, thermal cycles, working fluids, and system design (Nithesh & Chatterjee, 2016; Zhang et al., 2018). Thermodynamic analyses have also considered closed-cycle configurations

and alternative working fluids, including carbon-dioxide-based mixtures, while experimental studies have highlighted differences between ideal and practical system performance (Li et al., 2020; Liu et al., 2020; Wang et al., 2019). For open-cycle systems, OTEC can also provide freshwater in addition to electricity. Studies have examined simultaneous power generation and desalination, multi-objective optimization, and the economic value of utilizing OTEC by-products (Hernández-Romero et al., 2022; Kim et al., 2016; Liponi et al., 2022; Xiao et al., 2024).

Indonesia has favorable conditions for OTEC development because of its extensive tropical marine area and deep-water thermal gradients. Hammad et al. (2020) reported an average temperature difference of 23.57 °C and a Carnot efficiency of 7.7% in the northern Makassar Strait, while Putri & Fadliah (2023) also assessed the use of ocean heat for renewable electricity generation in the Makassar Strait. At the national scale, Langer et al. (2021) assessed OTEC plant siting and economic potential in Indonesia using a geographic information system and estimated substantial economic potential for large-scale plants. Langer et al. (2022) further showed that technological learning and economies of scale could affect the future economic viability of OTEC in Indonesia. However, these studies focused on the Makassar Strait or national-scale assessments rather than Cenderawasih Bay.

OTEC feasibility also depends on economic and environmental conditions in addition to the thermal resource. Previous studies have incorporated technical, geographical, socioeconomic, environmental, and economic criteria in identifying suitable OTEC locations (Garduño-Ruiz et al., 2021; Hall et al., 2022; Lopez et al., 2022; Soto Calvo & Lee, 2025). Economic analyses have identified capital cost, operating cost, plant lifetime, interest rate, net power output, and technological development as important factors affecting OTEC viability (Fan et al., 2024; Hu et al., 2024; Langer et al., 2020; Rashid et al., 2024; Yilmaz, 2019). Environmental effects associated with seawater intake and discharge have also received attention, including hydrodynamic processes, vertical water transport, and possible changes in biological productivity (Ma et al., 2026; Nickoloff et al., 2025b, 2025a; Rau & Baird, 2018; Zhang et al., 2018). OTEC feasibility therefore depends on the thermal resource as well as system performance, economics, and environmental constraints.

Most previous studies have focused on specific aspects of OTEC, such as thermodynamic optimization, site selection, economic analysis, desalination, or environmental effects. An integrated assessment that combines long-term ocean-temperature characteristics with OTEC efficiency, electrical power output, production cost, freshwater production, and environmental considerations remains limited, particularly for Cenderawasih Bay. Indonesian studies have mainly examined the Makassar Strait or national-scale potential, leaving Cenderawasih Bay less explored. This study assessed OTEC potential in Cenderawasih Bay using long-term World Ocean Atlas temperature data from station 21576 and an open-cycle OTEC model.

This study evaluated open-cycle OTEC potential in Cenderawasih Bay in terms of thermal conditions, power generation, freshwater production, production cost, and environmental implications. The analysis covered sea-surface and deep-water temperature characteristics, thermodynamic efficiency, electrical power output, electricity generation cost, freshwater production, and potential environmental impacts. By integrating these aspects in a single site-specific assessment, the study provided a quantitative basis for evaluating Cenderawasih Bay as a potential location for marine renewable-energy development in Papua.

RESEARCH METHODS

Location and Research Data

This study was conducted in the waters of Cenderawasih Bay, Papua, Indonesia. The study area was selected because the bay connects Papua, West Papua, and Central Papua and has potential for the utilization of marine renewable energy. The oceanographic data used in this study were secondary seawater-temperature data obtained from the World Ocean Atlas for the 1955-2018 period. The data were obtained from station 21576, located at approximately 135.5°E and 2.5°S in the waters of Cenderawasih Bay. The analysis focused on sea-surface temperature and temperature variation with depth to identify the thermal gradient available for Ocean Thermal Energy Conversion.

Materials and Equipment

The study used World Ocean Atlas temperature data and the technical parameters required to model an open-cycle OTEC system. The system parameters included seawater temperature, seawater

density, seawater flow rate, pipe dimensions and length, flow velocity, friction factor, turbine parameters, generator efficiency, investment cost, interest rate, plant lifetime, capacity factor, and operation and maintenance costs. The open-cycle OTEC configuration and its operating parameters were based on the references used in this study, including (Aprilia et al., 2019; Devis-Morales et al., 2014). Ocean Data View was used to process, visualize, and analyze the oceanographic data. The analysis yielded sea-surface temperature characteristics, vertical temperature profiles, thermal efficiency, electrical power output, freshwater production, electricity generation cost, and potential environmental impacts.

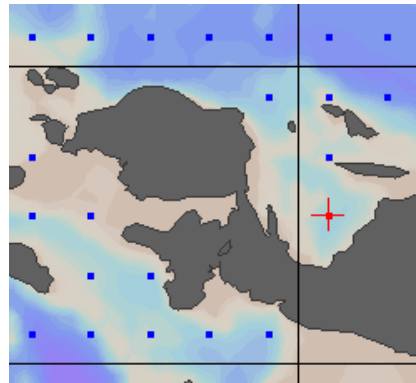


Figure 1. Location of observation station 21576 in the waters of Cenderawasih Bay, Papua, Indonesia.

Research Procedures and Data Analysis

The research was conducted in three main stages: pre-implementation analysis, implementation analysis, and post-implementation analysis. In the pre-implementation stage, the temperature characteristics of Cenderawasih Bay were analyzed using World Ocean Atlas data. Monthly sea-surface temperatures were examined to identify the minimum and maximum values, while temperature profiles with depth were analyzed to determine the available temperature difference between surface and deep seawater. Based on these characteristics, seawater temperature at a depth of 500 m was selected for the OTEC analysis. The implementation stage consisted of thermodynamic, electrical, freshwater, and economic analyses. The thermal efficiency of the OTEC system was estimated from the temperature difference between surface seawater and seawater at 500 m depth using the Carnot-efficiency approach. The open-cycle system was then analyzed by considering the warm-seawater intake, evaporator, turbine, generator, condenser, and cold-seawater intake. The electrical power output was estimated from the specified operating parameters, including seawater flow conditions, pumping requirements, turbine performance, and generator efficiency. Freshwater production was estimated from the condensation of low-pressure vapor generated from warm seawater. The resulting water mass was converted into freshwater volume using the adopted seawater density. The economic analysis estimated the electricity generation cost from the assumed investment cost, interest rate, plant lifetime, capacity factor, capital recovery factor, fixed cost, and operation and maintenance cost. The resulting production cost was subsequently compared with the average electricity generation costs of several conventional and renewable generation technologies. In the post-implementation stage, potential environmental impacts associated with the discharge of nutrient-rich seawater were evaluated. Particular attention was given to the potential occurrence of harmful algal blooms resulting from nutrient enrichment and changes in dissolved oxygen conditions. The environmental assessment also considered monitoring measures, including nutrient measurements at selected depths, plankton-abundance monitoring, monitoring of cold-water intake entrainment, and acoustic monitoring. The results from the three stages were subsequently integrated to evaluate the overall potential of open-cycle Ocean Thermal Energy Conversion in Cenderawasih Bay in terms of thermal resource availability, energy production, freshwater production, economic feasibility, and environmental considerations.

RESULTS AND DISCUSSION

Ocean Temperature Characteristics of Cenderawasih Bay

The World Ocean Atlas data showed that Cenderawasih Bay had relatively high sea-surface temperatures throughout the year. The lowest monthly mean sea-surface temperature was 28.79 °C in February, while the highest was 29.72 °C in October. The annual mean sea-surface temperature was 29.28 °C. The vertical temperature profiles showed a clear decrease in seawater temperature with increasing depth, with markedly colder water occurring below the surface layer. At a depth of 500 m, the mean seawater temperature was 8.19 °C.

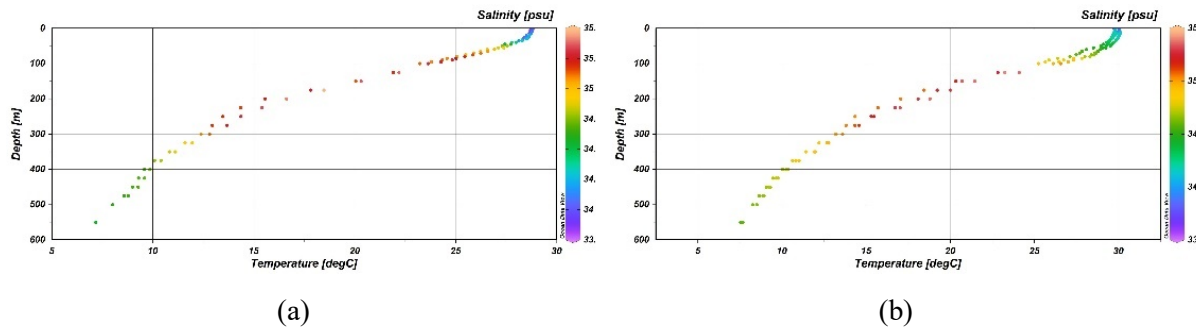


Figure 2. Vertical seawater temperature profiles in Cenderawasih Bay: (a) February and (b) October.

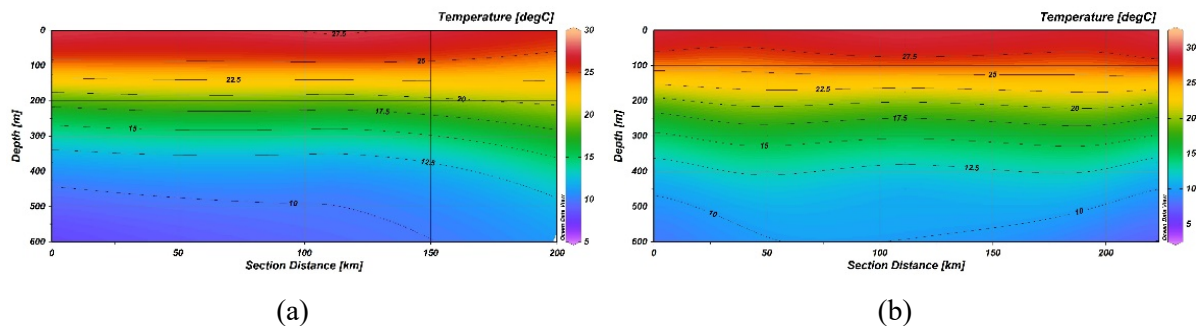


Figure 3. Cross-sectional seawater temperature distribution in Cenderawasih Bay: (a) February and (b) October.

The seasonal variation in surface temperature was associated with changes in solar heating and seasonal oceanographic conditions. The lower temperature observed in February occurred during the western monsoon and the beginning of the first transition season, when solar heating over the region was relatively lower. In contrast, the higher temperature in October coincided with stronger solar heating during the eastern monsoon and the second transition season. The temperature difference between the annual mean surface temperature and the temperature at a depth of 500 m was 21.09 °C, indicating a substantial vertical thermal gradient in the study area. The magnitude of the thermal gradient was comparable to that reported for other Indonesian waters. Hammad et al. (2020) reported an average temperature difference of 23.57 °C in the northern Makassar Strait, with an estimated average Carnot efficiency of 7.7%. The slightly smaller gradient in Cenderawasih Bay resulted in a lower theoretical thermal efficiency, as discussed in the following section. Nevertheless, the observed 21.09 °C temperature difference indicates that Cenderawasih Bay has a favorable thermal resource for further assessment of OTEC development.

Thermal Efficiency and Electrical Power Generation

The calculated average annual Carnot efficiency of the OTEC system was 6.98%. The monthly efficiency ranged from 6.82% in March to 7.14% in September. The variation followed the seasonal changes in the surface-water temperature because the deep-water temperature was considerably lower and more stable. The highest efficiency occurred when the surface temperature was relatively high, resulting in a larger temperature difference between the warm and cold seawater streams. The calculated efficiency was close to that reported for the northern Makassar Strait (Hammad et al., 2020), where the average Carnot efficiency reached 7.7%. The difference likely reflects the temperature gradient and the

selected cold-water depth. The present analysis used seawater at 500 m depth, whereas the Makassar Strait study considered deeper water and therefore obtained a larger temperature difference. The result indicates that the thermal resource in Cenderawasih Bay is sufficient for further OTEC assessment to support the basic thermodynamic requirement of an OTEC system, although the Carnot efficiency represented an ideal upper-bound efficiency rather than the net efficiency of a commercial plant.

The open-cycle OTEC model yielded an estimated electrical power output of 7,750 kW. This result was obtained after considering the seawater flow conditions, pumping requirements, turbine operation, and assumed generator efficiency. This output corresponds to a nominal generation capacity of 7.75 MW under the assumed operating conditions. This value is a theoretical estimate; actual power output would also depend on heat-transfer losses, parasitic pumping power, turbine performance, plant availability, and other engineering constraints. Studies of OTEC systems have likewise shown that practical performance depends strongly on operating conditions and system configuration rather than on the ideal temperature gradient alone.

Freshwater Production and Integrated Energy-Water Potential

In addition to electricity generation, the open-cycle configuration was estimated to produce approximately 22,622 L of freshwater per day. The freshwater resulted from condensation of the low-pressure vapor generated from warm seawater in the evaporator. The ability to produce both electricity and freshwater is particularly relevant to remote coastal areas with limited infrastructure for either service. The result is consistent with the main advantage of open-cycle OTEC reported in previous studies. Kim et al. (2016) showed that open-cycle OTEC could simultaneously produce electricity and desalinated water, with the production of both outputs strongly affected by warm-water temperature, cold-water intake, evaporator pressure, and condenser configuration. Hernández-Romero et al. (2022) also demonstrated that electricity and desalinated-water production can be treated simultaneously in the optimization of an open-cycle OTEC system. The estimated freshwater output further supports the potential of an integrated electricity-and-water application in Cenderawasih Bay. However, the freshwater value in this study was derived from the assumed operating parameters rather than from direct experimental measurements. Its practical production rate would depend on the actual vapor generation rate, condenser performance, seawater intake characteristics, and operational stability of the plant. The value of 22,622 L day⁻¹ should therefore be regarded as a preliminary engineering estimate rather than a guaranteed field production rate.

Electricity Generation Cost

The estimated investment cost of the proposed OTEC system was US\$6,000,000 for an output of 7,750 kW. Using the assumed interest rate of 10%, plant lifetime of 20 years, and capacity factor of 30%, the capital recovery factor was estimated at 0.11. Combining the capital, fixed, and operation and maintenance costs yielded a total electricity generation cost of US\$0.0336 kWh⁻¹, equivalent to approximately Rp539.448 kWh⁻¹. When compared with the average electricity generation costs, the estimated OTEC cost was lower than the values for coal-fired power plants (Rp705 kWh⁻¹), geothermal power plants (Rp975 kWh⁻¹), gas turbines (Rp1,611.79 kWh⁻¹), gas-steam combined cycles (Rp1,322.23 kWh⁻¹), and diesel power plants (Rp4,746.32 kWh⁻¹). However, it remained higher than the reported average hydropower generation cost of Rp432 kWh⁻¹. The estimated cost was lower than those of coal, geothermal, gas-turbine, combined-cycle, and diesel generation, but higher than hydropower. The economic result should be interpreted cautiously because OTEC economics are highly sensitive to capital expenditure, capacity factor, discount rate, and net power output. Langer et al. (2021), using a GIS-based assessment of 100 MWe OTEC systems in Indonesia, reported a national economic potential of 0-2 GWe and a lowest estimated levelized cost of electricity of approximately US\$0.156 kWh⁻¹. The difference may arise from differences in plant scale, cost assumptions, system boundaries, and calculation methods. This difference is important because the present value was obtained from simplified assumptions and should not be interpreted as a bankable or commercial-level cost estimate. A more detailed economic assessment would need to include site-specific infrastructure, cold-water-pipe costs, financing, plant utilization, maintenance, and other capital and operational expenditures.

Environmental Implications of OTEC Development

The environmental assessment identified nutrient-rich seawater discharge as one of the main environmental concerns associated with the proposed open-cycle OTEC system. Cold deep seawater contains higher concentrations of nutrients than surface seawater, and the discharge of large quantities of this water into shallower layers could alter local nutrient availability. Such enrichment may promote phytoplankton growth and increase the risk of harmful algal blooms, eutrophication, and reduced dissolved oxygen concentrations. These concerns are consistent with recent research showing that OTEC deployment can modify the vertical distribution of heat, nutrients, and biological production. (Nickoloff et al., 2025b) demonstrated that large-scale OTEC deployment can substantially alter ocean properties through artificial mixing and redistribution of deep seawater. Their results also showed that OTEC-induced circulation can affect biological productivity and the thermal structure of the ocean. The magnitude and direction of these effects depend on plant scale, discharge depth, local circulation, and the characteristics of the receiving environment.

Any future feasibility study for Cenderawasih Bay should therefore include environmental monitoring. This study proposed periodic measurements of nutrient concentrations at selected depths, monitoring of plankton abundance, observation of cold-water entrainment, and acoustic monitoring. These measures would provide baseline information for evaluating whether the discharge configuration produces measurable ecological changes. The environmental findings consequently indicate that the OTEC potential of Cenderawasih Bay cannot be evaluated solely from its temperature gradient and estimated electricity output; the characteristics of seawater intake and discharge must also be incorporated into subsequent site-specific design.

CONCLUSION

Cenderawasih Bay showed favorable thermal conditions for open-cycle Ocean Thermal Energy Conversion, with an annual mean sea-surface temperature of 29.28 °C and a temperature of 8.19 °C at 500 m depth. Under the assumed operating conditions, the system was estimated to generate 7,750 kW of electricity and approximately 22,622 L of freshwater per day, with an electricity generation cost of Rp539.448 kWh⁻¹. The estimates indicate potential for combined electricity and freshwater production, although the economic results remain sensitive to the assumptions used and nutrient-rich seawater discharge could pose environmental risks, particularly through increased biological productivity and harmful algal blooms. Further site-specific technical, economic, oceanographic, and environmental studies are needed before practical implementation.

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