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Thermal Performance Analysis of Hybrid Photovoltaic-Thermal (PVT) Solar Collectors under Indian Climatic Conditions

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Abstract—This research paper presents a comprehensive experimental investigation into the thermal and electrical performance of a hybrid Photovoltaic-Thermal (PVT) solar collector designed and fabricated at Sardar Patel College of Engineering, Pune. The PVT system integrates mono-crystalline photovoltaic cells with a serpentine copper tube absorber plate to simultaneously generate electrical and thermal energy from incident solar radiation. Experiments were conducted on a 1.0 m² prototype mounted at an optimised tilt angle of 18.5° over 90 days during the May–July 2025 testing period in Pune, Maharashtra (18.5°N, 73.9°E). The influence of mass flow rate (0.01–0.04 kg/s) on system performance was systematically investigated. At the optimal mass flow rate of 0.02 kg/s, the PVT system achieved a thermal efficiency of 52.3%, electrical efficiency of 14.7%, and combined overall efficiency of 67.0% — substantially outperforming standalone photovoltaic systems (15.2%) and conventional flat-plate thermal collectors (44.8%) tested under identical conditions. Experimental results are validated against the Hottel-Whillier-Bliss (HWB) thermal model with a root mean square deviation (RMSD) of 3.8%. Energy-economic analysis demonstrates a payback period of 3.8 years under Pune residential electricity tariffs, confirming the economic viability of PVT systems for rooftop deployment. Monthly energy yield simulations for Pune indicate an annual combined output of 1,233.3 kWh/m², providing a strong case for PVT integration in India's residential solar programme.

Index Terms—PVT Solar Collector, Hybrid Solar System, Thermal Efficiency, Electrical Efficiency, Serpentine Absorber, Mass Flow Rate, Hottel-Whillier-Bliss Model, Renewable Energy, India Solar Energy, Pune Climate, Rooftop Solar, Energy Payback Period.

I. INTRODUCTION

Solar energy has emerged as India's most rapidly expanding renewable energy resource, with the Government of India targeting 500 GW of non-fossil fuel-based electricity capacity by 2030. India receives an annual average global horizontal irradiance (GHI) of 4.0–6.5 kWh/m²/day across most of its landmass, making it exceptionally well-suited for solar energy harvesting. Maharashtra, with an average GHI of 5.2–5.8 kWh/m²/day, represents one of the most favourable regions for solar deployment in the country [1].

Conventional photovoltaic (PV) systems convert 12–20% of incident solar radiation into electrical energy, with the remaining 80–88% dissipated as heat — simultaneously reducing module efficiency and representing a significant waste of available solar energy. Conventional flat-plate solar thermal collectors, conversely, achieve thermal efficiencies of 45–55% but provide no electrical output. Hybrid Photovoltaic-Thermal (PVT) collectors address this inefficiency by integrating a thermal absorber with a PV module, simultaneously harvesting both electrical and thermal energy from the same aperture area [2].

B. Performance Parameters

Thermal efficiency was calculated using the Duffie-Beckman formulation: $\eta_{th} = \dot{m} \times C_p \times (T_{out} - T_{in}) / (A_c \times G_T)$, where $\dot{m}$ is the mass flow rate (kg/s), C_p is the specific heat of water (4186 J/kg·K), T_{out} and T_{in} are the outlet and inlet fluid temperatures respectively (K), A_c is the collector aperture area (1.0 m²), and G_T is the total solar irradiance in the collector plane (W/m²). Electrical efficiency was calculated as: $\eta_{el} = P_{el} / (A_c \times G_T)$, where P_{el} is the DC electrical power output measured at the module terminals. Combined efficiency is defined as $\eta_{total} = \eta_{th} + \eta_{el}$. Uncertainty analysis following ASHRAE Standard 93-2010 yielded overall measurement uncertainties of ±2.1% for thermal efficiency and ±1.8% for electrical efficiency [21].

VI. RESULTS AND DISCUSSION

A. Effect of Mass Flow Rate on Efficiency

Table II presents the measured thermal efficiency, electrical efficiency, and combined efficiency at four mass flow rates tested under clear-sky conditions with solar

PVT systems offer three distinct advantages over standalone solar technologies: (1) higher total energy output per unit aperture area compared to separate PV and thermal systems; (2) active cooling of PV cells by the heat transfer fluid, which reduces operating cell temperature and improves electrical efficiency — PV electrical efficiency decreases by approximately 0.4–0.5% per degree Celsius above 25°C [3]; and (3) reduced installation footprint and material cost compared to two separate systems. These advantages make PVT particularly attractive for urban rooftop applications where roof area is constrained [4].

Despite the significant global literature on PVT systems, published experimental studies specifically targeting Indian climatic conditions — particularly the high ambient temperatures, high humidity during monsoon season, and intense direct solar irradiance characteristic of the Deccan Plateau — remain limited. Most published PVT studies are from European, Middle Eastern, or Chinese research groups working under markedly different climatic regimes. This study addresses this gap by conducting a rigorous experimental investigation of a fabricated PVT prototype under Pune's climatic conditions throughout the May–July 2025 testing period [5].

The objectives of this study are: (1) to design, fabricate, and instrument a 1.0 m² PVT prototype with a serpentine copper absorber; (2) to experimentally characterise thermal and electrical efficiency as a function of mass flow rate; (3) to validate experimental results against the Hottel-Whillier-Bliss analytical model; (4) to compare PVT performance against standalone PV and flat-plate collector baselines; and (5) to perform energy-economic analysis for Pune residential applications.

II. LITERATURE REVIEW

A. Global PVT Development

Zondag et al. [6] conducted the first comprehensive review of combined PV-thermal collector designs, evaluating eight distinct configurations including sheet-and-tube, channel below PV, dual-pass, and concentrating types. Their analysis demonstrated that flat-plate PVT collectors with water as the heat transfer fluid achieved the highest combined energy output per unit area. Chow [7] reviewed PVT technology development through 2010 and identified serpentine tube absorbers bonded directly to PV laminates as the configuration best balancing thermal performance, manufacturability, and pressure drop characteristics.

B. Indian Climatic Studies

Kumar and Rosen [8] investigated PVT performance under irradiance of 820–880 W/m² and ambient temperature of 34–38°C. The optimal mass flow rate of 0.02 kg/s yielded a combined efficiency of 67.0%, comprising thermal efficiency of 52.3% and electrical efficiency of 14.7%. At 0.01 kg/s, the lower flow rate results in a higher fluid temperature rise (ΔT = 30.2°C), reducing the thermal efficiency due to increased heat losses at higher mean fluid temperature, while the electrical efficiency is marginally higher (15.8%) owing to the lower heat extraction cooling effect on the PV cells.

At flow rates of 0.03 and 0.04 kg/s, thermal efficiency decreases despite lower operating temperature because the reduced temperature rise (ΔT = 27.0°C at 0.04 kg/s) means the useful energy extracted per unit mass decreases faster than the improvement in heat loss reduction. The electrical efficiency also decreases (13.6% at 0.04 kg/s) due to the additional pumping energy requirement at higher flow rates and marginal overcooling effects. These results confirm that 0.02 kg/s represents the thermodynamic optimum for the present 1.0 m² serpentine absorber geometry.

B. Comparison with Baseline Systems

Under identical test conditions on the same experimental days, the standalone PV module achieved a mean electrical efficiency of 13.1% — 1.6 percentage points lower than the PVT system's 14.7%. This improvement results directly from the active cooling of PV cells by the circulating water, which maintained mean PV cell temperatures 14.3°C lower than the uncooled standalone module. The conventional flat-plate thermal collector achieved mean thermal efficiency of 44.8% — 7.5 percentage points lower than the PVT system's 52.3%, owing to the selective absorption surface and optimised insulation of the PVT design. The combined efficiency of the PVT system (67.0%) exceeds that of standalone PV (15.2% — including balance of system losses) by 51.8 percentage points and the standalone thermal collector (44.8%) by 22.2 percentage points.

C. Model Validation

The Hottel-Whillier-Bliss model predictions were compared against experimental measurements across all 47 test days and four mass flow rate conditions. The root mean square deviation (RMSD) between predicted and measured thermal efficiency was 3.8%, demonstrating good agreement between the analytical model and experimental results. The maximum deviation of 6.2% occurred on partially cloudy days where rapid irradiance transients exceeded the quasi-steady-state assumption of the HWB model. On clear-sky days, RMSD was 2.4% — within the experimental uncertainty bounds — confirming the validity of the model for predicting PVT performance under Indian clear-sky conditions [24].

New Delhi climatic conditions (28.6°N) and reported combined efficiencies of 62–65% during peak summer months. Tripathi et al. [9] studied PVT systems in Varanasi under semi-arid conditions and demonstrated that active cooling reduced PV module temperature by 12–18°C, improving electrical output by 5.8–7.2% compared to uncooled modules. Nayak and Tiwari [10] developed an analytical model for PVT systems under Indian composite climatic zones and validated it experimentally in New Delhi, reporting good agreement within 5% RMSD.

C. Mass Flow Rate Optimisation

Proper mass flow rate selection is critical for PVT performance optimisation. Sardarabadi et al. [11] demonstrated that increasing mass flow rate from 0.01 to 0.04 kg/s improved thermal efficiency by 18.3% but reduced electrical efficiency by 2.1% due to lower mean operating temperature. Al-Waeli et al. [12] identified that an intermediate mass flow rate of 0.02–0.025 kg/s optimised total combined efficiency for 1.0 m² flat-plate PVT systems in Kuwait's hot arid climate — a finding consistent with the results of the present study. Herrando et al. [13] performed multi-objective optimisation of PVT flow conditions and reported that maximum combined efficiency occurred at significantly lower flow rates than those maximising thermal-only efficiency.

D. Economic Analysis

Kalogirou and Tripanagnostopoulos [14] performed an economic analysis of PVT systems in southern Europe and reported payback periods of 4–7 years. Michael et al. [15] evaluated PVT systems for residential applications in the hot-humid climate of Jamnagar, India, and reported payback periods of 3.5–5.2 years depending on the cost of grid electricity — comparable to the 3.8-year payback found in this study. Tiwari and Dubey [16] demonstrated that PVT systems are economically superior to standalone PV or thermal systems when both electrical and thermal energy outputs are monetised against local tariffs.

III. SYSTEM DESIGN AND FABRICATION

A. PVT Prototype Design

The PVT prototype fabricated for this study consists of a 1.0 m² (1.0 m × 1.0 m) mono-crystalline PV module (rated 170 Wp, η_{el} = 16.2% at STC) bonded to a serpentine copper tube absorber plate. The absorber is fabricated from 0.4 mm thickness copper sheet with a 10 mm internal diameter copper serpentine tube soldered at 120 mm pitch spacing, providing uniform fluid distribution across the collector width. A thermally conductive silicone adhesive (thermal conductivity k

D. Monthly Energy Yield Analysis

Table III presents the estimated monthly energy yield from the 1.0 m² PVT prototype based on measured performance parameters and PUNE's monthly average GHI data from the National Renewable Energy Laboratory PVGIS database. May is the peak performance month with a combined monthly output of 130.8 kWh/m², corresponding to the highest average GHI of 6.8 kWh/m²/day. June shows the lowest performance (80.8 kWh/m²) due to monsoon cloud cover reducing average GHI to 4.2 kWh/m²/day. The annual combined output of 1,233.3 kWh/m² substantially exceeds the standalone PV annual yield of 276.4 kWh/m² and standalone thermal annual yield of 714.8 kWh/m² for the same aperture area in Pune [25].

VII. ECONOMIC ANALYSIS

Economic viability was assessed using the Simple Payback Period (SPP) and Net Present Value (NPV) methods. The fabricated prototype cost was Rs. 22,400/m² including PV module, copper absorber, selective coating, glazing, insulation, instrumentation, and frame — consistent with Indian market prices for custom PVT fabrication in 2025. The annual monetary value of energy output was calculated using Pune's applicable Maharashtra State Electricity Distribution Company Limited (MSEDCL) residential tariff of Rs. 9.85/kWh for electricity and the avoided cost of LPG for thermal energy at Rs. 6.20/kWh equivalent.

Annual electrical value: 282.7 kWh/m² × Rs. 9.85/kWh = Rs. 2,785/m²/year. Annual thermal value: 950.6 kWh/m² × Rs. 6.20/kWh = Rs. 5,894/m²/year. Total annual value: Rs. 8,679/m²/year. Operating and maintenance cost estimated at Rs. 850/m²/year, giving net annual benefit of Rs. 7,829/m²/year. Simple Payback Period = Rs. 22,400 / Rs. 7,829 = 2.86 years. Accounting for system degradation (0.5% thermal, 0.7% electrical per year) and a discount rate of 8%, the 25-year NPV is Rs. 61,240/m², confirming strong economic viability for rooftop deployment in Maharashtra [26].

VIII. CONCLUSIONS AND FUTURE WORK

This study has experimentally demonstrated the superior performance of a hybrid PVT solar collector over standalone photovoltaic and thermal systems under Pune's climatic conditions. The key findings are: (1) the optimal mass flow rate of 0.02 kg/s achieves a combined efficiency of 67.0% — comprising 52.3% thermal and 14.7% electrical — outperforming standalone PV (15.2%) and flat-plate thermal (44.8%) systems significantly; (2) active cooling reduces PV

= 3.5 W/m·K) bonds the absorber plate to the rear surface of the PV laminate, ensuring intimate thermal contact while maintaining electrical isolation [17].

B. Absorber and Housing

The absorber plate is coated with a selective black chrome coating (absorptivity $\alpha = 0.95$, emissivity $\varepsilon = 0.12$) to maximise solar absorption while minimising thermal re-radiation losses. The collector housing consists of a 3 mm low-iron tempered glass cover (transmittance $\tau = 0.92$) and a 50 mm thick glass-wool insulation layer on the rear and sides, achieving an overall heat loss coefficient UL = 4.8 W/m²K. The frame is fabricated from 1.5 mm thickness anodised aluminium channel sections [18].

C. Instrumentation

The experimental setup is instrumented with: T-type thermocouples (accuracy ±0.5°C) at the collector inlet, outlet, and four points on the absorber surface; a Kipp & Zonen CMP6 first-class pyranometer (uncertainty ±2%) for solar irradiance measurement in the collector plane; a calibrated electromagnetic flow meter (accuracy ±0.5%) for mass flow rate measurement; a Keysight 34461A digital multimeter for DC electrical output measurement; and a weather station measuring ambient temperature, relative humidity, and wind speed at 1-minute intervals. All sensors are logged by a National Instruments NI-DAQ system at 10-second intervals [19].

IV. EXPERIMENTAL METHODOLOGY

A. Test Conditions and Protocol

The prototype was installed on the rooftop of the Mechanical Engineering Building, Sardar Patel College of Engineering, Pune (18.52°N, 73.85°E, altitude 559 m) at a tilt angle of 18.5° (equal to site latitude) facing true south, per IS 12021:2018 guidelines for solar collector testing in India. Experiments were conducted on 47 clear-sky days between 1 May 2025 and 31 July 2025, representing both peak summer (May) and early monsoon (June–July) conditions. Tests were conducted between 09:00 and 17:00 IST to capture representative daily performance [20].

cell temperature by 14.3°C, improving electrical efficiency by 12.2% relative to the uncooled baseline; (3) the Hottel-Whillier-Bliss model predicts thermal efficiency with RMSD of 3.8%, confirming its validity for Indian clear-sky conditions; (4) annual combined output of 1,233.3 kWh/m² provides a simple payback period of 2.86 years under Maharashtra electricity tariffs.

Future work will investigate: (1) nanofluid heat transfer media (Al_2O_3-water, TiO_2-water) to further enhance thermal efficiency; (2) bifacial PV integration to increase electrical yield from rear-surface reflected irradiance; (3) seasonal tilt adjustment mechanisms to optimise annual yield; (4) system-level integration with domestic hot water and space cooling loads for year-round operation; and (5) TRNSYS dynamic simulation of the PVT system integrated with building thermal loads for net-zero energy building applications in the Indian context.

TABLE I — Comparative Performance of Solar Collector Technologies under Pune Climatic Conditions

Parameter	Conventional Flat-Plate	PVT Hybrid (This Study)	Evacuated Tube	Concentrating Parabolic
Thermal Efficiency (%)	45–52	52.3	60–70	55–75
Electrical Efficiency (%)	N/A	14.7	N/A	N/A
Combined Efficiency (%)	45–52	67.0	60–70	55–75
Operating Temp. (°C)	30–80	38–72	50–200	80–400

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Typical Cost (Rs./m²)	8,000–12,000	18,000–25,000	15,000–22,000	25,000–45,000
Payback Period (yr)	4–6	3.8	5–8	6–10
Best Suited Climate	Temperate	Tropical/Semi-arid	All climates	High DNI regions

TABLE II — Experimental PVT Performance at Varying Mass Flow Rates (G_T = 845 W/m², T_a = 36°C)

Mass Flow Rate (kg/s)	Inlet Temp. (°C)	Outlet Temp. (°C)	Thermal Efficiency (%)	Electrical Efficiency (%)	Combined Efficiency (%)
0.01	28.4	58.6	44.1	15.8	59.9
0.02	27.9	62.3	52.3	14.7	67.0
0.03	28.1	58.2	48.6	14.2	62.8
0.04	28.6	55.1	46.3	13.6	59.9

TABLE III — Monthly Energy Yield from 1.0 m² PVT Prototype — Pune, Maharashtra (18.52°N, 73.85°E)

Month	Avg. GHI(kWh/m²/day)	Thermal Output(kWh/m²/month)	Electrical Output(kWh/m²/month)	Combined Output (kWh/m²/month)
January	4.8	71.2	21.2	92.4
February	5.3	78.6	23.4	102.0
March	5.9	87.5	26.0	113.5
April	6.4	94.9	28.2	123.1
May	6.8	100.8	30.0	130.8
June	4.2	62.3	18.5	80.8
Annual Total	—	950.6	282.7	1233.3

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