Seasonal thermo-electrical performance of an actively air-cooled glazed photovoltaic system with forced convection

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Abstract:

The performance of photovoltaic (PV) panels is strongly influenced by operating temperature and environmental conditions, which motivates the development of effective thermal management strategies. This study presents an experimental investigation of the thermo-electrical performance of a glazed photovoltaic system with actively forced air cooling under real outdoor conditions. The analysis is based on a comparative approach, including a reference panel, a glazed panel, and a glazed panel with forced air flow.

The experiments were conducted for representative summer and transitional (autumn) periods to assess the seasonal variability of system performance. Under summer conditions, active cooling reduced the panel temperature by an average of 1.5°C (up to 3.6°C), resulting in an increase in electrical power output of approximately 5.5%. In contrast, under autumn conditions, the modified panel operated at higher temperatures but exhibited a significantly higher electrical output (21.2%), indicating a dominant influence of glazing-related optical and thermal effects.

In addition to electrical performance, the system demonstrated the capability for low-temperature heat recovery, with thermal power outputs of approximately 215 W and 167 W for summer and autumn conditions, respectively. The results reveal a dual-mode system behavior, where cooling effects dominate under high irradiance, while glazing effects become significant under lower irradiance conditions.

The proposed configuration shows potential as a simplified hybrid thermo-electrical system for building-integrated and distributed energy applications.

Keywords:

Photovoltaic panels; Active air cooling; Glazing; Thermo-electrical performance; Hybrid PV system.

1. Introduction

The continuous growth of photovoltaic (PV) installations has intensified the need to improve their operational efficiency under real environmental conditions. One of the key limiting factors affecting PV performance is the increase in cell temperature during operation, particularly under high solar irradiance. Elevated temperatures lead to a reduction in open-circuit voltage and, consequently, a decrease in electrical power output, making thermal management an essential aspect of PV system optimization. Numerous studies have reported that the power output of crystalline silicon panels decreases by approximately 0.4-0.5% per °C increase in cell temperature, highlighting the importance of effective cooling strategies [1],[2]. This behavior results directly from the thermal balance of PV panels, where increased temperature negatively affects voltage and overall efficiency [3].

In recent years, various approaches have been proposed to mitigate temperature-related efficiency losses, including passive ventilation strategies, heat sinks, and hybrid photovoltaic-thermal (PVT) systems. While liquid-based PVT systems offer high heat extraction efficiency, they introduce additional hydraulic complexity, increased costs, and operational challenges. Comprehensive reviews indicate that although liquid-based PVT systems can achieve high overall efficiencies, their practical deployment is often limited by system complexity and maintenance requirements [4],[5]. As an alternative, air-based cooling concepts have gained attention due to their structural simplicity, lower maintenance requirements, and suitability for building-integrated applications [6],[7].

A wide range of active cooling techniques has been investigated in recent years, including water-based systems, air cooling, hybrid approaches, and advanced concepts such as nanofluids or thermoelectric modules. Experimental studies have demonstrated that water cooling can significantly reduce PV panel temperature, even by over 20 K, and increase electrical output by approximately 10% under real operating conditions [8]. Similarly, recent research has shown that actively forced air cooling systems can improve power output by over 10% compared to uncooled configurations under controlled conditions [9]. These findings confirm that active thermal management is a viable and effective method for enhancing PV performance, although its implementation must consider additional energy consumption and system complexity.

A particularly interesting modification of conventional PV systems involves the introduction of an additional front glazing layer. Such a configuration alters both the optical and thermal boundary conditions of the panel. On the one hand, the glazing can reduce convective heat losses and modify radiative heat exchange with the surroundings, potentially leading to higher operating temperatures. On the other hand, it may influence optical transmittance and reflection losses depending on incidence angle and surface properties. Similar concepts are commonly applied in solar thermal collectors and hybrid PV/T systems, where glazing plays a key role in controlling heat transfer and improving overall energy utilization [10].

Since glazing directly affects the thermal conditions of the PV panel, it consequently influences its electrical behavior, particularly the shape and position of the I-V characteristics. An increase in cell temperature leads to a significant decrease in open-circuit voltage, while the short-circuit current changes only slightly, resulting in a reduction of the maximum power output. This behavior is well described by equivalent circuit models, where temperature-dependent parameters play a key role in shaping the I-V curve [11]. In hybrid and cooled PV systems, thermal conditions directly affect electrical performance. Experimental studies confirm that effective heat removal stabilizes I-V characteristics and improves energy conversion efficiency under varying operating conditions [12]. Therefore, analyzing temperature effects at the level of instantaneous I-V behavior is essential for understanding performance degradation and the potential benefits of cooling strategies.

Various cooling techniques have been developed to mitigate temperature-induced efficiency losses in photovoltaic systems, with both air- and water-based approaches widely investigated. Air cooling, particularly using heat sinks and optimized channel geometries, can reduce panel temperature and improve performance. However, its effectiveness strongly depends on design parameters such as fin spacing, height, and airflow configuration, typically leading to relatively limited temperature reductions [13]. In contrast, water-based cooling techniques provide significantly higher heat removal capacity due to the superior thermal properties of the coolant. Depending on the applied method, such as immersion, spray cooling, or jet impingement, electrical efficiency improvements can range from approximately 7-20%, with advanced configurations achieving even higher gains exceeding 40% under optimized conditions [14]. These systems also enable substantial temperature reduction and additional benefits such as increased energy yield and reduced CO_2 emissions.

Despite significant progress in photovoltaic cooling technologies, important limitations still affect their practical applicability. Water-based systems offer high thermal efficiency but require additional infrastructure, continuous water supply, and may face issues related to fouling and long-term reliability, which limits their scalability, especially in water-scarce regions. Air-based cooling systems are simpler and easier to implement, but generally provide lower heat removal efficiency. Their performance strongly depends on system geometry and airflow conditions, often resulting in non-uniform cooling. Moreover, most studies focus on rear-side cooling, without considering modifications to the front-side boundary conditions of PV panels.

Another important limitation is that the majority of existing studies investigate cooling strategies independently of optical modifications. In particular, the combined effects of altered optical conditions, such as additional glazing, and active thermal management are rarely analyzed in a unified framework. As a result, the interaction between increased thermal load due to glazing and its potential mitigation through controlled cooling remains insufficiently understood. Furthermore, many investigations are conducted under controlled or steady-state conditions, which do not fully capture the dynamic behavior of PV systems under real outdoor environments. This limits the ability to accurately assess the practical performance and scalability of proposed cooling solutions.

These limitations highlight the need for integrated experimental studies that simultaneously consider thermal, electrical, and boundary condition modifications in PV systems, particularly under realistic operating conditions.

To address these gaps, this study presents a comparative experimental investigation of the impact of front-side glazing and actively forced air cooling on the thermo-electrical performance of photovoltaic panels under real outdoor conditions. The analysis is based on a stepwise approach, including reference validation, assessment of glazing effects, and evaluation of active air cooling performance.

The main objective of the study is to experimentally identify the thermo-electrical interactions associated with PV glazing and to assess the effectiveness of forced air cooling under varying operating conditions. Particular attention is given to the seasonal dependency of system performance, based on representative summer and transitional (autumn) periods.

The results provide insight into the combined thermal and electrical behavior of the system and demonstrate its potential to operate as a simplified air-based hybrid thermo-electrical device. The study highlights the transition between cooling-dominated and glazing-dominated operating regimes, providing new insight into the seasonal behavior of hybrid PV systems and their potential application in building-integrated and distributed energy systems.

2. Materials and methods

This section describes the experimental methodology used to investigate the thermo-electrical performance of photovoltaic panels under different operating configurations. The study was designed to enable a direct comparative analysis between a reference PV panel and a modified panel equipped with additional glazing and, subsequently, active air cooling. Particular attention was given to ensuring identical environmental conditions and measurement consistency, allowing for reliable assessment of temperature effects and electrical performance.

2.1. Experimental setup

The experiments were conducted under outdoor conditions in Krakow, Poland (50°N, 19°E). The analysis was performed under naturally varying environmental conditions. The experimental setup consisted of two identical photovoltaic (PV) panels installed in parallel under identical environmental conditions to enable direct comparative analysis. Both panels were positioned with the same orientation and tilt angle, ensuring uniform exposure to solar irradiance and ambient conditions throughout the measurement period. The panels were installed at a tilt angle of 35° and oriented towards the south, with a slight deviation towards the west.

Each PV panel was connected to an individual microinverter (ENECSYS SMI-360-72), allowing independent operation and accurate tracking of the maximum power point for each panel. This configuration eliminates mismatch effects and ensures reliable comparison of electrical output between the tested units.

One of the panels (Panel 1) operated as a reference unit without any structural modifications, while the second panel was adapted according to the investigated configuration. In the modified setup (Panel 2), an additional glass cover was installed at a fixed distance of 0.10 m from the PV panel, forming an air cavity. The cover consisted of low-iron solar glass commonly used in solar thermal collectors, characterized by reduced iron oxide content to ensure high solar transmittance and minimal optical losses.

The glass cover was mounted using a supporting structure that ensured stable and uniform spacing across the entire panel surface. Depending on the test configuration, the air cavity was either open to the ambient environment, allowing natural convection (Series 1), or enclosed and connected to an air channel system enabling controlled airflow (Series 2).

The use of two identical PV panels operating simultaneously under the same environmental conditions minimized the influence of external factors, such as fluctuations in solar irradiance, ambient temperature, and wind speed, thereby ensuring high reliability of the comparative analysis. This parallel measurement approach allows for direct, time-resolved comparison of panel performance under identical boundary conditions.

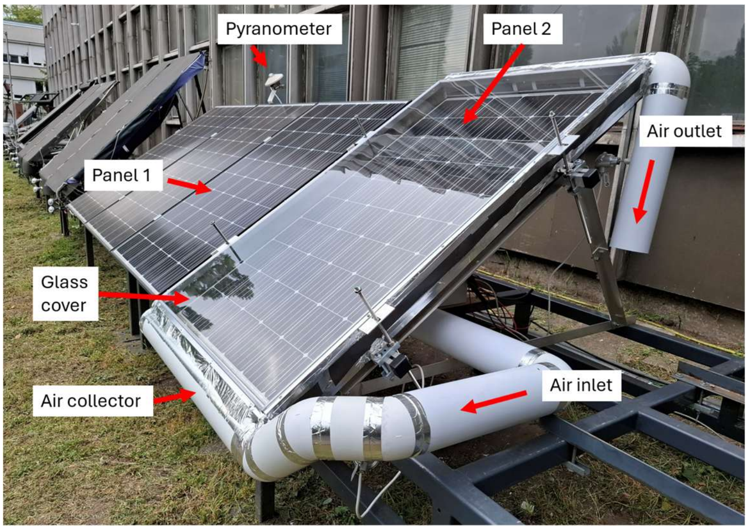

Figure 1. *Experimental setup of the PV panels with glazing and forced air cooling (Series 2).*

Figure 1 shows the experimental setup, including the reference PV panel (Panel 1) and the modified PV panel (Panel 2). The image corresponds to the configuration with forced air circulation (Series 2), where the modified panel is equipped with an additional glass cover and an integrated air channel system. In this configuration, ambient air is drawn into the system through the lower air collector (air inlet) and forced into the cavity between the PV panel and the glass cover using a fan. As the air flows through the cavity, it absorbs heat from the PV panel surface, resulting in an increase in air temperature. The heated air is then discharged through the upper outlet section of the system. For comparison, in Series 1 the system operated in an open configuration without air ducts, allowing natural convection within the cavity between the PV panel and the glass cover.

Table 1 summarizes the main technical parameters of the PV panels used in the experimental investigation. The panels were based on monocrystalline silicon cells and corresponded to the EGE-310M-60 model.

Table 1. *Main parameters of the PV panel.*

Parameter	Unit	Value
Nominal Power	Wp	310
Total length	m	1.640
Total width	m	0.992
Voltage in MPP	V	33.48
Current in MPP	A	9.26
Power temperature coefficient	%/°C	-0.41
Panel efficiency	%	18.44

During the measurements, the solar irradiance incident on the PV panels was continuously monitored using an LPPYRA02 pyranometer (DeltaOHM), together with the panel temperature (three sensors per panel) and ambient air temperature measured using thermocouples. Simultaneously, electrical parameters on the DC side, including voltage and current, were recorded, enabling the determination of the instantaneous electrical power output of each panel. All measurements were synchronized and recorded with a constant sampling interval, allowing for capturing the dynamic response of the system to changing environmental conditions.

In the configuration involving forced air circulation (Series 2), the air temperature at the inlet and outlet of the system was additionally measured using thermoresistors. In addition, the air velocity in the duct was measured using a vane anemometer (Extech AN300). Based on the measured velocity and the cross-sectional area of the air channel, the air flow rate was determined and subsequently used for the calculation of thermal power. This enabled the estimation of thermal energy gain and the calculation of the useful thermal power extracted from the system, providing insight into the hybrid thermo-electrical performance of the modified configuration.

Table 2. *Technical parameters of the sensors and measuring devices.*

Element	Description
Thermocouples	K-type thermocouple sensors (NiCr-NiAl) with a range from -200 °C to 1150 °C and tolerance ±2.0 °C or ±0.0075 × [t], where *t* is the measured temperature in °C
Thermoresistor	Thermoresistor PT100 with a range of -100 °C to 450 °C and tolerance 0.15 + 0.002 × [t], where *t* is the measured temperature in °C
Pyranometer	LPPYRA02 (DeltaOHM), range from 0 to 2000 W/m^2, spectral range from 283 to 2800 nm, uncertainty approx. ±2-5%, depending on environmental conditions
Voltage transmitter	Analog transmitter AV-1I (F&F) with a rage of 0-400 V DC, uncertainty: ±(0.5 V + 0.5% of measured value)
Current converter	Analog current converter AC-1I (F&F) with a rage of 0-20 A DC, uncertainty: ±(0.2 A + 0.5% of measured value)
Data recorder	Multi-channel data acquisition system APAR AR207 for recording analog signals (4-20 mA input)
Anemometer	Vane anemometer Extech AN300 for air velocity measurements (0.4-30 m/s), uncertainty: ±(2% of reading + 0.2 m/s)

All sensors used in the experimental setup were selected to ensure adequate measurement accuracy and reliability. Detailed specifications of the measurement equipment, including sensor types and their uncertainties, are provided in Table 2. All measurement data were acquired using an APAR AR207 data acquisition system, which enabled simultaneous multi-channel recording of analog signals. The system collected data from measurement transducers with a standardized 4-20 mA current output, ensuring high noise immunity and signal stability over the measurement distances. Data were recorded at a constant sampling interval of 5 s, allowing for time-resolved analysis of the system response under dynamically changing environmental conditions. The use of a centralized data acquisition system ensured synchronization of all measured parameters and consistent data logging throughout the experimental campaign. Measurements were conducted simultaneously for both panels, ensuring direct comparability. The measurement uncertainties of key parameters were considered in the analysis to ensure the reliability of the obtained results.

2.2. Experimental procedure

The experimental investigation was conducted under real outdoor conditions using two photovoltaic panels operating simultaneously: a reference panel (Panel 1) and a modified panel (Panel 2). The main objective was to evaluate the potential for improving PV panel performance through the application of active air cooling in the front-side region under realistic operating conditions.

The experimental campaign was divided into two stages (Series 1 and Series 2), preceded by a reference validation test. In this initial step, both panels operated without modifications to verify the consistency of their electrical performance. The results showed negligible differences, allowing one panel to be treated as a reference in subsequent analyses.

In Series 1, the influence of front-side glazing on PV performance was investigated by installing an additional glass layer at varying distances from the panel surface. Based on the results, an optimal spacing of 0.10 m was selected for further experiments.

In Series 2, the system was extended by enclosing the air cavity and introducing forced air circulation. The configuration included air ducts, an air collector, and a fan that induced airflow through the cavity, allowing simultaneous cooling of the panel and heat transfer to the air stream.

During the experiments, solar irradiance, ambient temperature, PV panel temperature (measured at three locations), and electrical parameters (DC voltage and current) were continuously recorded for both panels. In addition, air temperature at the inlet and outlet, as well as air velocity, were measured to determine the air flow rate and evaluate thermal performance. The use of individual microinverters ensured operation at the maximum power point (MPP).

Representative days corresponding to summer and transitional (autumn) conditions were selected for detailed analysis. These periods were characterized by stable weather conditions and used to illustrate the seasonal variation in system performance.

3. Results and discussion

The results presented in this section provide a comprehensive evaluation of the thermo-electrical performance of the investigated PV panels under different operating configurations. The analysis follows the sequence of the experimental procedure, starting with the validation of the reference performance and proceeding through the assessment of the glazing effect and the implementation of active air cooling. Particular attention is given to the interaction between thermal and electrical phenomena, as well as to the potential of the proposed system for simultaneous energy generation and heat recovery. The presented results are based on time-resolved measurements conducted under real outdoor conditions, allowing for the assessment of system performance under realistic and dynamically changing environmental conditions.

3.1. Reference validation

Prior to the analysis of the modified configurations, a reference validation was performed to assess the consistency of the electrical performance of the two PV panels operating under identical conditions. In this configuration, both panels operated without any structural modifications, enabling direct comparison of their behavior under the same environmental conditions.

Figure 2 presents the electrical power output of both PV panels together with the corresponding solar irradiance over a 2-hour measurement period. The results cover a wide range of irradiance levels, reaching up to approximately 1000 W/m², which allows for evaluation of panel performance under dynamically changing real outdoor conditions.

The comparison of the measured power output indicates a high level of agreement between the two panels across the entire measurement period. The differences in power output ranged from 0% to 8%, with an average deviation of 2.8%. Importantly, these differences do not exhibit any systematic trend with respect to irradiance, suggesting that both panels respond consistently to varying operating conditions. The highest deviations were observed during transient irradiance conditions, particularly during rapid fluctuations at the beginning of the measurement period.

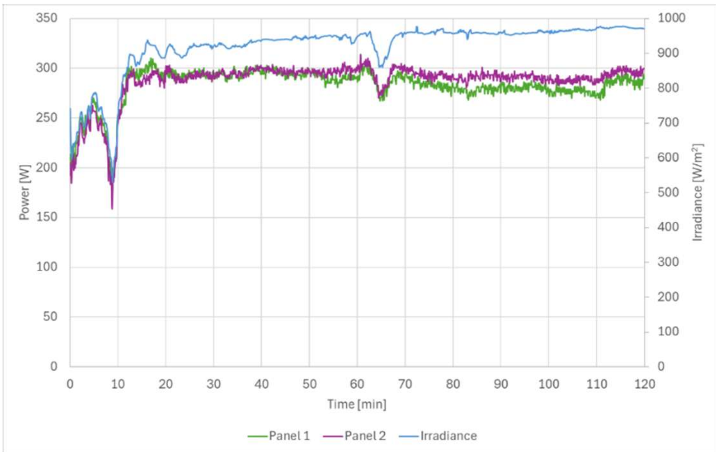

Figure 2. *Electrical power output of the reference PV panels and corresponding solar irradiance during the validation test.*

The observed variability can be attributed to minor measurement uncertainties and intrinsic differences in panel characteristics, which remain within an acceptable range for experimental studies. Overall, the results confirm that the panels can be considered functionally equivalent for the purpose of further analysis.

Based on this validation, Panel 1 was selected as the reference unit, while any deviations observed in Panel 2 in subsequent configurations can be attributed to the applied structural and operational modifications.

3.2 Effect of glazing

The second stage of the experimental investigation (Series 1) focused on evaluating the influence of the additional glass cover on the thermo-electrical performance of the PV panel. In this configuration, Panel 2 was equipped with a front glass layer positioned at a distance of 0.10 m from the panel surface, while Panel 1 operated as a reference without any modification.

Figure 3 presents the electrical power output of both panels together with the corresponding solar irradiance over a 5-hour period during a clear-sky day. The results reveal distinct differences in panel behavior depending on solar conditions, particularly at low irradiance levels and during periods of high incidence angles.

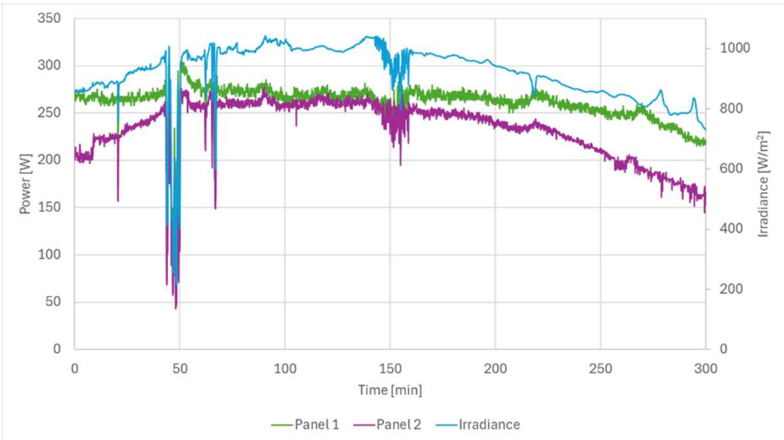

Figure 3. *Electrical power output of the PV panels with and without glazing and corresponding solar irradiance during Series 1.*

At the beginning and the end of the measurement period, significant discrepancies in power output between the panels can be observed. These differences are associated with lower solar irradiance and increased solar incidence angles, under which the presence of the glass cover leads to higher reflection losses and reduced transmittance of solar radiation. Additionally, the geometry of the experimental setup may contribute to partial shading of the PV panel when solar radiation arrives at a more oblique angle, further reducing the electrical output of the modified panel.

In contrast, during the central part of the measurement period (approximately 60-180 minutes), corresponding to near-noon conditions with relatively stable and high irradiance, both panels exhibit similar performance. In this interval, the difference in electrical power output between the panels was limited to approximately 4.7%, indicating that under favorable solar conditions the impact of glazing on electrical performance is relatively small.

The thermal behavior of the panels is presented in Figure 4, which shows the temporal variation of panel surface temperature. The results indicate only minor differences between the two panels, with an average temperature difference of approximately 1.1% in the representative period (60-180 minutes). This suggests that, in the open configuration, natural convection within the air cavity is insufficient to significantly alter the thermal conditions of the panel.

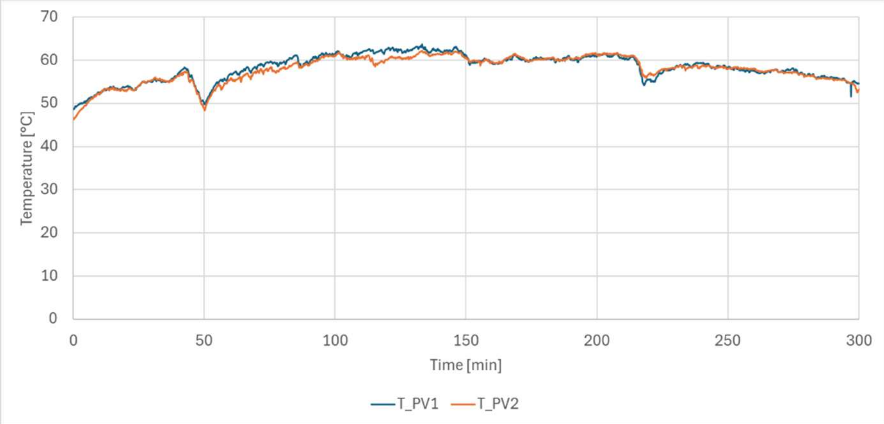

Figure 4. *Surface temperature of the PV panels with and without glazing during Series 1.*

Overall, the results indicate that the introduction of glazing alone does not provide a measurable thermal benefit under the investigated conditions, while it can lead to noticeable electrical losses under non-ideal solar angles. The combined effect results in a neutral or slightly negative impact on overall performance.

These findings highlight the necessity of introducing an active thermal management strategy. In particular, the limited temperature reduction observed in Series 1 indicates that passive heat removal is insufficient, and that forced air cooling is required to effectively reduce panel temperature and improve electrical performance.

3.3. Effect of cooling

The effect of active air cooling on the thermo-electrical performance of the PV panels was evaluated under both summer and autumn conditions, based on representative measurement days characterized by stable weather conditions. The summer conditions represent a high-irradiance operating regime, characterized by elevated solar radiation and increased thermal load on the PV panels, providing suitable conditions for evaluating the effectiveness of active cooling. The autumn conditions represent a transitional period between summer and winter operation.

3.3.1. Summer conditions

Figure 5 presents the temperature profiles of the PV panels together with the corresponding solar irradiance during a representative summer day. Under high irradiance conditions, the operating temperature of the reference panel (Panel 1) reached an average value of approximately 57.6°C, while the actively cooled panel (Panel 2) operated at a slightly lower average temperature of 56.1°C.

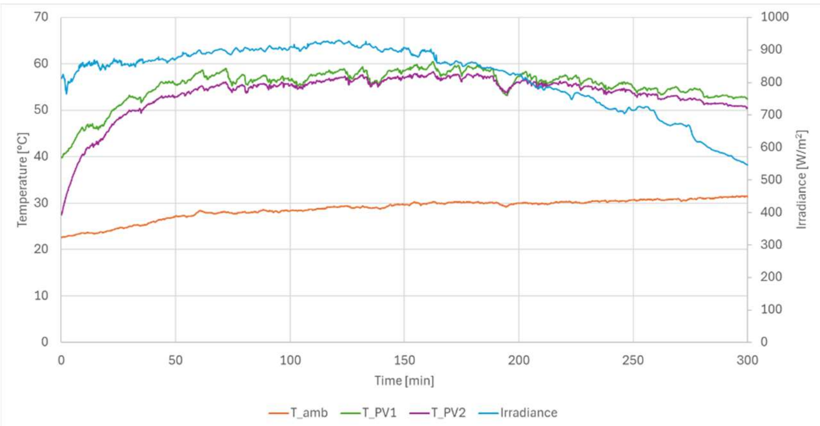

Figure 5. *Temperature profiles of the PV panels (T_PV1 – reference, T_PV2 – actively cooled) and ambient temperature (T_amb) together with solar irradiance during a representative summer day.*

The average temperature reduction achieved by active cooling was 1.5°C, with a maximum observed difference of 3.6°C during peak operating conditions. Although the absolute temperature decrease is moderate, it is consistent over the period of highest irradiance, confirming the effectiveness of forced convection compared to the passive configuration.

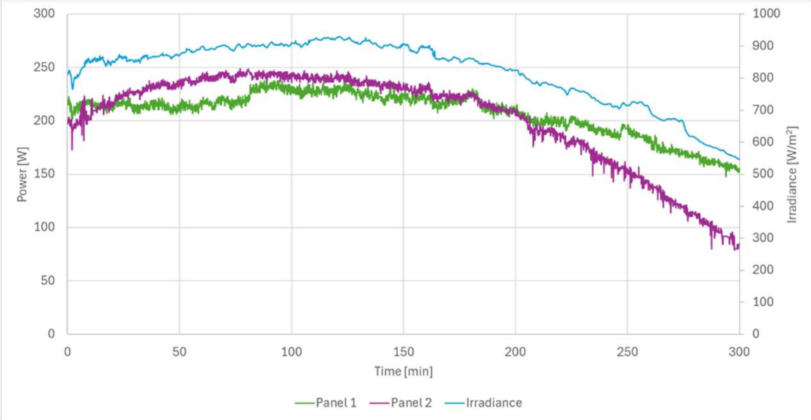

Figure 6. *Electrical power output of the PV panels (Panel 1 – reference, Panel 2 – actively cooled) and corresponding solar irradiance during a representative summer day.*

The corresponding electrical performance is shown in Figure 6. The actively cooled panel exhibits a higher power output than the reference panel, with an average increase of approximately 5.5%. This improvement is consistent with the temperature coefficient of the PV panel, indicating that even a small reduction in operating temperature leads to a measurable gain in electrical performance.

3.3.2. Autumn conditions

The behavior of the system under autumn conditions is presented in Figures 7 and 8. In this case, the average operating temperature of the reference panel (Panel 1) was 39.6°C, while the modified panel (Panel 2) reached a higher average temperature of 42.4°C.

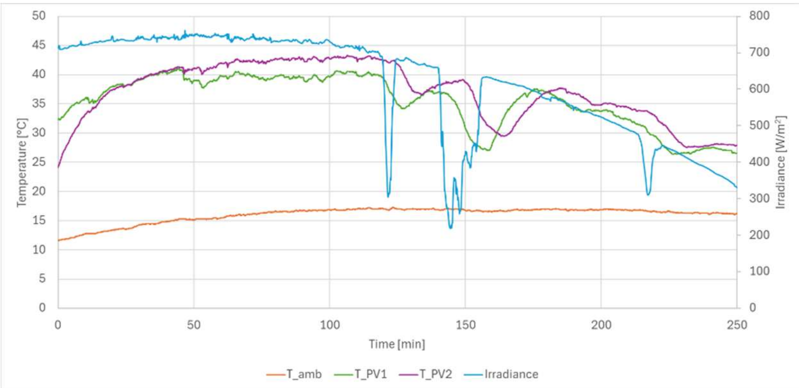

Figure 7. *Electrical power output of the PV panels (Panel 1 – reference, Panel 2 – actively cooled) and corresponding solar irradiance during a representative autumn day.*

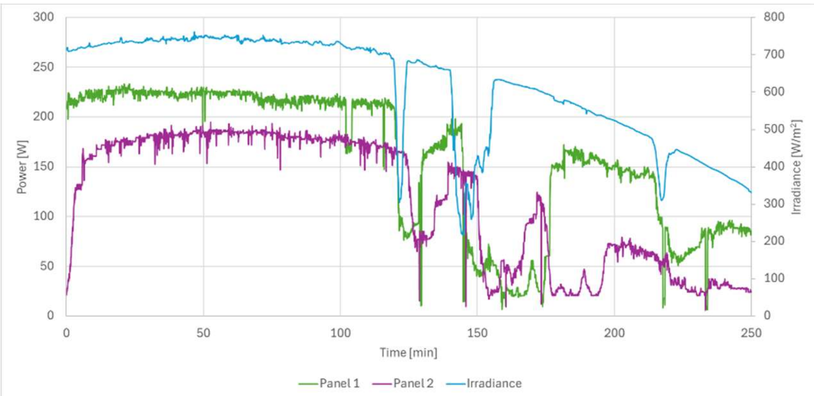

Figure 8. *Electrical power output of the PV panels (Panel 1 – reference, Panel 2 – actively cooled) and corresponding solar irradiance during a representative autumn day.*

Interestingly, the average temperature difference between the panels was 2.8°C (up to 3.6°C), with the glazed and actively ventilated panel operating at higher temperatures than the reference panel. This indicates that, under autumn conditions, the effect of the glass cover dominates over the cooling effect, leading to an overall increase in panel temperature.

Despite this increase in temperature, the electrical performance of the modified panel shows a significantly higher power output compared to the reference panel, with an average improvement of 21.2%. This behavior suggests that, under low irradiance conditions, the optical and thermal effects associated with the glazing may enhance energy absorption, compensating for the negative impact of increased temperature.

3.3.3. Comparative analysis

The comparison of summer and autumn results demonstrates a clear seasonal dependency of the system behavior. Under summer conditions, active cooling effectively reduces the operating temperature of the PV panel, leading to a moderate but consistent increase in electrical power output. In contrast, under autumn conditions, the thermal effect of cooling becomes less significant, and the presence of the glazing leads to higher operating temperatures.

However, the electrical performance in autumn conditions indicates that the system may benefit from improved solar energy capture due to the modified optical and thermal boundary conditions. This highlights the complex interaction between thermal and optical effects in the system, where the dominant mechanisms vary depending on environmental conditions.

These results confirm that the performance of the proposed system is governed by a combination of competing effects, and its effectiveness is strongly dependent on seasonal operating conditions. The thermal performance of the system, including heat recovery and air temperature rise, is discussed separately in Section 3.4.

3.4 Thermal performance

The thermal performance of the actively cooled glazed PV system was evaluated based on the air temperature rise across the flow channel and the average air flow rate. Representative periods corresponding to summer and autumn conditions were analyzed in order to assess the useful thermal output of the system under different irradiance levels. This approach allows for a direct estimation of the heat transfer from the PV panel to the air stream and provides insight into the system's capability for low-temperature heat recovery.

Figure 9 presents the inlet air temperature, outlet air temperature, ambient temperature, and solar irradiance during a representative summer day. Throughout the analyzed period, the outlet air temperature remained consistently higher than the inlet air temperature, confirming effective heat transfer from the PV panel to the flowing air. For the representative summer period, the average inlet air temperature was 27.8°C, while the average outlet air temperature reached 35.1°C, corresponding to an average temperature increase of 7.3°C. These results were obtained under solar irradiance levels in the range of approximately 850–900 W/m².

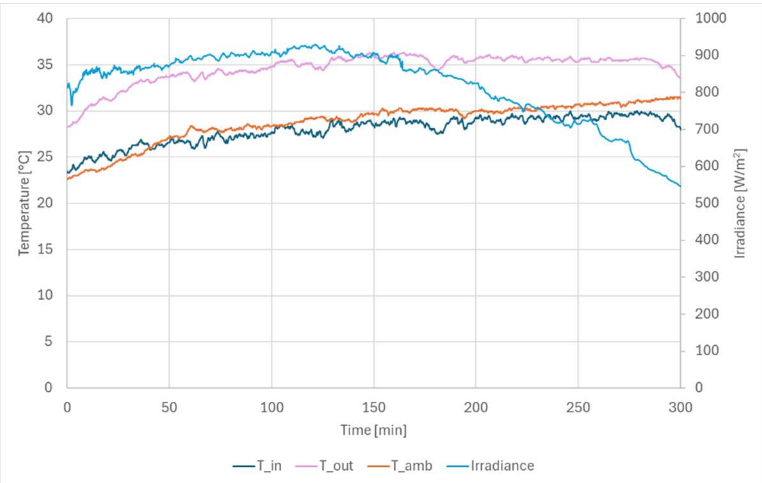

Figure 9. *Inlet and outlet air temperatures, ambient temperature, and solar irradiance during a representative summer day for the actively cooled glazed PV system.*

The relatively high temperature rise indicates that a significant portion of the absorbed solar energy is transferred to the air stream, which enhances the overall energy utilization of the system. The stable temperature difference observed during the peak irradiance period suggests that the forced convection mechanism provides consistent thermal performance under steady operating conditions. This confirms that the applied airflow configuration ensures effective heat extraction from the PV panel surface while maintaining continuous energy transfer to the working fluid.

For the representative autumn period, the average inlet and outlet air temperatures were 16.1°C and 21.5°C, respectively, resulting in an average air temperature rise of 5.4°C. Although the thermal effect was lower than in summer, the system still demonstrated a clear capability for useful heat recovery under reduced irradiance conditions of approximately 700-750 W/m².

The useful thermal power of the system was calculated using the relation:

$$\dot{Q} = \dot{m}\, c_p\, (T_{out} - T_{in}), \quad (1)$$

where $\dot{m}$ is the air mass flow rate, c_p is the specific heat capacity of air, and $T_{out} - T_{in}$is the measured temperature rise across the system. The calculations were performed using an average volumetric air flow rate of 92.2 m³/h for both analyzed periods.

Based on the measured temperature differences and the adopted air flow rate, the useful thermal power of the system was estimated at approximately 215 W for summer conditions and approximately 167 W for autumn conditions. The higher summer value is directly related to both increased irradiance and a larger air temperature rise, which intensify heat transfer from the PV panel surface to the flowing air.

These results confirm that the proposed system is capable of recovering a meaningful amount of low-temperature heat while simultaneously supporting the electrical performance of the PV panel. Although the thermal output remains lower under autumn conditions, the obtained values indicate that the system may still provide useful heat gain outside the peak summer season. This behavior supports the classification of the investigated configuration as a simplified air-based thermo-electrical system rather than only a front-side cooling arrangement.

The thermal output values correspond to representative operating periods and are intended to illustrate the seasonal variation in heat recovery potential rather than provide a full daily or seasonal energy balance.

3.5 Thermo-electrical interaction

The performance of the investigated system is governed by the interaction between thermal and electrical processes occurring simultaneously within the PV panel and the surrounding airflow. The results presented in Sections 3.3 and 3.4 demonstrate that both temperature-dependent electrical efficiency and heat transfer mechanisms play a crucial role in determining the overall system behavior.

In summertime, the predominant factor affecting electrical performance is the decline in PV panel temperature through forced convection. The actively cooled panel demonstrated a mean temperature reduction of 1.5°C (ranging up to 3.6°C), which corresponded to an average augmentation in electrical power output of 5.5%. This phenomenon aligns with the established negative temperature coefficient of crystalline silicon photovoltaic panels, wherein a decline in operating temperature results in an augmentation of open-circuit voltage, thereby elevating power output. In this regime, the system operates primarily as a temperature-controlled photovoltaic device, wherein the thermal subsystem facilitates electrical efficiency by removing excess heat.

Conversely, under autumn conditions, the interplay between thermal and electrical effects becomes more intricate. Despite the higher average operating temperature of the modified panel (by approximately 2.8°C), a significant increase in electrical power output (21.2%) was observed. This finding suggests that the optical and thermal boundary conditions imposed by the glazing layer assume a predominant role under conditions of reduced irradiance. The glazing has been shown to reduce convective heat losses and modify the radiative exchange, thereby effectively creating a semi-enclosed environment that enhances energy absorption.

This behavior suggests that, under transitional conditions, the system operates in a mode that differs from classical PV cooling. The system's primary function is not merely to reduce temperature; rather, it serves to optimize the overall energy balance of the panel. This enhancement, however, is often accompanied by an increase in the operating temperature. Consequently, the electrical performance is no longer solely governed by temperature effects; it is also influenced by changes in optical transmission, thermal retention, and local microclimatic conditions within the air cavity.

The thermal analysis presented in Section 3.4 lends further support to this interpretation. The system has been demonstrated to possess the capability to recover useful heat, with thermal power outputs of approximately 215 W during summer months and 167 W during autumn months. This finding indicates that a portion of the absorbed solar energy is efficiently transferred to the air stream, thereby establishing an additional energy pathway that extends beyond the conventional electricity generation process.

A thorough investigation of the system reveals a dual-mode behavior contingent upon operating conditions. In conditions of elevated irradiance, the cooling effect predominates, thereby enhancing electrical efficiency through the reduction of temperature. In conditions of reduced irradiance, the impact of glazing and modified boundary conditions becomes more pronounced, thereby enhancing energy capture despite elevated panel temperatures. This underscores the necessity of incorporating both thermal and optical effects in the design of hybrid PV systems that incorporate cooling or heat recovery functionality.

This dual behavior suggests that the system can be interpreted as a hybrid thermo-electrical device, whose dominant operating mechanism shifts depending on environmental conditions.

3.6 Practical implications

The findings of the present study suggest that the practical applicability of the proposed system is contingent upon operating conditions and the intended use of the installation.

In conditions of high irradiance, the system has been demonstrated to enhance electrical performance through the implementation of active cooling mechanisms. In such cases, the implementation of forced air flow systems has been demonstrated to be particularly advantageous in installations exposed to high solar loads, such as rooftop systems or building-integrated photovoltaic solutions with limited natural ventilation.

Beyond the enhancement of electrical performance, the system facilitates the recovery of low-temperature heat. The obtained thermal power levels suggest that the system may be effectively integrated with low-temperature applications, including ventilation air preheating or support for heat pump systems. This augmentation in the energy utilization of the installation has the potential to enhance system efficiency.

However, the implementation of active cooling necessitates additional components, such as fans and air channels, which in turn increases system complexity. The overall effectiveness of the system is contingent upon achieving an optimal balance between three factors: the additional electrical output, the recovered thermal energy, and the energy consumption of auxiliary devices.

From a pragmatic standpoint, the system ought to be regarded as a hybrid solution, the advantages of which are contingent upon the particular operating conditions and the specific application context. The utilization of this system is most substantiated in contexts where both the enhancement of electrical performance and the recovery of low-temperature heat can be efficiently employed.

Subsequent research endeavors should prioritize the optimization of system operation and the assessment of net energy gain, encompassing the effect of auxiliary energy consumption.

4. Conclusions

This study investigated the thermo-electrical performance of an actively air-cooled glazed photovoltaic system under representative summer and autumn conditions. Based on the experimental results, the following conclusions can be drawn:

1. The application of an additional glass cover without active cooling does not provide a significant thermal benefit and may lead to electrical performance losses under non-optimal solar incidence angles due to increased optical losses.
2. Under summer conditions, active air cooling reduced the operating temperature of the PV panel by an average of 1.5°C (up to 3.6°C), resulting in an increase in electrical power output of approximately 5.5%. This confirms that even moderate temperature reduction can lead to measurable improvements in PV performance.
3. Under autumn conditions, the actively cooled and glazed panel operated at higher temperatures than the reference panel (by an average of 2.8°C), yet exhibited a significantly higher electrical power output (21.2%). This indicates that, under lower irradiance conditions, the influence of glazing and modified boundary conditions can dominate over temperature effects.
4. The system demonstrated the ability to recover useful thermal energy, with thermal power outputs of approximately 215 W under summer conditions and 167 W under autumn conditions. This confirms the potential of the system to operate as a combined thermo-electrical device.
5. The results reveal a clear seasonal dependency of system performance. Under high irradiance conditions, the system operates primarily as a cooled PV panel, while under transitional conditions it behaves more similarly to a glazed solar device with enhanced energy absorption.
6. The investigated configuration can be considered a hybrid thermo-electrical system, whose dominant operating mechanism depends on environmental conditions and system configuration.

The obtained results demonstrate that actively cooled glazed PV systems offer a promising approach for improving solar energy utilization, particularly in applications where both electrical performance enhancement and low-temperature heat recovery can be effectively utilized.

Future work should focus on optimizing airflow control and evaluating the net energy gain of the system, including auxiliary energy consumption.

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