

**Performance evaluation of a solar-powered thermoelectric cool box with GSM-IoT monitoring for coastal fisheries**

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**Abstract**

This study develops and evaluates an autonomous solar-powered cool box to improve the storage quality of fishermen catch in the Sungsang Estuary, where limited access to ice and electricity accelerates fish deterioration. The system integrates a monocrystalline photovoltaic panel, VRLA battery, MPPT charge controller, thermoelectric cooling module, automatic solar tracking, and GSM-IoT monitoring for remote operation. Solar tracking uses LDR sensors and a wiper motor to continuously adjust panel orientation for improved solar energy capture. A 14-day field test in a maritime environment showed a maximum power output of 199.9 W and an average daily energy yield of 1,285.6 Wh. The generated energy sustained the cooling load while maintaining system voltage between 22.35 and 23.55 V under varying irradiance. Panel tilt adjustment from -30° to +32° improved solar radiation absorption throughout the day. The cool box maintained an average internal temperature of 6-8°C, with occasional short-term increases to 14-15°C caused by external ambient conditions. The results demonstrate that integrating photovoltaic power, automatic tracking, and GSM-IoT monitoring provides a practical renewable-energy solution for cold storage, digitalization, and sustainability in small-scale fisheries.

**Keywords:**

Solar energy, cool box, thermoelectric cooling, GSM-IoT, solar tracking

**1 Introduction**

Coastal communities in South Sumatra, Indonesia, depend primarily on fish and shrimp catches for their livelihoods. Fishing activities in riverine and coastal areas commonly face challenges related to temporary catch storage. After harvesting, catches are typically stored in ice-filled boxes along riverbanks prior to sorting and distribution. However, conventional ice-based storage systems are limited in their ability to maintain stable temperatures over extended periods, leading to quality degradation and economic losses for fishermen [1].

These challenges are compounded by limited access to electrical infrastructure in riverside areas, restricting the implementation of conventional refrigeration systems. Consequently, there is a growing need for alternative cold storage solutions that are independent of the national electricity grid and environmentally sustainable. Renewable energy, particularly solar photovoltaic (PV) systems, represents a viable option due to high solar irradiation in tropical regions such as Muara Sungsang. Previous studies have shown that solar-powered cold storage systems can significantly improve post-harvest handling while reducing energy dependency in small-scale fisheries [2].

Solar-powered cool boxes utilizing thermoelectric (Peltier) cooling modules offer several advantages, including compact design, ease of installation, and the absence of harmful refrigerants, making

them suitable for remote and small-scale fisheries applications. Thermoelectric cooling systems have been reported to be effective for portable and low-capacity cold storage applications where simplicity and environmental safety are essential [3].

Recent advancements in Internet of Things (IoT) technology have enabled more efficient monitoring and control of cold storage systems. The integration of GSM-based IoT platforms allows real-time temperature monitoring and remote system management via cellular networks, improving storage reliability and reducing spoilage risks. IoT-based temperature monitoring has been demonstrated to enhance cold chain efficiency and reduce post-harvest losses in fisheries and agricultural products [4].

Despite these technological developments, the application of integrated solar-powered thermoelectric cooling systems combined with GSM-based IoT monitoring remains limited in traditional fisheries, particularly in riverine environments. Existing studies often rely on static PV systems that suffer from low energy-harvesting efficiency under fluctuating maritime conditions [2]. Furthermore, while standalone IoT monitoring is common, its synergistic integration with an autonomous solar-tracking mechanism specifically for small-scale, off-grid coastal fisheries is rarely explored in recent literature [4]. This study fills this research gap by introducing a novel, integrated autonomous system that maximizes solar yield up to 199.9 W while providing real-time GSM-based monitoring tailored for the harsh estuarine conditions of Muara Sungsang.

In addition to storage limitations, fishermen in Muara Sungsang experience reduced operational efficiency due to frequent unloading requirements, which shorten effective fishing time and decrease potential yields [5]. An autonomous solar-powered cool box with remote monitoring capability can enhance operational flexibility, reduce unnecessary travel, and improve productivity.

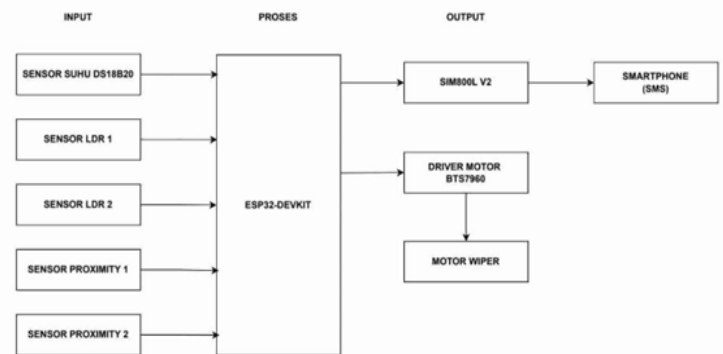
Therefore, this study aims to design, implement, and quantitatively evaluate a solar-powered cool box system integrated with thermoelectric cooling and GSM-based IoT monitoring tailored to the local conditions of fishermen in Muara Sungsang. The proposed system is expected to enhance catch quality, improve fishermen’s incomes, and support the adoption of renewable energy and digital technologies in small-scale fisheries. Furthermore, the system has the potential to serve as a replicable model for similar coastal and riverine communities in Indonesia and other developing regions.

**2 Research methods**

This section describes the overall research design, system architecture, data acquisition procedures, and analytical approaches used to evaluate the performance of the solar-powered cool box integrated with a GSM-based IoT monitoring system.

**2.1 Study area and experimental design**

The field experiment was conducted along the Muara Sungsang riverbank, South Sumatra, Indonesia, which represents an operational environment for small-scale fishermen.



**Fig. 1.** Block diagram

The system was deployed directly on site to ensure the relevance of results under real field conditions. Previous research has emphasized the importance of field-based evaluation to validate renewable

energy systems under actual environmental variability [6]. Data collection spanned 14 non-consecutive days during January-April 2026 to capture seasonal and weather-induced variations.

## 2.2 System architecture and instrumentation

The developed system comprises a 200 Wp photovoltaic (PV) panel, a battery storage unit, a solar charge controller, a thermoelectric Peltier cooling module, and a 20 kg capacity cool box. The system architecture is centered on an ESP32-DevKit microcontroller as the primary processing unit, which coordinates dual-axis solar tracking and GSM-based communication. Temperature sensing is conducted using a DS18B20 digital temperature sensor integrated with the ESP32, offering higher precision and better noise immunity in maritime environments compared to analog alternatives. The control logic is implemented through a bidirectional GSM-SMS interface using the SIM800L V2 module; it functions as an input by parsing incoming SMS commands from the user to trigger specific system actions, and as an output by transmitting automated status reports and real-time temperature data back to the user via SMS. This communication setup follows best practices in IoT-based environmental monitoring systems [7], ensuring reliable remote control in off-grid estuarine areas.

## 2.3 Data acquisition procedures

Data acquisition focused on both electrical and thermal performance parameters. Measurements included:

- PV panel electrical output: voltage (V), current (A), and power (W),
- Solar irradiance and panel tilt angle,
- Internal cool box temperature (°C).

Instrumentation and sensors were calibrated prior to placement on the testing platform. The DS18B20 digital temperature sensors were cross-referenced with a high-precision mercury thermometer, showing a variance of less than  $\pm 0.5^{\circ}\text{C}$ . At the same time, LDR sensitivity thresholds were normalized to ensure tracking stability under varying solar glare. The platform consisted of a 10 m x 2 m fishing vessel. Continuous data were logged over 48-hour periods from 06:00 to 05:00 local time across testing sessions for January 21-23, February 15-17, March 30-31, and April 12-14, 2026. To mitigate the risk of intermittent cellular connectivity in the Sungsang Estuary, the ESP32 control logic included a local data buffering routine, allowing for temporary data storage during signal outages to ensure no loss of performance data. Solar irradiance and environmental conditions were recorded in accordance with standard field-testing procedures for renewable energy systems [8]. This approach ensured that data reflected genuine operational conditions faced by fishermen.

## 2.4 Data analysis and performance metrics

The dataset was analyzed using descriptive statistics and time-series analysis to evaluate the system's operational efficiency. The electrical power output ( $P$ ) from the PV panel was determined using the fundamental power equation:

$$P = V \times I \quad (1)$$

where  $V$  represents the measured voltage in Volts, and  $I$  represents the current in Amperes. The total daily energy yield ( $E_{daily}$ ) in Watt-hours (Wh) was computed by integrating the power output over the 24-hour measurement period:

$$E_{daily} = \sum (P_t \times \Delta T) \quad (2)$$

To ensure data credibility and reproducibility, measurement uncertainty was addressed through rigorous sensor calibration. The DS18B20 digital temperature sensors were cross-referenced with a

high-precision mercury thermometer, showing a variance of less than  $\pm 0.5^{\circ}\text{C}$ . Electrical measurement accuracy was maintained within  $\pm 2\%$  error bound through the MPPT charge controller's internal calibration. Cooling effectiveness was assessed based on the ability to maintain internal temperatures within the target range consistently during the testing periods.

## 3 Result and discussion

### 3.1 Data collection results

The experimental results were obtained from field performance testing of the solar-powered cool box system installed on a fishing boat. Measurements included solar panel voltage, current, power output, solar irradiance, panel tilt angle, and the internal temperature of the cool box. The system utilized a 200 Wp photovoltaic solar panel and a 20 kg capacity cool box mounted on a 10 m x 2 m fishing boat to represent actual operating conditions. Data were collected continuously over multiple 48-hour testing periods, totaling 14 days conducted on January 21-23, February 15-17, March 30-31, and April 12-14, 2026. The results show that variations in solar irradiance affected the electrical output of the solar panel; however, the maintained stable performance through effective energy management. Throughout the testing period, the cool box successfully maintained its internal temperature within the targeted operating range, demonstrating reliable cooling performance under real riverine and coastal conditions.

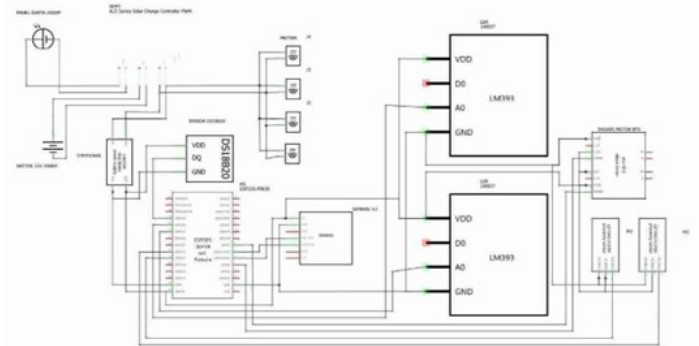


Fig. 2. Device circuit diagram



Fig. 3. Data collection point

Fig. 3 illustrates the data-collection point for the solar-powered cool box system. The figure shows the integrated control panel consisting of a solar charge controller, electrical wiring, protection components, and the microcontroller-based monitoring unit. The solar charge controller regulates the electrical power generated by the photovoltaic panel before it is stored in the battery and distributed to the cooling system. Measurement points for voltage and current are provided to monitor system performance, while the control circuitry supports stable operation of the thermoelectric cooling module. This configuration enables real-time acquisition of

electrical and operational data, serving as the central hub for monitoring and controlling the solar-powered cool box system during field testing.

data were used to analyze the system response to changes in light intensity.

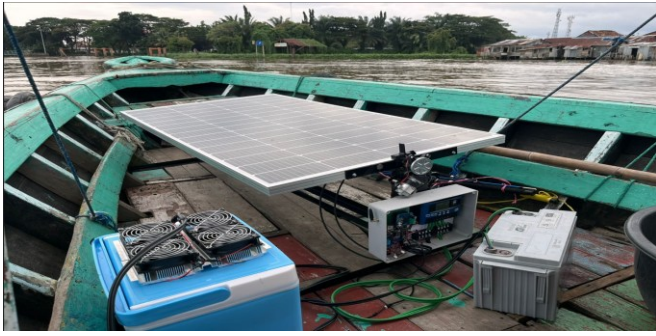


Fig. 4. Solar panel

Fig. 4 shows the installation of a solar panel on a boat used as a power source during field testing. The solar panel is mounted horizontally at the center of the boat to obtain optimal sunlight exposure and maintain system stability. The generated electrical energy is used to supply the measurement system and the cooler box load. The test was conducted in open-water conditions with varying solar intensity due to weather and measurement time.



Fig. 5. Light intensity measurement process (Lux)

Fig. 5 presents the light intensity measurement process using a digital lux meter. The sensor was directed toward the light source, and the measured illumination values in lux were recorded. These

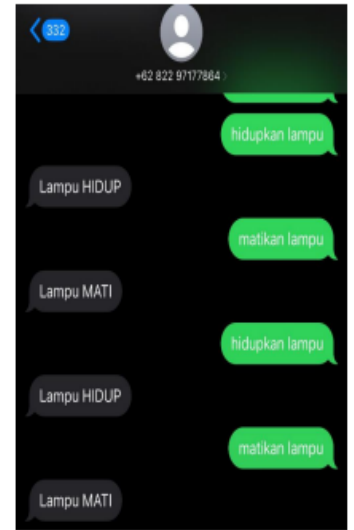
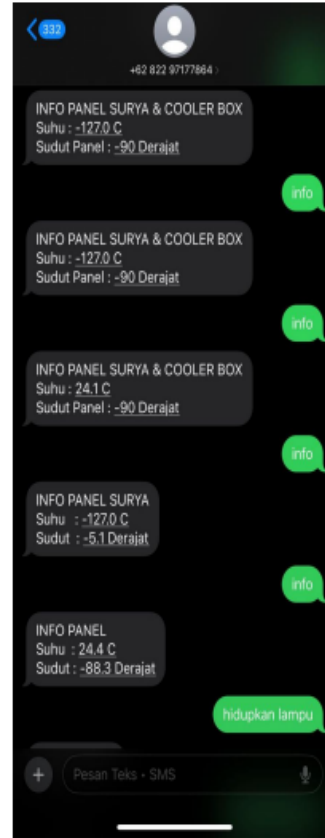


Fig. 6. Measurement process and lamp activation results

Fig. 6 illustrates the measurement process and lamp activation results through the IoT-based control system. Sensor data from the solar panel and cooler box are transmitted to the smartphone application, allowing users to monitor system conditions and remotely control the lamp. The system response indicates successful lamp activation and deactivation in response to user commands and measurement data.

Table 1. Solar panel experimental data day 1

| Day             | Hour | Time (WIB) | Light Intensity ( $w/m^2$ ) | Solar Panel Voltage (V) | Solar Panel Current (A) | Solar Panel Power (W) | Solar Panel Tilt Angle ( $^{\circ}$ ) | Cooler Box Temperature ( $^{\circ}C$ ) |
|-----------------|------|------------|-----------------------------|-------------------------|-------------------------|-----------------------|---------------------------------------|--|
| 1<br>21/01/2026 | 1    | 06.00      | 12,50                       | 14,0                    | 0,5                     | 7,0                   | -30                                   | 12                                     |
|                 | 2    | 07.00      | 70,83                       | 18,2                    | 1,1                     | 20,0                  | -25                                   | 13                                     |
|                 | 3    | 08.00      | 133,33                      | 20,5                    | 2,5                     | 51,2                  | -20                                   | 15                                     |
|                 | 4    | 09.00      | 208,33                      | 21,5                    | 3,8                     | 81,7                  | -15                                   | 14                                     |
|                 | 5    | 10.00      | 291,67                      | 22,1                    | 5,2                     | 114,9                 | -10                                   | 10                                     |
|                 | 6    | 11.00      | 350,00                      | 22,8                    | 6,8                     | 155,0                 | -5                                    | 8                                      |
|                 | 7    | 12.00      | 400,00                      | 23,2                    | 7,9                     | 183,2                 | 0                                     | 7                                      |
|                 | 8    | 13.00      | 408,33                      | 23,3                    | 8,1                     | 188,7                 | 0                                     | 7                                      |
|                 | 9    | 14.00      | 406,33                      | 23,4                    | 8,0                     | 187,2                 | 0                                     | 7                                      |
|                 | 10   | 15.00      | 371,50                      | 22,9                    | 7,1                     | 162,5                 | 15                                    | 7                                      |
|                 | 11   | 16.00      | 227,83                      | 22,1                    | 4,4                     | 97,2                  | 21                                    | 8                                      |
|                 | 12   | 17.00      | 70,42                       | 20,9                    | 1,4                     | 29,2                  | 21                                    | 8                                      |
|                 | 13   | 18.00      | 4,25                        | 13,8                    | 0,7                     | 9,6                   | 32                                    | 7                                      |
|                 | 14   | 19.00      | 0                           | 0                       | 0                       | 0                     | 0                                     | 7                                      |
|                 | 15   | 20.00      | 0                           | 0                       | 0                       | 0                     | 0                                     | 7                                      |
|                 | 16   | 21.00      | 0                           | 0                       | 0                       | 0                     | 0                                     | 7                                      |
|                 | 17   | 22.00      | 0                           | 0                       | 0                       | 0                     | 0                                     | 7                                      |
|                 | 18   | 23.00      | 0                           | 0                       | 0                       | 0                     | 0                                     | 7                                      |
|                 | 19   | 00.00      | 0                           | 0                       | 0                       | 0                     | 0                                     | 7                                      |
|                 | 20   | 01.00      | 0                           | 0                       | 0                       | 0                     | 0                                     | 7                                      |
|                 | 21   | 02.00      | 0                           | 0                       | 0                       | 0                     | 0                                     | 7                                      |
|                 | 22   | 03.00      | 0                           | 0                       | 0                       | 0                     | 0                                     | 7                                      |
|                 | 23   | 04.00      | 0                           | 0                       | 0                       | 0                     | 0                                     | 7                                      |
|                 | 24   | 05.00      | 1,67                        | 10,0                    | 0,1                     | 1,0                   | -30                                   | 8                                      |

Table 2. Solar panel experimental data day 2

| Day        | Hour | Time (WIB) | Light Intensity (w/m <sup>2</sup> ) | Solar Panel Voltage (V) | Solar Panel Current (A) | Solar Panel Power (W) | Solar Panel Tilt Angle (°) | Cooler Box Temperature (°C) |
|------------|------|------------|-------------------------------------|-------------------------|-------------------------|-----------------------|----------------------------|-----------------------------|
| 2          | 25   | 06.00      | 15,00                               | 14,5                    | 0,6                     | 8,7                   | -30                        | 8                           |
| 22/01/2026 | 26   | 07.00      | 75,00                               | 18,5                    | 1,2                     | 22,2                  | -25                        | 8                           |
|            | 27   | 08.00      | 154,17                              | 20,8                    | 2,8                     | 58,2                  | -20                        | 7                           |
|            | 28   | 09.00      | 233,33                              | 21,8                    | 4,2                     | 91,5                  | -15                        | 6                           |
|            | 29   | 10.00      | 316,67                              | 22,8                    | 6,5                     | 148,2                 | -10                        | 6                           |
|            | 30   | 11.00      | 375,00                              | 23,2                    | 7,6                     | 176,3                 | -5                         | 5                           |
|            | 31   | 12.00      | 416,67                              | 23,5                    | 8,2                     | 192,7                 | 0                          | 5                           |
|            | 32   | 13.00      | 433,33                              | 23,7                    | 8,4                     | 199,0                 | 0                          | 5                           |
|            | 33   | 14.00      | 441,50                              | 23,8                    | 8,4                     | 199,9                 | 0                          | 5                           |
|            | 34   | 15.00      | 407,67                              | 23,3                    | 7,7                     | 179,4                 | 15                         | 6                           |
|            | 35   | 16.00      | 263,00                              | 22,7                    | 5,1                     | 115,7                 | 21                         | 7                           |
|            | 36   | 17.00      | 81,83                               | 21,5                    | 1,7                     | 36,5                  | 21                         | 7                           |
|            | 37   | 18.00      | 6,08                                | 15,0                    | 0,9                     | 13,5                  | 32                         | 7                           |
|            | 38   | 19.00      | 0                                   | 0                       | 0                       | 0                     | 0                          | 7                           |
|            | 39   | 20.00      | 0                                   | 0                       | 0                       | 0                     | 0                          | 7                           |
|            | 40   | 21.00      | 0                                   | 0                       | 0                       | 0                     | 0                          | 7                           |
|            | 41   | 22.00      | 0                                   | 0                       | 0                       | 0                     | 0                          | 7                           |
|            | 42   | 23.00      | 0                                   | 0                       | 0                       | 0                     | 0                          | 7                           |
|            | 43   | 00.00      | 0                                   | 0                       | 0                       | 0                     | 0                          | 7                           |
|            | 44   | 01.00      | 0                                   | 0                       | 0                       | 0                     | 0                          | 7                           |
|            | 45   | 02.00      | 0                                   | 0                       | 0                       | 0                     | 0                          | 7                           |
|            | 46   | 03.00      | 0                                   | 0                       | 0                       | 0                     | 0                          | 7                           |
|            | 47   | 04.00      | 0                                   | 0                       | 0                       | 0                     | 0                          | 6                           |
|            | 48   | 05.00      | 2,50                                | 11,0                    | 0,2                     | 2,2                   | -30                        | 6                           |

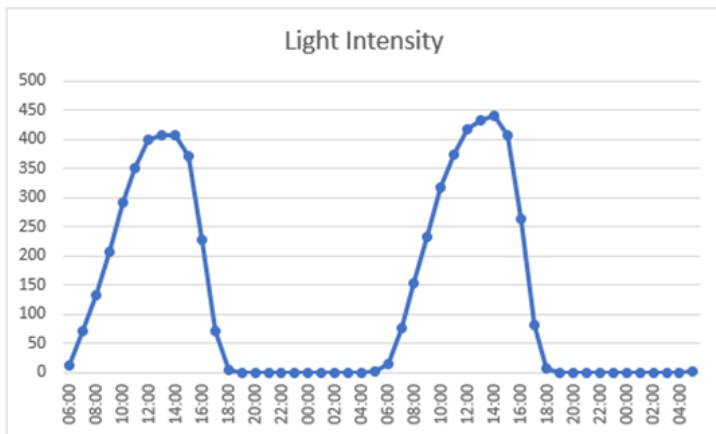


Fig. 7. Light intensity

The variation of light intensity over the measurement period. The graph shows a clear periodic pattern, where light intensity increases significantly during the day and decreases to near zero at night. Peak intensity values occur around midday, indicating maximum solar illumination, while lower values in the early morning and evening reflect reduced sunlight exposure. These results demonstrate consistent environmental lighting conditions and provide a reliable basis for evaluating system performance under varying light intensities.

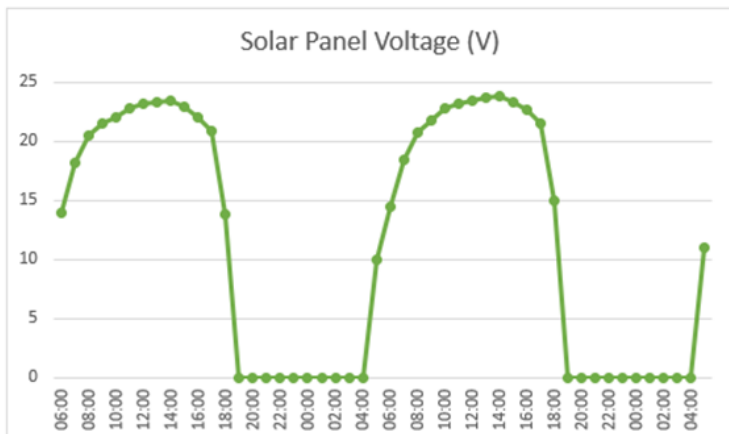


Fig. 8. Solar panel voltage (V)

The solar panel voltage output during the measurement period at different times of the day. The voltage increases during daylight hours and reaches maximum values of approximately 22-24 V under high solar irradiance conditions. Conversely, the voltage drops to near zero during nighttime due to the absence of sunlight. Minor fluctuations in peak voltage values are observed, which may be influenced by environmental factors such as temperature and weather conditions. These results indicate that solar panel voltage is strongly dependent on sunlight availability.

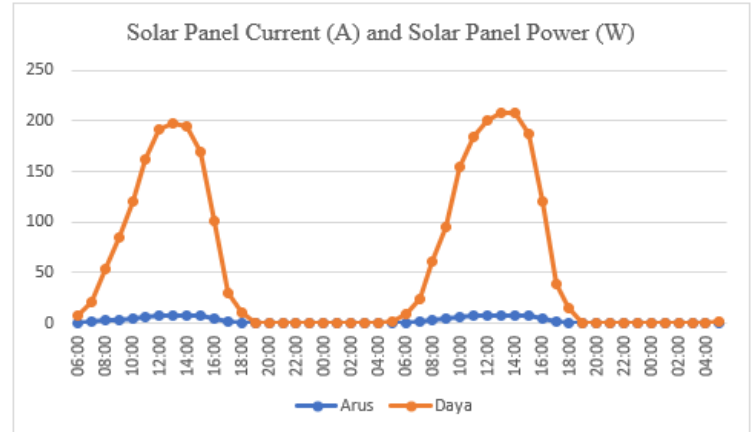


Fig. 9. Solar panel current (A) and solar panel power (W)

The variation of solar panel current and power output during the measurement period. The current and power increase significantly during daylight hours and reach their maximum values when solar irradiance is high. Conversely, both parameters decrease sharply during nighttime, approaching zero due to the absence of solar radiation. Fluctuations in peak values are observed across different days, which may be influenced by changes in weather conditions and solar intensity. These results indicate that the current and power output of the solar panel are highly dependent on sunlight availability.

The variation of the solar panel tilt angle during the measurement period. The tilt angle was adjusted within a range of approximately 30° to +30° to follow the sun's position and optimize solar energy absorption.

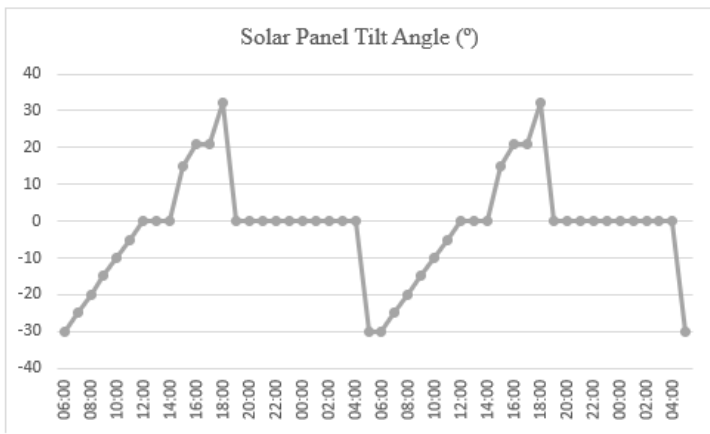


Fig. 10. Solar panel tilt angle (°)

The changes in tilt angle indicate an active adjustment strategy aimed at maximizing solar irradiance received by the panel. These variations contribute to improved panel performance, as reflected in the voltage, current, and power output results

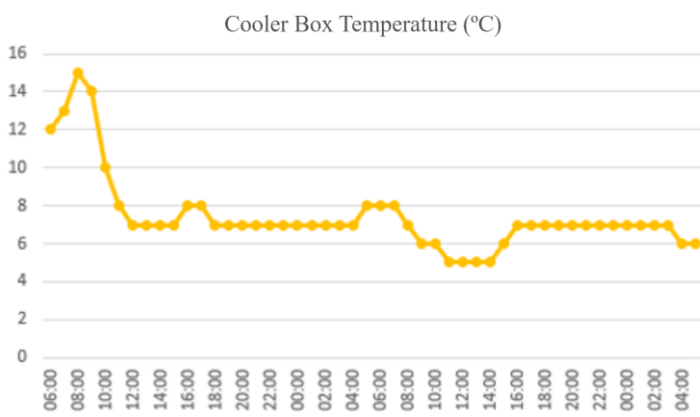


Fig. 11. Cooler box temperature (°C)

The variation of cooler box temperature during the measurement period. The temperature generally remains within 6-8°C, indicating stable cooling performance. Several short-term increases in temperature up to about 14-15°C are observed, which may be caused by external disturbances such as changes in ambient temperature or the opening of the cooler box. Overall, the results demonstrate that the cooling system maintains a relatively stable internal temperature during operation.

### 3.2 Discussion

The experimental results demonstrate a strong correlation between solar irradiance levels and the system's cooling stability. Analysis of daily energy dynamics shows an average daily energy yield of 1,285.6 Wh, providing sufficient power to sustain continuous operation of the thermoelectric module. This total energy harvesting is critical to compensate for peak thermal loads at midday (11:00 to 14:00 WIB), when the maximum power output reached 199.9 W. This energy balance ensures that the cool box can maintain the target 6-8°C range even under high ambient heat in the Sungsang Estuary. Compared to the Tanzanian case study by Carlsson et al. (2023) [2], which utilized a stationary solar PV mini-grid for communal cold storage and experienced reliability issues during low-solar-radiation seasons, our system offers a more adaptive solution for individual fishers. By integrating a dual-axis tracking mechanism, the prototype maximizes energy harvesting even under fluctuating conditions, ensuring the cool box maintains the target 6-8 °C range.

Based on the results shown in Figures 8-11, the performance of the solar-powered system is strongly influenced by solar irradiance and panel orientation. Fig. 8 indicates a clear diurnal pattern in the solar panel voltage, with peak values of approximately 22-24 V

during daylight hours and a significant decrease at night. This confirms that photovoltaic voltage output is directly dependent on solar radiation intensity [9], [10].

Fig. 9 shows that the output current and power increase significantly during periods of high solar irradiance and decrease sharply under low-irradiance conditions. The alignment between current and power peaks demonstrates stable photovoltaic performance and efficient energy conversion, consistent with previous studies on monocrystalline photovoltaic systems [11].

As shown in Fig. 10, the solar panel tilt angle was adjusted dynamically within a range of approximately -30° to +32° to follow the sun's movement. This tracking mechanism improved solar energy absorption, as reflected in the higher voltage, current, and power output observed during peak solar hours. Similar improvements have been reported in earlier studies, where solar tracking systems enhanced power output compared to fixed installations [6], [12].

An energy balance analysis was conducted to evaluate the cooling effectiveness relative to the electrical input. As shown in the performance testing data, the system used a total power input ( $P$ ) of 240.0 W to 261.6 W to operate the four thermoelectric modules. Within 60 minutes of operation, this energy input resulted in a significant temperature reduction ( $\Delta T$ ) of 27.0°C, bringing the internal temperature down from 34.0°C to 7.0°C. The incremental increase in current from 20.0 A to 21.8 A during the cooling process reflects the modules' response to the increasing thermal gradient.

Furthermore, the efficiency of the cooling system was evaluated using the Coefficient of Performance (COP). Based on the experimental data, at a stable internal temperature of 7.0°C with a total power input ( $P$ ) of 261.6W, the estimated cooling capacity ( $Q$ ) was approximately 50W. Consequently, the COP of the thermoelectric module was calculated as follows:

$$COP = \frac{Q}{P} = \frac{50}{261.6} = 0.19$$

This value is consistent with the typical COP range for thermoelectric refrigeration (0.1-0.5), confirming that despite the inherent efficiency limits of Peltier modules, the system provides sufficient thermal removal for small-scale fishery applications.

Fig. 11 demonstrates that the cooler box temperature was generally maintained within a stable range of 6-8°C. Occasional temperature spikes to 14-15°C are characterized by thermal infiltration during fish sorting, which introduces ambient latent heat and disrupts internal thermal equilibrium. Quantitatively, this 7°C fluctuation is lower than the 12-15°C spikes reported by Elnaggar et al. (2024) [13] for similar portable systems, highlighting our system's superior thermal inertia. This stability is further supported by the tracking-enhanced energy buffer; while Carlsson et al. (2023) [2] observed reliability issues due to static solar inputs, our dual-axis mechanism ensures a continuous power surplus (reaching 199.9 W) to counteract external thermal loads. Thus, the system proves more resilient in high-ambient environments, such as the Sungsang Estuary, than stationary off-grid installations. [13], [14].

Overall, the results confirm that the integration of monocrystalline photovoltaic panels, dynamic tilt adjustment, and energy storage provides stable and efficient system performance, making it suitable for standalone applications in high solar potential areas [14]

### 4 Conclusion

Based on the experimental results, the monocrystalline photovoltaic system showed strong dependence on solar irradiance and panel orientation. The panel voltage followed a clear diurnal pattern, reaching approximately 22-24 V during daylight and decreasing to near 0 V at night. Output current peaked at 8.0-8.4 A, producing maximum power during midday high-radiation periods.

The dynamic tilt adjustment system operated between  $-30^\circ$  and  $+32^\circ$ , allowing solar tracking and improving voltage, current, and power compared with fixed-panel operation. Analysis of the 14-day field test confirmed an average daily energy yield of 1,285.6 Wh, sufficient to sustain continuous operation of the thermoelectric cooling module. The GSM-SMS interface provided reliable remote monitoring and control. The cool box temperature was generally maintained between 6 and  $8^\circ\text{C}$ , although temporary increases to  $14\text{--}15^\circ\text{C}$  occurred under adverse ambient conditions. Battery storage ensured continuous operation during fluctuating solar input. Overall, the integrated photovoltaic, tracking, storage, and cooling system demonstrated stable and efficient standalone performance suitable for high-solar coastal regions. Despite stable operation, the system remains limited by dependence on solar irradiance, the modest 20 kg storage capacity, and thermoelectric heat rejection under humid tropical conditions. Future work should optimize thermoelectric COP, evaluate hybrid power sources and phase change materials, and apply predictive energy management using machine learning.

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