Vacuum-Based Experimental Set-Up and Methodology for Simultaneous Thermal–Electrical Characterization of Hybrid Energy Conversion Devices up to 100 °C

Summary

This work presents the development of a vacuum-based experimental set-up for the simultaneous thermal and electrical characterization of energy conversion devices up to 100 °C under controlled thermo-radiative conditions. The system integrates a stainless-steel vacuum chamber with a calibrated solar simulator (1000 W/m²), enabling repeatable indoor testing with suppressed convective losses. The device under test is mounted on an actively temperature-controlled support, ensuring precise thermal regulation and reduced parasitic effects. Electrical performance is assessed through I–V measurements, while thermal output is quantified using a calibrated thin-film heat flux sensor. The methodology is applied to integrated photovoltaic-thermal (IPVT) devices at different temperatures up to 100 °C. Results show stable operation under prolonged thermal stress and good measurement reproducibility. The proposed approach provides a reliable framework for coupled thermal–electrical characterization of hybrid energy conversion devices in vacuum environments.

Keywords: Solar energy, Energy conversion devices, Hybrid Photovoltaic- Thermal collectors, Thermal characterization , Electrical characterization , Vacuum- based characterization

Field of application for the findings: Characterization and testing of hybrid solar energy conversion devices for photovoltaic-thermal (PVT) applications.

Addressed audience: Researchers, engineers, and industry professionals in solar energy.

1. Introduction

The integration of thermal energy recovery into photovoltaic modules has driven the development of photovoltaic–thermal (PV/T) technologies (Diwania et al., 2020), which enable the simultaneous generation of electrical and thermal energy from the same active surface. Within this framework, high-vacuum photovoltaic–thermal (HV-PVT) systems represent an advanced technological evolution designed to drastically reduce convective heat losses and sustain operation at moderate-to-high temperatures, up to 100 °C (Mellor et al., 2018).Unlike conventional PV/T systems, where design strategies typically prioritize electrical performance and treat thermal recovery as a secondary output, HV-PVT concepts are specifically engineered to enhance thermal energy production at elevated temperatures while still maintaining concurrent electricity generation (De Luca et al., 2023a). By operating in a high-vacuum environment, these systems shift the current state of the art in PV/T technology toward applications where medium-temperature heat recovery is a primary objective, expanding their potential use in industrial processes, building integration, and hybrid energy systems. (De Luca et al., 2023b). Accurate characterization of HV-IPVT devices requires simultaneous measurement of electrical and thermal outputs under controlled conditions. This presents experimental challenges, including reliable heat flux quantification and precise temperature control to isolate conductive and radiative contributions. To address these issues, this work presents the development and validation of a dedicated experimental setup capable of measuring the I–V characteristics of IPVT devices while simultaneously recording heat flux at controlled operating temperatures up to 100 °C. The setup enables the assessment of both electrical performance and thermal efficiency, providing a comprehensive framework for device evaluation and comparison.

2. Methodology

The dedicated setup for simultaneous electrical and thermal characterization of IPVT devices comprises a stainless-steel vacuum chamber (Mini Test Box) operating at pressures below 10^{-4} mbar, sealed with a transparent glass window to allow controlled irradiation. A calibrated solar simulator delivers uniform and reproducible irradiance across the device under test (DUT), closely replicating standard solar conditions and ensuring well-defined thermo-radiative operating environments (Fig 1a).

The DUT is mounted on a custom dual-stage support designed to ensure precise thermal control while minimizing parasitic losses. The primary stage consists of a cylindrical aluminum disk with an embedded heater (MAIN), while the secondary stage allows independent adjustment of height and temperature (BASE). A calibrated thin-film heat flux sensor is positioned directly beneath the DUT, with thermal contact ensured through high-conductivity grease enabling accurate measurement of the heat flux delivered by the device (Fig.1 b).

Electrical contacts are established via a copper block that supports the cell (Fig.1 c). The back of the cell is secured with a thin layer of silver paste while the front contact is connected through fine copper wires to the vacuum feedthrough. The copper block is electrically insulated and thermally coupled to the heat flux sensor using thermal conductive silicon paste. This arrangement ensures stable and reliable electrical connections without compromising thermal measurements.

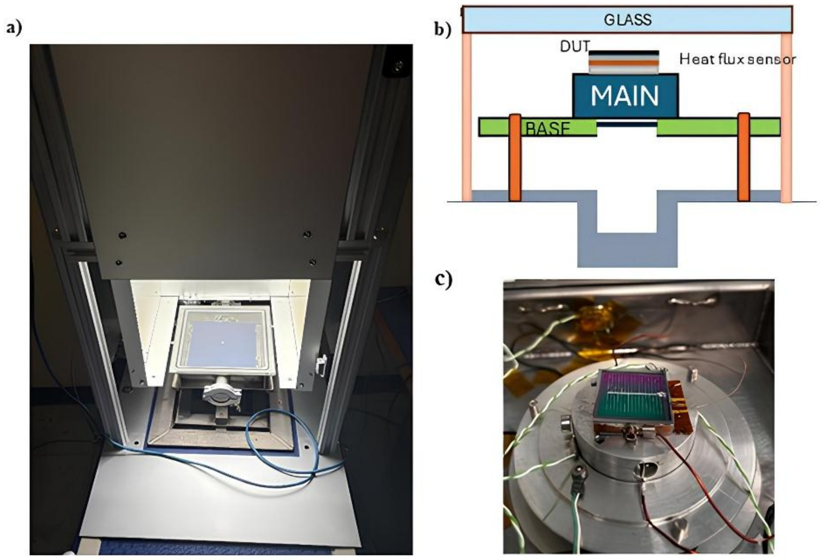

Figure 1: (a) Internal view of the experimental setup featuring the vacuum chamber and calibrated solar simulator; (b) Cross-sectional schematic of the dual-stage support assembly: the DUT is placed on the heat flux sensor embedded in the cylindrical MAIN disk, which is supported by the adjustable BASE; (c) Close-up photograph of the DUT mounted on the MAIN disk, showing electrical connections and thermocouples for simultaneous measurement of electrical output and heat flux.

The temperatures of the DUT and surrounding components (glass window, chamber walls, support base, MAIN) are monitored using type-K thermocouples, and the sensor voltage is converted to heat flux through prior calibration. Temperature is actively controlled using PID-regulated heaters, allowing the DUT to operate across a range of conditions representative of typical photovoltaic-thermal applications. I–V measurements are performed to evaluate electrical performance, while the heat flux is simultaneously monitored to quantify thermal output. Thermal efficiency is derived from the measured heat flux, corrected for system-related losses, and normalized to the incident solar irradiance, providing an accurate assessment of device performance under realistic conditions.

The experimental setup was validated using a reference IPVT cell, demonstrating reproducibility, stable operation, and reliable integration of electrical and thermal measurements. This methodology establishes a robust framework for comprehensive characterization of high-vacuum photovoltaic-thermal devices.

3. Results

A reference silicon-based IPVT device was experimentally characterized through simultaneous I–V and heat flux measurements to evaluate both its electrical and thermal performance. Measurements were conducted at multiple operating temperatures, including room temperature, 60 °C, 80 °C, and 100 °C, while the heat flux collected by the device was continuously recorded using a calibrated thin-film heat flux sensor.

Figure 2a presents the measured I–V characteristics alongside the corresponding power-voltage (P–V) curves for the reference cell at the different temperature setpoints. Thermal efficiency was derived from the heat flux measured by the sensor.

During the tests, the device under test (DUT) was illuminated with a solar simulator set to 1000 W/m² and heated using integrated heaters at the base and main support until the target temperatures were stabilized. Initially, the I–V characteristics were recorded at ambient temperature to establish the baseline electrical performance. Once thermal equilibrium at the target temperature was reached, a second I–V measurement was performed to identify the maximum power point (MPP) voltage at that temperature. The DUT was then powered at this MPP voltage while the heat flux was continuously monitored at steady state.

Figure 2b shows the acquisition for the reference IPVT cell held at a setpoint temperature of 100 °C. The heat flux $q\,(\mathrm{W/m^2})$ is calculated from the sensor output voltage V_{HFS} using the sensor sensitivity C_t $(\mu\mathrm{V/(W/m^2)})$ according to:

$$q = \frac{V_{\mathrm{HFS}}}{C_t} \qquad \text{(eq.1)}$$

where C_t is the calibration constant of the heat flux sensor.

In the figure, the blue curve represents the cell temperature, while the highlighted yellow and green areas correspond to changes in heat flux during the I–V measurement and the subsequent application of the MPP voltage, respectively.

a)
b)

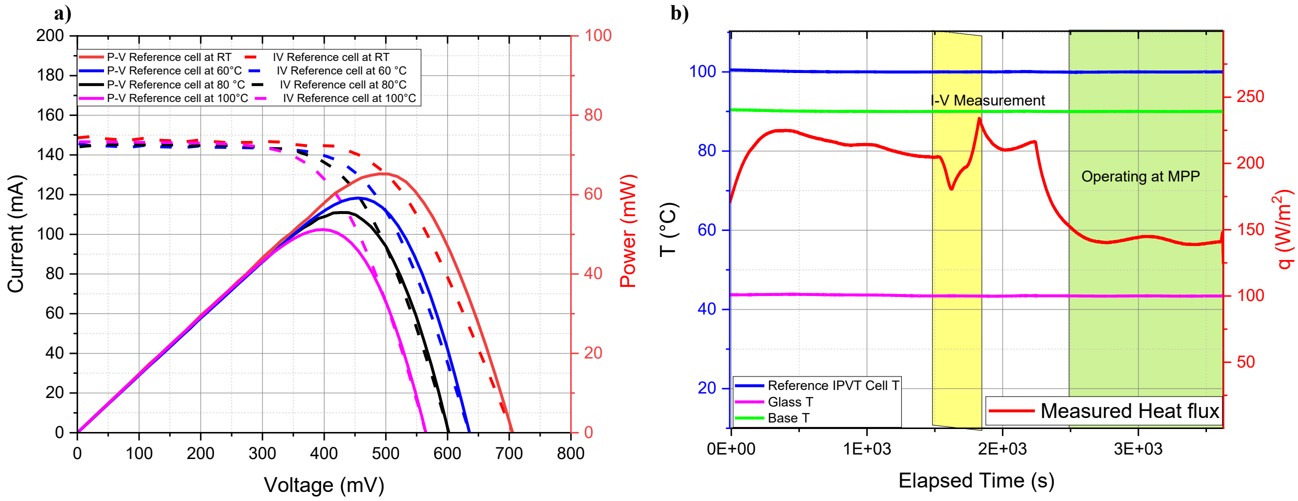

Figure 2: (a) Current-voltage (I–V) and power-voltage (P–V) characteristics of the silicon-based reference IPVT cell measured at different temperatures (room temperature, 60 °C, 80 °C, 100 °C); (b) Example time-resolved measurement of cell temperature (blue), glass temperature (purple), base temperature (green), and collected heat flux (red) at a setpoint temperature of 100 °C. The highlighted areas indicate the periods of I–V characterization (yellow) and operation at the Maximum Power Point (MPP) (green).

4. References

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