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Design Options for Uncovered Photovoltaic-Thermal Glass-Glass Panels

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Abstract

The use of glass-glass photovoltaic modules in uncovered photovoltaic-thermal (PVT) panels can provide for a longer durability of the solar cells and for higher design flexibility compared to other encapsulating technologies, thus representing an attractive solution for building integration. After giving an overview of available design options and of their impact on the efficiency of the PVT, the paper presents and analyzes the thermal performance of different prototypes by means of measurements in open circuit (OC) mode according to ISO 9806. The customized panels are assembled from commercially available components and intended for the integration into ventilated glass façades. As cell technology, wafer-based crystalline silicon (c-Si) and thin film copper indium diselenide (CIS) are implemented. For the front cover, clear glass with high and low iron content as well as special low emissivity and colored glass with high solar transmittance developed for solar applications are considered. In combination with c-Si solar cells, we additionally compare the use of black enameled rear glass and multilayer black encapsulant as a solution to mask the heat exchanger. The results show the significant impact of the design on the thermal performance of the PVT panels: we report zero-loss efficiency values between 0.61 and 0.78 and heat loss coefficients $b_{1.5m/s}$, evaluated at a wind speed of 1.5 m/s, between 10.2 and 17.8 W/m²K. Concerning both performance and aesthetics, the best results are achieved with CIS photovoltaic modules and low-emissivity front glass panes.

Keywords: *photovoltaic-thermal collectors, hybrid collectors, uncovered collectors, building integration*

1. Introduction

Photovoltaic-thermal (PVT) collectors have been regarded since longer than 40 years as a promising solution to supply both for renewable electricity and heat with a single device. Compared to the common separate installation of solar thermal and photovoltaics, a higher solar yield and lower costs per unit area, a more appealing design as well as an improvement of the electrical efficiency of the solar cells in case of low-temperature applications with uncovered panels can be mentioned as main advantages. Still far away from being an established technology, PVT collectors have been receiving a renewed interest in the last time, not only in research works but also among manufacturers and end users, as a consequence of the recent development of the photovoltaic market and the energy performance requirements set by the new European building regulation.

Similarly to the case of solar thermal and photovoltaics, building integration represents a very efficient way to improve the architectural quality and reduce the cost of the installations, by replacing existing building components and their associated embodied energy with active solar ones. Both aspects represent a key approach for a successful deployment of these renewable energy systems. Most of the available design and integration options (type of cell technologies, glass, encapsulants, coatings, etc.) are known from previous experiences with photovoltaics (Farkas, 2013; Jelle et al., 2013) and their effects have been commonly investigated with regards to the electrical efficiency or to the reliability of the solar cells. Furthermore, developments aiming at improving the design of the modules are often carried out for specific commercial projects and seldom comprehensively documented in the scientific literature (Perret-Aebi et al., 2014).

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Nomenclature		
$b_{1.5m/s}$	collector heat loss coefficient at w = 1.5 m/s	[W/m²K]
G	hemispherical solar irradiance	[W/m²]
G”	net irradiance	[W/m²]
T_a	ambient temperature	[°C]
T_m	mean fluid temperature	[°C]
w	wind speed	[m/s]
α	solar absorptance	[-]
γ	temperature coefficient of the maximum power	[%/K]
η	thermal efficiency	[-]
η_0	zero-loss thermal efficiency	[-]
η_{el}	electrical efficiency	[%]
ε	thermal emittance	[-]
τ	solar transmittance	[-]

In the framework of a current research project we have been investigating the design and the integration of uncovered liquid-based glass-glass PVT panels into ventilated glass façades (s. Figure 1). The specific façade system consists of vertical aluminum profiles screwed to the main bearing wall and equipped with clip fasteners able to support glass claddings with different thickness, size and geometry and, thus, best suitable also for PV and PVT panels.

The glass-glass encapsulating technology can generally provide for a longer service life of the solar cells thanks to the higher mechanical durability and the improved degradation behavior, thus representing a reliable choice if combined with an additional heat exchanger as for photovoltaic-thermal applications. The wider range of design options makes it furthermore an attractive and flexible solution for building integration. As drawbacks, higher costs and a higher thermal resistance due to additional rear glass have to be taken into considerations if compared to the common use of thin plastic backsheets or to the direct lamination of the PV cells on the heat exchanger, a manufacturing approach already tested in previous research works (Rockendorf et al., 1999; Dupeyrat et al., 2010; Matuska et al. 2015).

Fig. 1: Examples of ventilated glass façades with common glass panels (left, source: Konvortec) and PV panels (center, source: Konvortec) as well as schematic representation of the ventilated façade with glass-glass PVT panels under development (right)

After giving an overview of relevant design options for glass-glass PVT panels and analyzing their correspondent impact on the collector performance, the work presents and discusses selected results of thermal efficiency measurements on different large-sized prototypes, assembled on the basis of commercially available components.

2. Overview of design options

Liquid-based, uncovered glass-glass PVT panels basically result from the combination of a glass-glass PV-module and a heat exchanger, which can be connected to each other by using different mechanical or/and adhesive fixings. This section briefly describes the single components of PVT panels, mainly considering commercial products and focusing on the influence of possible design configurations on the thermal efficiency of the panels.

2.1. Solar cell technology

Solar cells represent the core of PVT panels and can have a strong impact both on their energy performance and their design. They are basically distinguished in wafer-based silicon and thin film cells; under this last category amorphous silicon (a-Si), cadmium telluride (CdTe), copper indium diselenide (CIS) and copper indium gallium selenide (CIGS) are the most common and commercially relevant ones. Due to the different manufacturing processes implemented, the choice of a specific technology also affects the module assembly itself, i.e. the number and type of components used, as shown in Figure 2.

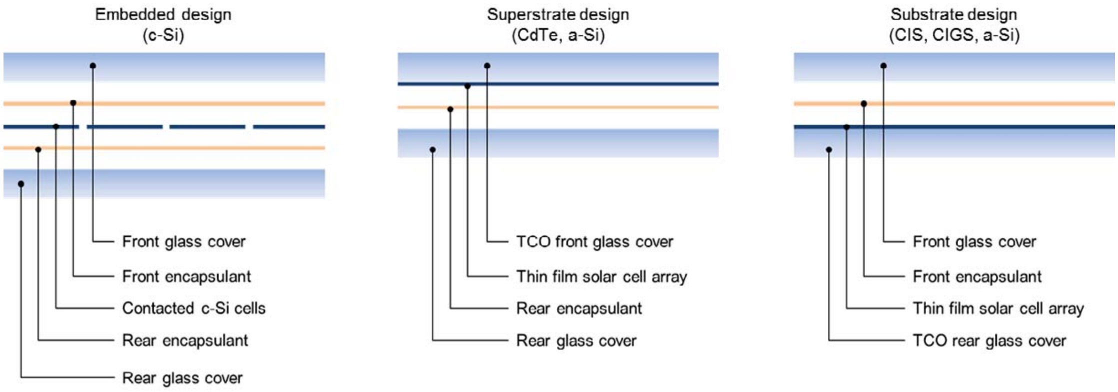

Fig. 2: Design of glass-glass photovoltaic modules for wafer-based (left) and thin film (center, right) solar cells

The photovoltaic performance is commonly characterized by the electrical efficiency η_{el} measured under standard conditions STC (irradiance: 1000 W/m²; spectrum: air mass AM 1.5; module temperature: 25°C). In commercially available PV modules it ranges between 10% (a-Si) and 16% (CdTe or CIGS) for thin films and between 16% (polycrystalline) and 20% (monocrystalline) for wafer-based silicon cells (Fraunhofer ISE, 2015). The electrical efficiency exhibits a significant temperature dependent behavior. The temperature coefficient γ, which describes the relative change of the power output of the module in %/K compared to measurements under standard conditions, roughly varies from - 0.45%/K (c-Si) to - 0.20%/K (CdTe). A lower coefficient is generally considered a negative property for common PV installations, as it can lead to lower energy production under operation. In typical applications with uncovered PVT panels, such as solar assisted heat pump systems, on the contrary, it can even be energetically advantageous, as the solar cells usually operate at temperatures below 25°C.

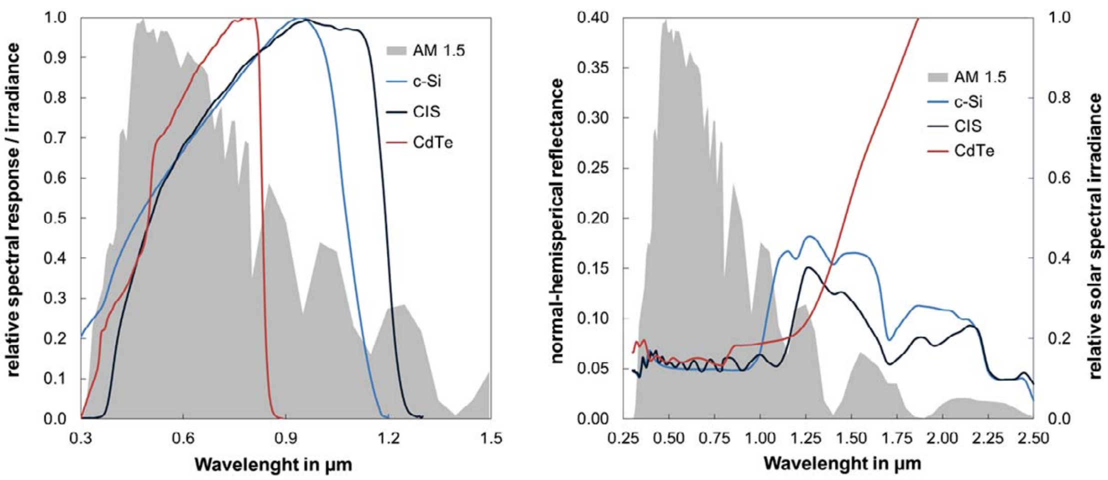

Fig. 3: Relative spectral response (left, data provided by manufacturers) and spectral reflectance (right, ISFH measurements) of PV modules based on different solar cell technologies.

To assess the impact of the PV cell as well as of other module components on the thermal performance of the PVT collector, more detailed data than the electrical efficiency are required: the spectral optical properties over the whole solar wavelength range and the spectral response of the PV module, describing the amount of current coming out of the device per incoming photon of a given energy and wavelength (or alternatively the quantum efficiency). Figure 3 compares exemplarily spectral response and reflectance of three PV modules based on different cell technologies. The modules' data were provided by manufacturers, the optical measurements were carried out at ISFH with a commercial double-beam spectrometer equipped with an integrating sphere.

The graphs show the different wavelength dependent behavior of the technologies especially in the near-infrared range, which has to be considered if combining the cells with spectral selective front covers or encapsulants. The reflectance measurements report otherwise similarly low integral values, ranging between 0.09 and 0.06, thus proving their suitability for the use as solar thermal absorbers.

The choice of a defined cell technology can also significantly influence the color and the final aspect of the module, thus playing an important role for building integration. Wafer-based silicon cells are typically available in dark blue or black and feature a homogenous or non-homogenous appearance, depending on the crystalline structure of the cell itself (mono or poly). The color is determined by the material and by the antireflective coating, which is usually optimized to achieve maximum electrical power under solar irradiation. Many research works have addressed the manufacturing of colored cells with low power losses by tuning the antireflective coating (Selj et. al., 2011; Chen et. al., 2012; Vogt et al., 2015) and several commercial products developed for building integration are already available on the market in different colors (green, red, etc., s. Figure 4). Beside the color, the shape and size of the cell still remain a limiting factor for the module design, affecting both its characteristic patterned appearance and its geometry.

Due to the specific manufacturing process, thin film technology presents a much more homogenous aspect and enables a customized and very flexible dimensioning of the modules, which make them more attractive as components of the building envelope. The cells are generally matt black, blue or brown. Different grades of transparency can be achieved by reducing the cell thickness and/or by removing small areas of the cell with laser treatment, which implies a correspondent efficiency loss. The combination of semitransparent cells with colored rear glass panes or films significantly extends the design options of this technology as shown in Section 2.3.

Fig. 4: Typical appearance of wafer-based c-Si and thin film cells. Left: common monocrystalline c-Si cell; center: colored mono- and polycrystalline c-Si cells (source: Loft Solar Corporation); right: CIGS cell

Reliability of solar cells is finally a complex and crucial aspect to be considered in the development of PVT panels, which is not specifically addressed by the present work. Manufacturers of photovoltaic modules generally guarantee 90% and 80% of the performance (power output) after 10 years and 25 years operation respectively, independently from the cell technology used. The operation in PVT systems can primarily lead to higher mechanical and thermomechanical stress, depending on the heat exchanger and bonding technology chosen. Comparative investigations on long-term reliability of PVT panels are not known to the authors. Degradation mechanisms and behavior of different PV modules are on the contrary well documented in the literature, for example in a recent work by Jordan et al. (2016).

2.2. Front and rear cover glass

The front cover of glass-glass PVT modules should provide for high mechanical stability and low optical losses. In case of PV modules with superstrate design (s. Figure 2), it also represents the substrate for the deposition of the thin film cell array. Tempered, soda-lime glass panes with a thickness of 3 to 4 mm and low-iron content are generally used both for photovoltaic and solar thermal applications (s. Figure 5). The impact of the iron content (mainly Fe_2O_3) on the PVT module performance depends on the spectral sensitivity of the considered cell technology and on the referred spectral range, as explained in section 2.2. For monocrystalline c-Si modules a power output decrease between 1% (Fe_2O_3 = 0.1 ‰) and 10% (Fe_2O_3= 1‰) compared to an ideal iron-free glass is reported for commercially available 3.2 mm samples in a recent work (Vogt et al, 2015). The thermal efficiency of uncovered PVT is less influenced by the iron content of the glass, as part of the solar radiation absorbed in the glass bulk is transferred by thermal conduction to the fluid and contributes as secondary heat gain to an increase of the conversion factor η_0.

To further reduce the optical losses of solar modules antireflective coatings are commonly deposited on the external surface of the front cover of premium products. In most cases porous SiO_2 layer stacks are used, which can improve the efficiency of photovoltaic and thermal collectors by about 0.02 for each side.

Aiming at improving the thermal performance of PVT collectors, the use of low emissivity, high transmittance coatings to reduce the radiative heat losses represents an additional option. This approach has been already investigated in previous works for different kind of flat plate collectors (Giovannetti et al., 2014) as well as for covered PVT (Lemmle et al. 2016). To minimize the optical losses and ensure long-time reliability in uncovered collectors coatings based on metal oxides (e.g. indium, tin or zinc) are suggested. The impact of the low-e coating for low-temperature applications is strongly dependent on the specific heating system design and on the operation mode: if the collector is working as heat exchanger below ambient temperature, the use of the coating can even lead to a lower performance if compared with non-selective panels.

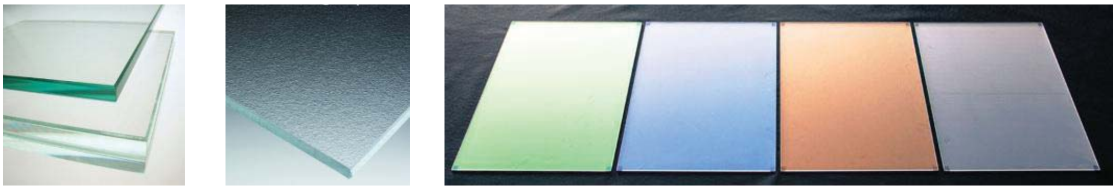

Fig. 5: Examples of front glass for solar applications. Left: clear glass with different iron content (source: Euroglas); center: textured clear glass (source: Interfloat Corporation); right: colored glass with high solar transmittance (source: Swissinso)

For architectural purpose, the use of colored or patterned glass is of high interest: most of the available products exhibit a considerably lower transmittance compared to common covers (in best case about -10%). Special spectrally selective coatings for solar glazing with improved optical properties were developed at the École polytechnique fédérale de Lausanne (EPFL) and are now manufactured by the Swiss company Swissinso (Schüler et al., 2005; Swissinso, 2016). These interference thin films can reflect a very small selected portion of the visible spectrum while letting the rest of the energy pass through. The glass panes are supplied in several colors, which according to manufacturers' data reduce the performance of thermal collectors by approximately 1% (grey) to 4% (yellow) and of photovoltaics by 2% to 6% (Swissinso, 2016). An additional light diffusing layer, achieved by etching the outside surface of the glass makes it possible to completely hide the absorber and obtain stable quality colors (s. Figure 5). Independently from the coloration, textured glasses and acid etching treatments are since long in use for solar applications with the aim of partially masking the solar absorber or the solar cells and improve the module appearance.

Rear cover glass is used similarly to front glass to ensure the durability of the glass-glass PV-modules and represents in case of PV modules with substrate design (CIS, CIGS or a-Si) the substrate for the cell deposition. The optical properties as well as the aesthetics play a role only in combination with wafer-based silicon or with semitransparent thin film cells. Colors or patterns can in these cases be used to hide the heat exchanger and better match the façade design, while affecting the solar absorptance of the glass and, thus, the thermal performance of the PVT panels.

2.3. Encapsulants

Encapsulants are primarily used in glass-glass PV modules to embed the solar cells between the glass panes and protect them from environmental stress. To provide for high performance and long-term durability several requirements have to be fulfilled, such as optical transparency, mechanical adhesion, electrical isolation, resistance to UV radiation, temperature and moisture penetration. For aesthetical purposes, colored or patterned encapsulants are also available on the market. These products are mainly combined with wafer-based silicon or semitransparent thin film cells in building integrated photovoltaics (Perret-Aebi et al., 2014) as shown in Figure 6 and can be similarly implemented in PVT panels to hide the heat exchanger. As for the glass panes, different colors result from different optical properties and can thus affect the energy efficiency of the panel.

Concerning the typical materials, ethylene vinyl acetate (EVA) represents today the most common choice for photovoltaics, thanks to its high transmittance, good durability but especially low cost. EVA films are transparent, white or black and supplied in different thickness. Silicon-, polyefine- or ionomer-based films offer alternative solutions for EVA products and exhibit even better optical performance and weatherability. Due to their higher costs, they haven't been able to gain a significant market share so far. The use of colored silicon films for solar energy applications is documented in recent research activities (Vogt et al., 2015). Finally polyvinylbutyral (PVB), commonly known as interlayer in laminated safety glass is also implemented as encapsulant material. These films are manufactured in many different colors, thus representing an attractive option for architectural applications. Furthermore, according to the current European building regulation PVB is the only material that can be integrated into façades without a special construction permit, which explains its prevalent use in building integrated photovoltaics. As relevant drawbacks, it exhibits inferior performance and durability if compared to the previously mentioned products.

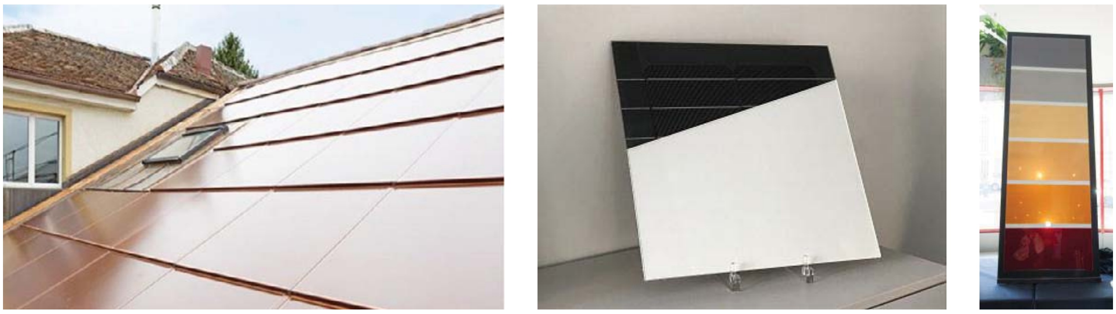

Fig. 6: Colored solutions developed for building integrated photovoltaics: Left: thin film PV with rear encapsulant as roof tile (source: NexPower). Center/right: Samples of modules with white and colored multilayer front encapsulants (source: Solaxxes)

Additionally to these standard encapsulants, special multilayer solutions embedding interference filters for tuning the color of the modules have been recently introduced to the PV market, on the basis of the research work carried out at the EPFL and at the Centre Suisse d'Electronique et Microtechnique (Perret-Aebi et al., 2015): deposited on microstructured films, these filters can selectively scatter visible light while transmitting infrared radiation, thus enabling the manufacture of perfectly homogenous colored and even white modules (Figure 6). Combined with heterojunction c-Si cells, which are particularly sensitive in the IR range, electrical power losses by about 40% were measured for white samples. For PVT applications also a significant decrease in thermal efficiency is expected.

2.4. Heat exchanger

Aim of the heat exchanger in PVT panels is to efficiently transfer the solar energy absorbed in the PV module to the fluid. For the challenging design two main aspects have to be taken into consideration: the low thermal conductivity of glass (λ = 0.8÷1.0 W/m*K), which requires a large contact area between the heat exchanger and the rear pane of the PV module in order to provide for a reasonable internal heat transfer coefficient; the combination of components consisting of different materials, which on the other side calls for an appropriate solution able to avoid critical thermo-mechanical stress under typical operation, and over the service life of the panels. One approach is to use materials for the heat exchanger exhibiting mechanical properties similar to those of glass as well as a suitable geometrical configuration. A second approach is to fix the heat exchanger to the PV module in a way that can tolerate and/or compensate the different thermo-mechanical behavior of the components. Commercially available products adopt for the heat exchanger materials (copper, aluminum, steel and plastics) and assemblies (sheet-and-tube, roll-bond, etc.) common in solar thermal collectors as well as customized designs (s. Figure 7). For the fixing, mechanical or adhesive solutions are used (Brotje et al., 2016).

Fig. 7: Examples of heat exchangers used in commercially available uncovered PVT-panels (sources from left to right: Fototherm, AnafSolar, DualSun, Poly Solar Solutions, CGA Technologies)

3. Experimental investigations

Our investigations focused on the thermal performance of different photovoltaic-thermal glass-glass modules. This section presents the selected assemblies as well as the details of the efficiency measurements.

3.1. PVT-panel design

The prototype panels were manufactured on the basis of commercially available components. Figure 8 gives an overview of the design selected for our investigations. Additional technical data are reported in Table 1.

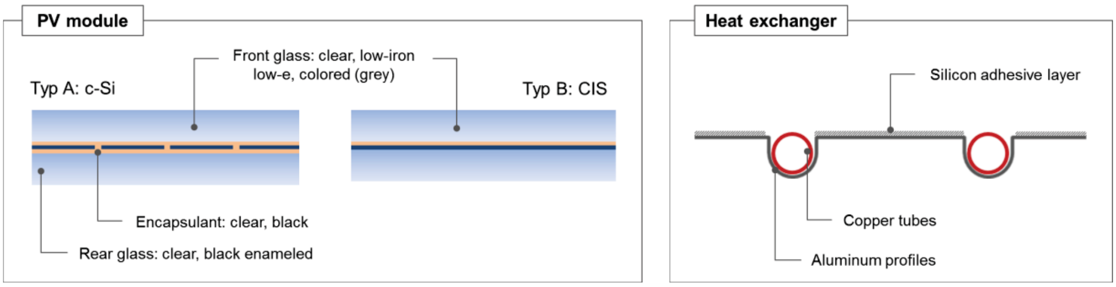

Fig. 8: Design of the investigated PVT panels

As solar cell technologies wafer-based crystalline silicon and thin film CIS were implemented. For the heat exchanger we chose a composite construction consisting of copper tubes with a serpentine geometry and aluminum omega-profiles, which enclose the tubes and are glued to the rear glass cover with a temperature resistant, two-component silicon adhesive layer (thickness about 0.8 mm; thermal conductivity λ = 0.3 W/m·K). This heat exchanger is produced by the German company Schmoele for heating and cooling panels as well as for solar absorbers of flat plate collectors. It enables an efficient and uniform heat transfer from the glass pane to the fluid and can compensate the thermo-mechanical stress originated by the different thermal expansion coefficients of glass ($\alpha = 9 \cdot 10^{-6}\ K^{-1}$) and aluminum ($\alpha = 23 \cdot 10^{-6}\ K^{-1}$) or copper ($\alpha = 17 \cdot 10^{-6}\ K^{-1}$) more effectively than other common solutions. The long-term durability of the fixing over the expected operating temperature range has been successfully proved at ISFH both by accelerated weathering laboratory tests on small samples (Seitz M., 2015) and by outdoor exposition tests on large-sized prototypes.

Tab. 1: Selected technical data of the investigated PVT panels

Module type	Area [m²]	Nominal power [W]	Packaging factor [-]	Coeff. γ [%/K]	Area HTX / Area glass	Distance tubes [mm]
c-Si	1.26	171 ÷ 175	0.71	-0.45	0.86	0.95

CIS	0.84	91 ÷ 94	-	-0.39	0.81	0.85

To analyze the impact of the front cover glass on the thermal performance of the PVT-panels four different panes were taken into consideration. Beside common clear glass typically used in architecture and glass with low iron content, two functional glasses with high solar transmittance specially developed for solar applications and already mentioned in Section 3 were selected: a colored (grey) glass intended for building integration and a low emissivity glass for improved thermal performance. Both coatings are deposited on a substrate with low iron content. The correspondent optical properties calculated according to ISO 9050 (solar spectral range) and EN 12898 (infrared spectral range) are reported in Table 2. The data of the clear and the grey glass were supplied by the manufacturers, the low iron and low-e glass were measured at ISFH by using the equipment already mentioned in Section 2.1 and a commercial Fourier transform infrared spectrometer.

Tab. 2: Relevant optical properties of the investigated front glass covers

Cover type	Solar transmittance τ	Solar absorptance α	Thermal emittance ε
Clear glass	0.85 ± 0.01	0.07 ± 0.01	0.84 ± 0.02
Low-iron glass	0.90 ± 0.01	0.02 ± 0.01	0.84 ± 0.02
Grey glass	0.88 ± 0.01	-	0.84 ± 0.02
Low-e glass	0.86 ± 0.01	0.07 ± 0.01	0.30 ± 0.02

For the PVT-modules with crystalline silicon cells, we further investigate two alternative solutions for the standard combination clear glass + clear encapsulant, with the purpose to effectively mask the portion of the heat exchanger visible through the cell interspaces, thus providing for a more homogeneous appearance, and to increase the solar absorptance of the panel. In the first case we use an opaque black enameled glass (color RAL 9005), with the enamel layer facing the heat exchanger. In the second case, the PV module was laminated with a multilayer encapsulant consisting of a black fluoropolymer backsheet embedded between two transparent EVA films. Spectrometric measurements on the two modules report very similar results, which exclude a possible different optical impact of the films on the thermal efficiency of the PVT panels.

3.3 Performance measurements

The performance of the PVT panels was investigated by means of indoor and outdoor measurements according to ISO 9806, both in open circuit (OC) and with the PV modules operating in maximum power point (MPP). As the panels are intended for the integration into ventilated glass façades, additional measurements were carried out by closing the air cavity (40 mm) between the rear side of the test specimen and the mounting plate, which is otherwise open to allow free air circulation. The paper presents and discusses the results in OC mode, thus focusing on the impact of the design on the thermal efficiency of the panels.

For the eight prototypes, we report zero-loss efficiency values η_0 between 0.61 and 0.78 (0.58 and 0.76 if referred to the hemispherical irradiance G and not to the net irradiance G”, as displayed in Figure 9 and 10) as well as heat loss coefficients $b_{1.5m/s}$ (heat loss coefficients evaluated at a wind velocity w = 1.5 m/s) between 10.2 and 17.8 W/m²K. The correspondently calculated stagnation temperature (G = 1000 W/m²; ambient temperature = 30 °C; no wind) ranges between 84 °C and 126 °C. Compared to the performance of commercially available products (Brötje et al., 2016) or to previous research works, the results attest the potential of this reliable PVT assembly, in spite of the additional thermal resistance due to the rear glass pane and show at the same time the strong impact of the considered design options. Further performance improvements are technically feasible by optimizing the thickness of the silicon-based adhesive layer or by more efficiently coupling the heat exchanger to the PV module (larger contacted area of the aluminum profiles, smaller distance of the copper tubes). For a comprehensive assessment, also economic and long-term reliability aspects are to be taken into consideration. The influence of the single design options is displayed in Figure 9 and 10 and can be summed up as follows:

- Low-emissivity coating (Figure 9, left): in comparison to an identically assembled module equipped with common low-iron glass, the use of a low-emissivity front cover improves the heat loss coefficient $b_{1.5m/s}$ of the panel by 2.0 W/m²K. Thanks to the high solar transmittance of the coated pane and the better thermal insulation, also the conversion factor η_0 is positively affected by the replacement of the cover. With refer to the specific boundary conditions (sky temperature T_{sky}) improvements up to 0.04 (0.07 if referred to the hemispherical solar irradiance G and not to the net irradiance G) are reported.

- Colored cover (Figure 9, right): the influence of grey glass was investigated on PVT modules both with c-Si and CIS solar cells. The performance results remain slightly below our expectations: In combination with c-Si cells, for example, we measured a lower η_0 than that of the module equipped with clear glass ($\Delta\eta_0$ = - 0.01), despite the higher solar transmittance declared by the manufacturer ($\Delta\tau$ = 0.03). This special combination of interference coating and light-scattering finishing proves to be an effective solution to modify the appearance of thin film modules and adapt them to the specific building design. In case of wafer-based silicon modules, on the contrary, the masking effect is not as satisfactory and the solar cells are still clearly visible under the cover. The aesthetical results are of course restricted to the selected glass and not transferable to other colors.

- Rear cover glass (Figure 10, left): non-transparent rear glass or encapsulants were used in combination with c-Si solar cells to mask the metallic heat exchanger and to enhance the solar absorptance of the PV module. The best performance was achieved by the panel equipped with a black enameled pane. Due to the higher thermal resistance between the heat sources (solar cell and black absorbing layer) and the fluid, the use of a fluoropolymer backsheet embedded between two EVA films leads to a decrease of the conversion factor by 0.04. The significant difference results not only from the position of the absorbing layer and the number of the sheets, but also from the low packaging factor of the PV module (71.4%). By using a single black EVA film as rear encapsulant and increasing the packaging factor lower deviations are expected. As further advantage of enameled glass the easier and more reliable processing has to be mentioned, which doesn't differ from the standard lamination procedure.

- Rear ventilation of the panels (Figure 10, right): Convective heat losses at the rear side of the PVT modules confirm to have a significant impact on their thermal performance. By closing the air gap and suppressing the ventilation between the modules and the mounting panel, we report a well reproducible reduction of the heat loss coefficient $b_{1.5m/s}$ between 5.6 W/m²K and 5.7 W/m²K, which corresponds to an increase of the stagnation temperature by about 15 K.

- Cell technology: due to the different size of the c-Si and CIS PV modules and the correspondently different configuration and tube distance adopted for the heat exchanger (s. Table 1), the results are not directly comparable. Assuming identical size and configuration, similar zero-loss efficiencies are expected and the discrepancy will depend more on the solution used to mask the heat exchanger in the c-Si module and on the packaging factor than on the photovoltaic technology itself. The choice of the solar cells has a much more significant impact on the aesthetics than on the performance of the panels.

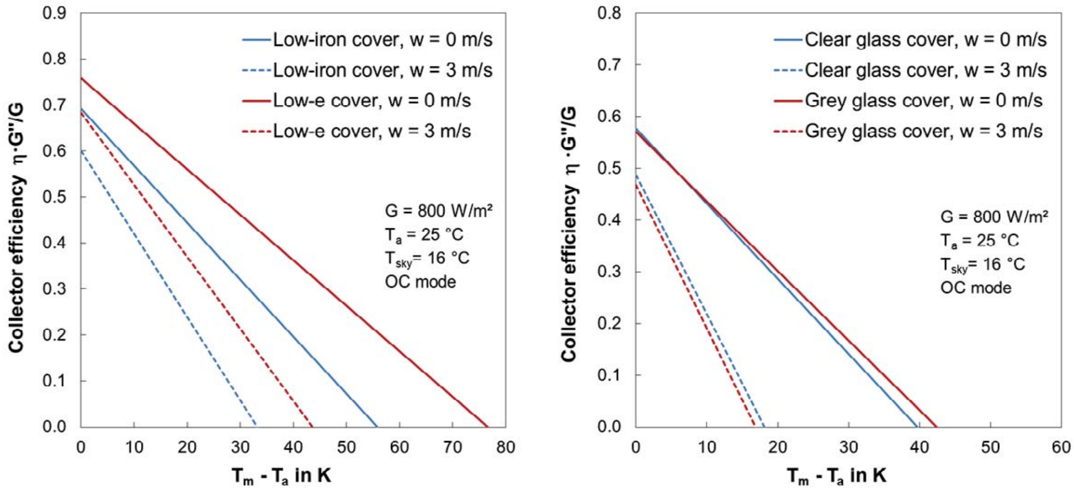

Fig. 9: Measured thermal efficiency of the investigated PVT panels. Left: comparison between prototypes with CIS PV modules featuring a low-iron and a low emissivity front glass cover (closed rear air cavity). Right: comparison

between prototypes with c-Si modules featuring a clear and a grey front glass cover (open rear air cavity). The results are displayed with refer to the hemispherical solar irradiance G and not to the net irradiance G".

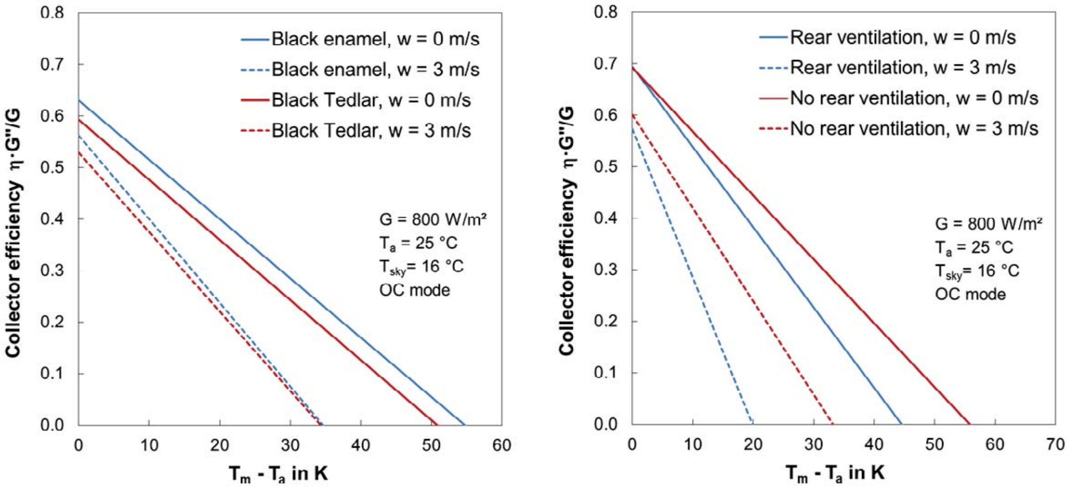

Fig. 10: Measured thermal efficiency of the investigated PVT panels. Left: comparison between prototypes with c-Si PV modules using a black enameled rear glass and a multilayer encapsulant embedding a black sheet to mask the heat exchanger (closed rear air cavity). Right: comparison between measurements on a prototype with a CIS PV module with and without ventilation of the rear air cavity. The results are displayed with refer to the hemispherical solar irradiance G and not to the net irradiance G".

4. Conclusion

Uncovered glass-glass PVT-modules offer a high design freedom by combining different types of solar cell technologies, front and rear cover glass as well as encapsulating sheets. We investigate the performance of 8 different modules by means of thermal efficiency measurements in open circuit mode. The results show the strong impact of the design options as well as the potential of this PVT assembly. We report conversion factors η_0 between 0.61 and 0.78 as well as heat loss coefficients $b_{1.5m/s}$ between 10.2 and 17.8 W/m²K. Considering both performance and aesthetics, the best results are achieved by combining a high transmittance low-emissivity front cover with a CIS thin film photovoltaic module.

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