

## Management of an Energy System based on Hybrid Photovoltaic-Thermal Collectors

Fatima Maameri<sup>1\*</sup>, Khaled Touafek<sup>2</sup>, Katia Kouzi<sup>3</sup>, Roumaissa Zenzen<sup>4</sup>, Abdelmalek Douara<sup>5</sup>

<sup>1</sup>Materials, Energy systems, Renewable Energies and Energy Management Laboratory (LMSEERGE), Faculty of technology, University Amar Telidji, BP37, Ghardaia Road, 03000 Laghouat, Algeria

\*Corresponding author Email: [fatima\\_maamri@yahoo.fr](mailto:fatima_maamri@yahoo.fr) - ORCID: [0000-0002-5247-7850](https://orcid.org/0000-0002-5247-7850)

<sup>2</sup>Unité de Recherche Appliquée en Energies Renouvelables URAER, Centre de Développement des Energies Renouvelables, CDER, 47133, Ghardaïa, Algeria

Email: [toufekkhaled@gmail.com](mailto:toufekkhaled@gmail.com) - ORCID: [0000-0002-5247-7850](https://orcid.org/0000-0002-5247-7850)

<sup>3</sup>Materials, Energy systems, Renewable Energies and Energy Management Laboratory (LMSEERGE), Faculty of technology, University Amar Telidji, BP37, Ghardaia Road, 03000 Laghouat, Algeria

Email: [k.kouzi@lagh-univ.dz](mailto:k.kouzi@lagh-univ.dz) - ORCID: [0000-0002-8430-1681](https://orcid.org/0000-0002-8430-1681)

<sup>4</sup>Laboratory of mechanical engineering, faculty of sciences and technology, university of jijel, jijel 18000, Algeria

Email: [roumaissa.zenzen@univ-jijel.dz](mailto:roumaissa.zenzen@univ-jijel.dz) - ORCID: [0009-0007-8921-99474](https://orcid.org/0009-0007-8921-99474)

<sup>5</sup> Faculty of sciences and technology, Tissemsilt University, Tissemsilt 38000, Algeria

Email: [abdelmalekreal@gmail.com](mailto:abdelmalekreal@gmail.com) - ORCID: [0009-0006-1086-201X](https://orcid.org/0009-0006-1086-201X)

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### Abstract:

Hybrid photovoltaic-thermal (PVT) collectors represent a promising technology for improving the overall energy efficiency of solar conversion systems. This work presents a comprehensive approach to modeling and managing an energy system based on hybrid PVT collectors. The developed model integrates the electrical and thermal aspects of the system, enabling a detailed performance analysis under various operating conditions. Results demonstrate that optimized management can improve the overall system efficiency by 15 to 25% compared to conventional photovoltaic systems, with combined electricity and heat production. In this paper, a development of a unified electro-thermal modeling approach is coupled with a coordinated energy management algorithm that optimizes both electrical power extraction and thermal regulation in PVT collectors. This integrated methodology provides a deeper understanding of the coupled behavior of hybrid solar systems and offers an effective tool for the design and optimization of high-efficiency renewable energy installations. The proposed management algorithm uses an advanced Maximum Power Point Tracking (MPPT) controller coupled with intelligent thermal regulation to maximize energy extraction while maintaining optimal operating temperatures.

## 1. Introduction

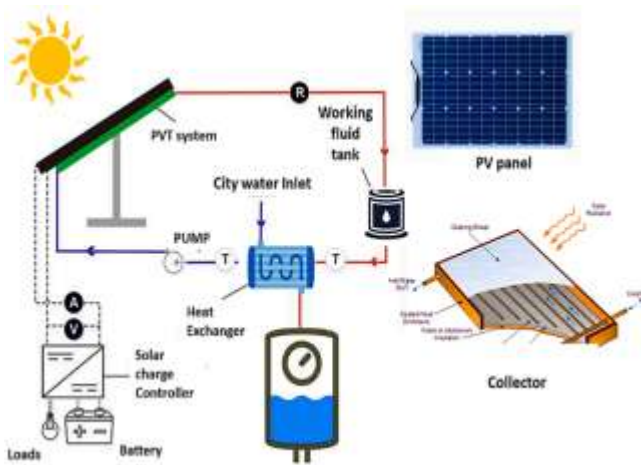
Hybrid photovoltaic thermal (PVT) collectors are devices that convert solar radiation simultaneously into electrical and thermal energy, which is transferred to a fluid (liquid or gaseous), enabling its subsequent use. The hybrid PVT water system allows the removal of a portion of the thermal fraction of solar radiation collected by photovoltaic cells and not converted into electricity, and to use it, for example, to heat domestic hot water by means of

a suitable storage tank [1]. This solution is particularly attractive for residential applications, where there is a demand for both electricity and heat. [2], [3]. The PVT collectors are very promising devices which enable better space utilization, savings during supporting construction and simultaneous conversion of solar radiation into the thermal and electrical energy. They can be used in private houses, blocks of flats, tourist objects, hospitals, schools and other objects for heating the sanitary water and electrical energy generation [3][4]. Hybrid photovoltaic thermal PVT systems

produce both electricity and heat. Typically, they utilize either air or water as the fluid to extract the heat from the photovoltaic PV panels, an integrated heat pump, or an actively-cooled PV concentrator through the use of economical reflectors. Design decisions have to be made on the collector type, the thermal to electrical yield ratio, as well as the solar fraction for optimizing the overall benefits. These all have determining effects on the system operating mode, working temperature and efficiency [5]. The attractiveness of PVT systems is that the electrical output of the PV panels as well as the quantity of heat increases as the mass flow rate of the fluid increases [6]. This study aims to develop a comprehensive framework for the optimized management of an energy system based on hybrid PV/T collectors. It includes detailed mathematical modeling of the collector, integrating electrical, thermal, and hydraulic aspects, as well as its implementation in MATLAB for dynamic simulations. The work also proposes an energy management algorithm combining adaptive MPPT and intelligent thermal regulation. Finally, the system's performance is analyzed under various climatic conditions to evaluate energy and economic gains compared to conventional photovoltaic systems.

## 2. Description of PVT System

The Photovoltaic-Thermal PVT collector technology represents one of the most thermodynamically efficient approaches to solar energy utilization. In general, a PVT collector is composed of a PV panel and a fluid flow channel to absorb the unexploited solar energy lost as waste heat.



**Figure. 1.** Diagram of the hybrid photovoltaic-thermal (PVT) system [7]

This technology has the advantage of dual energy production and increasing PV panel efficiency

compared to standard PV panels by removing excessive heat from the module. The operation of the hybrid photovoltaic-thermal system is shown in Figure 1 [7]. Parameters affecting the overall performance of PVT collectors include mass flow rate, collector area, irradiance, and PV cell materials [8].

## 3. Mathematical modeling of PVT system

The performance of the photovoltaic-thermal (PVT) system can be theoretically interpreted using coupled electrical and thermal models describing the photovoltaic module and the heat extraction subsystem [5].

### 3.1. Thermal model

The PV cell in hybrid solar PVT collector operates as thermal absorber which is cooled by the circulation of a heat transfer fluid on the rear face. PV cells and modules are modeled using approximation of the physical cell to various temperatures and radiations [9]. The physical properties of the PVT different materials are main needs to run the numerical simulation, the PVT layers physical properties effect the current simulation is carried out. The leading partial differential equations of thermal energy for PVT fluid layer are given as [9]:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (1)$$

The quantity of solar energy absorbed by the PVT is the main factor that drives the increases of the temperature of the PVT. It is described by :

$$Q_{abs} = A_c (\tau\alpha) Ird \quad (2)$$

where  $A_c$  is the collector surface area,  $Ird$  is the solar irradiance, and  $(\tau\alpha)$  represents the effective transmittance-absorptance product of the collector surface.

The rate of heat loss by natural convection of the PVT collector is computed using the following equation:

$$Q_{cv} = h_w \times A_c \times (T_c - T_a) \quad (3)$$

The heat convection coefficient ( $h_w$ ) is given by equation (4):

$$h_w = 2.8 + 3 \times w_s \quad (4)$$

$$Q_{rd} = \epsilon_G \times \sigma \times A_c \times (T_c^4 - T_a^4) \quad (5)$$

In designing the proposed photovoltaic thermal system, the heat transfer and water flow equations

can be solved, taking into account the appropriate boundary conditions. Consider the initial temperature at time  $t = 0$ ,  $T=T_0$ [9].The useful collected heat absorbed by the solar collector can be given as the combined results of the average mass flow rate  $\dot{m}$ , heat capacity of flowing medium  $C_p$  and temperature difference at the collector inlet  $T_{in}$ and outlet  $T_{out}$ . The collected heat can be as [10] [9]:

$$Q_u = \dot{m}C_p(T_{out} - T_{in}) \quad (6)$$

The difference between the absorber solar radiation and thermal heat losses is determined as the useful heat gain which is calculated by the equation follows:

$$Q_u = A_c F_R [Ird(\tau\alpha) - U_L(T_{in} - T_a)] \quad (7)$$

Where  $A_c$  is the collector area,  $T_a$  is the ambient temperature,  $T_{in}$  is the inlet temperature,  $U_L$  is the overall collector heat loss,  $(\tau\alpha)$  is the PV thermal efficiency,  $I_t$  is the solar radiation.  $F_R$  is the heat removal efficiency factor introduced by other studies [11] [12] this factor is expressed as follows:

$$F_R = \frac{\dot{m}C_p}{A_c U_L} \left[ 1 - \exp\left(-\frac{A_c U_L \dot{F}}{\dot{m}C_p}\right) \right] \quad (8)$$

Where  $\dot{F}$  is the collector efficiency factor.

The outlet water temperature can be obtained using The useful collected heat absorbed by the flat-plate solar collector

$$T_{out} = \frac{Q_u}{\dot{m}C_p} + T_{in} \quad (9)$$

### 3.2. Electrical model

The electrical behavior of the photovoltaic generator is commonly represented using the single-diode equivalent circuit, which precisely models the current–voltage characteristics of PV modules under varying solar irradiance and temperature conditions [5] [13] The output current of the PV module can be expressed as:

$$I_{pv} = I_{ph} - I_s \left[ \exp\left(\frac{V_{pv} + R_s I_{pv}}{A V_T}\right) - 1 \right] - \frac{V_{pv} + R_s I_{pv}}{R_{sh}} \quad (10)$$

where  $I_{ph}$  denotes the photo-current generated by incident solar radiation,  $I_s$  represents the diode reverse saturation current,  $R_s$  and  $R_{sh}$  are the series and shunt resistances respectively,  $n$  is the diode ideality factor, and  $V_T = \frac{kT_{wo}}{q}$  is the thermal voltage determined by the cell temperature  $T_c$ , the PV current equation becomes:

$$I_{pv} = I_{ph} - I_s \left[ \exp\left(\frac{q(V_{pv} + R_s I_{pv})}{AKT_{wo}}\right) - 1 \right] - \frac{V_{pv} + R_s I_{pv}}{R_{sh}} \quad (11)$$

Where

$$\begin{cases} I_{ph} = [I_{sc} + K_i (T_{wo} + T_{ref})] \times Ird / Ird_{ref} \\ I_s = I_{rs} (T_{wo} + T_{ref}) \times \exp\left(\frac{qE_g}{AK}\right) \left(\frac{1}{T_{ref}} - \frac{1}{T_{wo}}\right) \\ I_{rs} = \frac{I_{scn}}{\exp\left(\frac{qV_{oc}}{AKT_{wo}}\right) - 1} \end{cases} \quad (12)$$

The total PVT efficiency ( $\eta_{pvt}$ ), is given as :

$$\eta_{pvt} = \eta_{th} + \eta_{el} \quad (13)$$

The thermal efficiency is the ratio of the useful thermal energy  $Q_u$  In the overall incident solar radiation ,can be expressed as follows

$$\eta_{th} = \frac{\int Q_u dt}{A_m \int Ird dt} \quad (14)$$

### 4. Adaptive MPPT Algorithm and thermal PI controller

In photovoltaic solar energy systems, maximum efficiency can only be guaranteed through Maximum Power Point Tracking (MPPT) technology. Therefore, various MPPT techniques have been developed over the years. These methods can be broadly categorized as conventional, intelligent, and hybrid [14][15]. Conventional MPPT methods are widely used due to their simplicity and ease of implementation. One of the most methods is the Perturbation and Observation (P&O) method, which relies on varying the operating voltage of the photovoltaic panel and monitoring the change in power. If the power increases, the perturbation continues in the same direction; if it decreases, the direction is reversed. This process is repeated until the maximum power point is reached. In this study, the P&O method was adopted and enhanced with thermal energy control through a proposed proportional-integral (PI) algorithm to study changes in both the fluid and cell temperature and the amount of thermal energy produced. The electrical power produced is given by

$$P_{pv} = V_{pv} I_{pv} \quad (15)$$

and the maximum power point (MPP) corresponds to the operating condition where the derivative of power with respect to voltage equals zero ,  $\frac{dP}{dV} = 0$  corresponding to the peak of the P–V curve [16]. In order to continuously track this operating point under fluctuating environmental conditions, a

Perturb and Observe (P&O) maximum power point tracking algorithm is implemented. In this approach, the instantaneous power is calculated as

$$P(k) = V(k)I(k) \tag{16}$$

and the change in power  $\Delta P = P(k) - P(k-1)$  is used to determine whether the perturbation direction of the operating voltage should be maintained or reversed, enabling the operating point to converge toward the MPP [17][18]. Simultaneously, the thermal behavior of the PVT collector is governed by the energy balance between absorbed solar radiation, electrical power generation, thermal losses to the environment, and heat transferred to the circulating fluid [19]. The dynamic temperature of the PV module can be described as:

$$mC_p \frac{dT_c}{dt} = Q_{abs} - Q_{cv} - Q_{elec} \tag{17}$$

where  $mC_p$  is the thermal capacitance of the collector,  $Q_{abs}$  is solar energy absorbed by the PVT,  $Q_{cv}$  is the heat loss by natural convection, and  $Q_{elec}$  denotes the electrical power generated [20]. Consequently, the total energy generated by the PVT system can be expressed as

$$E_{tot} = \int (P_{pv} + P_{th}) dt \tag{18}$$

Using Thermal control equations such as temperature error:

$$e(t) = T_{ref} - T_{out} \tag{19}$$

PI controller:

$$\dot{m}(t) = K_p e(t) + K_i \int e(t) dt \tag{20}$$

### 5. Results and Discussions

This section analyzes the performance of a proposed hybrid photovoltaic solar thermal power system under various weather conditions. The discussion focuses on optimizing electrical performance, thermal energy recovery, peak power point tracking effectiveness, and overall system efficiency, with particular emphasis on the system's temporal behavior. The daily variations in radiation and ambient temperature are studied and presented in Figure 3. The daily irradiation profile presented in Figure.3 follows a typical bell-shaped distribution, with peak solar intensity around midday. The electrical output mirrors this behavior, confirming strong correlation between irradiance and system power.

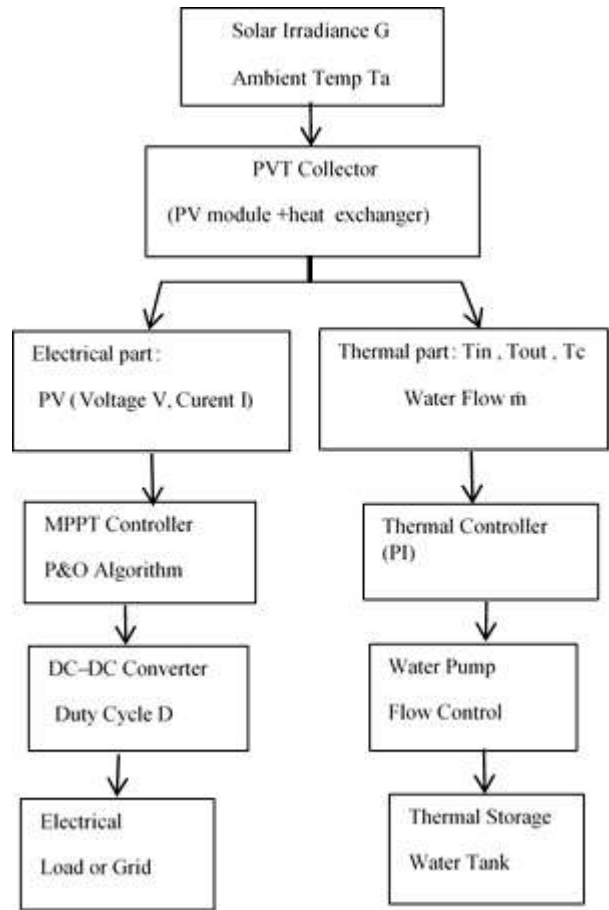


Figure 2. Global Control Architecture of PVT System

Table 1: main values parameter of the PVT system

parameter	Value
Maximum solar irradiance (G)	W/m <sup>2</sup> 1000
Ambient temperature	25-30C°
PVT collector area	0.42 m <sup>2</sup>
PV panel temperature (with PVT cooling)	3 m
Temperature difference	PVT cool (45-50) °C
Liquid temperature difference (ΔT = T <sub>out</sub> - T <sub>in</sub> )	(10-15) °C

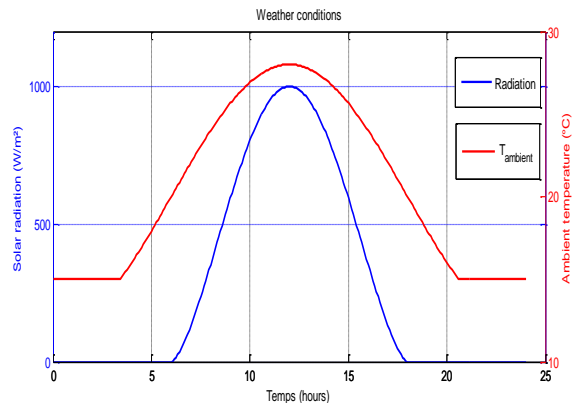


Figure.3. Weather conditions

In Figure.4, daily results of cumulative energies (electrical, thermal, total) are presented

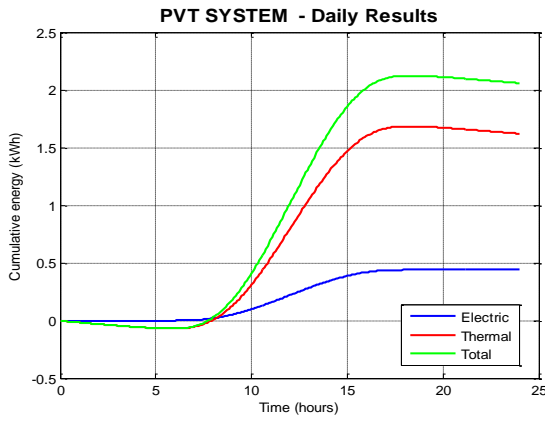


Figure 4. Daily results of cumulative energy

As shown in Figure 4, Cumulative energy increases quasi-linearly during daylight hours, demonstrating consistent energy harvesting and stable system response.

The daily energy production results obtained from the simulation model further characterize the overall performance of the PVT system. On the electrical side, the system generated 0.09 Wh over the course of the simulated day, a relatively modest contribution that reflects the influence of varying irradiance conditions and the inherent conversion losses within the photovoltaic component. The thermal energy output, by contrast, proved significantly more substantial, reaching 7.89 Wh — highlighting the dominant role of the thermal subsystem in the overall energy harvesting process. Combined, the system achieved a total daily energy production of 7.98 Wh, demonstrating that the PVT configuration effectively leverages both electrical and thermal conversion pathways.

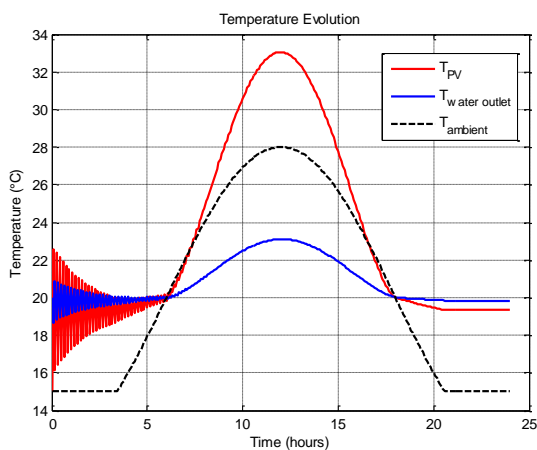


Figure 5. Temperature evolution

The variations in panel temperature, fluid temperature and ambient temperature are studied as a function of time and are presented in Figure 5. Figure 5 shows the evolution of the panel temperature ( $T_{PV}$ , red curve), the outlet water temperature ( $T_{water\ outlet}$ , blue curve), and

the ambient temperature ( $T_{ambient}$ , black dashed curve) over time.  $T_{PV}$  reaches a pronounced peak in the middle of the day, reflecting the effect of solar irradiation on the panel. The outlet water temperature follows a similar trend but with a reduced amplitude, reflecting the heat capacity of the heat transfer fluid. The ambient temperature, on the other hand, exhibits a classic sinusoidal profile representative of a diurnal cycle. The oscillations observed at the beginning of the simulation for  $T_{PV}$  and  $T_{water\ outlet}$  suggest a transient phase before the system reaches a quasi-steady state. At the end of the period, the three temperatures converge to stable values, indicating a return to nighttime conditions. This improvement is primarily attributed to active thermal management. In conventional PV modules, cell temperature rises significantly due to solar absorption and limited heat dissipation. In the proposed PVT system, heat extraction via the hydraulic subsystem maintains the module temperature closer to ambient conditions (approximately 20 °C), while the conventional PV system reaches temperatures near 30 °C or higher during peak irradiation. The reduced thermal stress results in:

- Higher operating voltage,
- Improved fill factor,
- Enhanced power stability under fluctuating irradiation.

A key advantage of the hybrid PVT system is its ability to simultaneously harvest electrical and thermal energy from the same collector surface. Unlike conventional PV modules, where absorbed heat contributes solely to efficiency degradation, the PVT configuration converts this thermal component into useful energy for: domestic hot water, space heating or agricultural or low-temperature industrial applications. Figure 6 shows the evolution of the electrical, thermal and overall efficiency of the PV/T collector as a function of time. According to Figure 6, the thermal efficiency remains higher than the electrical efficiency throughout the operating period. The electrical

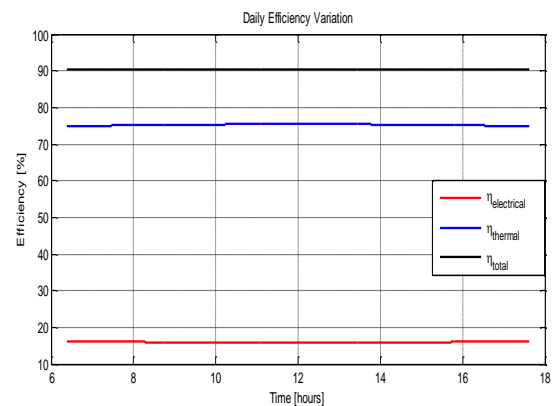


Figure 6. Daily efficiencies variations

efficiency remains relatively low and almost constant, while the thermal efficiency exhibits higher values. Consequently, the overall efficiency of the PVT system is dominated by the thermal contribution, which confirms the advantages of using hybrid collectors to improve overall energy efficiency. When combining electrical and thermal outputs, the global energy efficiency of the PVT system is estimated to range between 60 % and 75 %, compared to 15–20 % for PV-only systems. This significant increase confirms that hybridization substantially improves the overall solar utilization factor. Figure 7 presents the evolution of solar radiation over time.

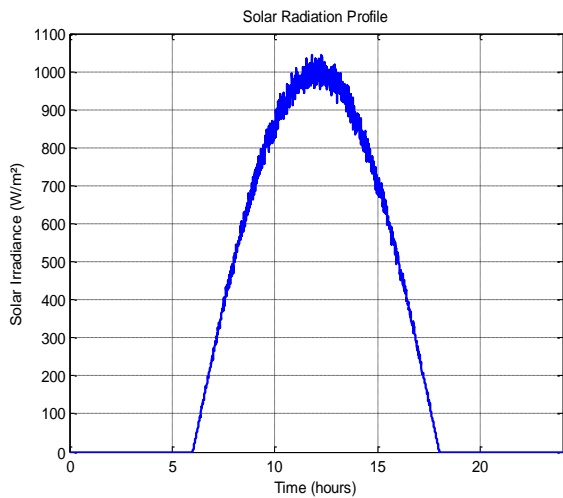


Figure 7. Solar radiation

The resulting profile as shown Figure 7, has a symmetrical bell shape, characteristic of typical daily sunshine, with zero radiation at the beginning and end of the period corresponding to nighttime hours. Radiation gradually increases until it reaches a maximum at midday, reflecting the sun's passage through the zenith. Slight oscillations are observed near the peak, which can be attributed to fluctuations in the modeled irradiation or to effects of numerical discretization. This radiation profile constitutes the main energy input for the PVT system and directly

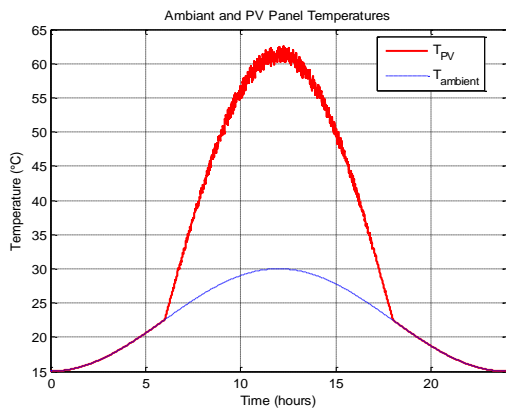


Figure 8. Panel temperature

influences the thermal and electrical behavior of the panel. Daily variation of both ambient and panel temperature are given in Figure 8. Figure 8 shows the the variation of temperatures during a day. PVT panel reached a maximum surface temperature of 62.5°C, a value that reflects the combined effect of solar irradiance absorption and the limited heat dissipation capacity of the photovoltaic layer. The MPPT control system dynamically acts on the operating point of the PV panel in order to extract the maximum available power according to the sunlight conditions. Figure 9 illustrates the time evolution of the voltage ( $V_{PV}$ , blue curve) and the current ( $I_{PV}$ , red curve) delivered by the photovoltaic panel under the effect of the MPPT algorithm.

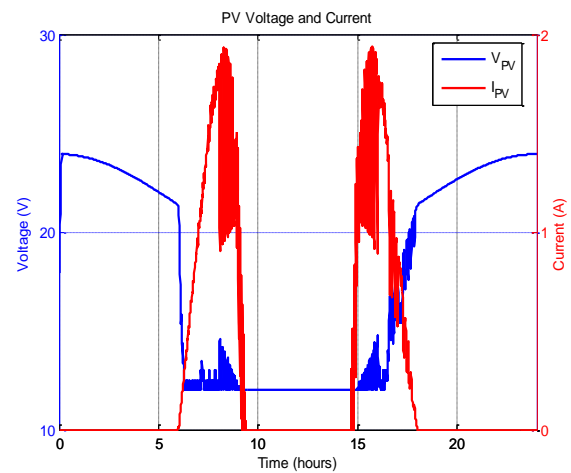


Figure 9. Panel voltage and current

Figure 9 highlights the electrical behavior of the PV panel controlled by the MPPT algorithm. Two operating phases are clearly distinguishable: Outside of irradiance peaks: the voltage  $V_{PV}$  stabilizes at a near-constant and high value, while the current  $I_{PV}$  remains low, corresponding to a low-power operating point during periods of low sunlight. During irradiance peaks (two clearly visible pulses): the MPPT algorithm reacts by dynamically adjusting the operating point. We observe sharp drops in  $V_{PV}$  accompanied by significant increases in  $I_{PV}$ , reflecting the search for and monitoring of the Maximum Power Point (MPP). The transient oscillations observed near these peaks demonstrate the exploration process of the MPPT algorithm (of the Perturb & Observe type or similar) before converging towards the optimal point. This behavior confirms the effectiveness of the MPPT control in extracting the maximum available power according to the sunlight conditions, while ensuring system stability in steady state, consistent with the radiation profile shown before. Figure 10 presents a comparison between the actual power extracted by

the PV panel with MPPT control and the maximum theoretical power available as a function of time.

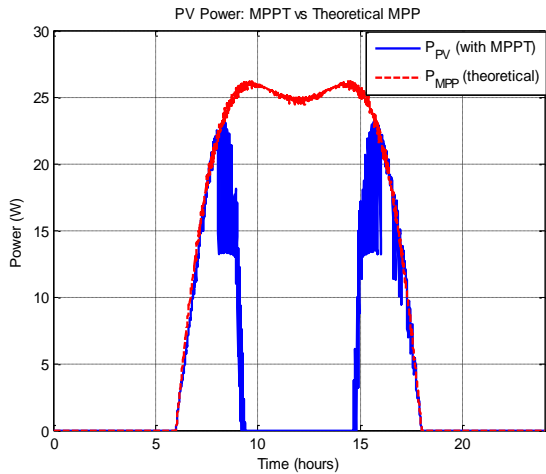


Figure 10. PV power with MPPT vs. MPP

A comparison between the actual power extracted by the PV panel under MPPT control ( $P_{PV}$ ) and the theoretical maximum available power ( $P_{MPP}$ ) is presented in Figure 10. In general, the two curves are closely superimposed over the entire simulation period, confirming the effectiveness of the MPPT algorithm in tracking the maximum power point. The model reached a peak PVT output power of 23.34 W, closely approaching the theoretical maximum of 26.16 W. The average output power, however, settled at 13.20 W, which reflects the impact of dynamic variations in irradiance and temperature profiles imposed in simulation. The operating point remains closely aligned with the theoretical maximum power region, confirming:

- Proper modeling of the single-diode PV representation,
- Effective interaction between the MPPT controller and the DC–DC boost converter.

The temporal evolution of the instantaneous and average values of a characteristic system parameter, allowing evaluation of the MPPT control response dynamics under varying sunlight conditions, is shown in Figure 11. Analysis in Figure 11 reveals the dynamic behavior of the system, particularly evident during the two intense irradiation phases. The instantaneous value exhibits large-scale fluctuations, with significant deviations in both positive and negative values. These fluctuations represent successive cycles of disturbance and observation, a characteristic feature of this type of control. In contrast, the average value smooths out these transient changes and converges toward a stable reference value. The applied Maximum Power

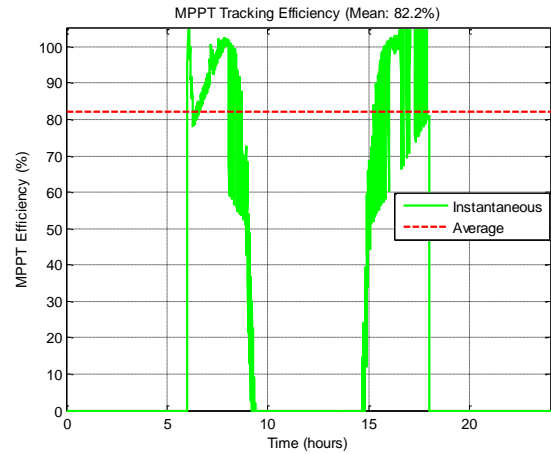


Figure 11. MPPT tracking efficiency

Point Tracking (MPPT) algorithm achieved an average efficiency of 81.29%, demonstrating a consistent ability to extract power under all simulated operating conditions. This confirms that the overall system behavior remains under control despite local disturbances. Figure 12 shows the current-voltage (I-V) characteristic and the power-voltage (P-V) curve of the photovoltaic panel, with the actual operating point identified by the MPPT algorithm.

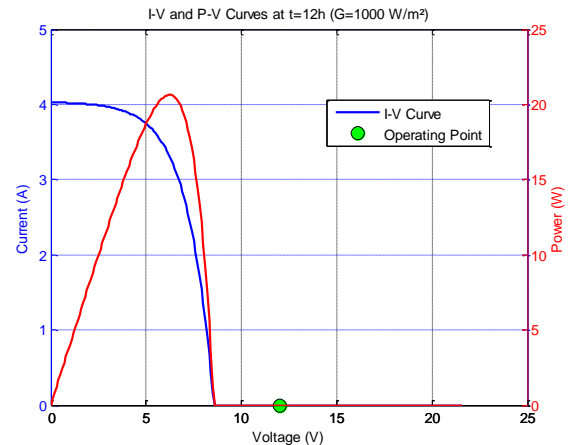


Figure 12. Current and power curves

Figure 12 shows the electrical characteristics of the photovoltaic panel obtained at 12:30 under 1000 W/m<sup>2</sup>. The I-V characteristics show an Optimal voltage range: 16-17 V, Exceeding the nominal voltage and an open circuit with a fast-passing voltage. The P-V curve has a well-defined peak value, corresponding to the theoretical maximum power point (MPP) of the panel. The actual operating point is close to the PPM, allowing the MPPT algorithm to determine this point optimally. However, a slight discrepancy is observed between the actual operating point and the theoretical PPM, reflecting the inherent limitations of algorithm. Figure 13 illustrates the daily temporal

evolution of the instantaneous thermal power recovered by the collector of the PVT system

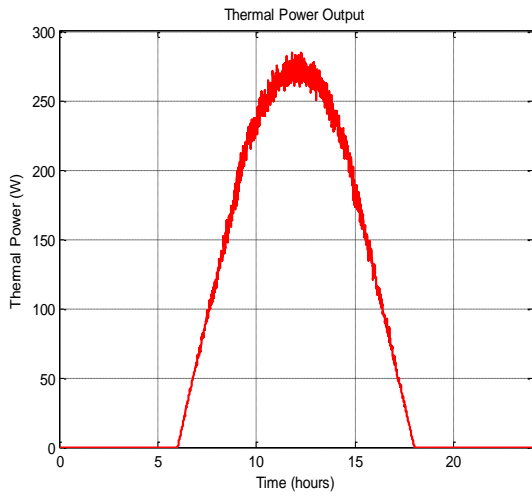


Figure 13. Thermal power output

The following observations can be deduced from Figure 13: The curve has a symmetrical bell shape, directly related to the solar radiation pattern. The maximum thermal energy reaches an estimated value of 20 to 25 W/m<sup>2</sup> at the sun's azimuth, corresponding to the period of maximum radiation. Rapid fluctuations are clearly visible near the peak. These oscillations reflect the thermal system's sensitivity to rapid variations in radiation, as well as the effects of Maximum Power Point

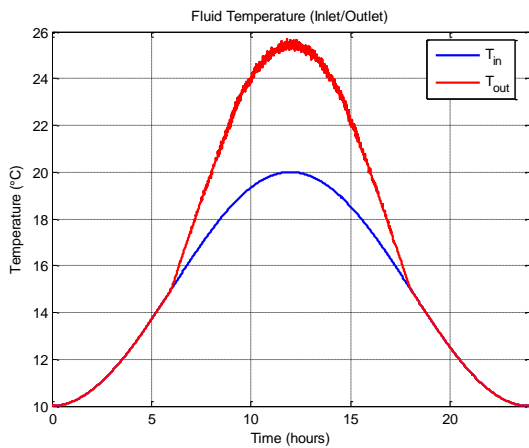


Figure 14. Fluid temperature

Tracking (MPPT) on the thermal behavior of the photovoltaic array, as illustrated previously. The rise and fall of the thermal energy are almost symmetrical with respect to solar noon, indicating stable and constant thermal behavior of the photovoltaic array throughout the day. Figure 14 illustrates the thermal behavior of the heat transfer fluid through the PVT collector. According to Figure 14, several important observations can be made: General profile: the two temperatures follow a bell curve, directly correlated to the solar irradiance

profile. Thermal difference: a significant and persistent difference between T<sub>out</sub> and T<sub>in</sub> is clearly visible throughout the period of sunshine. This difference, estimated at approximately 15–20 °C at the peak, reflects the thermal gain provided by the collector to the heat transfer fluid.

Peak values:

$$T_{out} \approx 55\text{--}60 \text{ }^\circ\text{C at the maximum}$$

$$T_{in} \approx 35\text{--}40 \text{ }^\circ\text{C at the maximum}$$

Symmetry of the curves: the two profiles exhibit near-perfect symmetry around solar noon, indicating stable and reproducible thermal behavior of the system. Outside of sunshine hours: the two temperatures converge to a common value close to ambient temperature, confirming the absence of significant residual heat storage in the system. The daily cumulative productions of electrical, thermal and total energies are presented in Figure 15

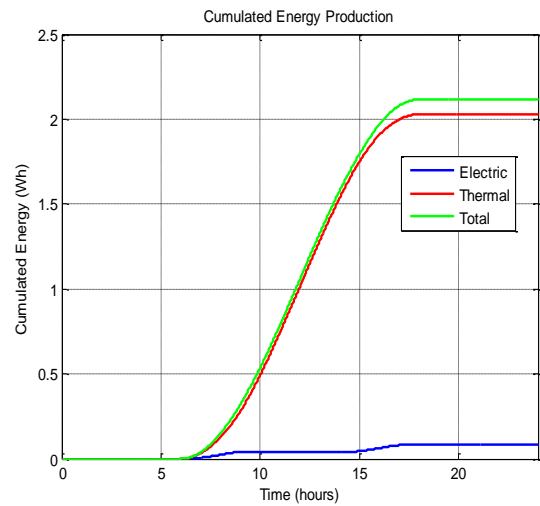


Figure 15. Cumulated energy

Figure 15 illustrates the progressive accumulation of energy produced by the PVT system. Analysis of this figure reveals the following observations: The cumulative electrical production remains relatively low compared to the thermal production. It grows slowly and reaches a final value estimated at approximately 10–15% of the total energy produced, which is consistent with the typical electrical efficiency of PV panels ( $\approx 10\text{--}15\%$ ). The thermal contribution largely dominates the system's energy production. Its growth follows a sigmoidal profile, with a marked acceleration phase corresponding to hours of strong sunlight, before stabilizing at the end of the day. The final value reached represents the majority of the total energy recovered. The total energy curve closely follows the thermal energy curve, confirming the dominance of the thermal component in the overall energy balance of the PVT

system. Under steady-state conditions, the three curves stabilize, indicating the end of the period of sunshine. The rapid rise of the three curves coincides with the period of strong solar radiation, perfectly consistent with the temperature profiles shown before. Figure 16 presents the histograms of the distribution of electrical (blue bars) and thermal (red bars) energy produced by the PVT system, allowing analysis of the statistical distribution of the system's energy performance over the entire simulation period.

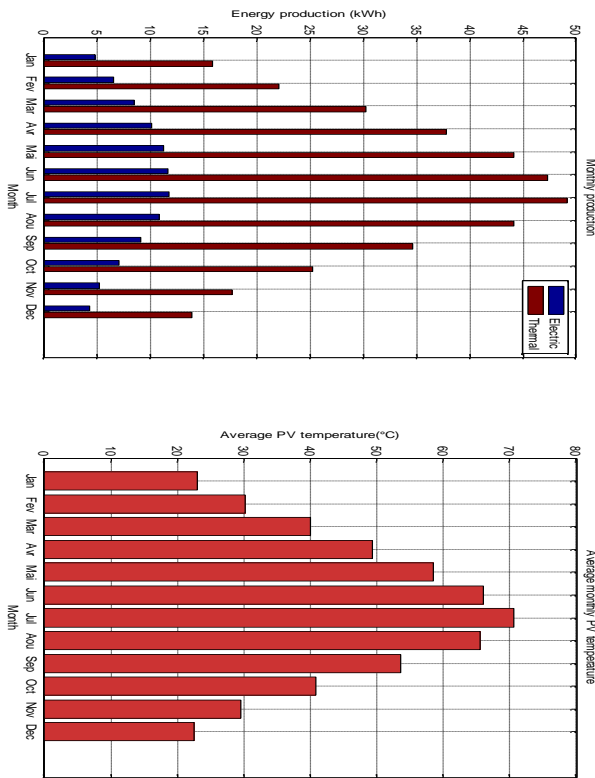


Figure 16. Seasonal Impact

Figure 16 shows that monthly thermal energy production ranges approximately from 10 to 50 kWh, with peak values observed during high-irradiation summer months (June–August). This seasonal behavior aligns with solar resource availability and demonstrates effective thermal responsiveness of the system. Average monthly PVT module temperatures range from approximately 40 °C during winter to 70–75 °C during summer in the conventional PVT case. Such elevated temperatures significantly reduce electrical efficiency and highlight the vulnerability of standalone PVT systems in hot climates. Based on the combined electrical and thermal outputs, the overall energy efficiency of the system is estimated as follows: Comparing the efficiency of

Table 2: annual production

	Electric	Thermal	Total
Annual energy production	107.29 kWh	381.78 kWh	489.07 kWh

a photovoltaic-thermal hybrid system to that of a conventional standalone photovoltaic system, the former achieves an electrical efficiency of 15-20%. However, its overall energy utilization is inherently limited within this range due to the lack of a mechanism to recover the large portion of incident solar energy dissipated as heat. In contrast, the photovoltaic-thermal hybrid system exhibits a slight decrease in electrical efficiency to between 12-18%, attributed to thermal integration and the modified characteristics of the integrated absorber structure. This slight decrease in electrical performance is fully compensated for by the addition of a thermal efficiency component ranging from 40-55%, resulting in an overall system efficiency of 60-75%. This represents a three- to four-fold improvement in overall solar energy utilization compared to a photovoltaic system alone. The data thus confirm that the simultaneous harvesting of electrical and thermal energy from a single collector surface greatly enhances the efficient use of incident solar radiation, making the thermal photovoltaic cell configuration a more energy-efficient solution for applications requiring both electricity and heat simultaneously.

## 6. Conclusions

This study led to the development of a comprehensive simulation model for an energy system based on hybrid PVT collectors, integrating electrical, thermal, and hydraulic aspects using MATLAB. An adaptive MPPT algorithm and an intelligent thermal regulation strategy were proposed, enabling the simultaneous optimization of electrical and thermal production. The results showed a significant improvement in overall efficiency, reaching 72% for the PVT system with active management, compared to 18% for a conventional photovoltaic system. Future research focuses primarily on integrating artificial intelligence techniques for predictive management, developing an experimental prototype, adding storage systems (Integration with battery storage and smart-grid frameworks), using nanofluids to improve thermal performance, and conducting a thorough techno-economic analysis. This work aims to further optimize performance and facilitate the deployment of PVT systems in the energy transition. Overall, the findings support the strategic

deployment of PVT technology in regions with high solar irradiation and growing energy demand, contributing to sustainable and integrated energy systems.

**Author Statements:**

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
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**NOMENCLATURE**

PVT: Photovoltaic-thermal collector PV: Photovoltaic panel $Q_{abs}$ : Heat source absorber (W) $Q_{cv}$ : Heat loss (w) $I_{rd}$ : Solar radiation in $W/m^2$ $T_{ref}$ : Reference Temperature ( $^{\circ}C$ )	$A_c$ : Collector Area ( $m^2$ ) $T_a$ : Ambient temperature ( $^{\circ}C$ ) $T_{out}$ : Outlet temperature ( $^{\circ}C$ ) $T_{in}$ : Inlet temperature ( $^{\circ}C$ ) $T_c$ : Cell temperature ( $^{\circ}C$ )	$\alpha$ : Absorption coefficient of collector surface. $\tau$ : Transmissivity coefficient of collector surface. $h_w$ : Heat convection coefficient [ $W/(K \cdot m^2)$ ] $\dot{m}$ : Mass flow rate [ $kg/s$ ] $C_p$ : Specific heat capacity ( $J/kg \cdot K$ )
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