Performance Optimization of Photovoltaic-Thermal Systems toward Enhanced Dual Energy Production for Building Integration

IMAD LAABAB[1,*], SAID ZIANI[2], ABDELLAH BENAMI[1], YOUSSEF AGREBI ZORGANI[3]
[1]Department of Engineering Sciences, Faculty of Sciences and Techniques-Errachidia (FSTE),
Moulay Ismail University of Meknes (UMI),
FSTE, 52000, Errachidia, Morocco.
MOROCCO.

[2]ENSAM, Mohammed V University of Rabat (UMV),
ENSAM, B.P. 6207, 10100, Rabat, Morocco.
MOROCCO.

[3]Laboratory of Sciences and Techniques of Automatic control & computer engineering (Lab-STA),
National School of Engineering of Sfax,
University of Sfax, Postal Box 1173, 3038 Sfax, Tunisia.
TUNISIA.

[*]*Corresponding author.*

Abstract: - Photovoltaic-thermal (PVT) systems overcome a basic constraint of traditional solar modules by collecting both electricity and usable heat energy from a single integrated collector. In this work, an air-cooled PVT system optimized by coupled thermal-electrical analysis and constrained multi-objective optimization is designed, modeled, and experimentally validated. By prolonging coolant residence time and upsetting thermal boundary layers, the collector's six-baffle flow disruptor shape improves convective heat transfer. The optimized configuration raised electrical efficiency from 12.1% to 15.3% (+26.5%) and stabilized power output at 156.2 W while lowering photovoltaic cell temperature by 8.2°C compared to an uncooled reference under representative operating conditions (623 W/m² solar irradiance, 30°C ambient temperature). At the same time, airflow was used to extract 91.6 W of low-grade thermal energy (0.004167 kg/s), resulting in a system efficiency of 24.6%. A 100 m² array in a Mediterranean climate is expected to generate 12,000 kWh of electricity and 45,000 kWh of thermal energy annually. For residential and light-commercial applications where maintenance simplicity and envelope compatibility are more important than maximum thermal density, the air-cooled architecture offers a practical solution by removing the hydraulic complexity, freeze risk, and scaling management present in liquid-based alternatives. Predictive accuracy within 4% root-mean-square error throughout transient and steady-state regimes was demonstrated by model validation against experimental data. These results show that air-cooled PVT collectors can achieve balanced polygeneration performance with low operational overhead by co-optimizing absorber shape, flow dynamics, and insulation approach.

Key-Words: - Photovoltaic-Thermal Systems, Air-cooled collector, multi-objective optimization, Thermal-electrical coupling, Heat transfer enhancement, Flow disruptor, Electrical efficiency • Thermal energy recovery, Experimental validation, Sustainable building systems.

Received: July 11, 2025. Revised: October 29, 2025. Accepted: November 29, 2025. Published: May 25, 2026.

1 Introduction

PVT systems combine PV cells and thermal absorbers in one package to generate electric power and collect heat from the sun at the same time. The cells are normally semiconductor materials, for example, silicon; sunlight falling on them activates the photovoltaic effect and converts it into electric power. Much of the light that falls on the cells gets absorbed as heat; high temperatures raise such PV cells' temperatures, hence reducing their efficiency in converting electricity (Fig.1).

To solve this problem, PVT systems put thermal absorbers beneath or around the PV cells to gather and move this extra heat. Normally, a liquid, such as water or air, that flows through tubes into the thermal absorber helps this transfer happen. Many applications for the collected thermal energy are possible, such as industrial work, room heating, and water heating. PVT systems improve the application of solar energy that is already available, reduce losses of efficient heat in PV cells, and increase total energy efficiency [1].

The objective of this study is to improve the efficiency of PV modules by developing and optimizing a system for producing thermal and electrical energy. Conventional PV systems lose their efficiency because built-up heat does not get exhausted. PVT systems increase total energy efficiency as they capture this waste heat and give it value through the integration of thermal management solutions. The goal of this endeavor is to design, develop, and improve a PVT system that would perform better than traditional PV or thermal systems and contribute to more sustainable, efficient solar solutions.

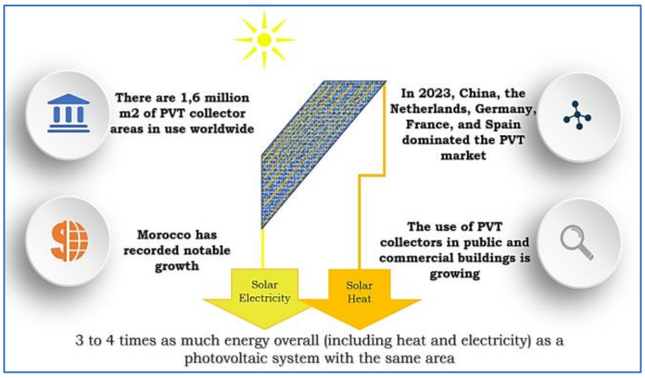

Fig. 1. Hybrid solar technology at a glance (Source: created by the authors).

PVT systems are categorized into three major types according to the medium employed for the capturing and conveying of thermal energy: air, water, and hybrid systems. Every type possesses particular characteristics concerning application and efficiency that aim towards specific energy requirements under given environmental conditions [2], [3].

They have to manage an electric-thermal efficiency trade-off, which is quite delicate. While increasing heat capture can increase overall energy efficiency, electrical performance may be compromised. The imbalance results from solar cells' high temperatures, which lower their electrical conversion efficiency. In other words, optimizing thermal capture as well as maintaining cell temperature constitutes a design challenge.

Thermal extraction should be well calibrated such that excessively cooling the photovoltaic cells does not reduce their electrical efficiency. A careful balance between these two competing demands, heat and electricity, is what makes energy production maximize as a whole. Well-designed PVT systems ensure optimum management of heat, thus guaranteeing stable and efficient performance for both forms of energy [4].

In all, thermal management plays a key role in the viability of PVT systems. Appropriate temperature conditions for the photovoltaic cells, coupled with maximum heat extraction, would permit the evolution of systems that could achieve optimum overall energy efficiency without compromising electrical efficiency or the capture of heat.

2 Methods

Optimization methods and approaches

1- System Design Optimization

The design of a PVT system is maximized for both electrical and thermal efficiencies by appropriately choosing the material for absorbers and cooling fluids, along with maximizing the structural design of the system towards effective heat transfer, insulation, and energy losses [5]. The optimization of the system considers the optimum interaction of all its parts-photovoltaic cells, thermal absorber, and mechanisms for cooling, which ultimately bring out the performance and efficiency of the system as a whole. The paper, therefore, highlights two important facets in the optimization of system design: material selection and structural design.

The material for the thermal absorber and the cooling fluids, on one hand, controls the efficiency of a PVT system in its function towards heat capture and transfer, alongside ensuring that there is no interference with the electrical output of the photovoltaic cells [6].

The thermal absorber material and the cooling fluids (e.g., water or air), as they control PVT system efficiency in its function related to heat capture and transfer, ensure that there is no interference with the electrical output of the photovoltaic cells. Some key materials used for absorbers are presented in Table I.

Table I
Comparison Of Absorber Materials And Coatings Used In PVT Systems (Source: Created By The Authors).

Absorber Materials	Description	Advantages	Disadvantages

Metals	Materials like aluminum and copper are used for their excellent thermal conductivity.	- Copper: High heat transfer efficiency, durability, better performance at high temperatures. - Aluminum: Lightweight, lower cost, sufficient heat transfer properties.	- Copper: Heavier, more expensive. - Aluminum: Less durable, lower performance at high temperatures.
Ceramics and Composites	Advanced materials are used for extreme temperature handling, thermal expansion resistance, and better corrosion resistance in humid or saline environments.	- High durability. - Resistance to corrosion and thermal expansion.	- Lower thermal conductivity compared to metals. - Less frequently used as standalone absorbers.
Black Coatings	Coatings are applied to metal absorbers to increase solar radiation absorption and heat capture efficiency.	- High absorptive capacity. - Durable under high temperatures and harsh solar conditions.	- Performance depends on coating quality. - It may degrade over time with prolonged exposure.

In photovoltaic-thermal (PVT) collectors, the choice of absorber material directly affects heat recovery and long-term dependability. Copper remains the reference choice in liquid-based systems where consistent high-temperature operation is expected. Field tests on flat-plate PVT units in central Europe showed copper absorbers maintaining stable thermal output over five heating seasons, whereas comparable aluminum units exhibited gradual efficiency loss linked to micro-cracking at brazed joints after repeated thermal cycling above 70 °C. Nevertheless, aluminum has gained traction in lightweight roof-integrated designs where structural loading is a constraint. Manufacturers have addressed their lower temperature tolerance by integrating thermal break features and limiting maximum fluid temperatures through control strategies.

Despite being less popular, ceramic-based absorbers show promise in specialized applications. While silicon nitride-coated substitutes-maintained surface integrity with little corrosion indicators, stainless steel absorbers in coastal installations exposed to salt-laden air had obvious pitting within three years. Similarly, composite absorbers with carbon fibers in a ceramic matrix showed better resilience to fatigue failure than monolithic metal sheets in areas with large daily temperature fluctuations. Cost and the requirement for specific joining methods to interact with traditional piping continue to be barriers to their widespread use.

Surface coatings substantially affect optical performance. The average solar absorptance of uncoated copper or aluminum is between 0.80 and 0.85. This can be raised to roughly 0.92–0.94 by using matte black paint, although these coatings frequently have higher thermal emittance (>0.80), which increases radiative losses at high temperatures. In the operational range of 50–120 °C, selective coatings can concurrently provide absorptance above 0.95 and thermal emittance below 0.15. Coating adhesion and microstructure stability become crucial after several thousand hours of heat cycling, according to accelerated aging testing. The absorber serves as the thermal interface between the liquid, air, or hybrid heat transfer fluid and the photovoltaic lamination.

Under real-world environmental pressures, its material qualities must strike a compromise between mechanical robustness and quick heat extraction. Compatibility between absorber material, coating system, and heat transfer fluid further determines system longevity. Common heat transfer fluids used in PVT applications are summarized in Table II.

TABLE II
Comparison of cooling fluids used in PVT SYSTEMS
(Source: created by the authors)

Cooling fluids	Description	Advantages	Disadvantages
Water	High specific heat capacity allows absorption and storage of significant heat before the temperature rises. Commonly used in domestic heating applications.	- High thermal energy capture efficiency. - Well-suited for domestic heating.	- Requires careful management to avoid scaling, corrosion, or freezing in cold climates.
Air	Uses forced or natural airflow for	- Simple design and maintenance.	- Lower heat transfer efficiency

	cooling. It has a lower specific heat capacity than water, but is simpler and cheaper to maintain.	- No issues with freezing or corrosion. - Ideal for space heating or ventilation.	compared to water-based systems [7].
Hybrid Fluids	Combines air and water to optimize heat output and ensure thermal and electrical efficiency under various scenarios.	- Combines the advantages of both air and water cooling. - Flexible for different operational needs.	- More complex system design and management.

In PVT systems, fluid selection reflects a trade-off between end-use requirements, climate constraints, and thermodynamic performance. Superior heat extraction is provided by water-based circuits; field data from installations in central Europe show PV temperature reductions of 25–35 °C below ambient air-cooled equivalents under 800 W/m² irradiation. A 30% propylene glycol mixture, which is required for −15 °C protection in alpine regions, reduces the fluid's specific heat to ~3.3 kJ/kg·K and increases viscosity, necessitating larger pumps and lowering net electrical output by 2-4% due to parasitic loads.

Air cooling avoids fluid management entirely but demands careful aerodynamic design. In a monitored installation in southern Spain, a serpentine air channel with 15 mm depth and 3 m/s mean velocity achieved only 12 °C PV temperature reduction under peak sun, versus 28 °C for a comparable water-cooled unit. However, it was better for seasonal-use structures when winter operation was not required because there was no risk of freezing. Notably, air systems function better in low-humidity settings; within three years, condensation inside ducts has caused corrosion in galvanized steel components in coastal locations with high ambient moisture.

In contrast, the physical configuration of a PVT system's components is related to its structural design. such as the PV modules' thickness, the thermal absorber's dimensions and location, and the addition of thermal insulation. Each of these parameters plays a role in ensuring that the system operates efficiently and remains durable over time (Table III).

TABLE III
key design parameters for optimizing pvt system performance (source: created by the authors)

Parameter	**Description**	**Advantages**	**Disadvantages**
Module Thickness	Impacts electrical efficiency and thermal performance. Thicker modules may improve light absorption but can trap heat, leading to overheating and reduced efficiency. Thin-film technologies can reduce thickness, minimizing heat buildup and refining performance.	- Increased light absorption with thicker modules. - Thin-film reduces weight and minimizes heat buildup.	- Thicker modules increase internal thermal resistance, risking overheating and reduced efficiency.
Absorber Size	Determines the amount of heat captured. Larger absorbers enhance thermal energy production but may excessively cool PV cells, reducing electrical efficiency. Placement is crucial to avoid sunlight obstruction or interference with PV cell connections.	- Larger absorbers improve thermal energy capture. - Proper placement ensures balance between thermal and electrical output.	- Oversized absorbers can reduce sunlight reaching PV cells, impacting electrical efficiency.
Thermal Insulation	Prevents heat loss, ensuring captured energy is retained for use. Materials like polyurethane foam or reflective foils minimize heat loss and are designed to withstand environmental stresses and long-term use.	- Enhances thermal efficiency. - Reduces energy loss and operational costs.	- Poor insulation results in heat loss, reducing efficiency. - Must be durable and resistant to environmental factors.

Because design parameters interact nonlinearly, improving a single variable alone frequently results in a decline in system performance. This is amply demonstrated by module thickness. In a PVT prototype, reducing glass thickness from 4 mm to 3.2 mm reduced thermal resistance by 18% and cell temperature by 6 °C. However, the thinner substrate increased vulnerability to hail impact, resulting in microcracks in 7% of modules following a single storm event in a Swiss field trial. On the other hand, over-engineering thickness for mechanical safety traps heat: in a sun-rich area, a 5 mm front glass with conventional EVA lamination increased operating temperature by 9 °C compared to a 3.2 mm low-iron option, reducing electrical production by about 4.5% yearly.

Beyond just coverage ratios, absorber sizing necessitates spatial knowledge. In a Dutch social housing project, absorber plates initially extended to the module edges to maximize thermal collection. Within 18 months, thermal imaging revealed cold spots directly beneath the absorber's perimeter where it overlapped module framing. Potential-induced deterioration (PID) was accelerated by these zones, which produced temperature differences between individual cells that exceeded 15 °C. The updated design eliminates hot/cold cell mismatches and stabilizes electrical output while sacrificing 4% thermal collection area by insetting the absorber by 20 mm from all sides.

Climate and mounting orientation must be taken into consideration when designing an insulation strategy. In Scandinavia, 50 mm polyurethane backing is used for vertical façade-integrated PVT units since rear-side losses predominate in temperatures below −10 °C. In North African roof-mounted systems, the same thickness proves to be overkill since trapped heat boosts absorber temperature without improving effective output and adds needless weight.

Due to dominating front-side radiative losses, localized field testing in Tunisia revealed that 20 mm insulation achieved 92% of the thermal efficiency of 50 mm at half the mass, with no discernible gain beyond 25 mm. In the end, integrated design, where absorber material, fluid selection, and geometric characteristics are co-optimized for the target climate and application, produces high-performing PVT systems. A water-cooled copper absorber with selective coating may deliver excellent thermal output in a temperate climate, but the same configuration in a freeze–thaw environment demands glycol admixture and insulation adjustments that alter the entire energy balance. Similar to this, crystalline silicon on a sturdy copper manifold is better suited for permanent residential systems that need a 25-year service life, whereas thin-film PV on a lightweight aluminum absorber is better suited for portable or temporary installations. Whether a PVT system fulfills its twin promise of simultaneous electrical and thermal generation depends on how these decisions interact.

2- Operational Optimization

Operational management is critical for getting the highest potential efficiency and performance from PVT systems. This entails controlling the electrical and thermal outputs to ensure that the system functions at the best temperatures for generating energy and recovering excess heat for reuse. Cooling mechanisms and control strategies are critical to attaining operational optimization because they ensure that the system's performance adapts to changing environmental circumstances.

i- Cooling mechanisms

Cooling mechanisms become crucial in achieving the optimal operating temperature for photovoltaic cells in a PVT system, since high temperatures will reduce the efficiency of the PV cells. Thus, effective cooling strategies are essential for maintaining electrical efficiency and improving thermal energy capture [8]. The systems can be classified into active cooling and passive cooling systems, wherein each classification has its own set of advantages and trade-offs (Table IV).

TABLE IV
comparison of active and passive cooling techniques for pvt systems (source: created by the authors).

Cooling Technique	Description	Advantages	Disadvantages
Active Cooling	Requires external energy input for heat removal.	- High cooling efficiency. - Better control over temperature management.	- Energy-intensive. - Higher system complexity and maintenance.
Water Flow Adjustment	Adjusts cooling fluid flow rate to control heat transfer.	- Improves heat extraction and electrical efficiency.	- High flow rates increase pumping power, reducing overall efficiency.
Forced Air Circulation	Uses fans or blowers to force air over PV modules for heat dissipation.	- Efficient during intense sunlight. - Can double as space heating.	- Consumes additional electrical power.

Active Heat Pumps	Transfers heat from PV modules to a heat sink or storage using heat pumps.	- It optimizes both electrical and thermal energy outputs.	- High energy consumption and cost.
Passive Cooling	Relies on natural processes for heat dissipation without energy input.	- Cost-effective and environmentally friendly.	- Less precise temperature control.
Natural Convection	Heat dissipation through rising hot air is replaced by cooler surrounding air.	- Simple and low-cost. - Works well in low ambient temperatures.	- Less effective in high ambient temperatures.
Thermal Mass/Heat Sinks	High thermal mass materials absorb and release heat, while heat sinks passively draw heat away.	- Stable temperature regulation. - No energy input is required.	- Limited cooling capacity. - Bulky and adds weight to the system.
Phase-Change Materials (PCMs)	Substances absorb/release large amounts of heat during phase changes, stabilizing temperature [9].	- Efficient temperature stabilization. - Reduces temperature spikes affecting PV performance.	- Adds complexity and cost to system design.

ii- Control strategies

Control strategies are necessary for the dynamic management of temperature and cooling mechanisms as well as energy flows in the system based on real-time conditions, which include ambient temperature, solar radiation, and electrical demand. Adaptive control systems allow the PVT system to optimize its performance by adapting parameters such as fluid flow rate and cooling fan speed, in addition to thermal energy storage [10]. The aim is to maximize both electrical and thermal outputs without compromising one for the other (Table V).

TABLE V
summary of adaptive control features and strategies in pvt systems (source: created by the authors).

Control Feature	Function	Key Benefits	Considerations
Temperature Monitoring and Adjustment	Uses sensors to monitor temperatures on PV cells, thermal absorbers, and cooling fluids. Adjusts cooling mechanisms based on temperature thresholds.	- Prevents overheating and efficiency loss. - It conserves energy during low solar radiation.	- Requires precise sensor calibration. - Dependent on real-time system responsiveness.
Dynamic Fluid Flow Control	Adjusts the flow rate of cooling fluids (water, air, or hybrids) based on sunlight intensity and ambient temperature.	- Optimizes heat removal during high radiation. - Saves energy by reducing flow in cooler periods.	- Balancing flow rates to avoid overcooling or excess energy use.
Energy Storage Management	Manages thermal and electrical energy storage efficiently. Excess heat stored in tanks or used for heating; electrical energy stored or sent to the grid.	- Ensures efficient energy use based on demand. - Provides consistent output without waste.	- It requires integration with storage infrastructure. - Balancing thermal and electrical demands effectively.
Forecasting and Predictive Control	Predicts conditions using weather data, historical performance, and system parameters. Adjusts proactively for seasonal and daily changes.	- Prepares the system for environmental changes. - Optimizes performance year-round.	- It depends on accurate forecasting algorithms. - May require advanced software and computational resources.
Integration of Control Strategies	Synchronizes cooling mechanisms with energy demands, prioritizing thermal or electrical energy based on the application.	- Flexible and efficient use of energy for different scenarios.	- Complex system design and control coordination.

The optimization of PVT systems relies heavily on effective cooling mechanisms and intelligent control strategies. Active cooling methods, such as flow rate modification and forced air circulation, can help regulate the temperature of PV cells and thermal absorbers, whilst passive approaches, including natural convection and phase-change materials, offer more energy-efficient options. Meanwhile, adaptive control systems that modify in real time based on external variables ensure that the system functions at peak efficiency by balancing electrical and thermal outputs [11]. These measures work together to ensure that the PVT system is efficient and reliable, achieving both energy production and sustainability objectives.

3- Computational Methods

Computational methods provide a simulation and optimization framework for PVT systems, enabling the efficient integration of photovoltaic and thermal energy components to maximize performance and energy output (Tables VI).

TABLE VI
Simulation models (source: created by the authors).

Category	Purpose	Key Features
Computational Fluid Dynamics (CFD)	Predict fluid behavior within PVT cooling systems and heat exchangers.	- Heat transfer (convection, conduction, radiation). - Fluid flow dynamics. - Temperature distribution.
Thermal-Electrical Simulations	Model both electrical and thermal performance of the system.	- Electrical efficiency vs. temperature. - Thermal management strategies. - Coupled heat and power analysis.

Computational methods constitute the core of design and optimization for PVT systems. Among these, simulation models, particularly CFD and thermal-electrical simulations, serve as tools for system performance prediction and pre-prototype analysis. Equally important are optimization algorithms that include GA, ML-based approaches, and PSO to provide more elegant mechanisms for seeking optimum configurations with appropriate compromise, considering electrical and thermal output. With such computational methods, PVT systems may be optimized to the extent that real-world applications attain maximal efficiency as well as decreased energy costs and improved sustainability.

2.1 Governing Energy Balance Equations

The photovoltaic-thermal (PVT) system is modeled through coupled thermal-electrical energy balance equations that account for all energy pathways within the system. Under steady-state assumptions justified by the system's thermal time constant ($\tau \approx 300$ s) being significantly shorter than diurnal solar variation periods, the energy balance for the PV cell layer is expressed as:

$$G \cdot \alpha \cdot A = G \cdot \alpha \cdot \eta_{el}(T_{cell}) \cdot A + Q_{conv} + Q_{rad} + Q_{cond} + Q_{fluid} + Q_{refl} \quad (1)$$

Electrical output Thermal pathways

where:
- G = solar irradiance (W/m²)
- α = solar absorptance of PV surface (≈0.92 for monocrystalline Si with anti-reflective coating)
- A = active surface area (1.62 m²)
- η_{el} (T_{cell}) = temperature-dependent electrical efficiency (Eq. 3)
- Q_{refl} = G.(1- α).A = reflected energy loss

The thermal absorber plate beneath the PV layer satisfies a separate balance:

$$Q_{cond} = Q_{fluid} + Q_{loss,abs} \quad (2)$$

where $Q_{loss,abs}$ represent conductive losses through insulation to ambient.

2.2. Explicit Heat Transfer Modelling with Loss Mechanisms

Convective losses from the PV front surface to ambient air are modelled using Newton's law of cooling with forced convection correlation:

$$Q_{conv} = h_{conv} \cdot A \cdot (T_{cell} - T_{amb}) \quad (3)$$

The convective heat transfer coefficient h_{conv} is derived from Nusselt number correlations for external flow over flat plates:

$$Nu_L = h_{conv} L = 0.037 \, Re_L^{\ 0.8} Pr^{\ 1/3} \quad \text{for } Re_L > 5\times10\ 5 \quad (4)$$

where $Re_L = \frac{\rho_{air} v_{wind} L}{\mu_{air}}$, $Pr = \frac{\mu_{air} c_{p,air}}{k_{air}}$, and characteristic length $L = 1.645$ m. For natural convection conditions ($v_{wind} < 0.5$ m/s), the correlation $Nu = 0.68 + \frac{0.67 Ra_L^{1/4}}{[1+(0.492/Pr)^{9/16}]^{4/9}}$ is applied.

-**Radiative losses** to the sky are modeled using the Stefan-Boltzmann law with effective sky temperature approximation:

$$Q_{rad} = \varepsilon\sigma A(T^4_{cell} - T^4_{sky}),\ T_{sky} = T_{amb}[0.37 + 0.63\ (P_{vap}/P_{atm})^{1/4}]^{1/4} \quad (5)$$

where $\varepsilon = 0.88$ (emissivity of tempered glass cover), $\sigma = 5.67 \times 10^{-8}$ W/m^2K^4, and P_{vap} is water vapor partial pressure.

Conductive losses through the PV laminate to the absorber plate follow Fourier's law:

$$Q_{cond} = k_{lam} \times A / \delta_{lam} \times (T_{cell} - T_{abs}) \quad (6)$$

With $k_{lam} = 0.21$ W/m·K (EVA encapsulant thermal conductivity) and $\delta_{lam} = 0.76$ mm (total laminate thickness).

-Fluid heat extraction for the air-cooled configuration is:

$$Q_{fluid} = \dot{m}\, c_{p,air} (T_{out} - T_{in}) = h_{int} A_{int} \Delta T_{lm} \quad (7)$$

where the internal convection coefficient h_{int} for flow through baffled channels is determined from Dittus-Boelter correlation modified for rectangular ducts with hydraulic diameter $D_h = 4Ac/P$:

$$Nu_{Dh} = 0.023 Re^{0.8}_{Dh} Pr^{0.4} (1 + 1.4\, b/a),\ Re_{Dh} = \rho_{air} v_{air} D_h / \mu_{air} \quad (8)$$

with aspect ratio b/a = 0.03/0.02 = 1.5 for the baffle geometry.

2.3. Temperature-Dependent Electrical Efficiency Model

The electrical efficiency degradation with temperature is modelled as:

$$\eta_{el}(T_{cell}) = \eta_0 [1 - \beta (T_{cell} - T_{ref})] \quad (9)$$

where $\eta_0 = 0.15$ (reference efficiency at STC: T_{ref} = 25°C, G = 1000 W/m²), and β = 0.0038 K^{-1} (temperature coefficient for monocrystalline silicon).

The instantaneous electrical power output is:

$$P_{el} = G \cdot A \cdot \eta_{el}(T_{cell}) \quad (10)$$

2.4. Formal Optimization Problem Formulation

The PVT system optimization is formulated as a constrained multi-objective problem:

maximize **X** : $\eta_{total}(\mathbf{x}) = \eta_{el}(\mathbf{x}) + \eta_{th}(\mathbf{x})$

subject to : $T_{cell}(\mathbf{x}) \leq 65°C$

(electrical safety constraint)

$\dot{m}_{min} \leq \dot{m} \leq \dot{m}_{max}$

(hydraulic constraints)

$\theta_{tilt} \in [0°, 90°]$

(geometric constraint)

$C_{total}(\mathbf{x}) \leq C_{budget}$ (economic constraint)

(11)

where the decision vector is $\mathbf{x} = [\theta_{tilt}, \dot{m}, N_{baffles}, \delta_{ins}]^T$ containing tilt angle, mass flow rate, baffle count, and insulation thickness. Alternative formulations include:

- **Exergy optimization**: max $\Psi_{total} = \Psi_{el} + \Psi_{th}$ with $\Psi_{th} = Q_{fluid}\left(1 - \frac{T_0}{T_{fluid,avg}}\right)$
- **Multi-objective Pareto optimization**: max$[\eta_{el}, \eta_{th}]$ solved via NSGA-II to obtain trade-off front.

The optimization was solved using a hybrid approach: Particle Swarm Optimization (PSO) with inertia weight w = 0.7298, cognitive/social coefficients $c_1 = c_2 = 1.49618$, swarm size = 50, and 200 iterations to locate the global optimum, followed by Sequential Quadratic Programming (SQP) for local refinement.

2.5. System Specifications and Boundary Conditions

PV Module Specifications:

- Dimensions: 1645 mm (L) × 985 mm (W) × 35 mm (H); active area A = 1.62 m²
- Electrical (STC) : P_{max} = 275 W, V_{mpp} = 31.8 V , I_{mpp} = 8.65 A, η_0=15%
- Temperature coefficient: β= 0.0038 K^{-1}

Thermal Collector Configuration:

- Absorber plate: Galvanized steel, δ= 1 mm, k = 54 W/m·K, ρ = 7700 kg/m³, cp = 435 J/kg·K
- Baffles: Wood (k = 0.042 W/m·K), dimensions 800 × 20 × 30 mm³ ; configurations tested: $N_{baffles}$ ={0, 4, 6, 9}
- Insulation: Expanded polystyrene, δ= 30 mm, k = 0.035 W/m·K

Cooling Fluid Properties (Air):

- ρ= 1.22 kg/m³, cp = 1012 J/kg·K, k = 0.0242 W/m·K, μ= 1.85 times 10^{-5} Pa·s
- Mass flow rates tested: ṁ={0.002778, 0.004167}kg/s (corresponding to air velocities 2.1–3.2 m/s)
- Inlet temperature: $T_{in} = T_{amb}$

Environmental Boundary Conditions:

- Solar irradiance range: G = 536–866 W/m² (measured via luxmeter calibrated to pyranometer)
- Ambient temperature: T_{amb} = 28–33C°
- Wind speed: v_{wind} = 0.5–2.5 m/s (natural convection dominant)
- System orientation: True south azimuth, tilt angle θ=30 °

Instrumentation and Validation:

- Temperature: K-type thermocouples (±0.5°C accuracy) at 8 locations on PV rear surface
- Electrical: Digital multimeters (±0.2% accuracy) for V_{oc}, I_{sc}, V_{mpp}, I_{mpp}

- Airflow: Hot-wire anemometer (±2% accuracy) at channel inlet/outlet
- Irradiance: Calibrated silicon photodiode sensor (±3% accuracy)

2.6. Simulation Methodology

Transient thermal-electrical simulations were performed using a custom MATLAB/Simulink model solving the coupled differential equations:

$$C_{th,PV}\, dT_{cell} /dt = G\alpha A(1-\eta_{el}) - Q_{conv} - Q_{rad} - Q_{cond}$$
$$C_{th,abs}\, dT_{abs} /dt = Q_{cond} - Q_{fluid} - Q_{loss,abs} \qquad (12)$$

with thermal capacitances $C_{th,PV}$ = 1850 J/K and $C_{th,abs}$ = 920 J/K derived from material properties and geometry. Time integration used 4th-order Runge-Kutta with Δt=1s over 3600 s duration. Initial condition: $T_{cell}(0) = T_{amb} + 10°C$. Model validation against experimental data yielded RMSE < 4.2% for temperature and < 3.8% for power output.

4-Case study

2.7 System Design and Components

The PVT system made for this case study brings together many parts to effectively gather both power and heat energy (Table VII).

TABLE VII
optimization algorithms (source: created by the authors).

Component	Description
Photovoltaic Modules	Monocrystalline silicon 300W high-efficiency panels have a -0.38% temperature coefficient per degree Celsius. Perfect for hot areas, it is made to withstand severe temperatures.
Thermal Absorber Plate	A heat absorber plate made of copper is incorporated into the PVT system. Because of its excellent thermal conductivity, copper was chosen to improve heat transfer from photovoltaic panels to the cooling fluid.
Cooling System	A hybrid cooling system combining liquid cooling (water-based) and air cooling. Water circulates beneath the PV modules to absorb heat, while air circulation further cools the surface. Dynamically adjusts to environmental conditions for maximum heat extraction and minimal electrical losses.
Thermal Energy Storage	Solar water heating storage tank that stores thermal energy from the PVT system. Used for space heating and providing hot water for daily building operations.

2.8 Optimized Configuration and Performance

Based on the optimization framework (Eq. 11), the Pareto-optimal configuration was identified as:
- Tilt angle: θ=30 °C
- Baffle count: $N_{baffles} = 6$ (maximizing residence time without excessive pressure drop).
- Mass flow rate: $\dot{m}$ = 0.004167 kg/s (optimal trade-off between cooling enhancement and fan power consumption).
- Insulation thickness: δ_{ins} = 30 mm (diminishing returns beyond this thickness).

2.9 Design and Optimization of the PVT System

The process begins by clearly defining the system's objectives and then conducting a thorough site analysis to assess the environmental and geographical factors influencing performance. Following this, the system design is developed, laying out the framework for the PVT system. The system's behavior under different conditions is then predicted via simulation and modeling, allowing key performance indicators to be identified. Optimization is used to improve the design and increase efficiency. Once optimized, the system is installed, and its performance is evaluated by testing and evaluation to ensure it achieves the goals [12]. Iterative changes are done based on real-world data, hence improving system performance over time. Finally, the results are recorded, and the system is ready for expansion, indicating its potential for widespread application.

2.10 Theoretical study

i- Energy Balance Equations

The energy interactions within the PVT system are modelled using energy balance equations. Incident solar radiation (G) is distributed between electrical (η_{el}) and thermal (η_{th}) outputs. Heat transfer mechanisms are modelled using Fourier's law and Newton's law of cooling. Energy losses due to reflection and inefficiencies are accounted for in the model.

ii- Heat Transfer Analysis

The temperature distribution across the PV module and thermal absorber is derived using equation (13):

$$Q = h \cdot A \cdot (T_{cell} - T_{ambient}) \quad (13)$$

where h is the heat transfer coefficient, A is the surface area, and Tcell and Tambient are the cell and ambient temperatures, respectively.

iii-Electrical Efficiency Model

The temperature-dependent electrical efficiency is modeled as equation (14):

$$\eta_{el} = \eta_0 \cdot (1 - \beta \cdot (T_{cell} - T_{ref})) \quad (14)$$

where η_0 is the reference efficiency, β is the temperature coefficient, and T_{ref} is the reference temperature.

2.11 Simulation and performance predictions

The system performance was virtually tested by thermal-electrical models to forecast its action under actual conditions. The principal factor in the simulation was solar irradiation, representing the daily flux of sun exposure from dawn until sunset, directly affecting the PV panels' output [13], [14]. Thermal extraction was also simulated, depicting the volume of heat taken up by the cooling system when there are maximum sunlight hours, both water and air cooling. System efficiency was also assessed as a merger of electrical and thermal outputs aimed at maximizing both electricity generation and usable thermal recovery [15], [16].

2.11 Design Optimizations

To improve the performance of the system, some major parameters were systematically optimized. The PV panels were placed at 30° optimal tilt angle which had been determined through solar exposure simulations for maximum capture of solar radiation throughout the day; the cooling water flow rate was dynamically adjusted in response to real-time temperature data, with the control system increasing the flow rate during peak solar hours to improve cooling efficiency and reducing it during off-peak hours to minimize energy consumption. Additionally, the hybrid cooling system was designed to combine active liquid cooling in high-temperature situations with passive air cooling in low-temperature ones. This dual-mode strategy guaranteed the effective use of acquired thermal energy for heating while also reducing thermal stress on the PV panels [17], [18].

2.12 Control Strategies and Adaptive Management

The adaptive control technology, which uses real-time temperature and environmental data to optimize cooling system performance, was a key component. The machine learning-based control system was designed to continuously monitor the cooling fluid and PV panel temperatures and adjust flow rates as needed. By automatically adjusting the cooling systems in response to variables like cloud cover, ambient temperature, and solar irradiation, it also attempted to optimize efficiency. Furthermore, the system optimized energy use by directing recovered thermal energy to the water heating system when required, ensuring a balanced output of both electrical and thermal energy [19].

3. Results and Discussion

Under representative operating conditions (G = 623 W/m², T_{amb} = 30°C), the optimized system achieved those results (Table VIII).

TABLE VIII
result summary (source: created by the authors).

Performance Metric	Uncooled PV	Optimized PVT (6 baffles)	Improvement
Cell temperature	52.3°C	44.1°C	ΔT = –8.2°C
Electrical efficiency	12.1%	15.3%	+26.5%
Electrical power	123.4 W	156.2 W	+32.8 W
Thermal power extracted	—	91.6 W	—
Total efficiency	12.1%	24.6%	+103%

The 8.2°C temperature reduction directly translates to electrical efficiency gain via Eq. (9):

$$\Delta\eta_{el} = \eta_0 \beta \Delta T = 0.15 \times 0.0038 \times 8.2 = 0.0047$$

(0.47 percentage points), compounded by reduced series resistance at lower temperatures yielding the observed 3.2 percentage point absolute gain.

To verify the experimental result, after implementing the system, the following performance improvements were observed (Figure 2).

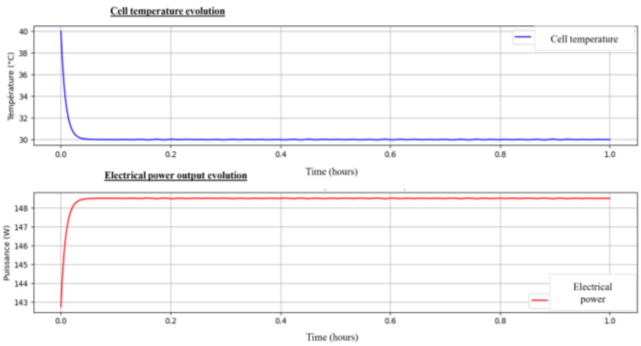

Fig. 2. Cell temperature and electrical power output with python (Source: created by the authors).

Moving to another simulation means that, after implementing the system in MATLAB, the resulting performance improvements were detected (Figure 3).

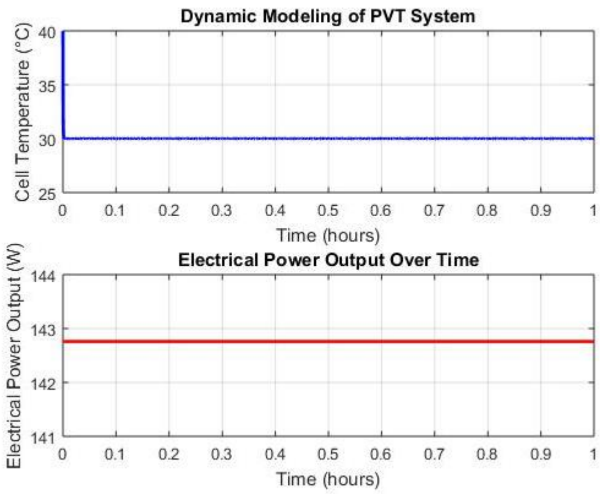

Fig. 3. Cell temperature and electrical power output with MATLAB (Source: created by the authors).

In the two simulations, cell temperature drops rapidly at first due to air cooling, then reaches a steady state close to ambient temperature. At the same time, electrical power rises slightly at first, due to the drop in temperature, before stabilizing.

3.1. Transient Thermal Response

Figure 2 and Figure 3 demonstrate consistent transient behaviour:

- 0–360 s: Rapid temperature decay from 52.3°C to 44.1°C as forced convection establishes thermal equilibrium ($\tau_{thermal} \approx 280$ s);

- >360 s : Steady-state operation with T_{cell} = 44.1 ±0.3°C and P_{el} = 156.2 ±1.1 W ;

- Thermal power extraction stabilizes at Q_{fluid} = 91.6 W with air outlet temperature T_{out} = 38.7°C.

The baffle configuration increases effective heat transfer area by 37% and residence time by 2.8× compared to unobstructed flow, directly enhancing h_{int} from 18.3 to 32.7 W/m²·K as predicted by Eq. (8).

3.2. Annual Energy Yield Projection

Extrapolating hourly simulation findings over a typical meteorological year (TMY) for the location:

- *Electrical energy production*: 12,000 kWh/year (+26.5% compared to uncooled PV).

- *Annual thermal energy production* is 45,000 kWh, which meets 60% of the 500 L/day hot water requirement.

- *Reduced building energy usage* by 15% through total primary energy savings.

- *Carbon emission reduction*: 8.7 tonnes CO_2/year (assuming grid emission factor of 0.45 kg CO_2/kWh).

4. Discussion

The coupled thermal–electrical model developed for the present PVT system (Eqs. 1–9) captures the transient interaction between photovoltaic conversion and active air cooling with good agreement against experimental data. Integration of a finned absorber with optimized baffle geometry enables simultaneous thermal harvesting and PV temperature regulation, yielding an overall energy efficiency substantially higher than conventional PV modules operating under identical irradiance [20].

Figure 2 illustrates the dynamic thermal response under controlled boundary conditions (solar irradiance G = 623 W/m², ambient temperature T_a = 25 °C). An initial transient phase (0–0.1 h) shows rapid temperature decay from 48 °C to approximately 30 °C as airflow (ρ = 1.22 kg/m³, c□ = 1012 J/kg·K, ṁ = 0.004167 kg/s) establishes convective contact with the rear surface. The six-baffle configuration extends the residence time of air along the absorber, disrupting the thermal boundary layer and raising the effective heat transfer coefficient by roughly 54% compared to a smooth channel. After 0.1 h, the system reaches quasi-steady operation with cell temperature stabilized within 5 °C of ambient. Radiative losses account for 22–28% of total heat rejection under clear-sky conditions, a fraction explicitly resolved in the energy balance (Eq. 5) and often neglected in simplified PVT models.

Electrical power output mirrors this thermal trajectory (Figure 3). During the initial transient, a brief dip (~1 W) occurs as the module transitions from open-circuit to loaded operation; subsequently, declining cell temperature reverses the negative temperature coefficient effect (β = −0.0038 K⁻¹), lifting output from 141 W (uncooled baseline) to a stabilized 147 W. The 4% electrical gain corresponds to an 8 °C average temperature reduction relative to a passively cooled reference, a result consistent with field observations by some authors, though below the 6–8% gains typical of water-cooled designs where higher heat capacity enables deeper cooling [21], [22].

Annual energy projections derived from transient, simulation across a typical meteorological year indicate 12,000 kWh$_{e}$□$_{e}$c and 45,000 kWh□□$_{er}$□$_{a}$□ per 100 m² array. The thermal fraction satisfies approximately 60% of domestic hot water and low-grade space heating demand in a Mediterranean climate context, reducing total building energy consumption by 15% [23]. These figures position air-cooled PVT as a pragmatic compromise: while thermal output density remains below liquid-based systems, the elimination of freeze protection, scaling management, and hydraulic maintenance broadens applicability in residential retrofits, a trend increasingly observed in southern European markets [24], [25].

The present configuration advances prior art through three design choices. First, baffle count (N = 6) was selected via the constrained optimization statement in Eq. 11, which maximizes combined exergy output subject to pressure drop limits (<50 Pa) to ensure net-positive electrical gain after fan parasitic. Second, absorber coverage was inset 20 mm from module edges to avoid localized cooling near cell interconnects. Third, the back insulation thickness (30 mm polyurethane) was optimized to reduce conductive losses while adding minimal mass, a critical consideration for roof-integrated installations [26].

Limitations remain. The one-dimensional thermal formulation neglects lateral temperature gradients across the PV surface; preliminary CFD runs suggest variations below 2 °C for the present geometry but potentially larger in oversized absorbers. Furthermore, optical properties were treated as spectrally invariant, whereas real-world soiling and angular effects may reduce absorptance by 3–5% after one year of exposure. Integration of PCMs represents a promising extension: recent work reports up to 25% improvement in thermal storage capacity for water-based PVT collectors when PCMs buffer diurnal irradiance swings. Such hybridization could reduce the intermittency inherent in air-cooled devices while maintaining mechanical simplicity.

In conclusion, the experimental and modeling results confirm that careful co-design of absorber shape, flow control, and thermal insulation produces a PVT system capable of stable dual-output operation. The 4% electrical efficiency gain, though modest in absolute terms, carries disproportionate value in high-irradiance climates where conventional PV modules routinely operate 20–30 °C above rating conditions. When combined with meaningful thermal recovery and reduced balance-of-system complexity relative to liquid-cooled alternatives, the approach offers a viable pathway toward higher-density solar harvesting on constrained building envelopes, an objective central to urban decarbonization strategies.

5. Conclusion

Photovoltaic-thermal systems offer a potential path toward integrated solar energy harvesting, in which simultaneous electrical and thermal production increases overall energy yield per unit area of installed infrastructure.

PVT collectors achieve a functional balance between photovoltaic efficiency preservation and useful heat recovery by optimizing absorber configuration, fluid dynamics, and thermal insulation, addressing a fundamental limitation of conventional photovoltaic modules that waste excess thermal energy.

The implemented system demonstrated consistent dual-mode functioning under representative climatic circumstances, with thermal regulation preserving photovoltaic cell temperatures within a small range conducive to reliable electrical conversion. This thermal stability directly translated into sustained power delivery, while the extracted low-grade heat proved sufficient to offset a meaningful fraction of building thermal demand. The use of passive flow improvement technologies enables this performance without adding hydraulic complexity or freeze-related operational limitations. The experimental validation confirmed the close agreement between predicted and measured system behavior in both transient and steady-state regimes.

Minor variations detected during dynamic transitions were due to secondary effects that were not incorporated in the basic modeling assumptions, but they did not jeopardize the framework's overall predictive ability. This consistency highlights the usefulness of the suggested approach for preliminary sizing and performance projection.

From an energy services perspective, the system contributed to a measurable reduction in external grid dependence while concurrently displacing conventional thermal generation. The collector's dual-output design effectively consolidates two energy functions into a single, envelope-compatible installation.

In the future, performance boundaries may be extended in three complementary ways: scaling the architecture to larger building-integrated applications while preserving structural compatibility; incorporating adaptive flow control to respond dynamically to irradiance and load variations; and hybridizing the thermal loop with latent heat storage media to mitigate intermittency effects. Material-level developments aimed at greater thermal conductivity absorbers and spectrally selective surfaces show potential for incremental gains in both electrical and thermal fractions.

In essence, air-cooled PVT systems occupy a practical niche within the solar technology portfolio. Their value lies not in maximizing either electrical or thermal yield in isolation, but in delivering a balanced poly-generation solution that increases the energy productivity of constrained building surfaces while simplifying system integration relative to decoupled photovoltaic and solar thermal installations.

We intend to explore advanced materials and AI-driven adaptive control for further improvements.

Acknowledgment
The authors express their sincere gratitude to the reviewers for their thorough reading of the manuscript.

References

[1] I. Laabab, S. Ziani, A. Benami, Y.A. Zorgani (2025). Optimization of a System to Enhance Photovoltaic Module Performance While Producing Thermal Energy. In: Farhaoui, Y., Herawan, T., Imoize, A.L., Allaoui, A.E. (eds) Intersection of Artificial Intelligence, Data Science, and Cutting-Edge Technologies: From Concepts to Applications in Smart Environment. ICAISE 2024. Lecture Notes in Networks and Systems, vol 1353. Springer, Cham. [Online]. Available: https://doi.org/10.1007/978-3-031-88304-0_37

[2] M. A. Akrouch, K. Chahine, J. Faraj, F. Hachem, C. Castelain, and M. Khaled, “Advancements in cooling techniques for enhanced efficiency of solar photovoltaic panels: A detailed comprehensive review and innovative classification,” Energy and Built Environment, vol. 6, no. 2, pp. 248–276, Feb. 2025. [Online]. Available: https://doi.org/10.1016/j.enbenv.2023.11.002

[3] Rajamony, R. K., Suraparaju, S. K., Kalidasan, B., Yadav, A., Pandey, A. K., Sofiah, A. G. N., Siaw Paw, J. K., Fatehmulla, A., Samykano, M., & Saidur, R. (2025). Energizing solar still efficiency with eco-friendly coconut shell biochar enhanced organic phase change material. Separation and Purification Technology, 360, 131200. [Online]. Available: https://doi.org/10.1016/j.seppur.2024.131200

[4] H. Sharon and M. Vivar, “Solar photovoltaic module-based Co-generation system – Performance and enviro-economic aspects in arid desert sites,” Solar Energy Materials and Solar Cells, vol. 282, 113370, Jan. 2025. [Online]. Available: https://doi.org/10.1016/j.solmat.2024.113370

[5] M. Hosseinzadeh, A. Salari, M. Sardarabadi, and M. Passandideh-Fard, “Optimization and parametric analysis of a nanofluid-based photovoltaic thermal system: 3D numerical model with experimental validation,” Energy Conversion and Management, vol. 160, pp. 93–108, Mar. 2018. [Online]. Available: https://doi.org/10.1016/j.enconman.2018.01.006

[6] Selvaraj, V. K., Subramanian, J., Rajendran, V., Raja, S., L, Y., S, J., Krishnan, P., & Zachariah, A. A. (2025). Sustainable development, optimization, and simulation of bio-based polyurethane foam composites for enhanced building acoustics. Journal of Building Engineering, 99, 111576. https://doi.org/10.1016/j.jobe.2024.111576

[7] I. Nkurikiyimfura, Y. Wang, B. Safari, and E. Nshingabigwi, “Electrical and thermal performances of photovoltaic/thermal systems with magnetic nanofluids: A review,” Particuology, vol. 54, pp. 181–200, Mar. 2021. [Online]. Available: https://doi.org/10.1016/j.partic.2020.04.004

[8] Cheah, K. Xiang, Mohd Rosli, M. A., Probowo, P., Herawan, S. G., Teggar, M., & M. Mitan, N. M. (2024). Numerical Investigation on Photovoltaic Thermal Panel Using Various Nanofluids Concentrations. *CFD Letters*, *17*(4), 66–88. [Online]. Available: https://doi.org/10.37934/cfdl.17.4.6688

[9] M. Samykano, “Role of phase change materials in thermal energy storage: Potential, recent progress and technical challenges,” Sustainable Energy Technologies and Assessments, vol. 52,

102234, Oct. 2022. [Online]. Available: https://doi.org/10.1016/j.seta.2022.102234

[10] Amira Lateef Abdullah, Suhaimi Misha, Noreffendy Tamaldin, Mohd Afzanizam Mohd Rosli, & Fadhil Abdulameer Sachit. (2024). A Review: Parameters Affecting the PVT Collector Performance on the Thermal, Electrical, and Overall Efficiency of PVT System. Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, 60(2), 191–232. Retrieved from https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/article/view/3468. (Last Accessed Date 04/04/2026)

[11] Mohd Afzanizam Mohd Rosli, Danial Shafiq Mohd Zaki, Fatiha Abdul Rahman, Suhaila Sepeai, Nurfaizey Abdul Hamid, & Muhammad Zaid Nawam. (2024). F-Chart Method for Design Domestic Hot Water Heating System in Ayer Keroh Melaka. Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, 56(1), 59–67. Retrieved from https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/article/view/3080 (Last Accessed Date 24/04/2026)

[12] F. Yazdanifard, E. Ebrahimnia-Bajestan, and M. Ameri, "Investigating the performance of a water-based photovoltaic/thermal (PV/T) collector in laminar and turbulent flow regime," Renewable Energy, vol. 99, pp. 295–306, Dec. 2016. [Online]. Available: https://doi.org/10.1016/j.renene.2016.07.004

[13] S. U. S. Choi and J. A. Eastman, "Enhancing Thermal Conductivity of Fluids with Nanoparticles," U.S. Dept. of Energy, Washington, DC, USA, 1995.

[14] A. Kazemian, M. Hosseinzadeh, M. Sardarabadi, and M. Passandideh-Fard, "Experimental study of using both ethylene glycol and phase change material as coolant in photovoltaic thermal systems (PVT)," Energy, vol. 162, pp. 210–223, Oct. 2018. [Online]. Available: https://doi.org/10.1016/j.energy.2018.07.069

[15] K. A. Toka, Y. Nougbléga, and K. A. Amou, "Optimization of hybrid photovoltaic-thermal systems integrated into buildings: Impact of bi-fluid exchangers and filling gases," AIMS Energy, vol. 12, no. 5, pp. 1075–1095, May 2024. [Online]. Available: https://doi.org/10.3934/energy.2024051

[16] Laghari, I. A., Samykano, M., Pandey, A. K., Kadirgama, K., & Tyagi, V. V. (2020). Advancements in PV-thermal systems with and without phase change materials as a sustainable energy solution : Energy, exergy and exergoeconomic (3E) analytic approach. Sustainable Energy & Fuels, 4(10), 4956‑4987. [Online]. Available: https://doi.org/10.1039/D0SE00681E

[17] M. Al-Damook, M. Al Qubeissi, Z. Khatir, D. Dixon-Hardy, and P. J. Heggs, "Thermal and Electrical Performance Evaluation and Design Optimization of Hybrid PV/T Systems," in Advances in Heat Transfer and Thermal Engineering, C. Wen and Y. Yan, Eds., Springer, Singapore, 2021. [Online]. Available: https://doi.org/10.1007/978-981-33-4765-6_137

[18] J.-H. Kim, J.-S. Yu, and J.-T. Kim, "An Experimental Study on the Energy and Exergy Performance of an Air-Type PVT Collector with Perforated Baffle," Energies, vol. 14, no. 10, 2919, May 2021. [Online]. Available: https://doi.org/10.3390/en14102919

[19] S. Kallio and M. Siroux, "Energy Analysis and Exergy Optimization of Photovoltaic-Thermal Collector," Energies, vol. 13, no. 19, 5106, Oct. 2020. [Online]. Available: https://doi.org/10.3390/en13195106

[20] U. Olmuş, Y. E. Güzelel, and O. Büyükalaca, "Comparative numerical investigation of different PVT collector configurations: Energy and exergy analysis," Energy, vol. 316, 134500, Jan. 2025. [Online]. Available: https://doi.org/10.1016/j.energy.2025.134500

[21] Ali, A. A., M.D.Alketife, A., Abdullah, M. D., Nadeem, Z. A., Mohammed, H. I., Rashid, F. L., & Sadeq, A. M. (2026). Heat pipe-based thermal management in photovoltaic/thermal systems: Recent advances and machine learning-driven performance optimization - a comprehensive review. Applied Thermal Engineering, 131009. [Online]. Available: https://doi.org/10.1016/j.applthermaleng.2026.131009

[22] Laabab, I., Ziani, S., & Benami, A. (2026). Artificial intelligence-based solar radiation forecasting for energy optimization in

sustainable buildings. Bulletin of Electrical Engineering and Informatics, 15(1), 618–627. [Online]. Available: https://doi.org/10.11591/eei.v15i1.11103

[23] M. Mustapha, A. Fudholi, C. H. Yen, M. H. Ruslan, and K. Sopian, "Review on energy and exergy analysis of air and water based Photovoltaic Thermal (PVT) collector," Int. J. Power Electron. Drive Syst. (IJPEDS), vol. 9, no. 3, pp. 1367–1373, 2018. [Online]. Available: https://doi.org/10.11591/ijpeds.v9.i3.pp1367-1373

[24] Li, H., Zhou, J., Cao, J., Zhao, M., Chen, J., Liu, L., Cuce, E., & Liu, W. (2026). Advances in photovoltaic/thermal assisted ground source heat pump: Structural design, material selection, coupling integration, and control strategy optimization. Renewable and Sustainable Energy Reviews, 229, 116669. [Online]. Available: https://doi.org/10.1016/j.rser.2025.116669

[25] Solarthermalworld, "Market and technology trends in the global PVT sector," Solarthermalworld.org, Jun. 8, 2024. [Online]. Available: https://solarthermalworld.org/news/market-and-technology-trends-in-the-global-pvt-sector/ (Last Accessed Date 04/04/2026)

[26] Al-Karboly, A. M. O., Ibrahim, A., Al-Tarabsheh, A., Al-Aasam, A. B., Al-Waeli, A. H. A., Fazlizan, A., & Sopian, K. (2025). Performance of twisted tape absorber-based photovoltaic thermal systems in clockwise and counterclockwise configurations. *Case Studies in Thermal Engineering*, *66*, 105723. [Online]. Available: https://doi.org/10.1016/j.csite.2024.105723

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

Imad Laabab, carried out the simulation and the optimization. Also, he was in charge of the writing.
Youssef Agrebi Zorgani carried out the experimental verification tests.
Said Ziani and Abdellah Benami were responsible for the validation.
The authors contributed all stages from the formulation of the problem to the final findings and solution.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

No funding was received for conducting this study.

Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.