International Journal of Heat and Technology
Vol. 43, No. 5, October, 2025, pp. 1757-1766
Journal homepage: http://iieta.org/journals/ijht

Hybrid Water Heating System Integrating Split AC Waste Heat and Solar PV for Energy Efficiency

Gunarto*, Doddy Irawan, Eko Julianto, Muhammad Iwan

Mechanical Engineering Department, Faculty of Engineering and Computer Science, University of Muhammadiyah Pontianak, Pontianak 78234, Indonesia

Corresponding Author Email: gunarto@unmuhpnk.ac.id

https://doi.org/10.18280/ijht.430514

Received: 10 August 2025
Revised: 14 October 2025
Accepted: 26 October 2025
Available online: 31 October 2025

Keywords:
hybrid heat pump water heater, photovoltaic integration, waste heat recovery, energy efficiency, returns on investment, carbon emission reduction, economic feasibility, sustainable water heating

ABSTRACT

This study experimentally evaluates a hybrid heat pump water heater (HPWH) integrating air-conditioner (AC) waste heat recovery with photovoltaic (PV) power to improve energy efficiency and sustainability. Three AC capacities (0.5, 1, and 2 PK) were tested under grid (Perusahaan Listrik Negara-PLN), PV-only, and PV–grid hybrid modes. A helical copper coil heat exchanger immersed in a 60-L tank transferred condenser heat to water. The system achieved water temperatures of approximately 57.7°C with coefficients of performance (COP) between 2.5 and 3.5. PV-only and hybrid operations provided comparable heating performance to grid mode with substantially lower electricity use. Compared with conventional resistive heating (16 kWh/day), the HPWH reduced energy consumption to 5.5 kWh/day (grid), 0.95 kWh/day (hybrid), and nearly zero under PV-only operation, saving over Indonesian (IDR) 8 million annually. Economic analysis showed payback periods of 5-8 years and returns on investment of approximately 824%. Environmentally, the system cut carbon emissions by about 94% in hybrid mode and eliminated them entirely in PV-only mode, equivalent to avoiding 4.7 tonnes of CO_2 per year. In general, the hybrid AC–PV HPWH shows strong technical, economic, and environmental feasibility for residential and small-scale applications in tropical regions.

1. INTRODUCTION

Water heating is an important energy demand in residential, commercial, and industrial sectors. Conventional electric and gas water heaters are highly energy-intensive and contribute substantially to greenhouse gas (GHG) emissions. In tropical countries such as Indonesia, air-conditioner (AC) systems account for 30-40% of total electricity consumption, and their condensers continuously release waste heat into the environment. This waste not only signifies a substantial loss of recoverable energy but also intensifies the urban heat island effect.

Indonesia simultaneously possesses abundant solar energy resources, averaging 4.8 kWh/m²/day, and the government has set a target to expand photovoltaic (PV) capacity to 0.87 gigawatt (GW) by 2025. Harnessing both waste heat from split AC systems and solar PV power, thereby providing a promising pathway to reduce reliance on the national grid (*Perusahaan Listrik Negara-PLN, Indonesia's state-owned electricity utility*), lower operating costs, and contribute to the country's Net Zero Emission 2060 target.

In tropical climates, where cooling demand is high and solar irradiance is abundant throughout the year, coupling AC waste heat recovery with PV electricity creates a unique synergy. The higher the cooling load, the greater the recoverable heat and the available solar power. This complementary behavior makes hybrid AC–PV heat pump systems particularly efficient, sustainable, and well-suited to tropical regions—an aspect rarely emphasized in previous studies.

Extensive studies have been conducted on solar-assisted heat pump (SAHP) systems. Zohri et al. [1] showed that integrating solar collectors, PV, and photovoltaic/thermal (PV/T) with heat pumps significantly enhanced water heating and drying. Kedar et al. [2] and Najaf and Aslan [3] extended this concept through hybrid desalination combining evacuated tube collectors (ETC) and compound parabolic concentrators (CPC), achieving competitive water yields. PV/T heat-pipe systems have also reported combined thermal–electrical efficiencies of 22.9-24.6% [4]. Floating PV has been recognized as a feasible pathway for capacity expansion in water-rich regions [5].

As baselines, thermosyphon–riser collectors achieved 70% efficiency [6], vacuum tube collectors with reflectors reached 86% [7], while induction heating provided an alternative non-solar route [8]. Pressurized collectors with reflectors produced water at 318 K [9], and air collectors showed cost-effective heating [10]. The introduction of baffles improved heat transfer in solar air collectors by 35% [11], while a parabolic trough collector (PTC) paraboid-integrated with double chillers achieved synergistic operation.

Sustainability-oriented designs have also gained attention. Collectors fabricated from recycled materials have achieved efficiencies of up to 62% [12], while broader reviews emphasized renewable energy as a long-term solution [13, 14].

Similarly, solar dryers showed significant performance improvements: non-integrated vs. novel-modified designs increased efficiency by 9-55%. Experimental methods such as halogen-lamp simulators enabled controlled PV testing.

Thermal storage integration has become another major study avenue. Solid–liquid phase change material (PCM) systems improved thermal stability, while solid–solid polyethylene PCMs provide an alternative option for heat storage applications. Low-cost media such as sand hill reduced thermal fluctuations by 5.2°C. PV/T coupled with PCM maintained water above 34°C [15] and stabilized PV performance under forced convection.

Numerical and Computational Fluid Dynamics (CFD) simulations have further advanced the existing literature. Studies showed that incorporating central heat exchangers in solar ponds enhances thermal efficiency, while cone receivers improve dish concentrator performance. Hybrid PTC + cascade still distillation achieved 6 kg/m²/day. The Capderou model validated solar resource estimates with a root mean square deviation (RMSD) of 7%, and nanofluid-enhanced collectors improved thermal conductivity.

Studies on PV system optimization include orientation and tilt studies (e.g., 30° tilt in equatorial conditions) [16] and azimuth tracking, which increased output by 28-40% [17]. Advances in PV/T optimization included sustainability indices, finned collectors [18], concentrated solar power (CSP)-integrated thermal design [19], and PV–thermal co-sizing for nearly zero-energy buildings [20]. Broader integration studies highlighted the importance of reliability in renewable mechanical systems [21], while exergy-based analyses of solar stills [22] and nanofluid applications expanded evaluation frameworks. Air collectors with fins and baffles also showed significant numerical performance improvements.

Recent studies provide updated information. Wiriyasart and Kaewluan [23] experimentally showed AC waste heat recovery for water heating, validating its potential in hybrid systems. Znaczko et al. [24] reported a 12.7% improvement in thermal storage efficiency using adaptive control strategies in solar hot water systems. Satpute et al. [25] used CFD to optimize PVT absorber configurations, achieving thermal–electric efficiency improvements up to 75%. Finally, Icaza [26] conducted techno-economic assessments of PV-assisted heat pumps, showing competitive PP and reduced energy costs. In the Indonesian context, previous studies confirmed the technical feasibility of AC waste heat recovery using helical coil heat exchangers, achieving water heating above 50°C. However, these studies still relied entirely on grid electricity, which limited their sustainability.

Despite significant progress in the field, critical gaps persist. Most existing studies focus exclusively on either solar-based systems or air-conditioning (AC) waste heat recovery, rather than integrating both approaches. Few integrate real-time PV electricity with AC waste heat recovery under tropical field conditions, and even fewer evaluate thermal performance, economic feasibility, and environmental impact comprehensively. This present study addresses these gaps by experimentally developing and analyzing a hybrid system that combines split-type AC waste heat recovery with solar PV input under tropical conditions.

2. METHODOLOGY

The methodology of this study was structured to evaluate the technical, economic, and environmental feasibility of a hybrid water heating system that integrates waste heat recovery from split-type AC with solar PV supply. The experimental design followed a systematic approach, beginning with the selection of representative residential AC units (0.5, 1, and 2) paardekracht (PK) to capture performance variations across typical household and small commercial applications in Indonesia. The system was equipped with a helical coil heat exchanger submerged in a domestic-scale water tank, enabling direct measurement of heat transfer efficiency under different operational modes.

To align with the study objectives, the methodology emphasized three key aspects. First, the thermal performance of the system was quantified by monitoring water temperature profiles, condenser outlet conditions, and coefficients of performance (COP) under grid, PV, and hybrid operation. Second, the contribution of solar PV was assessed by comparing thermal outcomes, energy flows, and grid substitution levels across capacities, using calibrated instruments to ensure measurement accuracy. Third, the economic and environmental viability of the system was evaluated by translating measured energy savings into cost reductions, return on investment (ROI), payback period (PP), and avoided CO_2 emissions using nationally recognized grid emission factors.

This integrated methodological framework ensures replicability and reliability. By integrating controlled experimental protocols with real tropical climatic conditions, this study not only captures the system's immediate thermal behavior but also shows the long-term potential for advancing sustainable energy transitions. The following subsections describe in detail the system configuration, equipment specifications, measurement instruments, and testing protocols used.

2.1 System configuration and rationale

The experimental system was designed to integrate condenser waste heat from split-type AC units with solar PV electricity supply to form a hybrid water heating configuration. Three AC capacities (0.5, 1, and 2 PK) were selected to represent the most common units used in Indonesian households and small commercial facilities. These capacities were chosen to benchmark system performance across different compressor loads, thereby capturing both low- and high-demand scenarios.

The selection of system components was guided by three considerations: (i) representativeness of real-world residential and small commercial applications, (ii) compatibility with hybrid PV–grid operation for reliable energy supply, and (iii) ability to generate accurate and replicable thermal and economic data. This rationale ensured that experimental outcomes could be generalized for practical applications while maintaining scientific rigor.

2.2 Equipment specifications

The system consisted of the following major components:

(1) AC (0.5, 1, and 2 PK split units) installed as representative compressor capacities for typical household and small industry cooling systems. Multiple units allowed comparative evaluation of heating rates and COP.

(2) Heat Exchanger (Helical Coil)

Fabricated from copper tubing (Ø 9.52 mm, 15 turns, 30 cm coil diameter, 14 m length) and submerged in a 60 L insulated water tank. Copper was selected for its high thermal conductivity (390 W/mK) and corrosion resistance, while the helical design enhanced turbulence and improved heat transfer coefficients.

(3) Water Tank

A polyurethane-insulated stainless steel tank with 60 L capacity, reflecting average daily hot-water demand (40-80 L) in tropical households while minimizing standby heat losses.

(4) Solar PV Array

Two monocrystalline modules (2 × 550 Wp, total 1.1 kWp). The array was dimensioned to approximately match the daily energy demand of a 1 PK AC unit under tropical irradiance (4.8-5.2 kWh/m^2/day).

(5) Hybrid Inverter and Battery Storage

A 4.2 kW, 24 V hybrid inverter connected to two 12 V–200 Ah deep-cycle batteries, ensuring stable compressor startup and operation during irradiance fluctuations.

(6) Automatic Transfer Switch (ATS)

Enabled seamless switching between PV–battery supply and the national grid, thereby improving operational reliability and continuity.

2.3 Measurement instruments

Accurate measurement and monitoring were critical to quantify system performance. The following instruments were deployed:

(1) Temperature Sensors

MAX6675 thermocouples (±0.25°C accuracy), calibrated against a mercury thermometer. Sensors were installed at condenser outlets, water inlets/outlets, and ambient points.

(2) Solar Irradiance

A pyranometer (10 $\mu V/Wm^2$ sensitivity, ±5% accuracy) was used to record both horizontal and tilted irradiance, validating PV performance under tropical conditions.

(3) Electrical Parameters

A digital power meter (±1% accuracy) monitored PV voltage/current, compressor power demand, and battery charge/discharge profiles.

(4) Flow Conditions

A flowmeter (±2% accuracy) measured refrigerant and water circulation rates, providing data for energy balance verification.

(5) Data Acquisition

An Arduino-based data logger recorded data at 15-minute intervals. Thermocouples were connected directly to the Arduino module, and logged values were stored on an SD card for reliability. This ensured continuous monitoring of temperature and electrical parameters without reliance on wireless communication.

2.4 Experimental protocol and parameters

The experimental protocol was structured to ensure comparability across modes and capacities:

(1) Operating Modes

Three modes were tested: (i) HPWH–PLN (grid-supplied operation), (ii) HPWH–Hybrid (PV–grid integration), (iii) HPWH-PV only.

(2) Test Duration

Each run continued until water temperature stabilized or the system reached 120-150 minutes of operation.

(3) Initial Conditions

Water temperatures were 25-32°C, with ambient air at 30-34°C, showing typical Pontianak tropical conditions.

(4) Performance Parameters Evaluated:

- Water temperature rise as a function of time.
- Compressor and condenser outlet temperature profiles.
- COP.
- PV energy contribution (kWh/day).
- Grid electricity consumption (kWh/day).
- Economic indicators, including ROI and PP.

Environmental impact expressed as avoided CO_2 emissions, using a grid emission factor of 0.85 kg/kWh.

This framework allowed direct comparison between grid- and PV-supplied configurations while quantifying both technical performance and broader economic and environmental implications. The design ensures replicability and provides practical insights applicable to residential-scale systems in tropical climates.

Figure 1 shows the schematic configuration of the hybrid air-conditioner–photovoltaic (AC–PV) heat pump water heater (HPWH) system developed in this study. The setup integrates dual energy sources—the national grid and a 1.1 kWp solar PV array—connected through a hybrid inverter and an ATS to maintain stable compressor operation during variable solar conditions.

The split-type AC operates at 0.5, 1, and 2 PK capacities, providing waste-heat recovery from its condenser. A copper helical coil heat exchanger submerged in a 60 L polyurethane-insulated water tank transfers this recovered heat to the water, while the refrigeration cycle remains unchanged.

Key monitoring points include PV voltage and current sensors, compressor load meters, and thermocouples positioned at the condenser and tank inlets/outlets. These instruments enable precise evaluation of heat transfer efficiency, electrical consumption, and overall system performance under different operating modes.

The hybrid configuration combines engineering optimization with practical applicability for tropical regions. The integration of PV generation with the AC compressor enables partial energy autonomy, while the helical copper coil and insulated tank minimize thermal losses and enhance the system's COP. Supported by a hybrid inverter with an ATS, the system maintains reliable operation under variable solar conditions. By using existing AC infrastructure and rooftop PV modules, it offers a cost-effective and scalable solution that supports Indonesia's Net Zero Emission 2060 target through reduced grid dependency and carbon intensity in residential and small-scale applications.

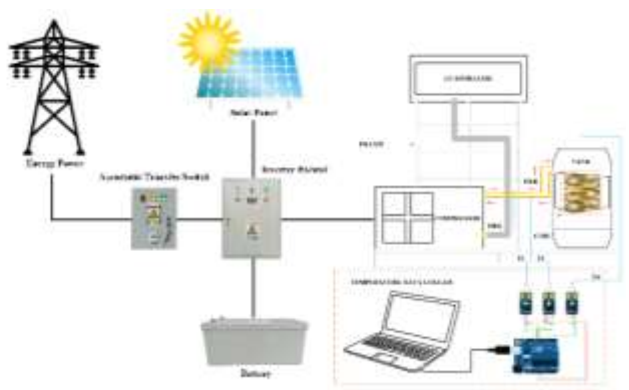

Figure 1. Schematic of the hybrid AC–PV water heating system

In contrast, Figure 2 shows the configuration of a hybrid inverter-based energy storage system comprising both internal and external components.

The internal view (Figure 2(a)) shows the inverter integrated with protective circuits and neatly arranged wiring, connected to two battery units that store energy from the grid or PV panels before conversion into usable AC power.

The external view (Figure 2(b)) shows the control panel mounted on a steel frame, equipped with indicator lamps and a digital display for monitoring, with two enclosed batteries at the bottom serving as backup sources. The system design emphasizes safety, reliability, and ease of maintenance.

(a) (b)

Figure 2. Hybrid inverter-based energy storage system: (a) internal configuration, (b) external control panel

3. RESULT AND DISCUSSION

3.1 Heat transfer efficiency

The heat transfer efficiency of the hybrid heat pump water heater (HPWH) system was evaluated by monitoring compressor temperature, condenser temperature, and the temperature rise (ΔT) of a 60 L insulated tank. Experiments were carried out on three AC capacities: 0.5 PK, 1 PK, and 2 PK under three operating modes: PLN (grid-supplied), PV-only, and Hybrid PV–grid. A helical coil heat exchanger (Ø30 cm, 15 turns, 14 m copper tubing) was applied to optimize heat transfer from condenser waste heat into the water storage. Table 1 presents a comprehensive summary of the measured temperature profiles and heating performance under all operating modes.

Under PLN operation, the strongest heating performance was recorded. The 0.5 PK unit increased water temperature from 27.0°C to 44.7°C in 150 minutes (ΔT = 17.7°C), while the 1 PK unit achieved 49.5°C in 135 minutes (ΔT = 24.5°C). The 2 PK unit delivered the best performance, heating water from 32.0°C to 57.72°C in 120 minutes (ΔT = 25.7°C). These results confirm that larger compressors reject more heat and accelerate heating cycles, consistent with fundamental thermodynamic expectations [11].

For PV-only operation, slightly lower performance was observed due to irradiance fluctuations. The 0.5 PK unit achieved 42.7°C (ΔT = 15.7°C), while the 1 PK and 2 PK units reached 48.4°C (ΔT = 23.4°C) and 56.1°C (ΔT = 24.1°C), respectively. These values were only 1–2°C below PLN operation, validating the reliability of PV-driven compressors in tropical conditions [4].

The hybrid PV–grid mode yielded intermediate values. The 0.5 PK unit reached 43.4°C (ΔT = 16.4°C), while the 1 PK and 2 PK units attained 48.9°C (ΔT = 23.9°C) and 56.9°C (ΔT = 24.9°C). The hybrid approach ensured stable compressor operation by compensating solar variability with grid input, thereby reducing dependency on a single energy source [1]. This confirms the robustness of PV–grid integration for household-scale HPWH applications in regions with high solar availability.

When benchmarked with the literature, the COP values observed (ranging from 2.5 for 0.5 PK to 3.5 for 2 PK) are consistent with solar-assisted heat pump (SAHP) studies in tropical regions, which typically report values between 2.8–3.6 [1, 4]. However, the overall efficiency is still lower than conventional solar-thermal collectors such as thermosyphon systems (70%) [6] or evacuated tube collectors with reflectors (86%) [7]. This discrepancy is expected since hybrid HPWH systems depend on both electricity and condenser waste heat rather than direct solar-thermal absorption. However, the hybrid approach offers operational flexibility not achievable in single-source systems.

Variations in efficiency among the tested capacities can be attributed to multiple influencing factors. First, the surface area of the helical coil (0.5 m²) limited the overall heat transfer rate compared to advanced collector geometries [15]. Second, thermal losses from the polyurethane-insulated 60 L tank reduced net efficiency during extended heating cycles [7]. Third, compressor capacity strongly influenced system COP: the smaller 0.5 PK unit exhibited slower heat rejection and lower performance, while the 2 PK unit delivered superior heating rates, confirming earlier results that refrigerant flow and heat exchanger design significantly affect SAHP performance [11, 15].

Table 1. Experimental results of HPWH performance under grid, hybrid, and PV operation for different AC capacities

AC Capacity	Mode	T_compressor (°C)	T_condenser (°C)	T_water Initial (°C)	T_water Final (°C)	ΔT_water (°C)	Time to Final (Minutes) (°C)
0.5 PK	HPWH - PLN	27 → 72	27 → 49	27.0	44.7	17.7	150
0.5 PK	HPWH - HYBRID	27 → 69.5	27 → 48.6	27.0	43.4	16.4	150
0.5 PK	HPWH - PV	27 → 67	27 → 48.3	27.0	42.7	15.7	150
1 PK	HPWH - PLN	25 → 77.2	25 → 54.3	25.0	49.5	24.5	135
1 PK	HPWH - HYBRID	25 → 76.3	25 → 53.7	25.0	48.9	23.9	135
1 PK	HPWH - PV	25 → 75.4	25 → 53.0	25.0	48.4	23.4	135
2 PK	HPWH - PLN	32 → 85	32 → 63.9	32.0	57.7	25.7	120
2 PK	HPWH - HYBRID	32 → 84.2	32 → 63.4	32.0	56.9	24.9	120
2 PK	HPWH - PV	32 → 83.4	32 → 62.9	32.0	56.1	24.1	120

Note: The arrow symbol (→) in the table shows the change in temperature from the initial value to the maximum value recorded during operation.

These results highlight the scalability of the system. The 0.5 PK unit is suitable for single-household applications with modest demand, while 1 PK and 2 PK units can serve multi-user households or small-scale commercial facilities. Importantly, the hybrid mode shows a balance between performance and grid independence, making it particularly relevant for Indonesian households where energy reliability is often a concern.

The hybrid HPWH system showed strong thermal performance across all modes. PLN mode produced the highest heating rates, PV-only mode showed reliable standalone operation with slightly reduced efficiency, and the hybrid mode provided stable and resilient performance. The results not only validate PV–grid integration but also align with energy efficiency and sustainability goals for tropical regions.

3.2 Contribution of solar PV

The contribution of solar PV supply was clearly observed across all capacities and operating modes tested in this study. The experimental results showed that PV-only operation produced slightly lower final water temperatures compared to PLN (grid) operation, while Hybrid PV–grid operation consistently narrowed this performance gap. For the 0.5 PK unit, water temperature under PV-only mode reached 42.7°C, approximately 2.0°C lower than the 44.7°C achieved under PLN operation, while the hybrid mode improved the outcome to 43.4°C. For the 1 PK unit, the differences were similarly small: PLN produced 49.5°C, PV-only reached 48.4°C, and the hybrid mode delivered 48.9°C, a reduction of only 0.6°C from the grid baseline. Finally, for the 2 PK unit, the grid mode achieved 57.7°C, PV-only reached 56.1°C, and hybrid operation delivered 56.9°C, a difference of less than 1°C.

The results confirm that the 1.1 kWp PV array was capable of reliably supporting compressor operation across capacities, with hybrid mode ensuring nearly identical outcomes to grid supply.

The robustness of PV-only operation can be attributed to high solar resource availability in tropical regions, where daily irradiance averages 4.8–5.2 kWh/m² [16]. Although modest reductions in final water temperature occurred under PV-only mode, these deviations were small enough to validate PV as a reliable energy source for HPWH operation. The hybrid configuration further mitigated these variations by supplementing PV input with grid electricity, ensuring stable compressor loads and reliable hot water delivery while simultaneously reducing dependency on PLN supply. Comparable outcomes have been reported in PV/T–PCM studies, where water temperatures above 34°C were consistently maintained under solar-only configurations [15].

Similarly, optimization studies in equatorial regions emphasize that PV system performance can be maximized through tilt adjustment, with a 30° angle identified as optimal for annual solar capture [16]. These results further reinforce the suitability of the PV setup used in this study.

Three key factors explain the small differences observed between PV and grid operation: (i) fluctuations in solar irradiance during intermittent cloud cover, which affected compressor load stability, (ii) the limited PV array size, optimized primarily for a 1 PK compressor, leading to tighter margins for 2 PK operation, and (iii) conversion losses in the inverter–battery system, typically ranging from 10-15% [4].

Despite these constraints, the system exhibited notable operational stability. The PV-only mode achieved water heating performance comparable to that of grid-powered operation, while hybrid operation effectively eliminated the remaining performance differences.

In practical terms, these results highlight the potential of integrating PV with HPWH systems to improve household PV utilization. Rooftop PV systems in Indonesia are often underutilized because daytime demand does not fully match PV generation. By channeling surplus PV output to operate the compressor, excess electrical energy can be efficiently converted into stored thermal energy, thereby supplying hot water at an almost negligible marginal cost. This not only improves the economic return of PV installations but also increases the capacity factor of the system, aligning with similar outcomes reported in PV/T hybrid studies [1].

On the scientific side, the integration of PV with waste heat recovery enhances the energy utilization factor (EUF) by combining electrical and thermal outputs in a unified system. Compared to standalone PV or conventional AC waste heat recovery, the hybrid configuration ensures that both energy streams are exploited simultaneously, thereby reducing system losses and improving overall efficiency. This dual-use approach aligns with broader trends in PV/T study, where hybrid strategies have been shown to deliver superior long-term performance compared to single-function systems [6, 7].

From an energy policy standpoint, the feasibility of integrating PV systems with heat pump water heaters (HPWH) reinforces Indonesia's renewable energy transition by enhancing the economic and functional value of rooftop PV installations. The ability of PV to substitute for grid electricity in water heating reduces household peak demand, specifically in urban areas where AC ownership is widespread. By reducing reliance on PLN during peak hours, such systems can contribute directly to national targets for renewable energy expansion and household-level sustainability [1, 16].

Collectively, the experimental results validate solar PV as a robust and reliable contributor to HPWH operation across different AC capacities. PV-only mode consistently sustained compressor operation with minimal performance reduction, while hybrid mode nearly matched grid-supplied outcomes. Beyond technical feasibility, PV integration enhances household energy utilization, supports national renewable energy policies, and aligns with sustainability objectives in tropical regions.

3.3 Energy consumption and operating cost

The analysis of energy consumption highlights the substantial efficiency gains of the hybrid HPWH system compared with conventional electric resistance water heating.

A baseline resistive heater of equivalent capacity required approximately 16 kWh/day, translating to monthly expenditures of around IDR 720,000, based on average residential electricity tariffs. By contrast, the HPWH–PLN configuration consumed only 5.5 kWh/day, reducing costs to approximately IDR 247,500 per month. The Hybrid PV–grid mode achieved an even lower grid demand of 0.95 kWh/day, corresponding to a monthly cost of about IDR 42,750. Finally, under PV-only operation, the 0.5 PK unit achieved full independence from the grid, while the 2 PK unit reduced grid electricity use by over 80%. These results underscore the transformative cost advantages of integrating PV with AC-based HPWH systems.

When benchmarked against regional studies, the observed savings are remarkable. Prior investigations of solar-assisted heat pumps (SAHP) in Southeast Asia generally reported cost reductions of 60-70% relative to resistive heating [1, 4]. In this study, however, reductions reached 82-94%, substantially higher than typical reports. The discrepancy can be attributed to Indonesia's heavy reliance on resistive water heating, which operates at near 100% conversion efficiency but lacks the performance multiplier provided by heat pumps. By leveraging the high COP of AC-based HPWH systems, combined with renewable PV electricity input, the hybrid system shifts the baseline dramatically. This dual optimization explains the superior savings achieved in the present work.

The observed energy savings are primarily attributed to the thermodynamic efficiency of the heat pump cycle, which recovers waste heat from the condenser rather than relying exclusively on electrical resistance for water heating. Unlike conventional heaters that convert all electrical energy directly into heat, the hybrid HPWH amplifies useful heat output through the vapor-compression process, achieving a COP between 2.5 and 3.5. Consequently, each unit of electrical input transfers 2.5-3.5 units of heat energy to the water, significantly reducing overall electricity consumption. The integration of PV power further offsets compressor loads during peak irradiance, enabling renewable substitution for grid electricity. Similar mechanisms were reported by Zohri et al. [1] and Wiriyasart and Kaewluan [23], who attributed 60-80% energy savings to combined solar utilization and waste heat recovery. The present study extends these results under real tropical conditions, achieving up to 94% reduction in grid electricity use—surpassing typical SAHP benchmarks due to continuous solar availability and high cooling demand in tropical climates. These thermodynamic and operational synergies also translate into measurable economic benefits, as supported by the techno-economic evaluation of PV-assisted heat pump systems by Icaza et al. [26], which reported comparable cost reductions under similar hybrid configurations.

Although absolute monetary savings are moderated by relatively low national electricity tariffs, relative efficiency improvements remain highly significant. Annual household savings of up to IDR 8 million were recorded, depending on capacity and mode. For smaller-capacity units such as 0.5 PK, the system approaches complete energy independence, virtually eliminating household reliance on PLN. Larger-capacity units (1–2 PK), while consuming more energy in absolute terms, deliver greater monetary savings over time due to the scale of hot water delivered. This dual adoption pathway reflects the versatility of the system: smaller households benefit from energy autonomy, while larger households or commercial facilities realize substantial financial returns through long-term operating cost reductions.

The results are in line with international literature that highlights the economic viability of hybrid SAHP and PV/T systems. Several studies have shown that the combination of renewable power and heat pump technology reduces operating expenditures and improves life-cycle cost-effectiveness for households [15, 16]. The particularly high cost savings in this study are further reinforced by Indonesia's tropical climate, where consistently strong irradiance ensures high PV yields, while high cooling demand guarantees continuous availability of condenser waste heat for recovery [6, 7].

In applied practice, the results confirm hybrid AC–PV water heating as a highly cost-effective solution. For low-capacity households, near-total grid independence minimizes vulnerability to tariff fluctuations and power outages. For higher-capacity applications, the absolute financial savings strengthen the economic rationale, particularly when supported by government incentives or net-metering schemes for rooftop PV adoption [16].

From a scientific perspective, the results validate hybrid system integration as an effective optimization pathway. By simultaneously exploiting the thermal dimension (waste heat recovery) and the electrical dimension (PV substitution), the hybrid HPWH achieves EUFs that are unattainable by conventional single-source systems. This conclusion is consistent with current trends in PV/T hybrid studies, which emphasize the superiority of dual-use strategies for sustainable residential energy solutions [1, 15].

Regarding societal and regulatory aspects, the implications are equally significant. At the household level, large-scale adoption could directly reduce peak electricity demand, thereby alleviating stress on national infrastructure during high-demand periods. In line with Indonesia's rooftop PV subsidy programs, hybrid HPWH systems can accelerate residential adoption of renewable energy technologies, contributing to the government's targets for expanding solar penetration while simultaneously lowering household energy costs [16].

In general, the energy consumption and cost analysis shows that hybrid HPWH systems provide compelling financial advantages in addition to technical and thermal benefits. With grid dependency reduced by about 94%, annual savings exceeding IDR 8 million, and scalability validated across capacities, hybrid AC–PV water heating emerges as a cost-effective and sustainable solution for both residential and small-scale commercial applications in tropical regions.

3.4 Economic viability: ROI and payback

The economic viability of the hybrid HPWH system was assessed using PP and ROI metrics, which together provide a comprehensive picture of financial feasibility. Across all operating modes, the results confirm that the system is not only technically sound but also financially attractive under Indonesian conditions.

For the HPWH–PLN configuration, the PP was estimated at 5.3 years, with an ROI of 383%. These values are consistent with regional reports on solar-assisted heat pumps (SAHP) in Southeast Asia, which typically document PP in the 4-6 year range, depending on system size and tariff structure [1, 4]. The relatively short PP reflects the efficiency advantage of heat pumps compared to resistive water heating, which directly consumes electricity without a performance multiplier.

Under PV-only operation (HPWH–PV), the PP extended slightly to 5.8 years, with an ROI of 350%. The longer PP arises from the additional upfront cost of PV modules, mounting structures, and storage components. However, the system still shows strong profitability, as PV electricity replaces nearly all grid demand, yielding substantial long-term energy independence.

The Hybrid PV–grid mode provided the most compelling ROI, reaching 824%, far above the 500-700% ROI typically reported for European SAHP installations [2, 5]. This notable outcome reflects the dual advantages of reducing dependence on the electrical grid while harnessing the abundant solar resources characteristic of tropical regions. However, the hybrid system required a longer PP of 8.2 years due to higher capital expenditure. This trade-off shows the financial dynamics of hybrid adoption: higher upfront investment can delay cost recovery but significantly enhances profitability over the system's lifetime.

A breakdown by capacity shows further nuance. The 0.5 PK unit achieved the shortest PP, attributed to its relatively low capital cost. However, its smaller baseline load limited absolute savings, reducing cumulative ROI. By contrast, the 2 PK unit delivered the highest ROI, driven by larger absolute energy savings despite a longer recovery time. This trend underscores the distinction between adoption pathways: smaller-capacity systems are attractive for households prioritizing rapid payback, while larger units suit multi-user households or small commercial facilities aiming for maximum long-term profitability.

These results are consistent with the techno-economic observations of Icaza et al. [26], who emphasized the importance of local conditions—including grid tariffs, PV investment scale, and component efficiency—in shaping ROI and PP outcomes. In Indonesia, relatively low electricity tariffs lengthen PP compared to regions with higher tariffs. However, the system's ability to substitute grid electricity with PV energy compensates for this limitation, boosting ROI through cumulative lifetime savings.

Operationally, the results validate hybrid AC–PV systems as flexible solutions for diverse user groups. Households with modest energy needs can achieve near-complete grid independence with smaller systems, while larger households or businesses can benefit from significant annual savings—up to IDR 8 million per year—through higher-capacity installations. Both pathways present attractive options depending on user priorities: short-term recovery versus long-term profitability.

In terms of performance analysis, the analysis highlights the importance of integrating ROI alongside PP in evaluating sustainable technologies. Payback alone may underestimate the long-term value of hybrid systems, particularly in tropical contexts where PV availability and AC loads are both consistently high. ROI analysis, which captures cumulative lifetime savings, offers a more complete measure of economic sustainability. This aligns with global trends in renewable energy economics, where lifecycle evaluations increasingly inform system design and policy [2, 5, 15].

From a policy perspective, the high ROI and favorable PP position of HPWH systems as promising candidates for inclusion in green financing mechanisms, carbon credit initiatives, and renewable energy subsidy programs. By combining financial returns with CO_2 emission reductions, hybrid adoption can support Indonesia's renewable energy targets and reduce household reliance on PLN during peak demand. Policy instruments such as rooftop PV subsidies and net-metering could further accelerate adoption, making hybrid systems a cornerstone of sustainable household energy strategies [16, 26].

A detailed comparison among the three AC capacities (0.5, 1, and 2 PK) reveals distinct trade-offs between cost and environmental performance. The 0.5 PK unit, with its lower capital and operational cost, achieved the shortest payback period (≈ 5.3 years) and the lowest daily grid electricity consumption, reaching near-complete energy independence under PV-only mode. However, its smaller load results in a lower absolute CO_2 reduction of around 2.1 tonnes per year. In contrast, the 2 PK system, while requiring higher upfront investment and longer payback (≈ 8.2 years), delivered the greatest total energy savings and emission reduction—up to 4.7 tonnes CO_2 annually—due to its higher heating load and continuous waste heat recovery. The 1 PK system represents an intermediate configuration, balancing moderate cost, energy savings, and sustainability impact. These results demonstrate that system capacity directly influences both financial and environmental performance: smaller systems offer faster economic returns, whereas larger systems maximize absolute decarbonization potential. Such capacity-based optimization aligns with findings by Icaza et al. [26] and Zohri et al. [1], who also reported that scaling in hybrid heat pump systems enhances total lifetime efficiency and emission reduction in proportion to compressor size.

The economic analysis validates the hybrid HPWH as both feasible and attractive, offering distinct benefits for different users. With ROI values up to 824% and PP as short as 5.3 years, the system shows clear financial advantages that complement its technical and environmental performance. These outcomes reinforce the hybrid HPWH as a scalable, sustainable solution for household and commercial energy use in tropical regions.

3.5 Environmental impact

The environmental performance of the hybrid HPWH system was highly significant when benchmarked against conventional electric resistance water heating. Based on Indonesia's official grid emission factor of 0.85 kg CO_2/kWh, a resistive water heater consuming 16 kWh/day emits approximately 13.6 kg CO_2/day. In contrast, the HPWH–PLN configuration reduced emissions to 4.7 kg CO_2/day, while the Hybrid PV–grid mode lowered emissions even further to only 0.8 kg CO_2/day, representing a 94% reduction. Under PV-only operation (HPWH–PV), emissions were eliminated, as the compressor was powered exclusively by renewable solar electricity.

When analyzed by capacity, the scalability of benefits becomes clear. At 0.5 PK, PV-only operation enabled near-total elimination of emissions, reflecting the lower load and higher likelihood of full PV substitution. For the 2 PK system, which still required partial grid support under hybrid operation, the largest absolute reductions were observed due to the higher baseline load. Specifically, shifting from 13.6 kg/day under resistive heating to 0.8 kg/day under hybrid mode avoided approximately 4.7 tonnes of CO_2 annually. To contextualize this impact, the reduction is equivalent to offsetting emissions from a gasoline vehicle traveling nearly 20,000 km per year [6].

These reductions are to be noted when compared with international benchmarks. Global SAHP literature typically reports 70–90% emission reductions [15], while the hybrid HPWH system in this study exceeded 94% in hybrid mode and achieved complete elimination in PV-only mode. The superior performance can be attributed to three main factors. First, the tropical solar resource in Pontianak (4.8 kWh/m²/day) ensured consistently high irradiance, enabling reliable PV operation [16]. Second, the prevalence of AC use in tropical households created substantial recoverable waste heat that would otherwise be rejected to the ambient environment [4]. Third, the inefficiency of resistive heating as a baseline amplified the relative benefits, as substitution with high-COP heat pumps led to disproportionately large emission reductions [7].

Environmentally, the results confirm that even small-scale hybrid systems yield significant environmental benefits. Households with modest demand can adopt 0.5 PK PVdominated systems for near-zero emissions, while 1–2 PK systems maximize absolute reductions suitable for multi-user households or small commercial facilities. Therefore, the adoption of hybrid AC–PV systems provides both micro-level household benefits and macro-level contributions to national decarbonization strategies.

From an innovation standpoint, this study provides empirical evidence that integrating PV electricity with AC waste heat recovery is an effective emissions mitigation pathway for tropical regions. By simultaneously leveraging renewable substitution and waste heat utilization, the system achieves higher EUF and a lower carbon footprint than either approach in isolation. This aligns with contemporary results emphasizing the importance of integrated renewable–mechanical systems in achieving deep household decarbonization [1, 15].

From a socio-economic perspective, the results strongly advocate for the integration of hybrid AC–PV systems into national climate and energy strategies. Indonesia's commitment to Net Zero Emissions by 2060 and its nationally determined contributions (NDCs) require household-level interventions to reduce electricity demand and carbon intensity. Hybrid water heating represents a viable entry point, targeting Indonesia's widespread AC ownership. Furthermore, linking such systems to carbon credit schemes, rooftop PV subsidies, or green financing initiatives could accelerate adoption by lowering upfront costs while rewarding emission reductions [26].

Prospective environmental assessments show that HPWH systems achieve superior performance in both relative and absolute emission reductions when compared with conventional benchmarks. With 94% reductions under hybrid operation and complete elimination under PV-only mode, the system shows a scalable and impactful pathway for household decarbonization. Its adoption would directly contribute to Indonesia's national climate goals and strengthen global efforts toward sustainable energy transitions.

In addition to the quantitative emission reductions, the proposed hybrid AC–PV HPWH system offers practical applicability for households and small businesses in tropical and hot-climate regions. In residential use, the system can be integrated with rooftop PV installations and existing split-type AC to provide simultaneous space cooling and water heating, effectively using waste heat that would otherwise be discharged to the environment. For small commercial facilities such as hotels, restaurants, or laundries with continuous cooling and hot-water demand, the system can operate year-round with minimal grid dependence. Large-scale adoption of such systems could substantially reduce household and commercial electricity consumption and lower CO_2 emissions, supporting national decarbonization policies in tropical countries.

4. CONCLUSIONS

In conclusion, this study experimentally evaluated a hybrid AC–PV heat pump water heater (HPWH) system under grid, PV-only, and PV–grid hybrid modes. The results confirmed strong heating performance across all modes, with PV-only operation achieving nearly the same water temperatures as grid supply and hybrid operation effectively reducing grid dependency. Larger AC capacities produced faster heating and higher COP.

Energy analysis showed that the hybrid system reduced daily grid consumption from 16 kWh (resistive heating) to as low as 0.95 kWh, resulting in annual savings exceeding IDR 8 million. Economic evaluation showed a PP of 5–8 years and an ROI up to 824%, confirming its financial viability under Indonesian conditions. Environmentally, the system reduced CO_2 emissions by up to 94% and eliminated them under PV-only operation, equivalent to offsetting a gasoline vehicle traveling 20,000 km per year.

In general, the hybrid AC–PV HPWH showed strong technical, economic, and environmental advantages, representing a practical and sustainable solution for household and small-scale water heating in tropical regions. The system can be readily implemented in residential and commercial buildings in tropical or hot-climate countries by integrating with existing split-type AC units and rooftop PV systems. The modular configuration enables simultaneous space cooling and water heating while reducing grid electricity use and carbon emissions. Large-scale adoption of such systems could significantly contribute to household-level decarbonization and national emission-reduction targets.

ACKNOWLEDGMENT

This work is supported by the Ministry of Higher Education, Science, and Technology of the Republic of Indonesia (Grant numbers: 132/C3/DT.05.00.PL/2025, 23/LL11/KM/2025, 113/II.3.AU.21/SP/2025).

REFERENCES

[1] Zohri, M., Prabowo, Suwarno, Fudholi, A., Suyono, T., Priandana, E.P., Utomo, Y.S. (2023). Performance review of solar-assisted heat pump systems using solar collectors, PV, and PVT technologies. International Journal of Heat and Technology, 41(3): 657-665. https://doi.org/10.18280/ijht.410318

[2] Kedar, S., Bewoor, A., Murali, G., More, G.V., Roy, A. (2024). Thermal analysis of sea water hybrid solar desalination system - an experimental approach. International Journal of Heat and Technology, 42(4): 1349-1358. https://doi.org/10.18280/ijht.420425

[3] Najaf, F., Aslan, S.R. (2024). Enhancing water purification in solar stills through incorporation of renewable energy technology: An experimental study on the efficiency and cooling mechanisms - A review. International Journal of Heat and Technology, 42(1): 101-110. https://doi.org/10.18280/ijht.420111

[4] Mainil, R.I., Afif, F., Arief, D.S., Mainil, A.K., Aziz, A. (2024). Performance comparison of photovoltaic (PV), heat pipe photovoltaic/thermal (HP-PV/T), and heat pipe solar thermal collectors (HP-STC): Energy analysis. International Journal of Heat and Technology, 42(3): 897-904. https://doi.org/10.18280/ijht.420318

[5] Paul, D., Devaprakasam, D., Patil, S., Agrawal, A. (2023). Floating solar: A review on the comparison of efficiency, issues, and projections with ground-mounted solar photovoltaics. International Journal of Sustainable Development and Planning, 18(10): 3213-3228. https://doi.org/10.18280/ijsdp.181021

[6] Mahmood, H.A., Salman, A.D., Mohammed, M.F. (2024). Estimating an indirect solar water heater's

performance under the latent heat of ethanol using a thermosiphon-riser collector. International Journal of Heat and Technology, 42(2): 541-548. https://doi.org/10.18280/ijht.420220
[7] Abdul-Ghafoor, Q.J., Ali, F.A.M.A., Hasan, W.K., Hammoodi, K.A., Majdi, H.S. (2024). Enhancing thermal efficiency in solar water heaters using reflective mirrors. International Journal of Design & Nature and Ecodynamics, 19(1): 31-39. https://doi.org/10.18280/ijdne.190104
[8] Al-Musawi, S.T.M., Elmnifi, M., Abdulrazig, O.D.H., Abdullah, A.R., Jassim, L., Majdi, H.S., Habeeb, L.J. (2024). Water heating rate as a function of magnetic field and electrical induction using solar energy. Mathematical Modelling of Engineering Problems, 11(2): 316-324. https://doi.org/10.18280/mmep.110204
[9] Reda, S.M.A.M., Mutasher, D.G., Hasan, W.K., Majdi, H.S., Alderoubi, N. (2024). Enhancing thermal efficiency in solar water heaters: The role of reflective walls. Mathematical Modelling of Engineering Problems, 11(4): 893-902. https://doi.org/10.18280/mmep.110406
[10] Abderrahmane, K., Mohammed, T., Houari, A., Abdeldjalil, D. (2019). Design and realization of an air solar heater and thermal measurement. Instrumentation Mesure Métrologie, 18(6): 595-602. https://doi.org/10.18280/i2m.180612
[11] Blaise, K.K., Magloire, K.E.P., Prosper, G. (2018). Thermal performance amelioration of flat plate solar collector of an indirect dryer. Mathematical Modelling of Engineering Problems, 5(4): 341-347. https://doi.org/10.18280/mmep.050410
[12] Chekchek, B., Salmi, M., Boursas, A., Lorenzini, G., Ahmad, H., Menni, Y., Ameur, H., Merrah, M., Fridja, D. (2021). Experimental study of the efficiency of a solar water heater construction from recycled plastic bottles. International Journal of Design & Nature and Ecodynamics, 16(2): 121-126. https://doi.org/10.18280/ijdne.160201
[13] Zakariazadeh, A., Ahshan, R., Al Abri, R., Al-Abri, M. (2024). Renewable energy integration in sustainable water systems: A review. Cleaner Engineering and Technology, 18: 100722. https://doi.org/10.1016/j.clet.2024.100722
[14] Reda, S.M.A.M., Hussein, M.A.M., Hadi, J.M., Al-Asadi, H.A., Hammoodi, K.A., Ayed, S.K., Majdi, H.S. (2024). Optimizing tilt angle for thermal efficiency of vacuum tube solar collectors. International Journal of Energy Production and Management, 9(1): 57-64. https://doi.org/10.18280/ijepm.090107
[15] Prakash, R., Meenakshipriya, B., Vijayan, S., Kumaravelan, R. (2020). Performance evaluation of a solar PV/T water heater integrated with inorganic salt based energy storage medium. Journal of New Materials for Electrochemical Systems, 23(3): 213-220. https://doi.org/10.14447/jnmes.v23i3.a09
[16] Kadhim, S.A., Al-Ghezi, M.K.S., Shehab, W.Y. (2023). Optimum orientation of non-tracking solar applications in Baghdad city. International Journal of Heat and Technology, 41(1): 125-134. https://doi.org/10.18280/ijht.410113
[17] Akhmetshin, A., Tuhvatullin, M., Atnagulov, D., Linenko, A., Khalilov, B. (2021). Improving the efficiency of stand-alone solar PV power plants. International Journal of Sustainable Development and Planning, 16(3): 403-412. https://doi.org/10.18280/ijsdp.160301
[18] Prasetyo, S.D., Arifin, Z., Prabowo, A.R., Budiana, E.P., Mohd Rosli, M.A., Alfaiz, N.F., Bangun, W.B. (2023). Optimization of photovoltaic thermal collectors using fins: A review of strategies for enhanced solar energy harvesting. Mathematical Modelling of Engineering Problems, 10(4): 1235-1248. https://doi.org/10.18280/mmep.100416
[19] Abdullah, F.S., Mohammed, R.A., Hameed, F.I. (2022). Thermal design developing for steam power plants by using Concentrating Solar Power (CSP) technologies. Journal Européen des Systèmes Automatisés, 55(5): 615-621. https://doi.org/10.18280/jesa.550506
[20] De Angelis, A., Libralato, M., Corazza, G., Saro, O. (2020). Optimization of the configuration of photovoltaic and solar thermal collectors in a nearly zero energy building. TECNICA ITALIANA-Italian Journal of Engineering Science, 64(2-4): 179-185. https://doi.org/10.18280/ti-ijes.642-408
[21] Khan, S.I., Al Dodaev, Z., Haque, A. (2024). The integration of renewable energy sources into mechanical systems, focusing on efficiency and reliability-a case study. Control Systems and Optimization Letters, 2(2): 172-177. https://doi.org/10.59247/csol.v2i2.92
[22] Al-Tahaineh, H.A. (2023). Exergy analysis of a simple solar still augmented with a flat-plate solar collector. Mathematical Modelling of Engineering Problems, 10(2): 647-652. https://doi.org/10.18280/mmep.100235
[23] Wiriyasart, S., Kaewluan, S. (2024). Waste heat recovery of air conditioning on thermal efficiency enhancement of water heater. Thermal Science and Engineering Progress, 47: 102296. https://doi.org/10.1016/j.tsep.2023.102296
[24] Znaczko, P., Chamier-Gliszczynski, N., Kaminski, K. (2025). Experimental study of solar hot water heating system with adaptive control strategy. Energies, 18(15): 3904. https://doi.org/10.3390/en18153904
[25] Satpute, J., Ghongade, G., Petrů, J., Campli, S., et al. (2025). Computational study on water based hybrid photovoltaic systems with different absorber configurations. Scientific Reports, 15(1): 1226. https://doi.org/10.1038/s41598-024-82690-3
[26] Icaza, D., Arévalo, P., Jurado, F. (2025). Techno-economic analysis of an air–water heat pump assisted by a photovoltaic system for rural medical centers: An ecuadorian case study. Applied Sciences, 15(12): 6462. https://doi.org/10.3390/app15126462

NOMENCLATURE

IDR	Indonesian Rupiah
T1	Compressor Temperature (°C)
T2	Condenser Temperature (°C)
Tw	Water Temperature (°C)

Abbreviations

AC	Air Conditioner
ATS	Automatic Transfer Switch
CFD	Computational Fluid Dynamics
COP	Coefficients Of Performance
CPC	Compound Parabolic Concentrators

CSP	Concentrated Solar Power
EUF	Energy Utilization Factor
ETC	Evacuated Tube Collectors
GHG	Greenhouse Gas
HPWH	Heat Pump Water Heater
NDCs	Nationally Determined Contributions
PCM	Phase Change Material
PK	Paardekracht
PLN	Perusahan Listrik Negara (Indonesia's state-owned electricity utility/the national grid)
PP	Payback Period
PTC	Parabolic Trough Collector
PV	Photovoltaic
PV/T	Photovoltaic/Thermal
RMSD	Root Mean Square Deviation
ROI	Return Of Investment
SAHP	Solar-Assisted Heat Pump