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Energy assessment and monitoring of a novel photovoltaic-thermal collector designed for solar-assisted heat pump systems

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Abstract: Hybrid photovoltaic-thermal (PVT) collectors have been widely investigated in recent decades since they ensure higher performances and compactness with respect to the two sub-components. In this study, a novel covered PVT water collector, specifically designed to be coupled with heat pumps, is presented. The PV-cells are directly laminated on the aluminium roll-bond absorber without the usual front glass layer, while a glass cover is added after the lamination, creating an air gap with the PV-absorber laminate. The novel collector has electrical features similar to those of uncovered PVTs, in which the front glass layer is laminated in contact with PV-cells and even better performances than a traditional covered collector, which has a second glass cover on top. The electric performances of the PVT, operated in stand-alone mode and solar-assisted mode, were monitored and compared with a traditional PV module, obtaining interesting results in both conditions. In particular, the novel PVT showed comparable and even better electric performances than the traditional PV when combined with the heat pump, thanks to PV-cells active cooling. The work proves that the proposed manufacturing technique could lead to a new generation of hybrid collectors, which may achieve competitive performances when integrated with heat pumps.

1 Introduction

The very recent years are characterised by an intense discussion regarding the decarbonisation pathways to reach the targets at the national and international layers (e.g. the reader may refer, for example, to the Italian targets defined in [1, 2]). Within these pathways, the large-scale deployment of solar-assisted technologies is a promising strategy to be pursued. In this perspective, solar-assisted heat pumps (SAHPs) are of particular importance, coupling heat pumps with solar collectors [3]. The coupling is particularly beneficial when considering photovoltaic-thermal (PVT) technology. PVT technology combines photovoltaic technology (PV) with solar thermal aiming at providing higher performances and compactness with respect to the two sub-components [4]. Taking into account the characteristics of PVTs, their connection with heat pumps is interesting to enhance the performances of the two sub-components (viz., by reducing the PV cell temperature [5] and by supporting heat pump evaporator operation [6]), to boost the performances at the 'system-scale' (viz., increasing the overall COP) [7]. Aiming to support the development of *S*AHPs, many researchers considered both the 'system-scale' (i.e. suitable system configurations for different climates) and the 'component-scale' (i.e. innovative PVT systems). This paper encompasses both aspects. It starts at the 'component-scale', by proposing a comprehensive experimental investigation to characterise innovative PVT collectors (which builds up from the previous study proposed in [8]); subsequently, it proposes a perspective towards the 'system-scale' by considering a whole SAHP system. To sum up, this paper clearly addresses the multi-scale topic in energy systems design.

Looking at the component, despite the above-mentioned advantages, although a certain number of commercial products have been proposed, the uptake of PVT systems has so-far been extremely modest [9], being a shortcoming in supporting SAHP technologies. Generally speaking, the most investigated technologies are based on 'covered' water-based PVT systems:

i. As for the system layout, covered collectors, compared with uncovered collectors, reduces the heat transfer losses towards the environment and they characterised by lower cells degradation, due to direct exposure to the moist ambient.
ii. As for the use of water, it has some well-known advantages compared with air in the heat transfer discussion, [10]) and it may allow an easier coupling of water-based PVT with heat pumps [11] (i.e. in direct systems).

Given the advantages above, this paper considers such technology and, in particular, focuses on innovative layouts: covered collectors are generally manufactured by coupling the absorber plate to the backside of a PV module (laminate with tedlar or glass on the back-layer and with glass on the front side). Subsequently, the whole component is enclosed within a frame and covered with another glass, thus ensuring an air gap. Given the present state-of-the-art, the work describes a novel PVT water collector manufactured by laminated PV cells on a roll-bond flat plate absorber and covering the whole system with only a layer of glass [8]; although the feasibility of such option has been recently demonstrated in [12, 13], few details and performance analyses are available to date. This layout is supposed to have better performances compared with the above-mentioned standard layout: (i) traditional covered collectors have two glasses which increase the optical losses; and (ii) the back sheet of the PV sandwich reduces the thermal transmission to the working fluid, with a further reduction of the thermal efficiency. To reach these goals, the paper proposes a comprehensive experimental study and is structured as follows. First, a critical analysis of PVT fabrication state-of-the-art and their integration with heat pumps is proposed. Then, the 'component-scale' is completely characterised. The advanced manufacturing process is described, and the electrical performance of the novel PVT is assessed. Finally, the perspective towards the 'system-scale' is proposed. To this end, field tests were carried out to evaluate the electricity and thermal performances and to further compare the present system with a traditional PV module, fabricated with analogous PV cells. In particular, the field study consists of two different operating conditions: (i) PVT connected to a water tank; and (ii) PVT connected with whole SAHP systems [14]. In summary, this paper is intended to provide

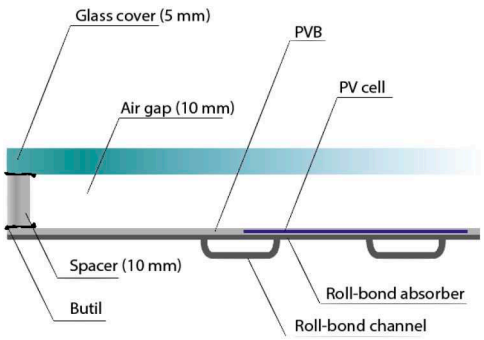

Fig. 1 *Section of the novel PVT collector*

clear and precise guidelines for fabricating innovative PVT collected intended for integration in SAHP systems.

2 Hybrid PVT collectors and their integration with heat pumps

As already mentioned, although over the last 30 years a large number of research about PVT collectors has been carried out, such technology has not still widely spread in the market due to aesthetical and technical issues.

According to the latter, one of the main weak points which affect the performance of the PVT components is the connection between the thermal absorber and the PV part [8]. The connection is generally manufactured using an adhesive layer [15–17], which however has several drawbacks. First of all, the air bubbles that can be entrapped between the two layers could increase the thermal resistance of the components [18–20]. Secondly, if the absorber and the PV layers do not adhere perfectly, the cells temperature distribution is affected by higher mismatch losses [21].

The connection could be also guaranteed by mechanical fixing only, where the absorber is fastened using specific brackets to the PV module [22]. Even if such a system can properly attach the PV sandwich to the thermal absorber, it cannot ensure the absence of a thin air gap between the PV layer and the thermal absorber. Furthermore, it requires custom carpentry which could affect also the cost and the weight of the component.

In such respect, in the last decade, several efforts have been carried out in developing a manufacturing process able to improve the overall performance of the PVT components. In detail, the most effective one consists of the direct lamination of glass, PV cells, electrical insulation, and absorber in a single step [23]. According to the experimental results, such a technique can provide a lower thermal resistance between PV and metal absorber [4] and thus better electrical and thermal performances [13]. Although such a manufacturing process can be considered promising, until now, few research papers show experimental results of PVT directly laminated in operative conditions [24].

Unless the most common application of PVT systems is for direct water production [25], the combination of hybrid solar collectors with vapour-compression heat pump systems in the so-called photovoltaic-thermal solar-assisted heat pumps (PVT-SAHP) systems has received increasing interest in recent years [26]. The heat pump may exploit both the electric and thermal PVT outputs, taking advantage of the electrical production to power the compressor and of the thermal output as an energy source for the evaporation. The heat recovered by PVT can be exploited directly, through the direct evaporation of the HP refrigerant in the hybrid collector, or indirectly, using an intermediate heat exchanger between the PVT working fluid and the refrigerant [27]. The first arrangement is simpler and cheaper, but the variability of solar radiation may lead to an unstable phase-change process and a consequent mismatch of compressor speed [28]. The use of an intermediate heat exchanger, plate-type [29] or a dual-heat-source composite evaporator [30], allows controlling evaporation conditions leading to more stable operating performances.

Solar energy exploited by PVT collectors may also be combined with another source of energy, usually external air [31] or geothermal energy [32], operating alternatively or in addition to the other source. The increasing complexity of those systems is justified in multi-functional applications where heating, cooling, and domestic hot water (DHW) production should be provided even in the absence of solar radiation.

3 Novel PVT collector

The novel PVT prototype was built according to the most advanced techniques, as a result of a deep analysis of different manufacturing methods and technical solutions described in the literature [22, 33–35]. The combination with heat pump guided the entire design phase towards precise choices in terms of electric conversion technology, absorber typology and its integration with the electrical components. The objective was to design a hybrid collector with high thermal and electrical performances, even though one is usually sacrificed to enhance the other [36].

3.1 Design and characteristics

The novel PVT component was built through the direct lamination of PV cells on an aluminium roll-bond absorber, encapsulated in four layers of PVB, one on the front and three placed between cells and absorber to ensure the electrical insulation. 5-busbar single-crystalline silicon (sc-Si) PV cells with a nominal peak power of 5.25 W_p and 21.5% of conversion efficiency were connected in series in a string of 25 cells, accounting for an overall peak power of 262 W_p in Standard Test Conditions (STC). Detailed electrical features, as well as mechanical properties of PV cells and string are reported in [8].

As already said, an aluminium roll-bond plate with parallel channels arrangement on the backside and flat on the front side, where PV cells are laminated, was chosen as the thermal absorber, since it perfectly suits for PVT applications [34, 37–39].

The electrical and thermal components were assembled in a vacuum laminator, at standard lamination conditions in terms of pressure load, vacuum and temperature, obtaining a PV-absorber functional laminate. The particularity of this lamination process is that a removable film was used as a top layer during the lamination process, instead of the conventional glass cover that is usually laminated on the PV-absorber package.

Then, a 5 mm thick extra-clear glass cover was fixed to the PV laminate by using an aluminium spacer, at a distance of 10 mm instead of being in contact. Thus, an air gap was created between the front glass cover and the PVT laminate, obtaining a so-called covered PVT collector, as shown in Fig. 1.

The PVT component is thus assembled with a manufacturing process similar to that adopted for traditional double-glazing, where one of the two glass layers is constituted by the PVT laminate. Avoiding the interposition of two separated glasses above PV cells, as occurs in standard covered PVT collectors, the optical losses are reduced, even if this manufacturing method presents challenges in the PV cells lamination without a rigid top glass layer [8]. The junction box, completely watertight (IP 67), is attached with silicone adhesive in the corner on the backside encapsulating solar bypass diodes. A view of the layout of the PVT component is reported in Fig. 2.

In detail, it is characterised by an overall dimension of 1765 mm × 960 mm and a packing factor equal to 0.73. The latter parameter should be considered quite lower with respect to usual values for standard sc-Si PVT modules, typically between 0.8 and 0.9 [13].

It should be noted that, based on a visual inspection, no delamination between the PVB layer and the aluminium absorber was observed after the production process [8]. In Fig. 3 the final prototype is shown.

3.2 Performance assessment

As a first step, electric performances were investigated in STC, in compliance with the methodology defined by IEC 61215-2:2016 and are reported in Table 1. As already described in the previous work [8], the novel PVT was compared with two different conventional PVT configurations, manufactured with the same PV

cells laminated on the absorber: a standard uncovered PVT collector and a standard covered collector. The first was fabricated with direct lamination of PV cells with front glass without an air gap; the second is equal to the standard uncovered collector, but a 5 mm thick front glass was placed at 10 mm from the PVT laminate, thus creating an air gap.

According to the flash test results reported in a previous research work [8], the maximum power point (MPP) power of the novel PVT was ~5.4% higher than that of the standard covered module, thanks to the lower optical losses of the novel PVT, manufactured without a glass layer. By the comparison of the novel component with the uncovered version, although a single glass layer is present in both the collectors, the latter demonstrated performance of about 6.8% higher.

The presence of the air gap between the external glass cover and the PVT laminate is responsible for additional absorption-reflection losses. As well, in some points, the PVB is not in full contact with PV cells and creates wrinkles, which are likely to be responsible for additional optical losses.

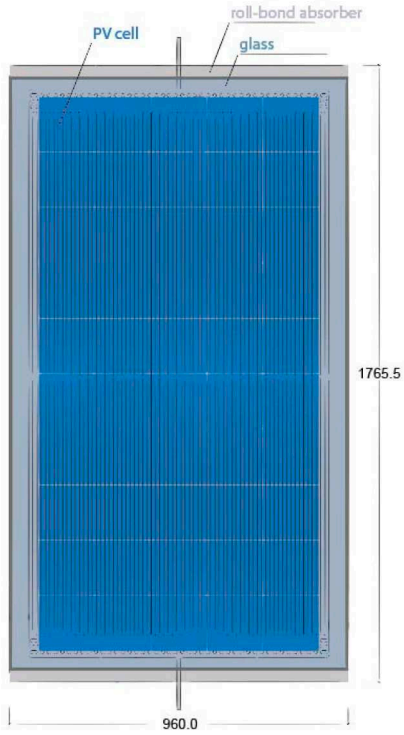

Fig. 2 *PVT front view and dimensions (sizes in mm)*

Fig. 3 *View of the PVT prototype after the manufacturing process*

Those losses cannot be the only reason for the lower electric performances measured in the novel PVT with respect to the standard uncovered collector ones. An electroluminescence check was carried out for this reason. Such a test is commonly adopted in the PV sector to assess potential defects and cracks in PV cells [40]. The test evidenced that few cells of the novel PVT are characterised by cracks, as reported in [8]. As a consequence, since the cracks can cause certain areas of the PV cell to become inactive, the power output of the module is proportionally reduced [41]. Specifically, 7 cells revealed cracks parallel to busbars, which were likely provoked by a deformation of the absorber plate in the lamination phase. The total PV cells area affected by cracks is likely to involve 5% of the total active area, being responsible for a proportional performance reduction.

The novel PVT resulted also adequate in terms of electric insulation, equal to ~63 MΩ, after a wet leakage test, carried out according to the IEC 61215-2:2016 [42] methodology. This confirms that the techniques of PV cell's direct lamination on the absorber is fully feasible for the manufacturing of advanced covered PVT collectors.

4 Experimental set-up and method

The electric performances of the novel PVT were experimentally investigated during a preliminary on-field monitoring campaign and compared with those of the traditional PV component fabricated with the same PV cells previously described, as a benchmark.

4.1 Experimental set-up and measurement techniques

The novel PVT collector was hydraulically connected to a water-glycol circuit (30% fraction of ethylene glycol) and monitored under two different operating conditions:

- *Configuration A*: Stand-alone mode, in which the PVT is directly connected to a water tank.
- *Configuration B*: PVT-SAHP mode, in which the PVT is integrated into a heat pump system.

In *Configuration A*, the novel PVT collector is hydraulically connected to water storage with 300 l of capacity and equipped with a circulation pump, as in traditional PVT systems for DHW production.

In *Configuration B*, the novel PVT collector is integrated with a heat pump system operated for space heating. Inlet and outlet PVT manifolds are connected in parallel to other 6 PVT prototypes, characterised by different features and monitored separately. The solar circuit is connected to the heat pump, in the so-called indirect-expansion SAHP configuration. The machine is a commercial dual-source heat pump, adapted for the specific test activity. The heat pump has a rated thermal power of 10 kW, a variable-speed compressor and two evaporators on the source side, being able to exchange energy both with external air and the solar circuit, according to the best available source. The refrigerant does not expand directly in the PVT collector as a water-to-gas heat-exchanger is interposed between the machine and the hybrid collector. In this configuration, when solar radiation is available, the thermal power produced by the novel PVT is exploited by the machine that may operate at higher evaporation temperatures, with benefits in terms of COP with respect to the simple air-source operation. The water-glycol mixture in the solar circuit is indeed refrigerated and pumped back to the novel PVT which takes advantage of the lower operating temperature compared to the

Table 1 Results of the flash test

	P_{mpp}, W	V_{oc}, V	I_{sc}, A	V_{mpp}, V	I_{mpp}, A	η_{nom}, %
novel PVT	198.1	33.0	8.1	26.8	7.4	11.7

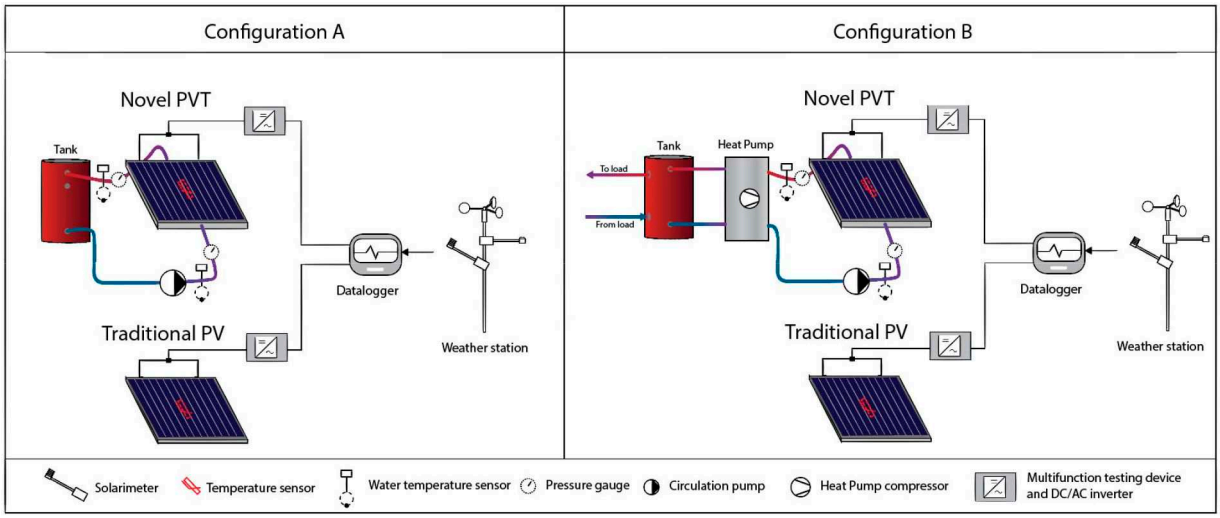

Fig. 4 *PVT monitoring system: configurations A and B*

Table 2 Details on experimental uncertainties

Parameter	Type	Uncertainties
temperature measurements of water	RTD Pt100 (1/5DIN)	±0.06°C (at 0°C)
water volumetric flow rate	electromagnetic flow meter	±0.5% read value
electrical consumption of the heat pump and power	multifunction power and energy meter	±0.2% read value
	transducer	±0.5% read value
outdoor air temperature	RTD Pt100 (Class A)	±0.15°C (at 0°C)
solar irradiance sensor	thermopile pyranometers	±1% read value

traditional arrangement with the water thermal storage. On the user side, the water thermal storage is kept at a setpoint temperature equal to 40°C by the heat pump, while hot water flows to an external heat exchanger, discharging energy in the environment to simulate the thermal load.

The hybrid PVT collector and the traditional PV module were installed in Milan at the experimental facility of the RSE (Ricerca sul Sistema Energetico) research centre, with a tilt angle of 45° and azimuth equal to 0°. The AC/DC conversion was operated through a single-phase transformerless micro-inverter with an MPP tracker, connected to each module.

A real-time monitoring system, as schematised in Fig. 4, was used to collect data on environmental conditions and energy performance in the two system arrangements. In detail, the monitoring system is composed of:

- One solar irradiance sensor, installed with the same tilt and azimuth angle of the two collectors, allowing to measure the global solar irradiance on the collector's plane;
- one temperature sensor for ambient air temperature;
- two temperature sensors (PT100) to measure collectors' temperature, positioned on the rear side of the PV module and the PVT collector, between the PV-absorber laminate and the insulating material;
- -two immersion temperature sensors, positioned respectively on the supply and return pipe to the water storage, measuring the temperature of the fluid at the inlet and outlet of the collector;
- two pressure gauges, to measure the pressure drop across the hybrid collector;
- Voltage and current sensors connected to the micro-inverters.

Table 2 summarizes the main uncertainties of the measurement devices.

4.2 Performance parameters

Daily electrical performances of the novel PVT and the traditional PV are compared in terms of performance ratio (PR) on power, as collectors' nominal electric power is different. This parameter allows to fairly compare on-field performances of modules with different nominal characteristics since it measures the deviation between the actual measured electrical performances of the PV and those theoretically achievable operating at STC [43]

$$\mathrm{PR}_i = \frac{P_i}{(I_t/1000) \times P_n} \tag{1}$$

where P_i (W) is the power output measured on field monitoring, I_t (W/m^2) is the solar irradiance on the collector plane (45°) and P_n (W) is the nominal electric power measured at STC, during the flash test previously described in Table 1.

Unless the novel PVT showed slightly lower electrical performances with respect an analogous traditional PV, the hybrid solar collector is also able to covert a fraction of solar energy into thermal energy, that can be calculated as follows:

$$\eta_{\mathrm{th}} = \frac{Q_{\mathrm{th}}}{I_t \times A_{\mathrm{mod}}} \tag{2}$$

where Q_{th} (W) is the thermal power recovered by the heat transfer fluid.

Since electricity is a higher grade of energy, it is useful to compare the two solar technologies in terms of primary energy savings (PES) efficiency [44], which is a useful parameter that weights electricity and thermal energy production. It is defined as follows:

$$\eta_{\mathrm{PES}} = \eta_{\mathrm{th}} + \frac{\eta_{\mathrm{el}}}{\eta_{\mathrm{power}}} \tag{3}$$

where η_{th} is the thermal efficiency, η_{el} is the electric efficiency and η_{power} is the average conversion efficiency of power plants at the national level. Many authors adopted 0.38 as a reference efficiency [24, 44, 45]. A value equal to 0.45 is instead typical when considering the conversion efficiency of Italian power plants.

5 Result and discussion

The novel PVT collector was tested under the two different operating conditions, in comparison with the traditional PV module. Weather conditions during the monitoring period are hereafter reported. The measured energy performances of the hybrid PVT collector in configurations A and B are reported and analysed, in comparison with the traditional PV module.

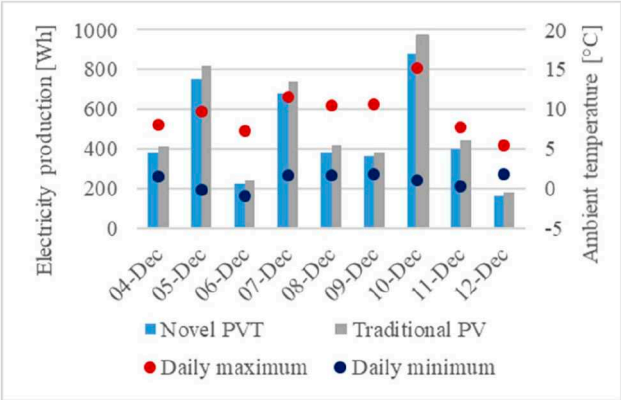

Fig. 5 *Daily electrical production in the first monitoring period: 4th – 12th December 2019*

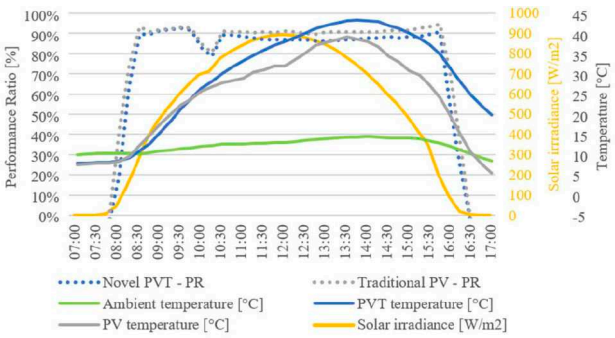

Fig. 6 *Measured data – 10th December – Sunny day*

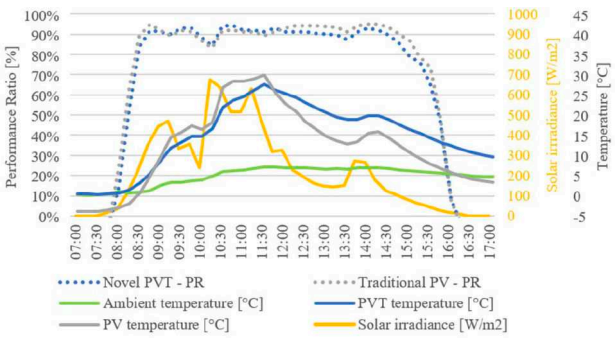

Fig. 7 *Measured data – 11th December – Cloudy day*

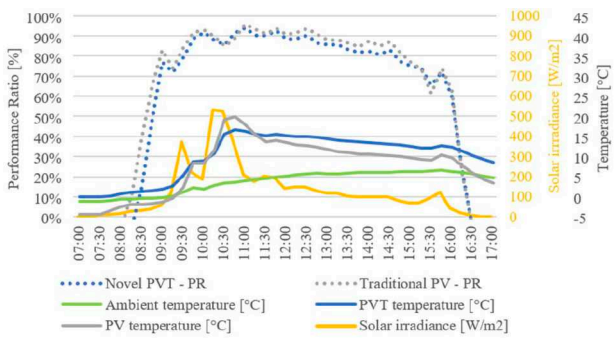

Fig. 8 *Measured data – 6th December – Rainy day*

5.1 Monitoring period

The two collectors were compared during two different periods of the winter season, arranged in *Configuration A* and *Configuration B*, as described in the previous section. The first monitoring period occurred from 4th to 12th December 2019, with average maximum and medium temperatures equal to 9.5°C and 0.9°C, respectively, and 3.2 kWh/m^2 of average daily irradiation on collectors' plane. The second monitoring period occurred from 20th to 27th January 2020, with average maximum and medium temperatures equal to 10.1°C and −0.1°C, respectively, and 2.9 kWh/m^2 of average daily irradiation on collectors' plane. Both periods were characterised by typical winter conditions in northern Italy, with variable weather including sunny, cloudy and rainy days.

Table 3 Daily mean performance ratio (PR)

	10th December sunny day, %	11th December cloudy day, %	6th December rainy day, %
novel PVT	89.1	92.6	91.8
traditional PV	91.9	95.4	93.0

5.2 Configuration A: stand-alone mode

The two modules were monitored for 9 days, from 7:00 to 17:00 (real solar hour) with a time step of 15 min. A general overview of electrical production and external temperatures during the first monitoring period is reported in Fig. 5 and is subsequently analysed in detail. As can be noticed, a slight difference in terms of electricity production is present between the two collectors. The higher nominal power of the traditional PV (about 6%) results in an analogous performance difference under real operating conditions.

The daily electricity output of the novel PVT recorded a maximum of 900 Wh under clear sky conditions (10th December), a minimum of 160 Wh under covered sky conditions (12th December) and an average of 470 Wh during the testing period. The traditional PV ranged between a pick of almost 1 kWh and a minimum of about 180 Wh, with an average of 500 Wh.

A detailed analysis of real collector performances in terms of electricity and thermal energy production is then provided. Three representative sample days, among those of the monitored period, are considered: a sunny day (10th December), a scattered cloudy day (11th December) and a rainy day (6th December).

PRs for the three sample days are reported in Table 3. The traditional PV shows around 3% higher PR than the novel PVT under sunny (10th December) and cloudy (11th December) weather conditions, while under rainy conditions (6th December), the difference is around 1%. Average daily PR during the monitored period resulted equal to 90.9% for the novel PVT and 92.8% for the traditional PV.

PR daily trends are reported in Figs. 6–8, as well as modules and ambient temperatures. The traditional PV showed slightly higher PR than the novel PVT. The reason can be attributable to two main factors: the different temperature of PV cells and the different reflection losses. The presence of an additional external glass cover and the rear insulation leads, as shown in Figs. 6–8, to higher collector temperatures when solar radiation is abundant, affecting PV cells conversion efficiency. Moreover, when solar rays hit the collector with an incidence angle different from STC (light normal to PV cells), the presence of the glass cover with the air gap entails higher reflections than those occurring in traditional PV, or conventional uncovered PVT where cover glasses are laminated in direct contact with the PV sandwich.

The daily mean thermal efficiency varied from a minimum of 17.8% under sunny conditions when both ambient and collector temperatures reached very high values, with consequent increase of thermal losses towards the environment, to a maximum of 31.1% under partially scattered sky conditions. The average daily thermal efficiency during the entire monitoring period resulted equal to 26.2%, which is satisfying with respect to state-of-the-art of covered PVT collector [39, 44].

The average daily PES efficiency of the novel PVT resulted equal to 50.0% while the traditional PV was able to convert solar energy into primary energy with an average efficiency of almost half of the PVT: 25.9%. Such values are promising since the average values of η_{PES} for hybrid collector reported in the literature are around 40% [20, 24, 39].

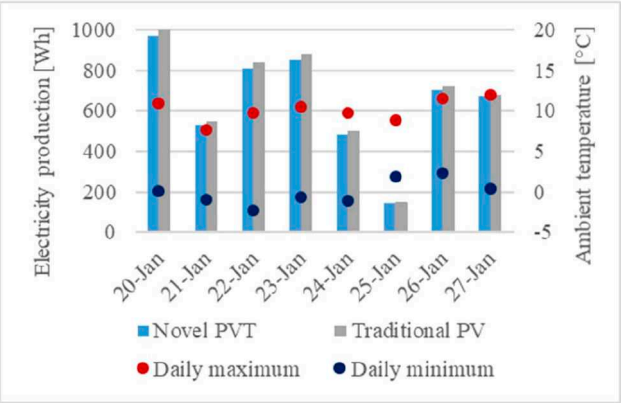

Fig. 9 *Daily electrical production in the second monitoring period: 20th–27th January 2020*

Table 4 Daily mean performance ratio (PR)

	23rd January sunny day, %	24th January cloudy day, %	25th January rainy day, %
novel PVT	95.3	96.6	97.1
traditional PV	92.3	94.1	93.5

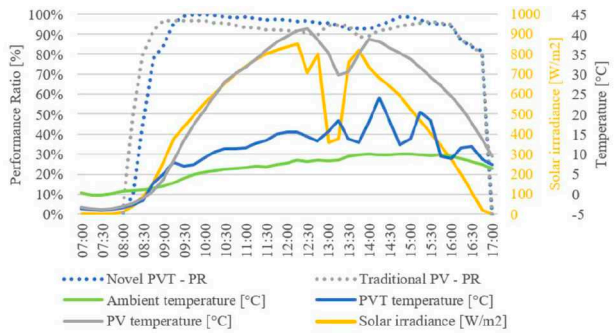

Fig. 10 *Measured data – 23rd January – Sunny day*

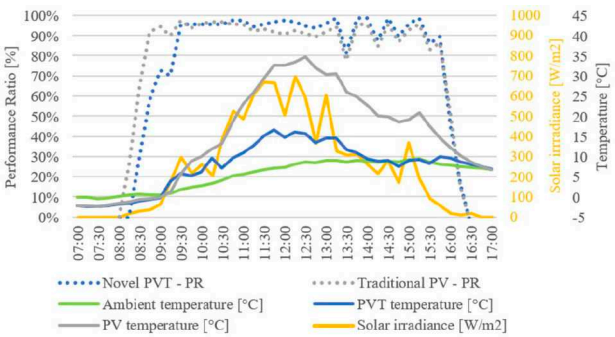

Fig. 11 *Measured data – 24th January – Cloudy day*

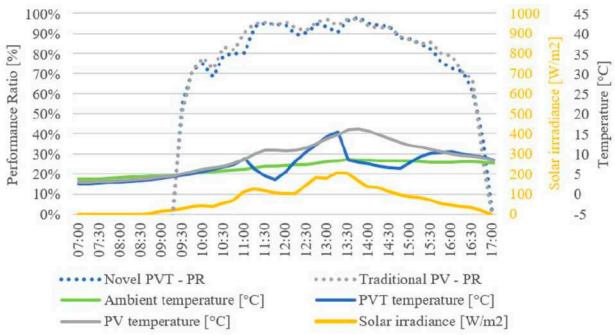

Fig. 12 *Measured data – 25th January – Rainy day*

5.3 Configuration B: PVT-SAHP mode

The two modules were monitored for 8 days, from 7:00 to 17:00 (real solar hour) with a time step of 15 min. A general overview of electrical production and external temperatures during the second monitoring period is reported in Fig. 9 and is subsequently analysed in detail. As can be noticed, the difference in terms of electricity production is around 3% lower than configuration A, even if the nominal power of the traditional PV is around 6% higher.

The daily electricity output of the novel PVT showed a maximum of 970 Wh under clear sky conditions (20th January), a minimum of 140 Wh under covered sky conditions (25th January) and an average of 650 Wh during the experimental period. The traditional PV ranged between a pick of almost 1 kWh and a minimum of around 145 Wh, with an average of 670 Wh.

A detailed analysis of real collector performances in terms of electricity and thermal energy production is again provided for this second period of monitoring. Three representative sample days, among those of the monitored period, are considered: a sunny day (20th January), a scattered cloudy day (24th January) and a rainy day (25th January).

In Table 4 the PR of the second monitoring period is reported. It is possible to notice that the novel PVT performed better than the traditional PV, as higher values of PR were registered in all climatic conditions. The novel PVT shows higher PR than the novel PVT under sunny (23rd January), cloudy (24th January) and rainy (25th January) weather conditions. Average daily PR during the monitored period resulted equal to 95.8% for the novel PVT, 3.6% higher than the traditional PV (92.5%).

Daily trends of PR for the three sample days are reported in Figs. 10–12, as well as modules and ambient temperatures. Unlike operation in configuration A, the novel PVT showed higher PRs than the traditional PV, especially when the temperature difference between the collectors is higher. The reason is the active cooling made possible by the heat exchange in the HP evaporator and the consequent refrigeration of PV cells.

As can be seen from sample-days graphs, the temperature level of novel PVT oscillates according to heat pump operating conditions. In general, novel PVT temperature remains slightly above ambient temperature during the sunny day when solar radiation is abundant and the thermal load is lower. Vice-versa, under cloudy and rainy weather conditions, with lower radiation and ambient temperature, indeed lower thermal load, the temperature of the novel PVT is closer to ambient one.

The active cooling leads to benefits also in terms of thermal efficiency, as a lower temperature allows to reduce thermal losses towards the environment, allowing for larger heat extraction from the PVT. During the second monitoring period, the daily mean thermal efficiency varied from a minimum of 39.3% to a maximum of 52.3% with an average of 46.5% during the entire period. Indeed, the average thermal gain of the novel PVT when combined to the heat pump system resulted 70% higher than values reached in configuration A, with a traditional system arrangement.

The average daily PES efficiency of the novel PVT resulted equal to 71.5%, almost triple than that of the traditional PV (25.8%).

6 Conclusions

In the context of decarbonisation of the building sector, the study, the enhancement and the diffusion of clean technologies for HVAC are fundamental. This work aims to experimentally prove that further optimisations in the design and manufacturing of PVT components can be achieved. An experimental novel water-based PVT collector, specifically designed to be coupled with heat pumps, was manufactured using a package lamination process. The aim was to improve thermal performances without sacrificing electrical ones, as heat pumps take advantage of both form energy, thus maximising the overall PVT-SAHP system performances. The direct lamination of PV cells on a roll-bond absorber, within an air gap with a single glass layer as a cover, represents a feasible solution to fabricate novel hybrid PVE collectors, characterised by

higher performances and competitive manufacturing costs compared to several commercial solutions.

The experimental analysis showed promising results in terms of electricity and thermal energy performances. The average PR of the novel PVT during the first monitoring period, when the novel PVT was directly connected to a water storage (Configuration A), was equal to 90.9%, slightly lower than the 92.8% measured for an analogous traditional PV used as a reference. The difference is principally due to the higher operative temperature and reflection losses with respect to the traditional PV. During the second monitoring period, the integration of the novel PVT into a heat pump system (Configuration B) led to an increase of electric productivity, with an average PR equal to 95.8%, 3.6% higher than that of the traditional PV, thanks to the active cooling due to the machine operation.

The average daily thermal efficiency of the hybrid collector resulted equal to 26.2% in Configuration A, increasing till 46.5% with the system arrangement of Configuration B. The average PES efficiency of the novel PVT was 50.0% in Configuration A, while reached 71.5% in Configuration B, respectively double and triples than the reference PV (25.9%).

The preliminary monitoring of the novel PVT showed promising results, demonstrating the benefit of the integration of hybrid PVT collectors and heat pump systems in terms of electric and thermal performance enhancement, thanks to the lower operating temperature of PV cells and thermal absorber.

The acquired information is sufficient to demonstrate that active cooling PVT collectors through the use of heat pumps may lead to important benefits in terms of electrical production of the solar collector with respect to the traditional configuration using a water tank. The principal drawback of hybrid solar collectors, e.g. high operating temperature, can be indeed solved, surpassing even the performance of traditional PV modules. The proposed PVT-SAHP configuration is indeed promising and worth further development. Some optimisations of the PVT manufacturing process are needed to avoid PVB wrinkles and PV cells cracks, obtaining better electric performances. Furthermore, in a second stage of the research, an advanced control logic, which allows the optimisation of operating temperatures, will be implemented and a more extended testing campaign in outdoor conditions will be performed.

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