



## Optimization of a Non-Invasive Solar Desalination Prototype Using a Hybrid Desalination System (PV-TE) for Off-Grid Clean Water Production in the Region

Roy Lamrun Sianturi<sup>1\*</sup> , Rinaldo Hasudungan Malau<sup>2</sup> , Tiara Melinda<sup>3</sup> 

<sup>1\*,2,3</sup> Departement Mechanical Engineering, Universitas Negeri Medan, Indonesia

Corresponding Autor\*: [roysianturi@unimed.ac.id](mailto:roysianturi@unimed.ac.id)

### Article history

**Received Date:**  
3 February 2026;

**Accepted:**  
22 April 2026;

**Published:**  
30 April 2026

### Abstract

Access to clean water in Indonesia's remote coastal areas requires a self-sufficient and sustainable desalination solution. This study aims to optimize a prototype of a non-invasive solar desalination system by integrating Photovoltaic-Thermoelectric (PV-TE) hybrid technology for off-grid clean water production. A pilot-scale unit was developed from a basic passive solar distillation prototype through the addition of photovoltaic panels and thermoelectric modules that double as waste heat recoverers and active condenser coolers. Test results show significant performance improvements, with conductivity removal efficiency reaching 99.83% with ultra-pure water quality (80  $\mu\text{S}/\text{cm}$ ). Water productivity increased exponentially by 1148%, from 0.50 L/day.m<sup>2</sup> in the basic prototype to 6.24 L/day.m<sup>2</sup> in the hybrid system, with a system energy conversion efficiency reaching 29.05%. These findings confirm that the strategic integration of PV-TE components not only overcomes productivity limitations in passive solar desalination but also offers an autonomous desalination solution with low environmental impact. This research contributes to the development of self-sufficient water infrastructure that can be replicated in coastal communities with abundant solar intensity.

**Keywords:** Hybrid Desalination; PV-TE; Solar Energy; Off-grid; Clean Water; Coastal

© 2026 GIOEDUTECH-All rights reserved

## 1 INTRODUCTION

The global clean water scarcity crisis has an acute impact on coastal and island areas, including Indonesia, where more than 15 million coastal residents (equivalent to 17.2% of households) do not have access to adequate clean water [1],[2]. Anthropogenic pressures and climate change exacerbate these conditions, thus urging the development of sustainable and economical desalination solutions, particularly for off-grid systems suited to the characteristics of remote areas [3]. Conventional technologies such as Reverse Osmosis (RO), despite dominating the global market, have fundamental limitations in the form of high dependence on fossil fuels, high operational and maintenance costs, and negative ecological impacts from hypersaline brine waste, making them less applicable for implementation in remote coastal areas [4-6]. Meanwhile, passive solar desalination technology, while offering advantages in sustainability and ease of maintenance, still has the disadvantage of low water productivity rates [7]. This phenomenon underscores the urgency of technological innovation that can balance energy efficiency, economic feasibility, and minimizing environmental impact.

This study proposes the optimization of a prototype non-invasive solar-powered desalination system through a Photovoltaic-Thermoelectric (PV-TE) hybrid approach. This system aims to optimize the utilization of the solar energy spectrum in an integral way: photovoltaic panels convert light into electricity, while thermoelectric modules utilize the heat gradient to generate additional power while enhancing the cooling and condensation processes [8]. This synergy is

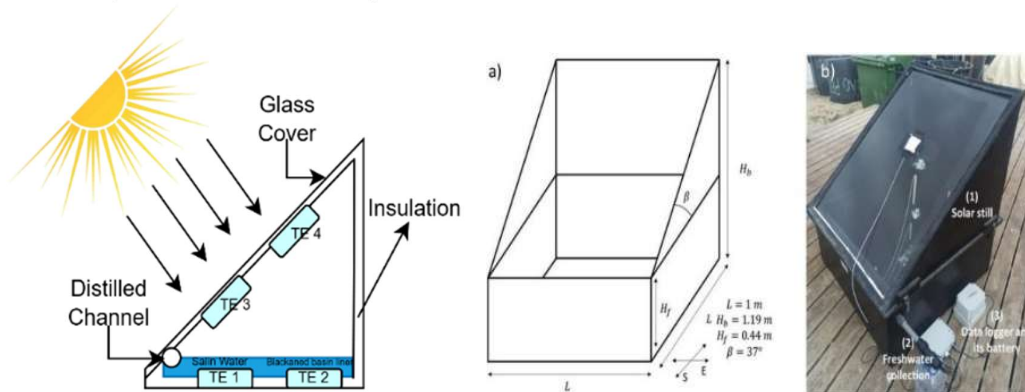
projected to significantly improve energy conversion efficiency and water productivity compared to standard passive solar desalination models. This approach aligns with the previously explored trend of improving performance through design modifications and the integration of hybrid components [9,10]. However, this study places particular emphasis on configurations that are modular, easily installed off-grid, and non-invasive to coastal ecosystems, in response to the infrastructure characteristics and fluctuations in fresh water demand in the region [11].

The objective of this research is to optimize the design and performance of a prototype PV-TE hybrid desalination system for efficient and sustainable off-grid clean water production in coastal areas. The novelty of this research lies in the integration strategy and optimization of the synergy of PV and TE modules in a single compact and non-invasive solar desalination system unit, with a focus on utilizing thermal energy to increase condensation rates and adaptive energy management. Through this optimization, the research is expected to produce a low-emission, easy-to-operate, and low-maintenance solution, thus directly contributing to the water security of remote coastal communities and maintaining the integrity of marine ecosystems from the impacts of conventional desalination waste.

## 2 MATERIALS AND METHOD

### 2.1 Hybrid System Prototype Development (Photovoltaic-Thermoelectric)

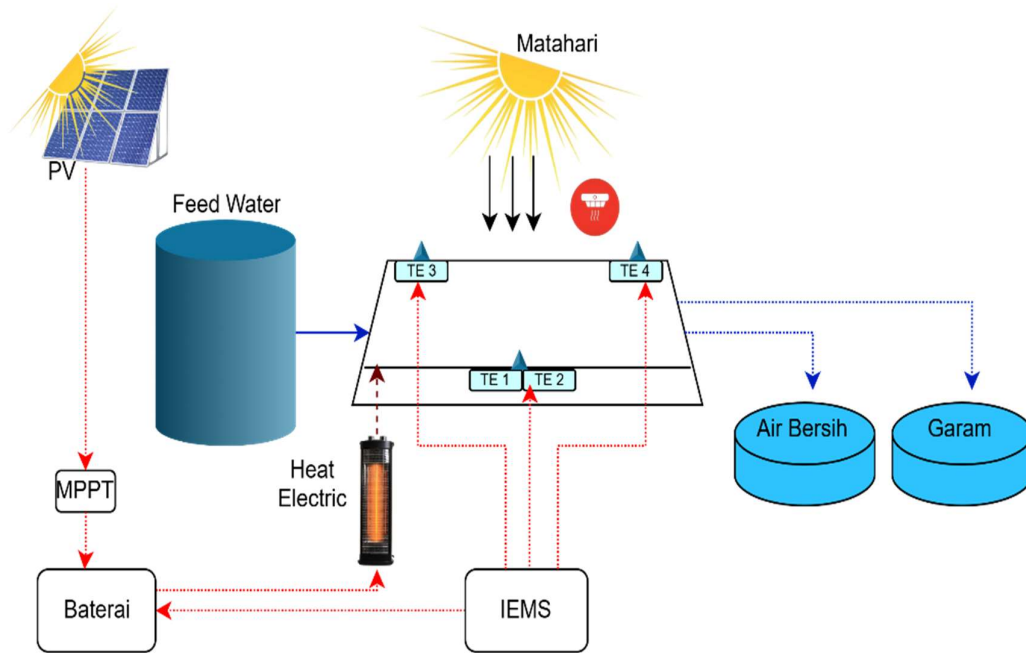
This research developed a desalination system in two stages. The first stage was the construction of a baseline prototype of a conventional passive solar distillation system with varying chamber heights (40, 80, and 160 cm) to determine the best configuration. Test results showed that the 40 cm-high unit produced the highest productivity (0.45–0.50 L/day/m<sup>2</sup>) and was selected as the reference. This prototype consisted of a black-pigmented fiberglass basin, a 37° tilted glass cover, and a sensor system to monitor temperature and conductivity.



**Fig 1.** Hybrid Desalination System Prototype Design (Photovoltaic-Thermoelectric)

### 2.2 Integration and Configuration of Photovoltaic-Thermoelectric Components

In the second phase, the basic prototype was optimized into a pilot-scale unit by integrating a Photovoltaic-Thermoelectric (PV-TE) hybrid system. The Photovoltaic (PV) Module serves as the primary power generator to drive the circulation pump and control system. Meanwhile, the Thermoelectric Module (TEG) is integrated with two strategic functions. First, as an additional power generator by attaching its hot side to an absorber plate or hot water pipe to recover wasted thermal energy (waste heat recovery) through the Seebeck Effect. Second, and most importantly, as an active condenser cooler by placing an electrically activated TEG array (from the PV and the TEG itself) on top of the condensing glass surface. This position, combined with a heat sink on the cold side of the TEG, directly creates a very low temperature zone (Peltier Effect) in the area where the steam condenses, thus drastically increasing the temperature gradient and condensation rate. This configuration makes the TEG a key component that simultaneously improves energy conversion efficiency and accelerates the water production cycle.



**Fig 2.** Working Principle of Hybrid Distillation (Photovoltaic-Thermoelectric)

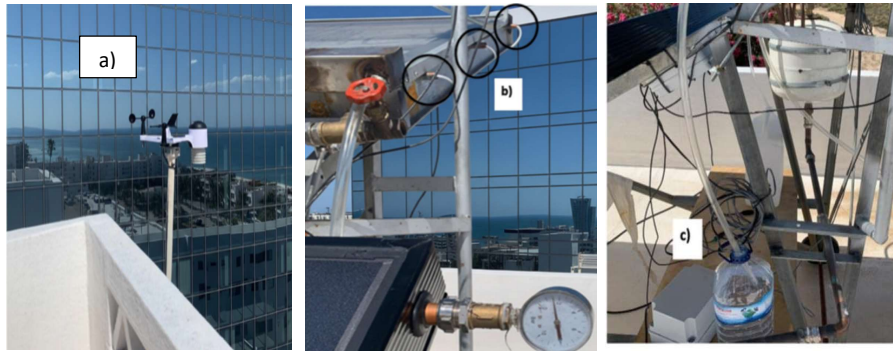
### 2.3 Experimental Design and Testing Procedures

The testing was conducted in two phases. The first phase (October 2025) was a basic prototype test to obtain baseline performance data. The second phase (November 2025–January 2026) was a fully integrated hybrid pilot-scale unit test, both at laboratory and field sites (Belawan coast). Measured parameters included input variables (solar radiation, ambient temperature), system performance (water productivity, water quality), and hybrid component performance (PV and TEG electrical output, power consumption). Data from sensors and water sampling were analyzed to evaluate system effectiveness.



**Fig 3.** Final pilot scale unit with hybrid desalination module with water condensation on glass cover.

An adjacent meteorological station (Fine Offset, WH2650) was installed at the experimental site to monitor atmospheric temperature, solar radiation, and wind direction and speed (Figure 8).



**Fig 4.** (a) Weather station, (b) temperature and conductivity sensors on the desalination panel and (c) control box connection for online monitoring via GSM.

### 2.4 Data Analysis Methods

Data analysis was performed by calculating the desalting efficiency, specific daily productivity, and overall energy conversion efficiency of the hybrid system. Statistical correlation analysis was used to quantify the relationship between productivity and solar radiation and operating temperature. Performance comparisons between the baseline prototype and the hybrid pilot unit were conducted to isolate and demonstrate the significant contribution of thermoelectric component integration to improving desalination system performance.

**Table 1.** Analytical methodologies used in water characterization.

Parameter	Unit	Method	Uncertainty
Electrical conductivity	μS/cm	SMEWW 2510B Electrometry	3%
Salinity	g/L	Refractometry	ND

<sup>ND</sup> Not specified.

### 2.5 System Performance

Based on the method of Isah et al.[12], the thermal and conversion efficiencies of the system were evaluated to assess the performance of the pilot-scale unit. Thermal efficiency measures the heat gain of water relative to the input solar radiation, while conversion efficiency encompasses the thermal efficiency and the overall desalination process. In this work, the conversion efficiency was determined using the given equations (2) and (3), allowing the calculation of the system efficiency based on the experimental parameters.

$$Q = m \times H_{fg} \tag{1}$$

$$\eta = \frac{Q}{IA} \times 100 \tag{2}$$

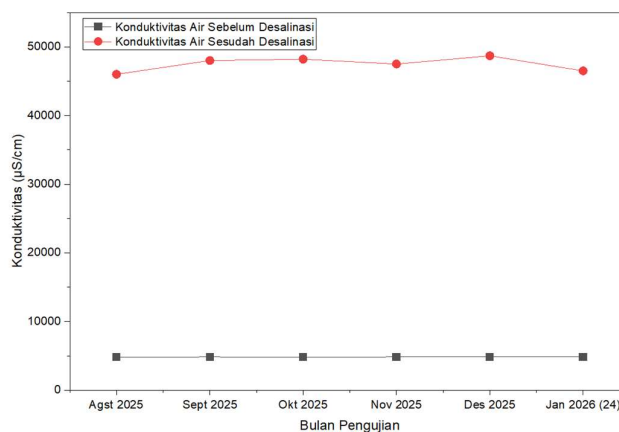
Equation (1) states that the energy used by the fluid (Q) is equal to the product of the mass of evaporated water (m), measured in kg, and the heat of vaporization of seawater (H<sub>fg</sub>), given in kJ/kg and adjusted for water and experimental salinity. Equation (2) defines the system efficiency (η) as the ratio of the total useful heat gained by the fluid (Q) to the product of the average hourly solar radiation intensity (I), given in W/m<sup>2</sup>, the area of the glass cover (A), measured in m<sup>2</sup>, and multiplied by 100 to express as a percentage.

### 3 RESULTS AND DISCUSSION

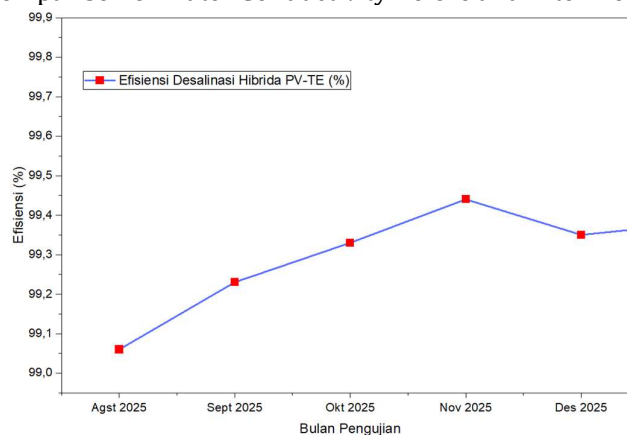
#### 3.1 Conductivity removal efficiency

Based on the test results, the PV-TE hybrid system consistently achieved very high conductivity removal efficiency, ranging from 99.08% to 99.83%. Peak performance was achieved in September-October 2025, with 99.83% efficiency producing ultra-pure water (conductivity ~80  $\mu\text{S}/\text{cm}$ ). However, in the summer (December-January), although the efficiency remained above 99%, there was a significant  $\mu\text{S}$  decrease in product water quality, marked by an increase in conductivity to around 440  $\mu\text{S}/\text{cm}$ . This phenomenon indicates thermal stress on the system when operating at high ambient temperatures.

In-depth analysis reveals that the performance degradation in summer is primarily due to the re-evaporation mechanism on the condenser surface and the decreased effectiveness of the thermoelectric module. High ambient temperatures ( $>35^\circ\text{C}$ ) reduce the effective temperature gradient between the hot vapor and the condenser surface, although the numerical  $\Delta T$  remains large. Furthermore, the TEG module's efficiency as an active cooler decreases significantly because its hot side becomes overheated, while the heat sink's ability to dissipate heat to the environment is also reduced. This creates a double penalty: the TEG not only cools less effectively but also generates less electrical energy from waste heat recovery. As a result, the net condensation rate decreases and the condensed water tends to re-evaporate before being collected, thus reducing the final product quality even though energy conversion efficiency remains intact.



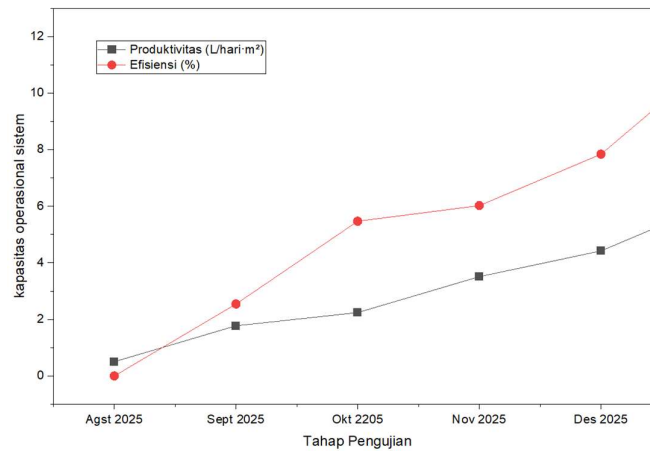
**Fig 5.** Comparison of Water Conductivity Before and After Desalination



**Fig 6.** Monthly Efficiency Trend of PV-TE Hybrid System

### 3.2 Freshwater productivity

Freshwater productivity, measured as water produced per square meter of desalination panel per day (L/day.m<sup>2</sup>), is a key indicator of the system's efficiency and operational capacity.



**Fig 7.** Freshwater Productivity Trends and Efficiency of Hybrid Desalination (PV-TE)

Freshwater productivity test results show an exponential and conclusive increase from 0.50 L/day·m<sup>2</sup> in the baseline prototype (August 2025) to 6.24 L/day·m<sup>2</sup> in the PV-TE hybrid pilot-scale unit (January 2026), representing an increase of 11.48% or 12.5-fold. This gradual and consistent productivity surge from 1.77 L/day·m<sup>2</sup> (September), 3.51 L/day·m<sup>2</sup> (November), to 4.42 L/day·m<sup>2</sup> (December), directly validates the effectiveness of the integration and optimization of the hybrid system, where the Photovoltaic (PV) modules guarantee a stable energy supply for operation, while the Thermoelectric (TEG) modules' dual function as waste heat recoverers and, most importantly, as active coolers in the condenser, drastically increases the temperature gradient and accelerates the condensation rate, thus transforming the productivity limitations that are the fundamental weaknesses of conventional passive solar desalination.

### 3.3 System performance analysis

The performance analysis of the PV-TE hybrid desalination system was carried out by evaluating the thermodynamic parameters and energy conversion based on the method of Isah et al.[12]. This system achieves a conversion efficiency of 29.05%, a figure that significantly exceeds the efficiency of conventional passive solar desalination systems which generally range between 7-15%. This high efficiency achievement is the result of optimal synergy between Photovoltaic (PV) and Thermoelectric (TEG) components, where the PV panel is responsible for the conversion of visible light spectrum into electricity to drive the pump and control system, while the TEG module performs a critical dual function: first, as an additional electricity generator through the utilization of waste heat recovery from the absorber and solar collector by utilizing the Seebeck Effect; and second, which is a major contributor to increasing system efficiency as an active cooler on the condenser surface through the application of the Peltier Effect. This active cooling creates a low temperature zone (10-15°C) on the condensation plane, thus drastically increasing the temperature gradient ( $\Delta T$ ) between the hot saturated steam (60-75°C) and the condenser surface. This increase in  $\Delta T$  is the primary driver of the acceleration of the latent heat transfer rate during condensation, which directly translates into increased water productivity and overall system thermal efficiency. Thus, the integration of PV-TE not only successfully increases overall solar energy recovery but also creates a positive feedback mechanism whereby normally wasted thermal energy is converted into a means to increase the efficiency of the desalination process itself.

## 4 CONCLUSION

This research successfully proves that the optimization of the Photovoltaic-Thermoelectric (PV-TE) hybrid desalination system significantly improves the performance of off-grid clean water production for coastal areas, with conductivity removal efficiency reaching 99.83%, water productivity increasing by 1148% to 6.24 L/day, m<sup>2</sup>, and system energy conversion efficiency of 29.05%. This success is driven by the dual function of the TEG module as a waste heat recoverer and active condenser cooler, which creates a high temperature gradient to accelerate the condensation cycle. For future development, it is recommended to focus on: optimization of system thermal management, such as the integration of phase-change materials, to maintain TEG performance at extreme temperatures; exploration of more advanced absorber and condenser materials; implementation of a machine learning-based intelligent control system in the IEMS; and economic feasibility studies and long-term trials in various coastal locations for commercialization validation.

## References

- [1] APE kowati and MFD Lusno, "Analysis of Achievements and Challenges of Access to Safe Drinking Water in Indonesia Towards SDGS 6.1. 1," *J. Penelit. Inov.*, vol. 5, no. 2, pp. 1707–1714, 2025.
- [2] BPS Indonesia, "Percentage of Households Having Access to Improved Drinking Water Sources by Province - Statistical Table." Accessed: Feb. 06, 2026. [Online]. Available: <https://www.bps.go.id/id/statistics-table/2/ODQ1IzI=/percentage-of-households-having-access-to-safe-drinking-water-sources-by-province.html>
- [3] RDLufira, U. Andawayanti, and NZ ST Fitriani, *Water Resources Crisis: Innovative Approaches and Sustainable Solutions*. CV. AE MEDIA GRAFIKA, 2025.
- [4] E. Jones, M. Qadir, MT Van Vliet, V.Smakhtin, and S. Kang, "The state of desalination and brine production: A global outlook," *Sci. Total Environ.*, vol. 657, pp. 1343–1356, 2019.
- [5] M. Goosen, H. Mahmoudi, Y. Alyousef, and N.Ghaffour, "Solar desalination: A review of recent developments in environmental, regulatory and economic issues," *Sol. Compass*, vol. 5, p. 100034, Mar. 2023, doi: 10.1016/j.solcom.2023.100034.
- [6] G. Hasaninet *al.*, "The microbial growth potential of antiscalants used in seawater desalination," *Water Res.*, vol. 233, p. 119802, Apr. 2023, doi: 10.1016/j.watres.2023.119802.
- [7] HG Hameed, HANDiabil, and MA Al-Moussawi, "A numerical investigation of the enhancement of single-slope single-basin solar still productivity," *Energy Rep.*, vol. 9, pp. 484–500, Dec. 2023, doi: 10.1016/j.egy.2022.11.199.
- [8] RL Sianturi and WS Nababan, "Hybrid Energy (Thermoelectric Generator-Archimedes Screw Turbine) Study and Experiment as a Green Energy Generator Based on the Internet of Things (IoT)," *J. Mech. Eng. Manuf. Mater. ENERGY*, vol. 8, no. 2, pp. 147–156, 2024.
- [9] AS Abdullah, WHAlawee, SA Mohammed, A. Majdi, ZM Omara, and FA Essa, "Increasing the productivity of modified cords pyramid solar still using electric heater and various wick materials," *Process Saf. Environ. Prot.*, vol. 169, pp. 169–176, Jan. 2023, doi: 10.1016/j.psep.2022.11.016.
- [10] A. Negi, GS Dhindsa, and SS Sehgal, "Experimental investigation on single basin tilted wick solar still integrated with flat plate collector," *SCPINM-2021*, vol. 48, pp. 1439–1446, Jan. 2022, doi: 10.1016/j.matpr.2021.09.210.
- [11] U. Habitat, "World cities report: Envisaging the future of cities," *UN Hum. Settl. UN-Habitat Nairobi Kenya Programme*, 2022.
- [12] AS Isah, HBTakaijudin, BS Mahinder Singh, UA Abubakar, SJ Mohammad, and T. Oladoyin abimbola, "Assessing the performance, sustainability, and economic viability of a photovoltaic-based solar desalination system for water scarce regions," *J. Clean. Prod.*, vol. 421, p. 138528, Oct. 2023, doi: 10.1016/j.jclepro.2023.138528.