Electrical characterization and comparison of a novel covered PVT collector

F. Leonforte*, C. Del Pero*, N. Aste* and A. Miglioli*
*Architecture, Built environment and Construction Engineering Department, Politecnico di Milano, Via Ponzio 31, 20133 Milano (Italy)

***Abstract*— Hybrid photovoltaic-thermal (PVT) collectors have been widely investigated in recent decades, since they include in a single device the two most diffused solar technologies: photovoltaic and solar thermal, ensuring higher overall performances and compactness with respect to separated components. In this study a novel PVT collector, able to reduce the optical losses as well as to increase the heat transfer toward the working fluid, is presented. In detail, the PV cells are directly laminated on the aluminium roll bond absorber without the front cover glass, which is added at the end of the lamination process above a spacer, creating an air gap. Obtained results showed that the novel collector maintains similar electrical characteristics to an uncovered PVT and even better performances than a traditional covered collector. Moreover, due to the air gap between cells and glass, the overall thermal losses from the surface are heavily reduced, with benefits in terms of thermal efficiency. The work proves that the direct lamination of PV cells above a roll-bond absorber within an air gap with a single glass layer as a cover could lead to a new generation of hybrid PVT collectors.**

***Index Terms*—Photovoltaics; PVT; hybrid collector; roll-bond; direct lamination;**

I. Introduction

PV technology converts solar radiation in electricity with an efficiency ranging from 5% to 25%, meaning that a significant part of the incident solar energy is reflected or transformed in thermal energy. This leads to an increase in the PV cells working temperature and, consequently, to a drop of electricity conversion efficiency. For such reason, over the years, many research efforts have been spent on the development of hybrid photovoltaic-thermal (PVT) technology (using water or air as an heat-transfer fluid) [1,2], ensuring higher overall performances and compactness with respect to separated components (i.e. thermal and photovoltaic) [3].

In spite of the above-mentioned considerations, although a number of commercial products have been put on the market, the uptake of PVT has so-far been extremely modest [4]. In fact, the installed capacity is currently too low to be reported, demonstrating that the potentiality of such technology has not been exploited.

In such context, the most investigated PVT technologies in recent time are based on systems using water as heat transfer fluid, because they achieve higher overall efficiencies than air systems [5] due to the greater heat capacity of water and the possibility to be easily integrated with heat pumps [6] . PVT modules can also be classified depending on the presence or absence of an air gap formed between the transparent frontal cover and the absorber, being respectively named as "covered" or "uncovered". In uncovered collectors, the front side of the module is in direct contact with the environment, thus the heat losses are considerable. Indeed, the fluid temperatures are particularly influenced by external ambient conditions (e.g. air temperature, wind speed, etc.).

It should be underlined that this type of collector is typically called "uncovered", despite the presence of the PV cover-glass, since there is no additional glazing layer to provide thermal insulation by means of an air gap. The cover glass on PV cells is in fact required to prevent the cells degradation due to direct exposure to the moist ambient air and, more in general, to provide protection from external conditions. From a thermal point of view, is therefore more convenient to adopt covered collectors, in order to decrease the convective and radiative heat losses from the front side, and hence to increase the transmitted thermal fraction to the working fluids.

Covered collectors are generally manufactured by coupling the absorber plate to the back side of a commercial PV module, that is already laminate with a glass on the front side and with tedlar or glass as back-layer. The component is than enclosed into a frame and covered by another glass not attached directly to the PV laminate, creating so the air gap in between.

In such respect the traditional covered collectors have two glasses which increase the optical losses due to reflection and refraction, affecting the electrical performance of the component. Moreover, the back sheet of the PV sandwich reduces the thermal transmission to the working fluid, with a further reduction of the thermal efficiency.

A possibility to decrease these losses and also to optimize manufacturing costs is to laminate PV cells directly on the absorber plate and to remove the cover glass on PV cells, thus leaving just the glass layer needed to form the air gap. Although the feasibility of such option has been recently demonstrated [7,8], very few details and performance analyses are reported in literature.

For such reasons, the present work focuses on the

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design, manufacturing and preliminary test of a covered PVT water collector manufactured with PV cells directly laminated on a roll-bond flat plate absorber, which is finally covered with just one layer of glass.

The electrical performance of the novel prototype is assessed in comparison to a module manufactured with the same cells laminated with a traditional process (without air gap) and the latter with a further glass which reproduce the traditional covered collector. Finally, the electric insulation of the module under wet operating conditions was verified according the procedure of the IEC 61215-2:2016 [9].

II. State-of-Art on Connection Among PV and Absorber

As already introduced, the connection between the photovoltaic components and the flat-plate thermal absorber is one of the main manufacturing steps that affect the overall efficiency of a PVT component.

The most widely used and low-cost solution to do such connection is to use an adhesive layer. The entire PV laminate is therefore bonded to the flat plate by means of thermo-conductive glues, generally silicone [10], which are resistant to high temperatures.

The adhesive method by glue has been widely applied in several research projects in the past [11–13]. However, this technique presents several problems, such as the risk of condensation between the two parts or an increase in thermal resistance. In fact with the gluing technique, some air bubbles trapped between the PV laminate and the plate could decrease the thermal exchange coefficient and do not allow a full homogeneity in the cells temperature distribution [14,15]. Van Helden [3] reports a theoretical value of thermal exchange coefficient between photovoltaic laminate and copper plate, glued with an epoxy aluminium oxide adhesive with a thermal conductivity of 0.85 W/mK, equal to of 100 W/m^2K.

The same material was analysed experimentally in a c-Si PV laminate glued onto the surface of a standard thermal absorber. The measured thermal exchange coefficient was equal to 45 W/m^2K, a lower value with respect to the theoretical one provided by the previous research [3]. This effect, according to the authors, is precisely due to the air bubbles trapped between the two surfaces [16].

As a second option, the connection could be also manufactured by mechanical fixing; in such regards the absorber, generally made with plastic material, is pressed against the backside of the PV module and fastened with several specially-designed mounting brackets [10]. Although such system fixes firmly the PV sandwich to the thermal absorber, it needs additional profiles, joints, screws and clips, which increase the overall cost and weight of the component. Moreover, mechanical connection cannot prevent the presence of a thin air gap between the PV layer and the thermal absorber, which may result in a non-negligible thermal resistance and weaken the overall performance of the PVT module in long-term operation.

A more advanced technique is the lamination of the whole package (Glass, PV cells, electrical insulation and absorber) in one step [17]. The primary aim of the package lamination is to minimize the thermal resistance between the PV-cells and the metal absorber; in fact, instead of the three different layers (encapsulant, polyvinyl fluoride film and adhesive) normally used in the gluing method, in the whole package lamination only one layer is necessary. However, if a metal absorber is used, particular care should be taken about the distance between the latter and PV cells. Therefore, normally an additional electrically insulating foil of ethylene–vinyl acetate (EVA) or polyvinyl butyral (PVB) is laminated between the cells and the absorber, but also an electrical insulating coating may be applied directly to the absorber [14].

Regarding the achievable thermal performances, Van Helden shows a heat transfer coefficient of 125 W/m^2K for the two elements coupled by lamination, compared with the value of 100 W/m^2K reported for simple elements bonding [3].

Dupeyrat [8] analyses the electrical and thermal efficiencies of two PVT modules, which differ only for the coupling method (gluing and lamination). Lamination ensures a thermal efficiency greater than 10% with respect to the glued module, due to a higher heat exchange coefficient, and an improvement of the electrical performance due to the decreases of cells temperature, thus confirming the potential of such manufacturing solution.

III. Design of the Novel PVT Component

The novel prototype collector was built through the direct lamination of PV cells on a customized aluminium roll-bond absorber. More in detail, a 0.75 mm thick PVB film was used as a front layer of the cells while 3 layers (0.75 mm thick each) of the same material were placed between cells and the absorber to guarantee the electrical insulation. PVB has a good temperature stability as well as UV resistance, thus can be successfully used in a vacuum laminator.

The roll-bond aluminium absorber was manufactured with parallel channels arrangement on the back side, while it is totally flat on the upper side (one-side-flat manufacturing process). This type of absorber is one of those characterized by the best performance for PVT applications: the parallel pipe configuration, as known [1,18–20], ensures slow temperature gradients between input and output and a good temperature distribution on the whole absorber surface, with electrical and thermal benefits on the PVT collector efficiency. Moreover, in order to obtain a better flow distribution in the channels, an optimized layout of the header manifolds was chosen according to the PVT state of the art [21].

The selected PV cells consist in 5-busbar monocrystalline high-efficiency solar cells, with a nominal peak power of 5.25 W_p. The cells are characterized by a temperature power coefficient of about -0.39 %/K and are able to convert solar energy into electricity in a wide spectrum, between 300 and 1200 nm, with a higher quantum efficiency in the near-infrared band.

For each module, 50 cells have been connected in series, so the string is able to provide around 262 W_p in nominal conditions.

The main features of the cells and of the string are reported in table 1 and 2.

TABLE I
MAIN FEATURES OF THE PV CELLS

MECHANICAL DESIGN	
Square length	156.75 ± 0.25 mm
Diameter	210 ± 0.5 mm (round chamfers)
Thickness	200 ± 30 um
Front surface	Alkali textured, silver bus bar blue anti-reflecting silicon nitride coating
Back surface	Aluminium oxide back-surface field silver soldering pads for the backside electrodes
Base material	p-type Mono-crystalline silicon wafer
Junction	Phosphorous diffused N on P

TABLE II
ELECTRICAL FEATURES OF THE PV CELLS AND THE STRING

	Efficiency [%]	**Pmpp [W]**	**Voc [V]**	**Isc [A]**	**Vmpp [V]**	**Impp [A]**
Cell	~21.5	5.25	0.664	9.786	0.566	9.277
String	-	262.5	33.20	9.786	28.30	9.277

All these layers were assembled together in a vacuum laminator using standard PV lamination conditions in terms of pressure load, vacuum and temperature, in order to obtain a functional PVT laminate. Finally, the front glass cover was added, to create an air gap, by using an aluminium spacer 10 mm high that was glued using a 895 Doucone silicone (characterized by high durability); the spacer was attached on the lower side on the edges of the absorber and on the upper side on an extra-clear glass 5 mm thick, as shown in figure 1. In such regard, the PVT module is made with a similar manufacturing process to a traditional double-glazing, avoiding the interposition of two separated glasses above PV cells. The solar transmission of the adopted glass is equal to 88.8%. One of the main challenges that was faced is the lamination of PV cells on the absorber avoiding the presence of a second rigid layer on the front. This required different tests using removable flexible layers in the lamination process.

The overall dimension of the module is (L x W) 1765 mm x 960 mm, as shown figure 2. The junction box, completely water tight (IP 67), is placed in the corner on the back side and is attached with silicon adhesive. It encapsulates solar bypass diodes that keep solar power flowing in one direction and prevent it from feeding back to the PV cells. Besides, such component allows the installation of Multi-Contac connectors (MC4) with a 6 mm^2 cable.

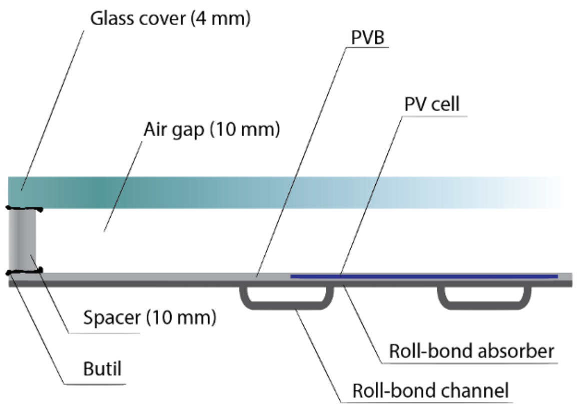

Fig. 1. Section of the novel PVT

Fig. 2 shows a view of the ratio between the solar cell active area and the absorber surface (packing factor) as well as the overall dimensions of the component. In detail, the packing factor of the novel PVT is 0.73; such value typically ranges between 0.8 and 0.9 in standard sc-Si modules [8].

It should be noted that no delamination between PV encapsulant and metal absorber was observed after the manufacturing process, but of course a thorough durability analysis is necessary in the future.

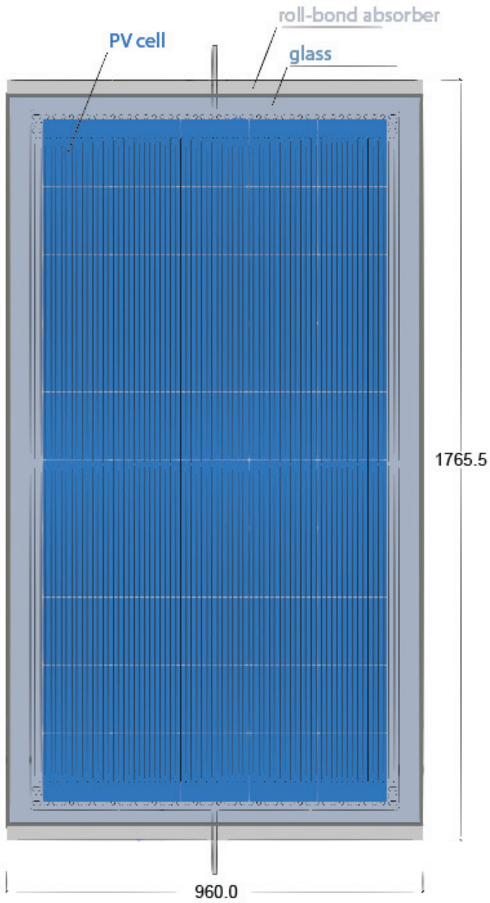

Fig. 2. PVT front view and dimensions (sizes in mm)

The final prototype is shown in figure 3.

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

IV. PERFORMANCE ASSESSMENT

As already introduced, the described collector, namely hereafter novel PVT, has been compared with two modules manufactured with the same PV cells laminated on the absorber but with 2 different configurations:

A. directly laminated with a front glass without an air gap: this configuration represents a standard uncovered PVT collector;
B. with the same configuration of type A but adding a further glass 5 mm thick placed at a distance of 10 mm from the first, thus with the same size of the novel PVT; this option represents a standard covered collector.

The configuration of the 3 modules is represented in figure 4. In this phase of the research, electric performances were firstly assessed in standard test conditions (STC), according to the procedure defined in IEC 61215-2:2016.

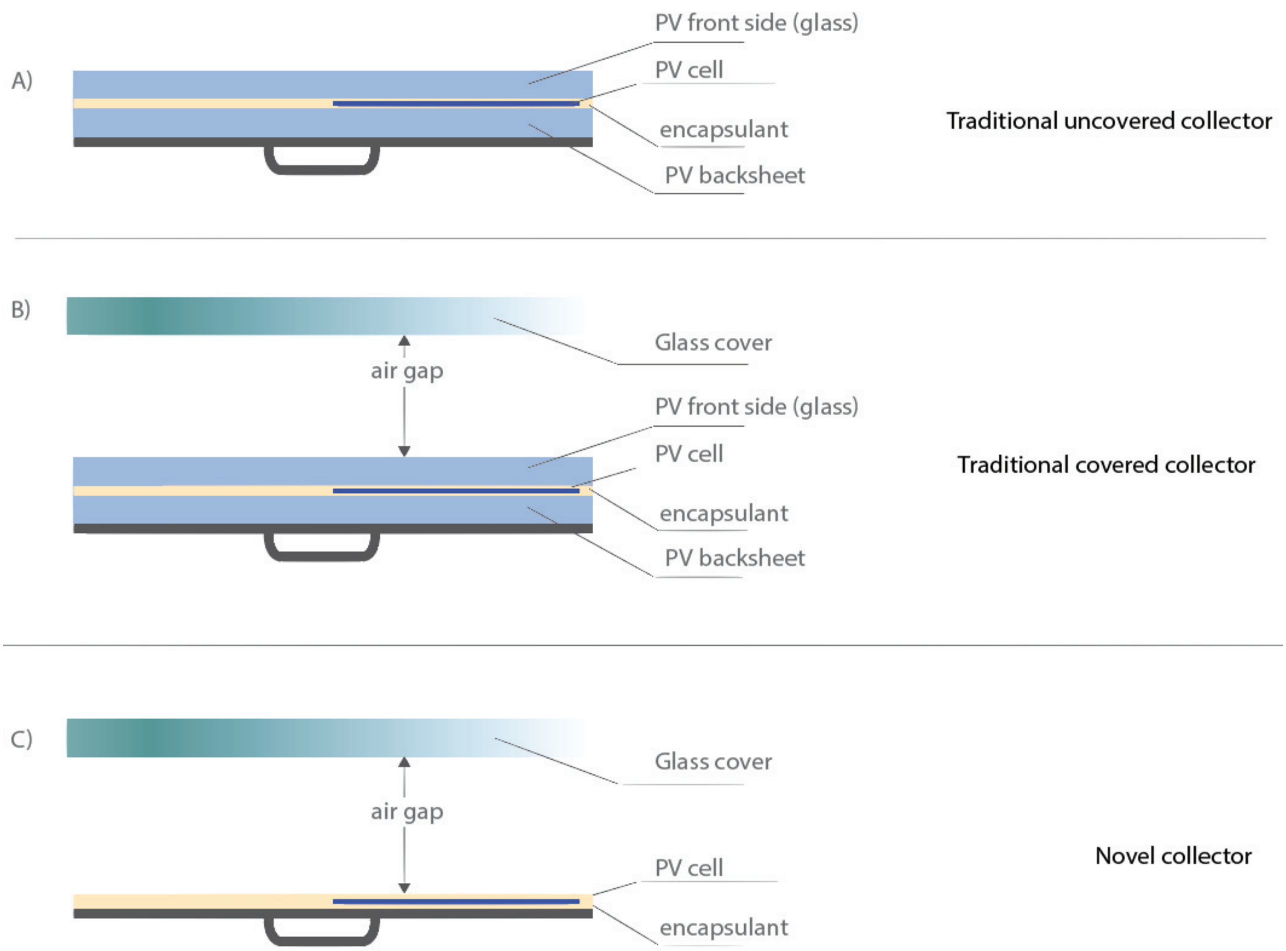

Fig. 4. Detailed features of the tested PVT collectors

According to obtained results, reported in table 3, the rated power at maximum power point of the novel PVT is about 5.2% higher than that of the standard covered module. In fact, as previously reported, the latter collector has more optical losses due to the additional cover glass compared to the novel component. However, it should be noted that the higher performance is not of the same magnitude order of the solar transmission of the glass, which is almost 88.8%. In fact, comparing the novel component with the uncovered version, although both have been manufactured with just one glass, the latter has a performance about 6.4% higher.

TABLE III
RESULTS OF THE FLASH TEST

	Pmpp [W]	Voc [V]	Isc [A]	Vmpp [V]	Impp [A]
Novel	198.1	33.0	8.1	26.8	7.4
Uncovered	211.7	33.6	8.4	26.8	7.9
Standard covered	187.9	33.5	8.0	26.8	7.0

According to a detailed visual inspection, part of the abovementioned losses can be due to wrinkles on the PVB, which in some points is not perfectly in contact with PV cells (Figure 5).

Fig. 5. Detail of wrinkles on the PVB

A. *Electroluminescence characterization*

In such respect, since the losses cannot be due just to the presence of an air gap between the cover glass and the cells, an electroluminescence of the modules has been carried out. The method is widely adopted in PV sector to analyse defects and cracks in PV cells [22].

As shown in figure 6, a few cells of the novel PVT are characterized by cracks. Thus, since the cracks may remove portions of the cells from the electrical contact, the power output of the module decreases consequently [23]. In detail, 7 defective cells generated during the assembling of the novel component were identified; they are mainly affected by cracks parallel to busbars, probably caused by a deformation of the roll-bond absorber during the handling or lamination phases. The adopted roll bond panel is in fact more flexible than a traditional glass layer.

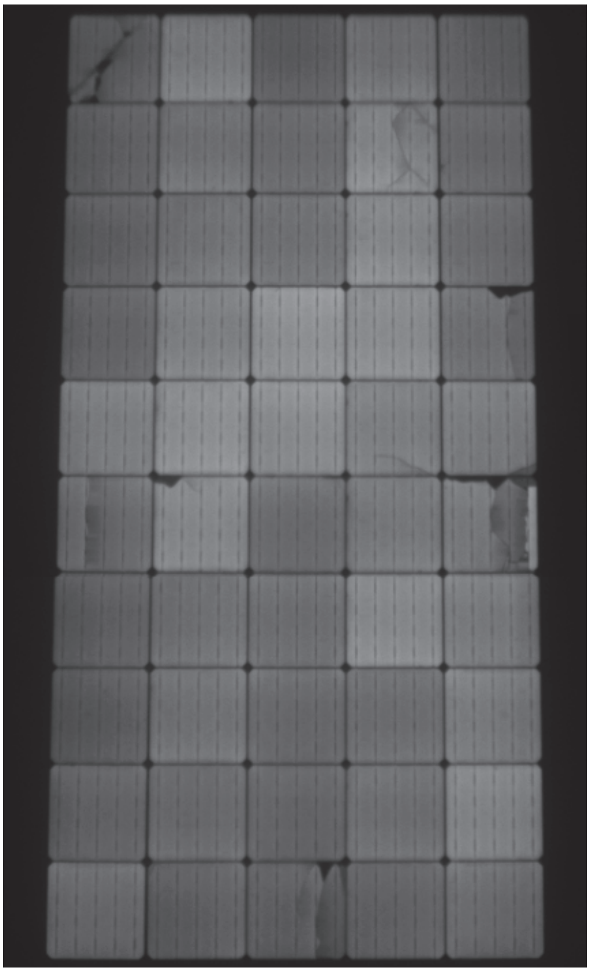

Fig. 6. Electroluminescence of the novel PVT collector

Considering the area of the cells affected by cracks, and assuming to reduce proportionally the power rate, it can be stated that the possible performance reduction due to cracking is about 5%. In such respect, the electrical output of the novel PVT collector can be considered almost equivalent to that of the uncovered one, which however is expected to perform better in terms of thermal yield.

It must be noted that the type and the position of cracks exclude an intrinsic problem of the adopted manufacturing process, which would have caused the breaking of a greater number of cells with a certain regular pattern. This leads to believe that the problem can be solved by optimizing the process in the further steps of the research.

In addition, it's important to underline that obtained performances are not the best achievable, since further improvements can be introduced. For instance, the used glass has not an anti-reflective coating, thus its solar transmission can be increased. In addition, a black PVB was used: this typically increases thermal performances but slightly decreases electric ones, since there is not reflected radiation from the surface among PV cells.

B. Wet leakage test

Finally, in order to evaluate the electric insulation of the novel module under wet operating conditions and to verify that moisture from rain, fog, dew or molten snow does not enter in the active parts of the module, a wet leakage test was carried out, following the procedure of the IEC 61215-2:2016 [9].
In particular, the module was totally immersed in a water solution (figure 7) applying a voltage of 1000 V for 2 minutes, during which the electric insulation resistance was measured.

Fig. 7. View of the novel PVT prototype during the wet leakage test

The results showed a proper value of insulation, equal to approximately 63 MΩ, which thus confirms that the direct lamination of the cells on the absorber can be adopted for the manufacturing of advanced covered PVT collectors, since multiple PVB layers ensure sufficient electric insulation.

V. CONCLUSION

The present work aims to experimentally demonstrate that further optimizations in the design and manufacturing of PVT components can be achieved. An experimental novel PVT collector was manufactured using a package lamination process, with the aim to improve thermal performances without sacrificing electrical ones, while also reducing the number of layers in the components and thus the related cost. In details, obtained results preliminary prove that the direct lamination of PV cells on a roll-bond absorber within an air gap with a single glass layer as a cover could lead to a new generation of hybrid PVT collectors, which is characterized by higher performances and lower manufacturing costs compared to several commercial solutions.

At this stage of the research, the acquired information is enough to demonstrate that the proposed configuration is promising, also if the first testing phase was carried out just on electric performances. Some optimizations of the manufacturing process are required to avoid wrinkles in the PVB layer above PV cells and also cracks. In addition, in a second stage of the research, a glass with an anti-reflective coating will be adopted and a detailed testing campaign in outdoor conditions will be carried out, analysing also thermal performances.

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