

ANALYSIS OF THE EFFECT OF FLOATING SOLAR PANEL DISTANCE ON WATER AS A PASSIVE COOLING SYSTEM

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Abstract

Solar panels are devices that convert solar energy into electrical energy, with performance being highly sensitive to operational temperature. An increase in panel surface temperature can significantly reduce energy conversion efficiency. One promising method to mitigate this thermal degradation is the utilization of passive cooling through the water body in a floating solar panel (FPV) system. This study aims to empirically analyze the effect of varying the vertical distance between a floating solar panel and the water surface (10 cm, 20 cm, and 30 cm) on the system's output power and overall efficiency. Furthermore, it compares the performance of series and parallel circuit configurations under these conditions. The research was conducted through direct field testing using a 200Wp monocrystalline solar panel mounted on an adjustable floating platform. Key parameters, including solar intensity, panel temperature, ambient temperature, voltage, and current, were measured every 10 minutes from 09:00 to 15:00 WIB under clear weather conditions. The collected data were used to calculate input power (P_{in}), output power (P_{out}), and system efficiency (η). The results revealed that the 10 cm distance, despite yielding a lower average output power of 4.04 W, achieved the highest average efficiency of 2.68% in the parallel configuration. This indicates that the passive cooling effect is most pronounced at closer proximity, enhancing the energy conversion rate even if total solar irradiance is slightly reduced. In contrast, the 20 cm and 30 cm distances produced higher average power (4.65 W and 4.76 W, respectively) but with lower efficiencies (2.60% and 2.38%). The parallel configuration generally provided more stable performance, which is advantageous in the dynamic FPV environment.

Keywords: Floating Photovoltaic, Passive Cooling, Energy Efficiency, Panel Air Gap, Series-Parallel Configuration

INTRODUCTION

The escalating global energy demand, coupled with the pressing challenges of climate change and the finite nature of fossil fuels, has catalyzed a worldwide transition towards sustainable and renewable energy systems. Among the various renewable technologies, solar photovoltaic (PV) power generation stands out as a particularly promising solution due to the sun's abundant and widely distributed energy. For nations situated in the equatorial belt, such as Indonesia, the consistent and high solar irradiance throughout the year presents a significant opportunity to harness solar energy for both localized and grid-scale applications. However, the practical efficiency of PV technology is fundamentally constrained by environmental and operational factors, chief among them being the thermal degradation of the solar cells.

Globally, FPV technology has transitioned from a custom concept to a mainstream energy solution, with exponential growth in installed capacity in the last decade. Market reports show that countries with high population density and fierce land use competition, especially in Asia, are leading the adoption of FPV. This growth is driven by the recognition that FPV not only saves valuable land but also offers the potential for increased energy yields due to the effects of natural cooling. Therefore, research focused on FPV system design optimization, such as the one presented here, has significant international relevance, providing crucial empirical data for projects around the world (Rahajoeningroem and Jatnika 2022).

Beyond land conservation, FPV systems offer important additional ecological benefits. By shading the water surface, FPV installations significantly reduce evaporation rates, a critical advantage for reservoirs and lakes in areas prone to water scarcity. In addition, restricting the penetration of sunlight into the water column helps to suppress excessive algae growth (eutrophication), thereby improving water quality and the health of aquatic ecosystems. These dual benefits clean energy production and water resource conservation reinforce the argument for the adoption of FPV as a holistically sustainable technology (DURMUŞ ŞENYAPAR 2023).

The performance of a photovoltaic panel is inversely proportional to its operating temperature. The nominal power rating of a PV module is determined under Standard Test Conditions (STC), which specify an operating temperature of 25°C and an irradiance of 1000 W/m². In real-world operating conditions, solar panels often absorb a significant amount of thermal energy, causing their surface temperature to rise well above 25°C. This increase in temperature elevates the internal resistance of the semiconductor material, leading to a reduction in the open-circuit voltage and, consequently, a decrease in the overall power output and conversion efficiency.¹ This thermal performance degradation is a critical bottleneck that limits the energy yield of conventional solar installations and necessitates the development of effective thermal management strategies.

Fundamentally, the passive cooling mechanism in an FPV system is governed by the principles of natural convective heat transfer. The warmer lower surface of the solar panel heats the air layer above the cooler water surface, creating a density gradient that promotes air circulation. This heat transfer rate is determined by the convective heat transfer coefficient, which is a complex function of the geometry of the air gap, the temperature difference between the panel and the water, and the thermophysical properties of the air. In thermal engineering, this relationship is often characterized using dimensionless numbers such as Rayleigh (Ra) and Nusselt (Nu) numbers, which indicate that the relationship between gap distance and cooling effectiveness is not always linear (Çengel and Ghajar 2020).

In response to this challenge, as well as the increasing competition for land use, Floating Photovoltaic (FPV) technology has emerged as an innovative and dual-purpose solution. By installing PV arrays on bodies of water such as lakes, reservoirs, and ponds, FPV systems not only conserve valuable land resources but also benefit from the natural cooling effect of the underlying water body. The proximity to water facilitates continuous heat dissipation from the panels through conduction and convection,

thereby mitigating the extent of thermal degradation and potentially enhancing energy yield compared to their land-based counterparts.

The concept of utilizing water for solar panel cooling has been explored in various studies. Research has consistently demonstrated that active or passive water-based cooling can significantly improve panel performance. For instance, (putra and Rika Wahyuni Arsianti 2022) developed a system that uses water to wet the panel surface, finding that the most significant improvement was in the output current, leading to faster battery charging times. Similarly, (Rahajoeningroem and Jatnika 2022) designed an automated system to circulate water on the back surface of a panel, achieving a notable 2.47% increase in efficiency compared to an uncooled panel. Further investigations by (Jatmiko, Marausna, and Setiawan 2023) explored different water flow configurations, reinforcing the conclusion that elevated temperatures lead to significant drops in voltage, current, and overall power output. (Haldianto et al. 2023) These studies collectively affirm the principle that effective thermal management is crucial for optimizing PV system performance.

The working principle of a solar panel is rooted in the photovoltaic effect, where photons from sunlight strike a semiconductor material (typically silicon), exciting electrons and generating an electrical current. The power generated is a function of both the incident solar irradiance (I_{rad}) and the panel's conversion efficiency (η). The input power (P_{in}) available to the panel is determined by the irradiance and the panel's surface area (A), as described by the equation:

$$P_{in} = I_{rad} \times A$$

The electrical output power (P_{out}) is the product of the panel's output voltage (V_{pv}) and current (I_{pv}):

$$P_{out} = V_{pv} \times I_{pv}$$

Consequently, the system's conversion efficiency is the ratio of the electrical power produced to the solar power received:

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

While the benefits of the general cooling effect in FPV systems are acknowledged, a critical gap remains in the understanding of how the physical configuration of the system specifically, the vertical distance between the solar panel and the water surface influences the efficacy of this passive cooling mechanism. The proximity to water governs the intensity of heat transfer processes, but it may also introduce other complex optical and thermal phenomena, such as reflected radiation. Furthermore, the electrical configuration of the panels (series versus parallel) can interact with these environmental factors to affect overall system performance, as series circuits are more sensitive to performance mismatches between cells, while parallel circuits offer greater resilience (Jatmiko et al. 2023).

The selection of electrical circuit configurations series or parallel is a critical design parameter that can interact with unique FPV operating conditions. The series series is particularly susceptible to performance losses due to mismatches between cells, a condition that can be exacerbated by factors such as partial shadowing caused by wave ripples, uneven dirt build-up, or temperature gradients throughout the module. In contrast, parallel circuits offer greater fault tolerance and higher performance stability under such non-uniform conditions. Therefore, the investigation of these two

configurations is important to determine the most resilient and efficient electrical setting for dynamic FPV environments (Nanda, Gumelar, and Mulyadi 2024).

This study aims to address this knowledge gap through a systematic experimental investigation. The primary objectives are:

1. To quantitatively analyze the influence of varying panel-to-water distances (10 cm, 20 cm, and 30 cm) on the thermal profile, power output, and energy efficiency of a floating monocrystalline solar panel.
2. To compare the performance and efficiency of the FPV system under both series and parallel circuit configurations to determine the optimal electrical setup for such applications.

By providing empirical data on these relationships, this research seeks to offer valuable insights for the design and optimization of FPV systems, contributing to the advancement of more efficient and reliable solar energy technology.

RESEARCH METHOD

This study was conducted using an experimental and comparative research design to systematically investigate the influence of a floating solar panel's proximity to the water surface on its thermal and electrical performance. The experiment was structured to isolate the panel-to-water distance as the primary independent variable while measuring key performance indicators under real-world, dynamic solar conditions.¹

Experimental Setup and Materials

The core of the experimental apparatus consisted of a 200Wp monocrystalline solar panel with a total surface area of 0.2925 m². This panel was mounted on a custom-built floating platform constructed from PVC pipes and iron framing, which provided buoyancy and structural stability on the water surface. A key feature of the mount was its adjustable height mechanism, which allowed the vertical distance between the bottom surface of the panel and the water to be precisely set at the three experimental variations: 10 cm, 20 cm, and 30 cm.

For comparative analysis, a control experiment was established by placing an identical solar panel on land, adjacent to the water body. This setup represented a baseline scenario with no passive water-cooling effect and was tested under a series circuit configuration.¹

The instrumentation used for data acquisition was selected to ensure accurate and reliable measurements of the relevant physical parameters :

- A digital multimeter was used to measure the DC voltage (V) and current (A) generated by the solar panel.
- An infrared thermometer was employed to measure the panel's surface temperature (°C) non-intrusively.
- A lux meter was used to quantify the incident solar irradiance, with readings later converted to W/m².

- A measuring tape was used to verify the panel-to-water distances before each experimental run.

The complete system also included auxiliary components typical of an off-grid solar installation, such as a solar charge controller (SCC) to regulate battery charging, a battery for energy storage, and an inverter to convert DC to AC, although the primary measurements were taken directly from the panel's DC output to assess its raw performance.

Procedure and Data Collection

The field experiments were conducted at Danau Bantal, a lake located in Tangerang, Indonesia. The site was chosen for its open exposure to sunlight, free from significant shading from buildings or trees, ensuring that the panel received maximum direct solar radiation during the testing period.

The data collection protocol was executed under the following conditions :

- **Time Frame:** Experiments were run on clear, sunny days to minimize the impact of cloud-induced variability. Data was recorded between 09:00 and 15:00 WIB, capturing the period of highest solar irradiance.
- **Measurement Interval:** To obtain a high-resolution temporal profile of the panel's performance, all parameters (solar irradiance, panel temperature, voltage, and current) were measured and recorded at 10-minute intervals.
- **Experimental Runs:** A complete set of measurements was taken for each of the three distance variations (10 cm, 20 cm, and 30 cm). This entire process was conducted for both parallel and series electrical configurations to allow for a comprehensive comparison. The land-based control experiment was conducted for the series configuration.

Data Analysis

Following the data collection phase, the raw measurements were processed to derive key performance metrics. The analytical methods were based on fundamental photovoltaic principles :

1. Input Power (P_{in}): The solar power incident on the panel's surface was calculated by multiplying the measured solar irradiance (I_{rad} in W/m^2) by the known surface area of the panel ($A = 0.2925 m^2$).

$$P_{in} = I_{rad} \times A$$

2. Output Power (P_{out}): The electrical power generated by the panel was calculated as the product of the measured DC voltage (V_{pv}) and current (I_{pv}).

$$P_{out} = V_{pv} \times I_{pv}$$

3. Conversion Efficiency (η): The efficiency of the panel in converting solar energy into electrical energy was calculated as the ratio of the output power to the input power, expressed as a percentage.

$$\eta = \frac{P_{out}}{P_{in}} \times 100 \%$$

These calculated values were then tabulated and plotted against time to analyze the dynamic performance of the FPV system under each experimental condition. The

results were compared across the different distances and circuit configurations to draw conclusions regarding the optimal setup for maximizing performance through passive cooling.

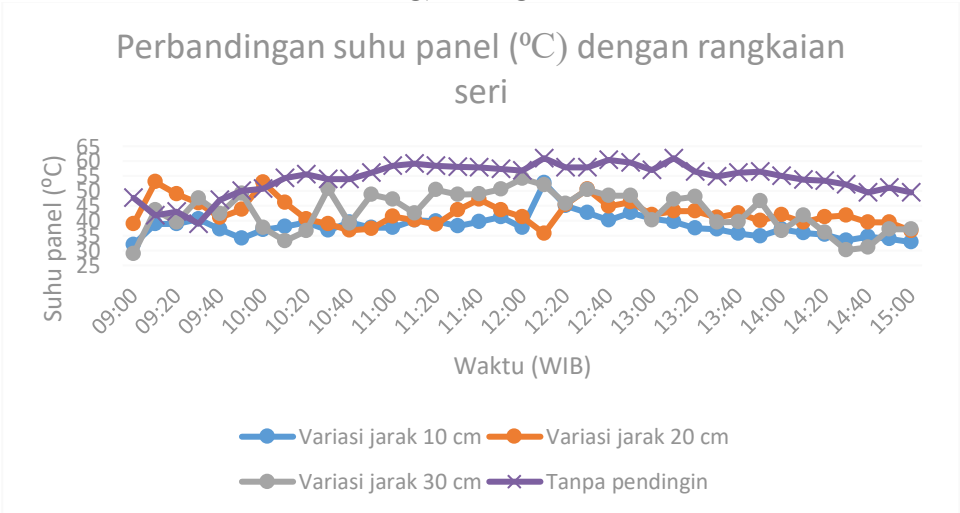
RESULT AND DISCUSSION

The analysis of the experimental data provides a detailed understanding of the complex interplay between panel-to-water distance, thermal regulation, and electrical performance in a floating solar panel system. The discussion is structured to first examine the fundamental efficacy of passive water cooling, followed by a detailed performance analysis of the parallel and series configurations, and concluding with a critical evaluation of the study's experimental limitations.

The Efficacy and Complexity of Passive Water Cooling

The primary hypothesis of this study was that the proximity of a solar panel to a body of water would provide a significant passive cooling effect, thereby improving its performance. This was unequivocally confirmed by comparing the thermal profiles of the floating panels against the land-based control panel in the series configuration tests. As illustrated in Figure 1, the uncooled land-based panel consistently reached surface temperatures between 55°C and 62°C during the peak irradiance hours of 11:00 to 13:00. In stark contrast, all floating configurations maintained significantly lower temperatures, demonstrating the potent heat-sinking capability of the underlying water body.

Figure 1. Comparison of Panel Surface Temperature for Floating vs. Land-Based (No Cooling) Configurations



However, a more detailed examination of the data reveals that the relationship between panel-to-water distance and temperature is not linear, presenting a more complex thermal dynamic than initially anticipated. It was hypothesized that heat transfer via conduction and convection would be most effective at the shortest distance, making the 10 cm setup the coolest. The experimental results contradicted this expectation. As shown in Figure 2, the 20 cm distance configuration consistently

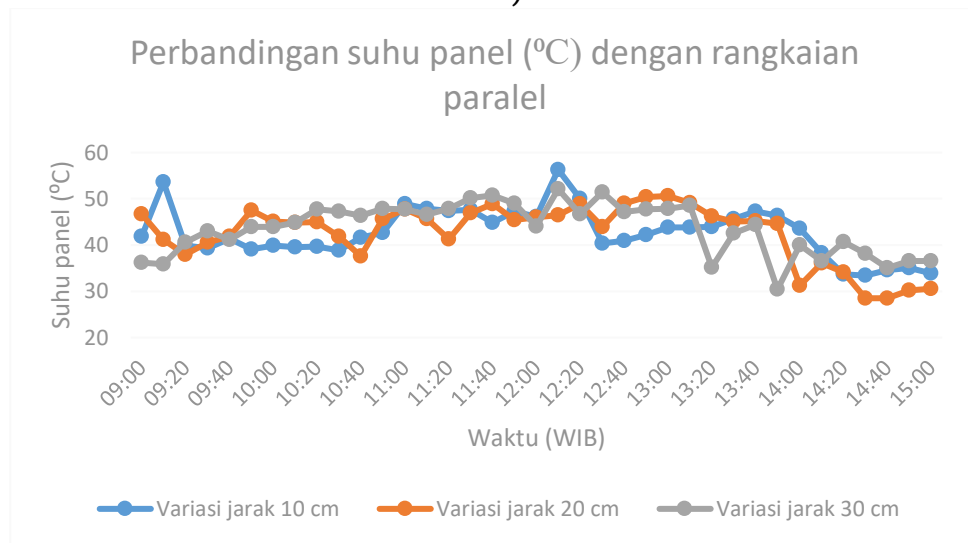
yielded the lowest and most stable panel temperatures throughout the day. Surprisingly, the 10 cm setup resulted in the highest average temperatures among the floating configurations, frequently exceeding the temperatures recorded for the 30 cm setup.

The result of a parallel configuration, where a distance of 30 cm results in the highest average power ($P_{out} = 4.76 \text{ W}$) while a distance of 10 cm results in the highest average efficiency ($\eta = 2.68\%$), is not a contradiction, but rather an illustration of a classical engineering exchange. The higher power output at a distance of 30 cm is most likely due to the higher reception of net irradiance. In contrast, the superior efficiency at a distance of 10 cm suggests that the combination of the cooling effect and the possible optical gain of the reflected photons increases the energy conversion rate. The optimal design choice, therefore, depends on the main objectives of the project: whether to maximize the absolute energy yield (kWh) or to maximize the long-term utilization of resources and the health of the panels, which are often the focus in techno-economic analyses (Abdullah et al. 2024).

This counter-intuitive finding suggests the presence of a competing thermal mechanism. While closer proximity enhances convective cooling from the water's surface, it may also subject the panel to a greater intensity of reflected thermal (infrared) radiation from the water. At a very short distance of 10 cm, it is plausible that this reflected heat gain partially negates or even overwhelms the benefits of improved convective heat loss, leading to a net increase in the panel's equilibrium temperature. The 20 cm distance appears to represent an optimal balance point, or "sweet spot," where the panel is close enough to benefit from substantial passive cooling but far enough to mitigate the adverse effects of reflected thermal radiation. This non-linear thermal response is a critical finding for the design and optimization of FPV installations.

The empirical findings of the study, which identified a distance of 20 cm as the 'optimal point' for cooling, are in line with the results of a numerical modelling study. Computational fluid dynamics (CFD) simulations have confirmed the existence of optimal air gaps that maximize convective heat dissipation. However, these models also show that the exact value of these optimal gaps is highly dependent on the surrounding environmental conditions, such as wind speed and relative humidity. Therefore, the experimental findings of 20 cm in this study serve as valuable validation data points, which can be used to refine and calibrate such numerical models under specific field conditions (Kaban, Jafri, and Gusnawati 2020).

Figure 2. Panel Surface Temperature at Different Floating Distances (10 cm, 20 cm, 30 cm)



Performance Analysis: Parallel Configuration

In the parallel circuit configuration, the system's performance was evaluated across the three distance variations. The average performance metrics, calculated from the data collected over the six-hour testing period, are summarized in Table 1.

Table 1. Average Performance Metrics under Parallel Configuration

Distance to Water	Average Pout (W)	Average Efficiency (%)	Average Panel Temp (°C)
10 cm	4.04	2.68	42.7
20 cm	4.65	2.60	42.3
30 cm	4.76	2.38	43.5

The data in Table 1 presents a nuanced picture of system performance. The original thesis concluded that the 10 cm distance was optimal because it produced the highest average efficiency (2.68%). While this is factually correct, a broader analysis suggests that labeling it as "optimal" is an oversimplification. The 10 cm setup also produced the lowest average power output (4.04 W) and, as previously discussed, did not achieve the lowest average temperature.

Conversely, the 30 cm configuration generated the highest average power output (4.76 W), likely due to receiving higher net irradiance with less interference from water surface effects. However, this came at the cost of the lowest average efficiency (2.38%) and a higher average temperature. The 20 cm setup, which proved to be the most thermally stable with the lowest average temperature, produced a high power output (4.65 W) and a strong efficiency of 2.60%.

This highlights a critical trade-off for system designers: is the primary goal maximum raw power output or maximum conversion efficiency and thermal stability (which correlates with long-term panel health)? The marginal efficiency advantage of the 10 cm setup, despite its higher temperature, may be attributable to an optical effect. The proximity to the water could increase the number of reflected photons reaching the panel surface, boosting current generation (I_{pv}) enough to slightly increase the efficiency calculation, even as the higher temperature reduces voltage (V_{pv}). Therefore, the choice of an "optimal" distance depends on the specific performance priority. For overall system health and reliable performance, the 20 cm distance presents the most compelling case.

Figure 3. Comparison of Power Output for Different Floating Distances in Parallel Configuration

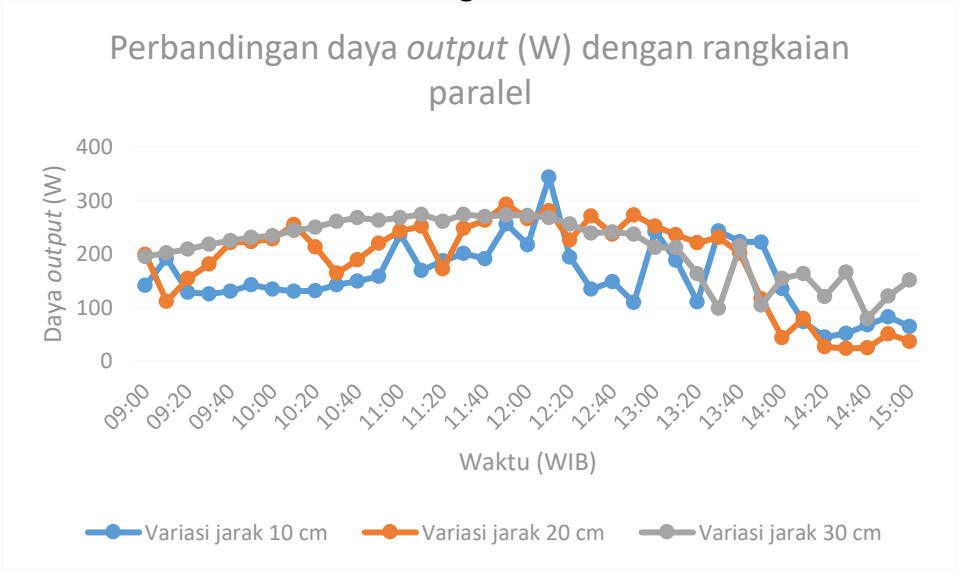
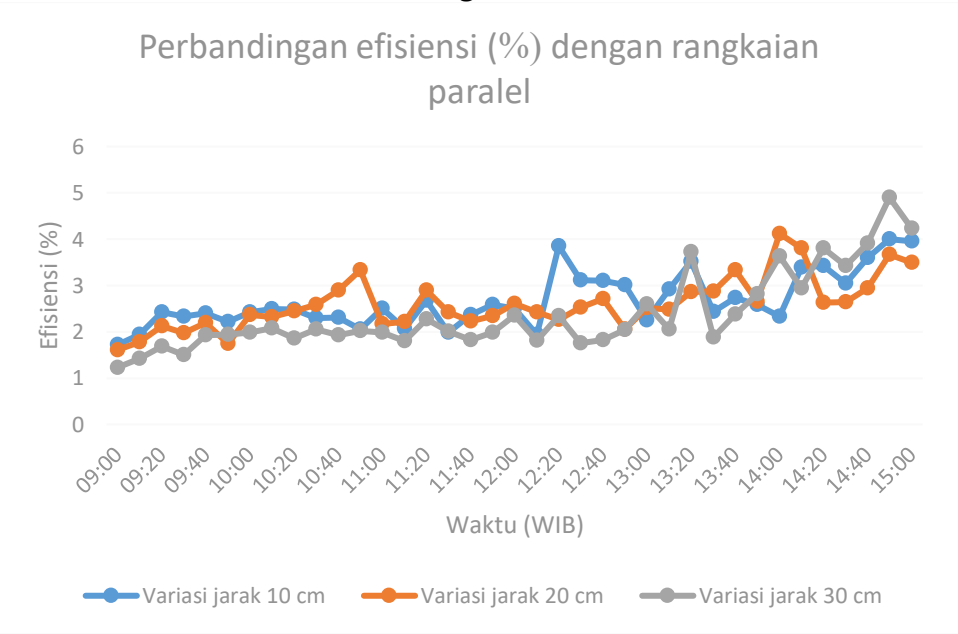


Figure 4. Comparison of System Efficiency for Different Floating Distances in Parallel Configuration



Performance Analysis: Series Configuration and Control Comparison

The series configuration tests included the crucial land-based control, allowing for a direct assessment of the cooling effect on performance. An initial review of the data presents an apparent contradiction: the uncooled land-based panel generated the highest absolute power output throughout the testing day. This result seems to defy the physical principle that cooler panels should perform better.

However, this discrepancy is explained by a significant limitation in the experimental methodology: the tests for each configuration were conducted on different days, leading to large variations in the primary energy input solar irradiance. The data clearly shows that the solar irradiance was substantially and consistently higher on the day the land-based panel was tested compared to the days the floating systems were evaluated.¹ This disparity in input power (P_{in}) was the dominant factor driving the higher output power (P_{out}).

To address the confounding variables of solar irradiation that differ between test days, standard practice in PV field research uses the performance normalization method. Methodologies such as *Performance Ratio* (PR) calculations, which compare actual energy yields with theoretical yields under the same conditions, or the use of temperature-corrected efficiency metrics, are commonly used to filter out the effects of varying irradiance and temperature. The application of these techniques will allow for a more direct comparison of the variables being studied in this case, air gaps by isolating their effects from daily weather fluctuations. Failure to normalize the data is a significant limitation that must be overcome in future research (Rinaldi and Mulyono 2021).

To properly isolate the effect of cooling, it is essential to analyze the conversion efficiency (η), which normalizes the output power against the available input power. When efficiency is considered, the true benefit of passive cooling becomes evident. Figure 5 shows that while the land-based panel's efficiency was volatile and plummeted during the hours of peak temperature, the cooled panels particularly the 10 cm and 20 cm configurations maintained significantly more stable and, on average, higher efficiencies.

Figure 5. Comparison of System Efficiency for Floating vs. Land-Based Configurations in Series Circuit

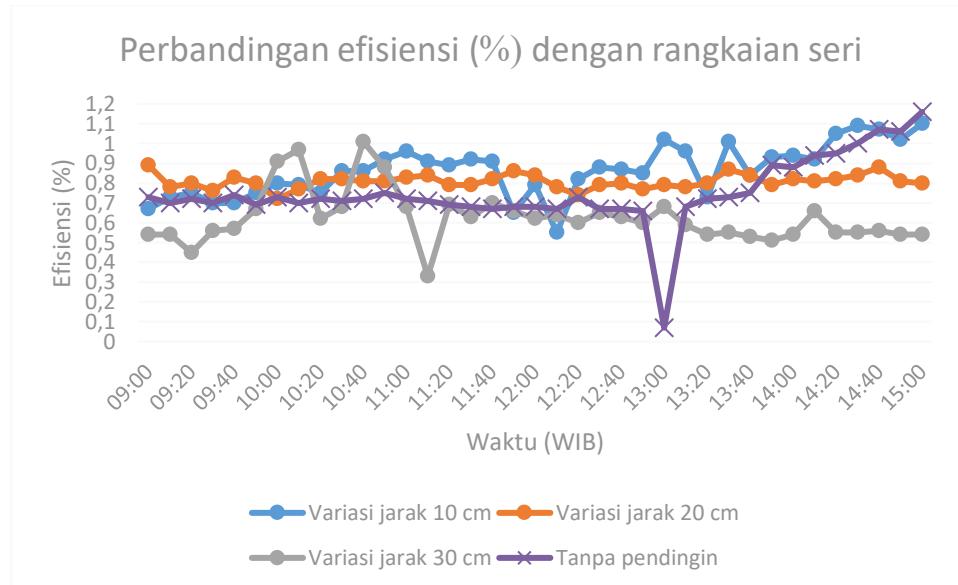


Table 2 summarizes the average performance metrics for the series configuration. The 10 cm setup achieved the highest average efficiency among all tested configurations, demonstrating that even with lower irradiance, its ability to convert that energy to electricity was superior. This confirms that passive cooling enhances and stabilizes the *conversion efficiency* of the panel. The experimental outcome highlights that while the efficiency gain was substantial, it was not sufficient in this specific instance to overcome the large difference in daily solar irradiance, resulting in a lower absolute power output for the floating systems.

Table 2. Average Performance Metrics under Series Configuration, Including Control

Configuration	Average Pout (W)	Average Efficiency (%)	Average Panel Temp (°C)
10 cm (Floating)	0.93	0.86	38.4
20 cm (Floating)	1.22	0.81	42.1
30 cm (Floating)	1.21	0.63	42.8
No Cooling (Land)	1.76	0.77	54.3

Discussion on Experimental Limitations

A rigorous scientific analysis requires acknowledging the limitations of the study. Two significant issues are apparent from the data. First, there is a large and unexplained discrepancy in the magnitude of the measured performance between the parallel and series tests. The parallel configurations yielded output powers up to 7.5 W and

efficiencies approaching 4.9%, whereas the series tests produced a maximum power of only 2.0 W and efficiencies barely exceeding 1.1%.¹ Second, the absolute power outputs recorded in both configurations are extremely low for a panel with a nominal rating of 200Wp, suggesting that the panel was not operating near its maximum power point.

These systematic discrepancies may stem from several factors, including the use of different electrical loads for each set of tests, potential inaccuracies in the measurement of low current values, or issues with the panel's wiring and connections that may have introduced high series resistance. Consequently, while the *relative trends* observed within each experimental set (e.g., the effect of distance on temperature, the stability of efficiency with cooling) provide valid and valuable insights, the absolute performance values should be interpreted with caution. A direct quantitative comparison of the performance between the series and parallel configurations is not advisable based on this dataset. This honest appraisal underscores the need for further, more controlled research in this area.

(Damanik and Silaban 2023) *solar charge controller* (SCC) dan kondisi pengisian baterai tidak sesuai dengan tegangan operasi optimal panel, yang mengakibatkan ketidaksesuaian impedansi yang parah. Penggunaan SCC tipe *Pulse Width Modulation* (PWM) sederhana, yang tidak secara aktif mencari MPP, adalah penyebab yang paling mungkin. Keterbatasan ini, meskipun signifikan, menggarisbawahi pentingnya instrumentasi yang tepat dan penggunaan kontroler MPPT dalam studi lapangan untuk memastikan bahwa kinerja panel yang diukur secara akurat mencerminkan potensinya di bawah kondisi yang diuji.(Damanik and Silaban 2023)

CONCLUSION

This experimental study investigated the impact of panel-to-water distance on the performance of a floating photovoltaic system, providing valuable insights into the efficacy and complexities of passive water cooling. The findings lead to several key conclusions:

Floating solar panel configurations provide a highly effective passive cooling mechanism. The proximity to water significantly reduces panel operating temperatures, with observed reductions of up to 15-20°C compared to an identical land-based installation under similar peak irradiance conditions. This confirms the fundamental thermal benefit of FPV technology.

The relationship between cooling effectiveness and panel-to-water distance is non-linear. A distance of 20 cm was found to provide the most effective and stable cooling. The 10 cm distance, contrary to initial expectations, resulted in higher average panel temperatures, a phenomenon likely attributable to the competing effects of enhanced convection and increased reflected thermal radiation from the water surface.

Passive cooling leads to more stable and generally higher energy conversion efficiencies. This effect was most pronounced during periods of high solar irradiance when thermal degradation is most severe. In the parallel configuration, the 10 cm distance yielded the highest average efficiency of 2.68%, potentially due to a combination of cooling and optical gains from reflected light.

The absolute power output of a PV panel remains predominantly dictated by the incident solar irradiance. In this study, variations in weather conditions between different test days were a significant confounding variable, which in some cases masked the absolute power gains expected from improved efficiency due to cooling.

Based on these findings and the identified experimental limitations, several recommendations for future research are proposed. Future studies should employ a methodology that eliminates solar irradiance as a variable, either by testing all configurations simultaneously or by using a controlled environment such as a solar simulator. Further investigation, potentially including computational fluid dynamics (CFD) modeling, is warranted to better understand and quantify the non-linear thermal effects observed at close panel-to-water proximities. Finally, to validate the commercial potential of these findings, the study should be replicated on a larger scale with multiple FPV modules, incorporating a thorough techno-economic analysis to assess the practical benefits of optimizing panel height in real-world applications.

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