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MAXIN

Pre-development of a solar energy module that converts the solar irradiation into heat and power with high efficiency due to a maximized (optimized) integration of the two technologies (solar collectors and PV) into one completely new designed product. (proof of concept)

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1 Project goals

PhotoVoltaic-Thermal (PVT) collectors combine photovoltaic and thermal conversion of the solar irradiation in a single device (for extensive reviews and entry points to the literature see e.g. Refs. [1] and [2]). Like pure thermal solar collectors, PVT collectors can be categorized in covered and uncovered types. Uncovered PVT-collectors resemble standard PV modules equipped with a heat exchanger on their rear side. This type of collector largely dominates the PVT market [3]. It is, however, suitable only for low-temperature applications like borehole regeneration or domestic hot water pre-heating. Covered PVT collectors are equipped with an additional transparent or translucent top layer that reduces convective thermal losses. They can efficiently provide heat at temperature levels typical for solar thermal flat plate collectors and hence be used in similar applications, like e.g. domestic hot water preparation and space heating.

The design of covered PVT collectors is much more challenging compared to uncovered collectors, which usually are simple extensions of standard PV modules. The main difficulty is related to the higher temperature levels and changes reigning in a covered collector, which impose considerably stronger requirements on the materials used. Further, aspects like optical efficiency and thermal absorber efficiency have to be optimised specifically for the case of combined heat and electricity production. The very few existing products do not present satisfactory solutions to these issues.

The present project aims at the development of a new design for a covered PVT collector, which from the beginning is guided by the requirements of the combined electrical and thermal energy harvesting, i.e. which neither is based on the design of a standard PV-module nor on the design of a standard thermal collector.

The design concept envisaged is illustrated in Figure 1. Bifacial BiSoN PV cells are glued directly onto a “Glasolo” absorber, which acts as the heat-carrier element (see Ref. [4]). The “Glasolo” absorber consists of two parallel glass sheets mounted together with a distance of about 1 mm. A heat transfer fluid is circulated through this 1 mm slit. Thus, the “Glasolo” absorber is a so called “fully wetted absorber”. As the thermal expansion coefficient of the glass used is very close to the one of the PV cells, and since the glass is a very good electrical insulator, the glue layer between cells and glass can be extremely thin, which saves costs and reduces the heat resistance between the cells, where most of the heat is generated, and the heat carrier liquid. Additionally, the NIR irradiation that cannot be converted into electrical power and is transmitted through the bifacial cells can be absorbed by the heat carrier liquid itself, which will additionally increase the overall efficiency. A glass cover will be placed with a distance of about 1 cm above the cells, forming an insulating air-gap. The air-gap will be sealed technology known from the manufacturing of insulating glass units (IGU).

The aim of the present project is to analyse the feasibility of the new concept. Materials for the different collector components are selected and characterized. A functional prototype of the covered PVT collector is built, and its electrical and thermal performance is measured.

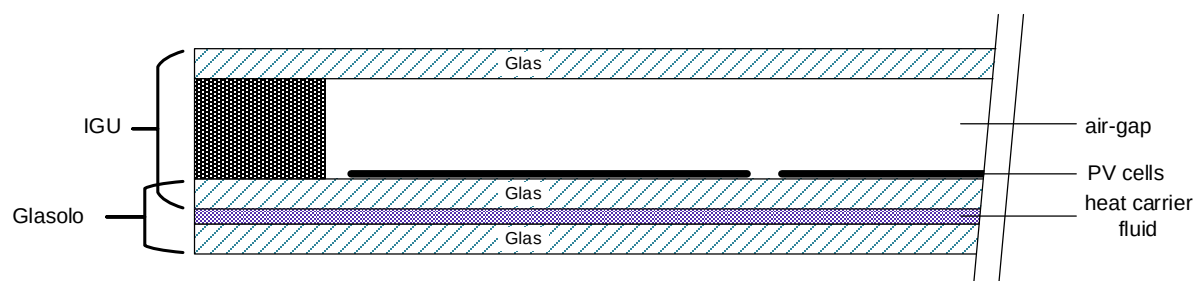


Figure 1: Schematic of the covered PVT collector being developed in the project.

2 Completed tasks and achieved results

2.1 Optical characterisation of the materials and design of PVT collector (WP 1 & 4)

As a basis for the optimization of the collector design, the optical properties of the involved materials and of the assembly were characterized. The optimization target is a maximal absorption of the solar irradiation.

Different samples of cells laminated to the glass substrate were produced (cf. Figure 2 and Figure 3). Sample Mod 0 consists of the cell laminated to the 3 mm glass substrate by means of a 0.5 mm EVA layer. The top surface of the cell, which would be in contact with the air gap of the collector, is unprotected. In sample Mod 1, the assembly is covered with an additional EVA layer. Samples Mod 2 and Mod 3 are in addition endowed with an ETFE or FEP layer on top.

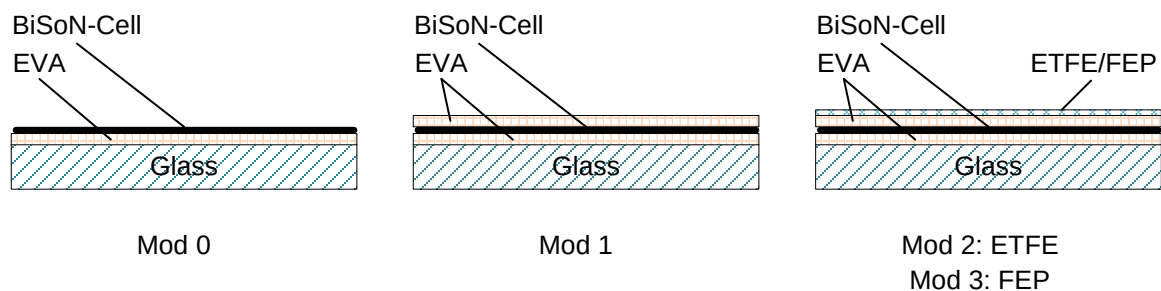


Figure 2: Schematic representation of the different cell-glass-laminates



Figure 3: Example of a cell-glass-laminate sample

The transparent layers put on top of the cell can protect it from direct contact with the air gap. Whether such a protection is needed, will depend on the final design of the collector. If the IGU part is hermetically sealed, protection will not be necessary. If the IGU is realized such that humidity can be exchanged between the air-gap and the environment, protective layers might be needed. However, apart from their role of protecting the cell, the transparent layers put on top of it also have an influence on the optical properties of the assembly. For instance, in some spectral regions, they can reduce reflection losses via a better matching of refractive indices.

The wavelength-dependent reflection $\rho(\lambda)$ and transmission $\tau(\lambda)$ of the different samples were measured and the corresponding absorption $\alpha(\lambda)$ was computed as $\alpha = 1 - \rho - \tau$. Results are shown in Figure 4.

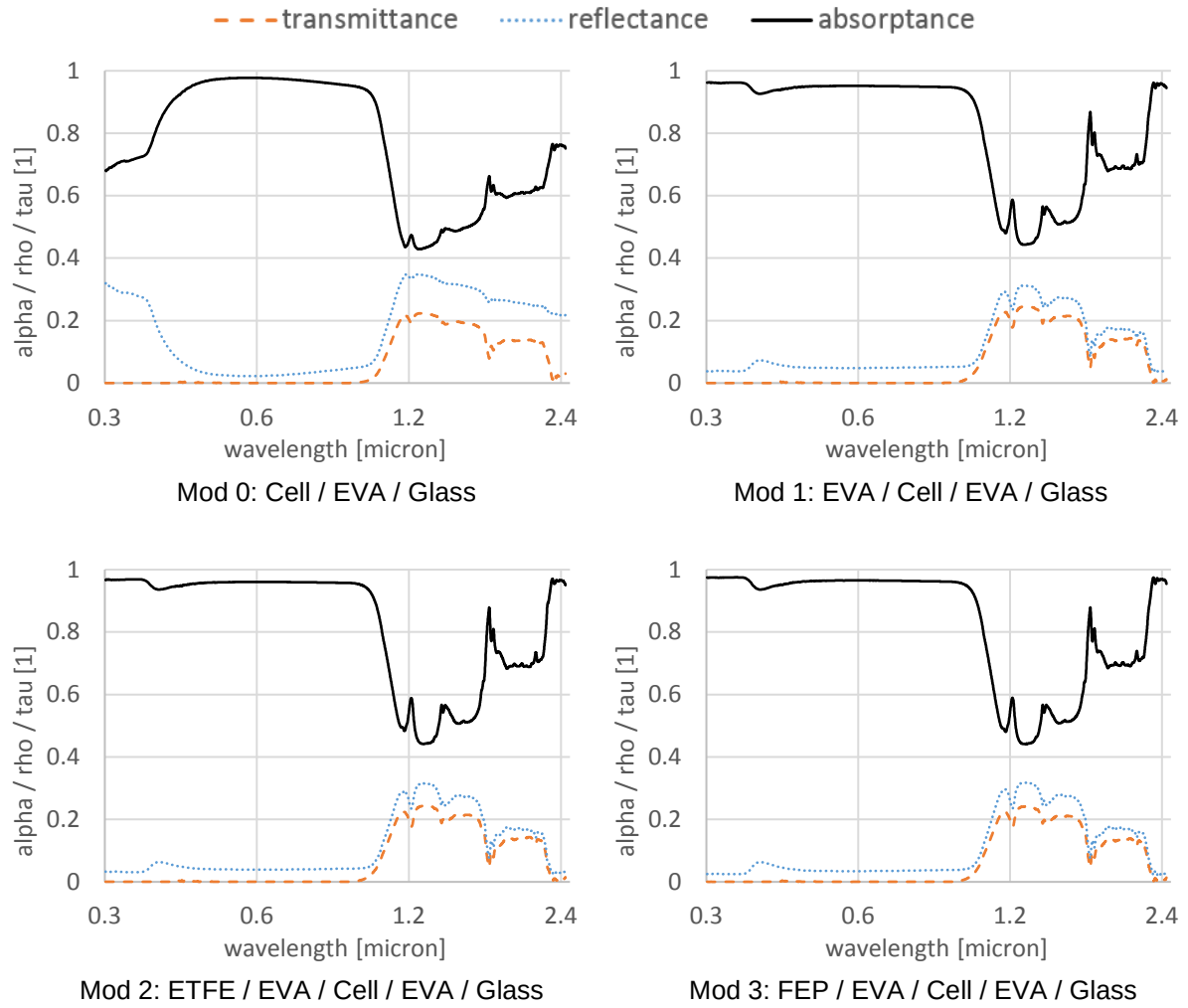


Figure 4: Transmission, reflection and absorption spectra measured for the different laminates

For the determination of the optical efficiency of the complete collector assembly, also the optical properties of the front glass and of the Glasolo unit were measured. The corresponding spectra are shown in Figure 5. The Glasolo unit consisted of a cuvette made of two parallel glass plates with a 1 mm space in between. The channel between the plates was filled once with water and once with a water/antifreeze-mixture (Tyfocor), as commonly used in thermal collectors. The glass used for both the front cover and the Glasolo unit (the front glass of which will finally be the substrate of the PV cells) was 3 mm low-iron glass.

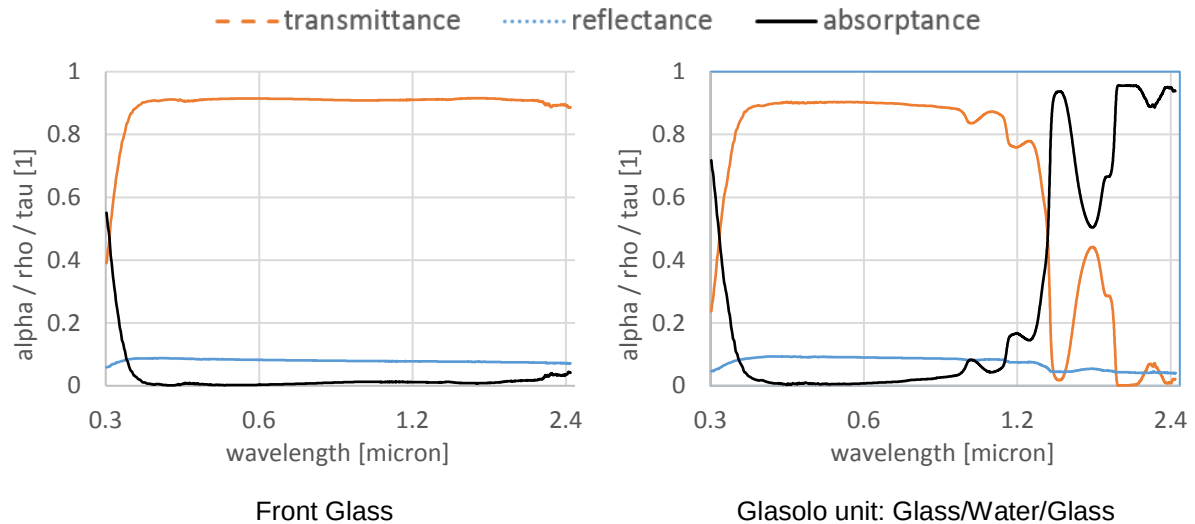


Figure 5: Transmission, reflection and absorption of the cover glass and of the Glasolo unit

The transmission-absorption product of the collector assembly can be approximated by the following first order formula

$$(\tau\alpha)_{collector} = \tau_{front\ glass} \cdot (\alpha_{Mod} + \tau_{Mod} \cdot \alpha_{Glasolo}^{corr}),$$

where $\tau_{front\ glass}$ is the transmission of the front glass (collector cover), and α_{Mod} and τ_{Mod} are the absorption and transmission of the cell-glass-laminate. $\alpha_{Glasolo}^{corr}$ is the absorption of the Glasolo unit filled with either water or water/Tyfocor and computed as $\alpha_{Glasolo}^{corr} = 1 - \tau_{Glasolo} - (\rho_{Glasolo} - \rho_{glass}/2)$, i.e. corrected for the reflections that occur at the first interface between air and glass when the Glasolo unit is measured independently, but do not occur in the complete collector assembly. The transmission-absorption product for collectors built with different laminates and water as heat carrier fluid is shown in Figure 6 together with the spectral distribution of the solar irradiance (Air Mass 1.5) and the spectral response of a crystalline silicon PV-cell.

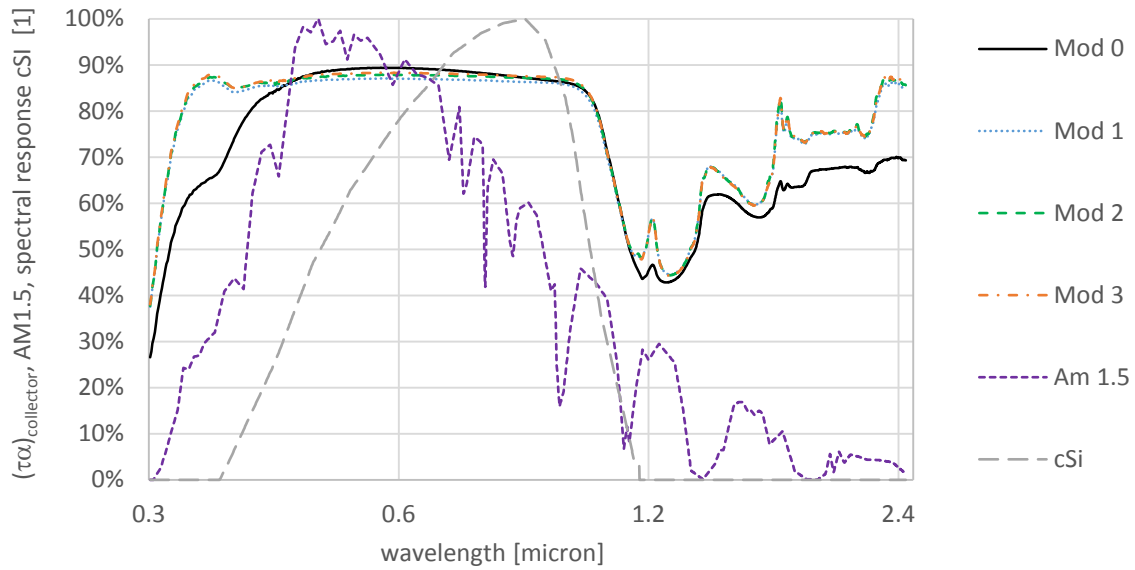


Figure 6: Plots of the transmission-absorption products for a collector built with different laminates as well as of the solar spectrum AM1.5 and the spectral response of a crystalline silicon PV-cell.

The relevant quantity characterizing the optical efficiency of the PVT collector is the transmission-absorption product weighted with the solar spectrum

$$(TA)_{collector} = \frac{\int (\tau\alpha)_{collector}(\lambda) \cdot AM1.5(\lambda) d\lambda}{\int AM1.5(\lambda) d\lambda}.$$

$(TA)_{collector}$ can be understood as the efficiency of the collector for the absorption of the solar irradiance, irrespective of whether the absorption takes place in the cell or in the Glasolo unit, and irrespective of whether it can potentially be converted to electricity or not. The fraction that is not converted to electricity will be converted to heat.

Further, it is interesting to also compute the absorption of the PV laminate only, weighted with the distribution of the solar spectrum and with the spectral response of the crystalline silicon cell

$$A_{Mod}^{PV} = \frac{\int \alpha_{Mod}(\lambda) \cdot AM1.5(\lambda) \cdot cSi(\lambda) d\lambda}{\int AM1.5(\lambda) \cdot cSi(\lambda) d\lambda}.$$

The quantity A_{Mod}^{PV} is the efficiency of the laminate for the absorption of the solar irradiance that can be converted to electricity. For a pure PV module, A_{Mod}^{PV} needs to be optimized. In the case of a PVT collector, generally a high value of $(TA)_{collector}$ will be targeted, since in this case also photons that cannot create an electrical current can create useful energy in the form of heat.

The figures resulting for the different variants are presented in Table 1. The results in Table 1 were obtained for a Glasolo unit filled with water. For the case of a mixture of water with Tyfocor L (50 %), the results are practically the same (differences are of the order of 0.1 %).

Laminate variant	Layer structure	A_{Mod}^{PV} [%]	$(TA)_{collector}$ [%]
Mod 0	Cell/EVA/Glass	96.0	80.1
Mod 1	EVA/Cell/EVA/Glass	94.3	80.7
Mod 2	ETFE/EVA/Cell/EVA/Glass	95.3	81.5
Mod 3	FEP/EVA/Cell/EVA/Glass	95.7	81.7

Table 1: Weighted absorption values of the different laminates and of the complete collector.

The EVA layer put on top of the cell slightly increases the reflections in the spectral range where the cell has a high sensitivity. As a consequence, Mod 1 has a lower value of A_{Mod}^{PV} compared to Mod 0. However, the absorption of the laminate at short wavelength (below ~ 0.4 microns) and long wavelengths (above ~ 1.2 microns) is higher, which overcompensates the effect of the increased reflection and finally results in higher value of $(TA)_{collector}$ thanks to the EVA layer. The addition of an ETFE or FEP layer, both having refractive indices that are better matched to the one of air than is the case for EVA, bring the reflections in the PV relevant spectral region slightly down. This results in Mod 2 and Mod 3 having higher values of A_{Mod}^{PV} , in the case of Mod 3 very close to the value of Mod 0, and correspondingly higher values of $(TA)_{collector}$.

Judging by the optical efficiency of the collector, the variant with laminate Mod 3, where the cell is covered by an EVA layer plus a layer of FEP, appears to be the most favourable. As these layers at the same time protect the cell from direct contact with the environment, they provide a double advantage. The disadvantage, of course, might be higher material and production costs. As the differences in optical efficiencies are small, we consider that at the present moment none of the variants need to be excluded. It has to be mentioned here that ultimately EVA will be replaced by a more temperature-stable encapsulant (cf. next section). This will again entail slight changes of the optical performance of the assembly.

2.2 Evaluation of an appropriate adhesive system for gluing the pv cells onto the glass substrate (WP 3)

Since the inside of the covered PVT-collector is going to reach high temperatures $\geq 150^\circ\text{C}$, an important aspect is to define, which type of encapsulant can be used for this application. The selected encapsulant should be stable at such high temperatures, i.e. it should not melt, change colour or change transparency in the UV-VIS-IR spectrum.

The tested encapsulants were of the following types: Ethylene Vinyl Acetate (EVA), Polyolefin (PO), Thermoplastic Polyurethane (TPU) and Silicone. The following encapsulant products were laminated on a 5cm x 5cm glass and tested in an oven at around 190°C in order to evaluate their resistivity to high temperature:

- Bridgestone S88 (EVA) – commercial
- Mitsui (PO) – commercial
- STR 3550P/PL (PO) – commercial
- DNP CVF 2559 (PO) – commercial
- MN72 R9 (PO) – CSEM made
- MN37 R5 (PO) – CSEM made
- MA17 (PO) – CSEM made
- DNP CVF 1509N4 (PO) – commercial
- Hangzhou F806 (EVA) – commercial
- TPO 10 Parts (PO) – CSEM made
- Momentive SilTRUST E110 (Silicone) – commercial
- Argotec ST-6050 (TPU) – commercial

Spectral transmission measurements for wavelengths between 250 nm and 2000 nm were performed before and after aging of the samples in the oven. The majority of the polymers failed the test after only 20 hours. This is the case, for instance, for the Bridgestone S88 EVA (Figure 7).

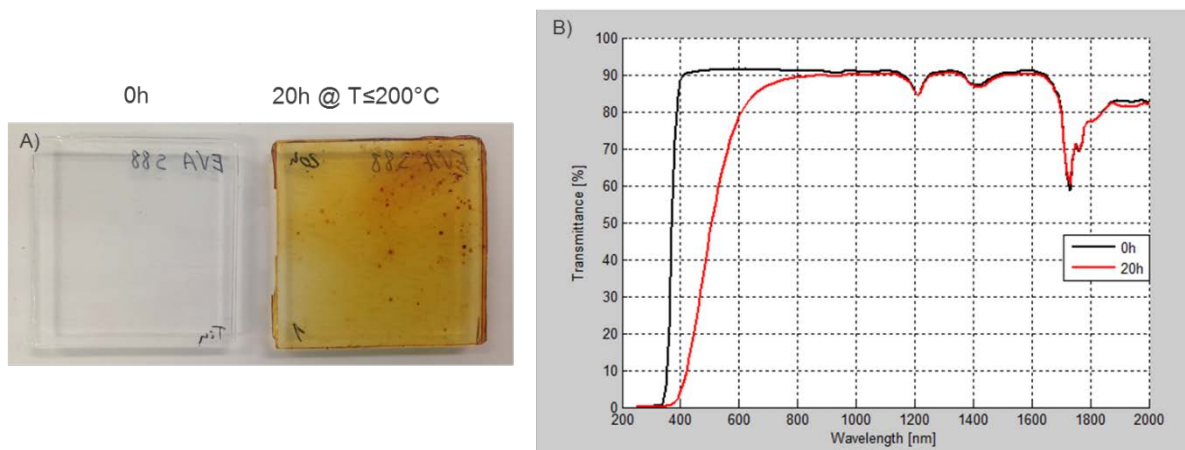


Figure 7: Degradation of encapsulant Bridgestone S88 (EVA) after 20h at 190°C. A) Pictures before and after temperature exposure, B) Transmission before and after temperature exposure

Most of the samples tested turned yellow (due to thermal degradation) or melted after less than one day in the oven. Others, like polyolefin MN72 R9 or TPO 10 Parts showed better resistance, as shown in Figure 8 and Figure 9, respectively. However, the degradation is still too severe for them to be considered as viable encapsulants. The only polymer that resists and is stable to such temperatures is the silicone, as shown in Figure 10.

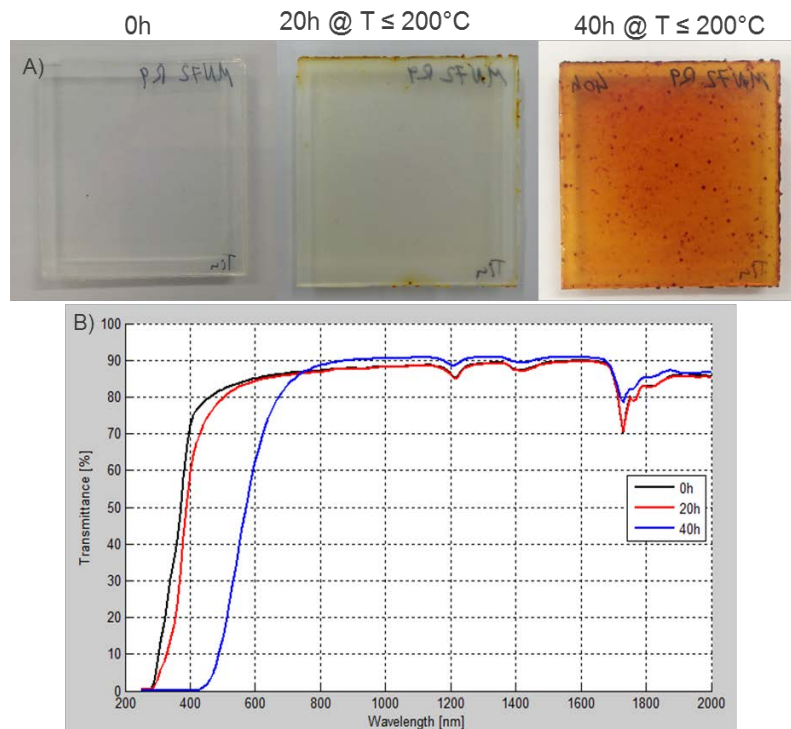


Figure 8: Degradation of encapsulant MN72 R9 (Polyolefin) after 20h at 190°C. A) Pictures before and after the test, B) Spectrometer measurement before and after the test

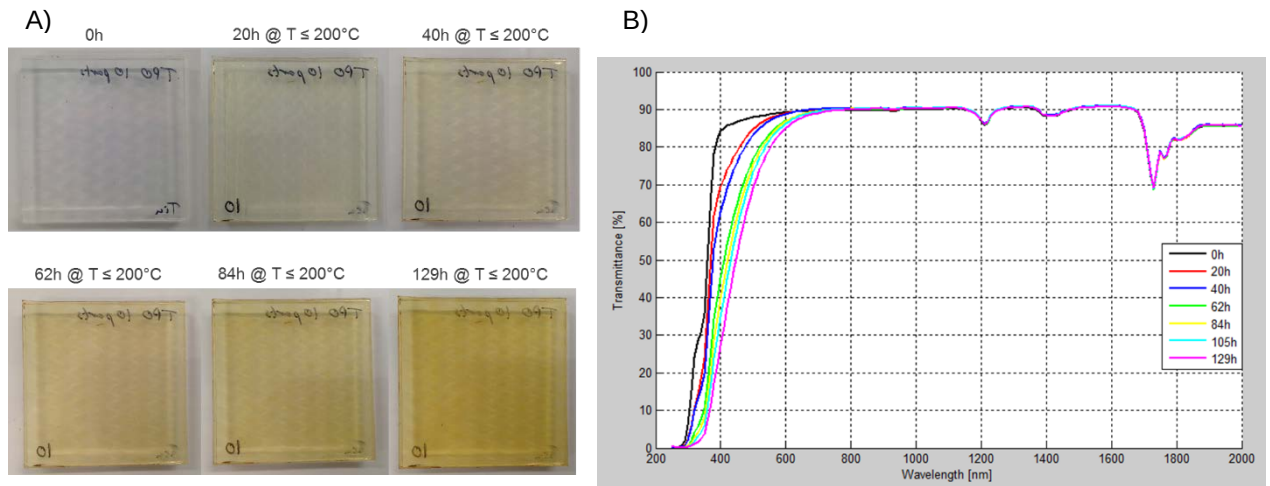


Figure 9: Degradation of encapsulant TPO 10 Parts (Polyolefin). A) Color degradation, B) Transmittance degradation

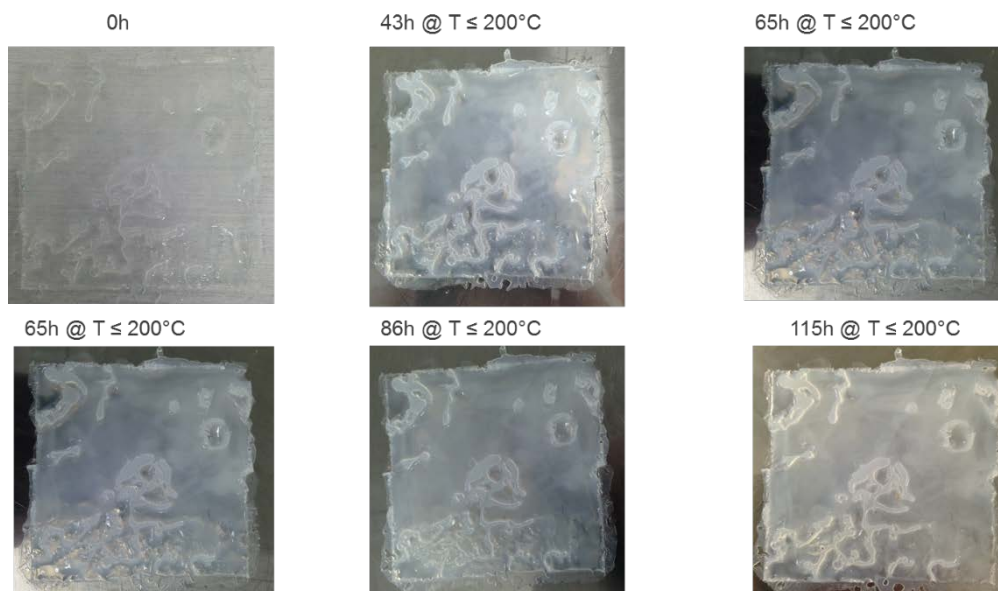


Figure 10: Evolution of the silicone encapsulant after more than 100 hours at 190°C. No degradation is observed

The temperatures applied in the tests were chosen to be higher than the temperatures occurring in a covered PVT collector, in order to obtain a first qualitative assessment of encapsulants. A more detailed study of activation energies of the different degradation modes of the different encapsulant materials would be needed, in order to deduce quantitative conclusions about the durability of encapsulants exposed to a realistic temperature stress profile.

2.3 Full-scale prototype (WPs 5-8)

2.3.1 Construction

A complete prototype with the dimensions $1\text{ m} \times 1.2\text{ m} = 1.2\text{ m}^2$, an aperture size of $0.96\text{ m} \times 1.15\text{ m} = 1.1\text{ m}^2$ and 42 BiSoN PV cells ($15.6\text{ cm} \times 15.6\text{ cm}$ each) was built. The design is shown in Figure 11. All three glass layers were made of low-iron glass of 3 mm thickness.

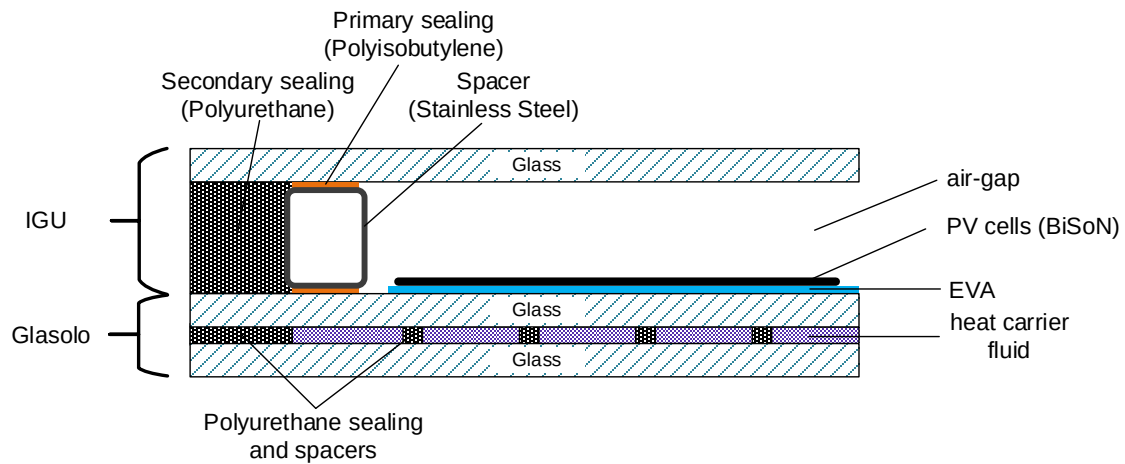
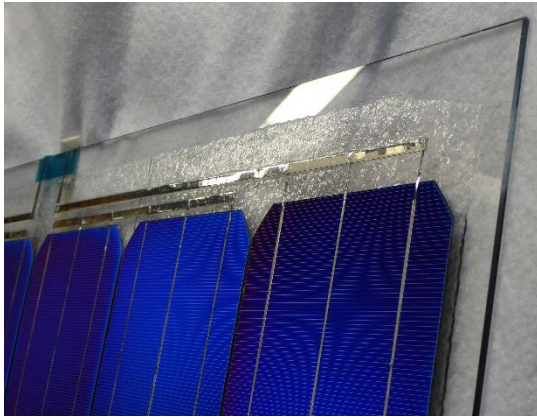


Figure 11: Schematic of the full-scale prototype

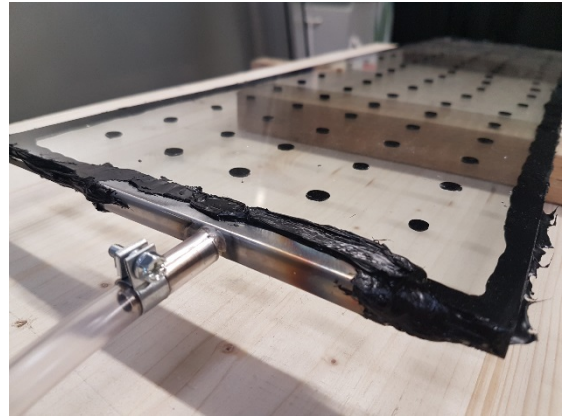
The manufacturing proceeded in the following steps (cf. Figure 12):

- 1) The cells were connected and laminated onto the glass substrate. For this prototype, a standard EVA product (Bridgestone EVASKY) was used as encapsulant, the EVA film being much easier to handle manually than the silicone encapsulant. No additional protective layer was put on the PV cells (laminate of type Mod 0).
- 2) The Glasolo unit was built by connecting the PV unit with an additional glass pane. Both, edge sealings and spacers were made by the use of a Polyurethane adhesive (Sikaflex 265). In order to obtain a well-defined gap thickness, glass beads of 1 mm diameter were integrated in the adhesive. The width of the edge sealings was 2 cm. The spacers with a diameter of $\sim 0.8\text{ cm}$ were distributed evenly with a distance of 4 cm between neighbouring spacers. This solution for constructing the Glasolo part was chosen, because it allowed to manually fabricate a functional prototype. It is not a solution that could be used in a final product, since the PU adhesive is not resistant to high temperature ($> 90\text{ }^{\circ}\text{C}$) and humidity stress in the long term. Hydraulic connectors made of stainless steel were attached at diagonally opposite corners.
- 3) For the insulating glass unit (IGU), commercial stainless steel spacers obtained from Glas Trösch, of 7 mm width, 12 mm height and 0.2 mm material thickness were used. The desiccant filling was removed from the spacers. The primary sealing, mainly responsible for the gas-tightness was made with a Polyisobutylene (PIB) tape ($\sim 1\text{ mm}$ thickness). For the secondary sealing, mainly responsible for the mechanical stability, the Polyurethane adhesive was used. The width of the secondary sealing was around 23 mm on the edge with the electric connection cables and 13 mm on all other edges. The height of the air gap between cells and front glass was around 14 mm, slightly above the optimum for the minimisation of convective heat losses. Four additional spacers were distributed evenly over the module area in order to stabilise the front glass (Figure 12 d). At the position where the electrical connection cables had to be guided through the edge seal, an additional layer of PIB tape was applied, in order to avoid contact with the metal spacer. This insulation later turned out to be insufficient. In fact, electrical measurements of the complete collector indicated that the module was short-circuited. And, presumably, this short circuit is due to a contact of the wires with the steel frame.

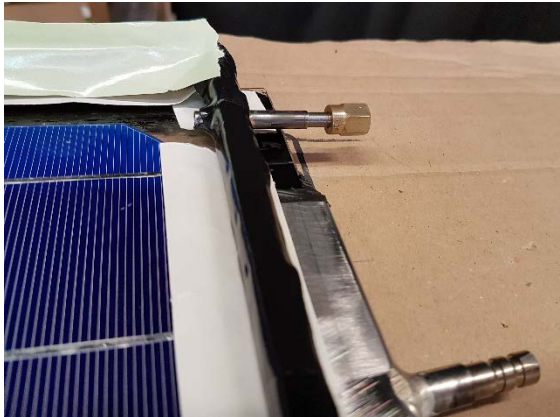
a)



b)



c)



d)



Figure 12: Manufacturing details of the full-scale prototype. a) Cells electrically connected and laminated on glass; b) Glasolo unit (the picture shows a preliminary sample of smaller size and without cells, made in order to test the feasibility); c) Assembly before putting the front glass. The picture shows the stainless steel spacers endowed with PIB tape, the hydraulic connector (bottom right corner) and the pneumatic connector. d) Spacer in the air gap between cell plane and front glass.

2.3.2 Electrical and thermal performance

Before assembling the complete PVT collector, the electrical performance of the PV unit was measured. Figure 13 shows the current voltage characteristics and an electroluminescence image is shown in Figure 14. The electrical performance at standard testing conditions (STC) is 176.6 ± 5.3 W, corresponding to an electrical efficiency of 14.7 % related to the gross collector surface area and 16 % related to the aperture area. The performance is slightly suboptimal, due to a number of cells with defects that lead to a lower short circuit current. In particular, the cell in the top left corner of Figure 14 lead to a strong hot spot in later exposure tests with the module short-circuited. The non-optimal electrical performance of the module is not a mayor concern for the development of the PVT collector, as this problem can in principal be solved by only using intact and well-matched cells. Still, the possible occurrence of hot spots, which in practice cannot be excluded, may impose stronger requirements on the temperature resistance of materials used in a covered PVT collector. After addition of a front glass with a transmittance of 91 %, the electrical performance of the collector will reduce to 13.4 % related to the gross area and 14.6 % related to the aperture area.

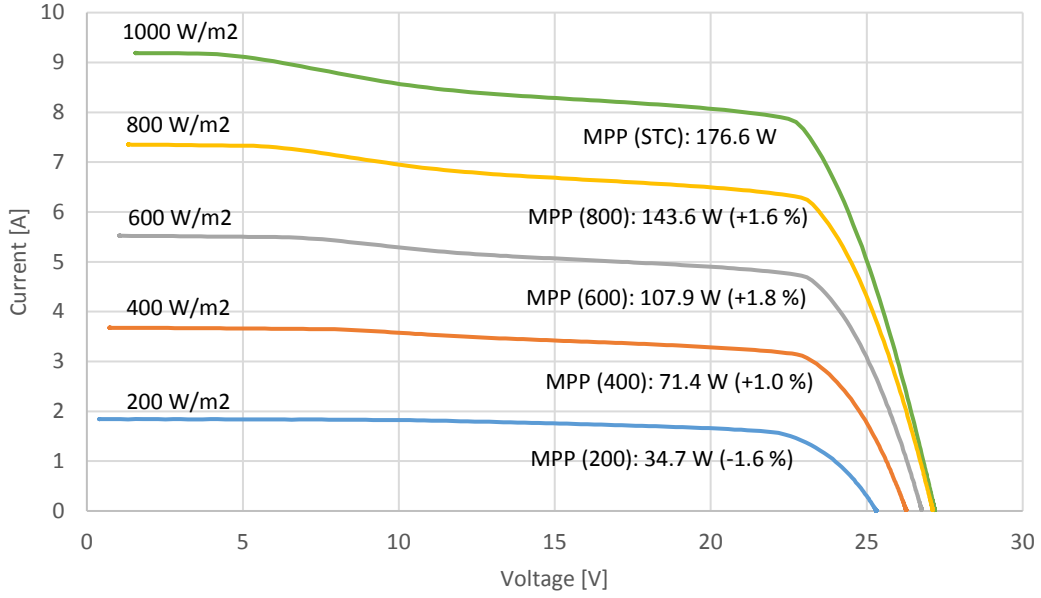


Figure 13: Current-Voltage characteristics of the PV unit (without front glass) for different irradiation levels. The percentage numbers indicate the deviation from the value obtained by scaling down the STC power with the irradiation.



Figure 14: Electroluminescence image of the PV unit

The thermal performance of the prototype was measured in the indoor solar simulator (Figure 15). During the measurements, the PV unit was in the short circuit mode (cf. Section 2.3.1), which, regarding the thermal performance, should be equivalent to the open circuit mode. The collector was placed on insulation material, 2 cm of mineral wool plus 3 cm of expanded polystyrene, and mounted with an inclination angle of 45°. According to ISO 12975, the thermal efficiency is expressed as

$$\frac{\dot{Q}}{G \cdot A} = \eta = \eta_0 - a_1 \frac{T_m - T_a}{G} - a_2 \cdot G \cdot \left(\frac{T_m - T_a}{G} \right)^2,$$

with the thermal power $\dot{Q}$, the irradiation G , the reference area A , the mean fluid temperature T_m and the ambient temperature T_a . The parameters η_0 , a_1 and a_2 are obtained by fitting the curves to the measurement data.

Measurements were done for conditions without wind and for wind speed of 3 m/s. The obtained performance coefficients and extrapolated stagnation temperatures are listed in Table 2. The corresponding efficiency curves are shown in Figure 16. In addition to the curves obtained from the measurements in the short circuit mode, curves were computed for the case with the collector operated in the MPP mode. This was done by replacing η_0 by $\eta_0 \cdot (1 - \eta_{el}/(TA)_{collector})$, where the electrical efficiency was set to $\eta_{el} = 14.6 \% \cdot (1 - \gamma_{MPP} \cdot (T_m - 25^\circ\text{C}))$ with the temperature coefficient $\gamma_{MPP} = 0.0038/\text{K}$.

Table 2: Thermal performance coefficients related to the aperture area and stagnation temperatures of the full-scale prototype.

	Short circuit (measured)		MPP (calculated)	
	No wind	Wind 3 m/s	No wind	Wind 3 m/s
η_0	0.82	0.79	0.67	0.65
a_1 [W/(m ² K)]	5.4	6.4	4.8	5.9
a_2 [W/(m ² K ²)]	0.017	0.025	0.017	0.025
T_{stagn} [°C] ($T_a=30^\circ\text{C}$, $G=1000$ W/m ²)	142	121	132	112



Figure 15: Full-scale PVT prototype mounted in indoor solar simulator.

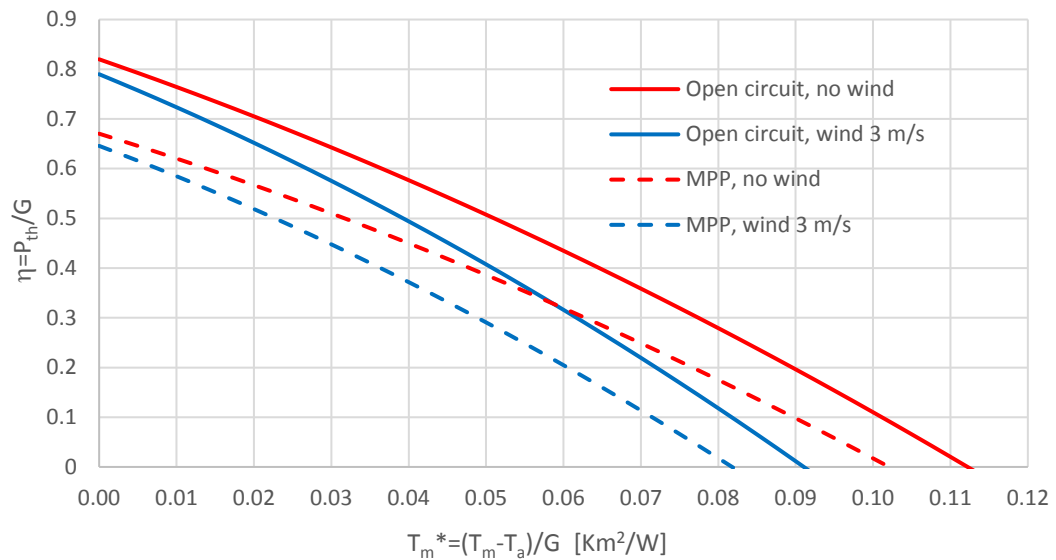


Figure 16: Thermal efficiency curves (related to the aperture area) for an irradiance of 1000 W/m², with and without wind, in open circuit mode (based on measurement) and in MPP mode (calculated extrapolating from open circuit curves).

The thermal performance of the prototype in the short circuit mode is comparable to the performance of a thermal flat plate collector with a non-spectrally-selective absorber. It has a considerably higher η_0 -value compared to commercially available covered PVT collectors (with η_0 typically around 0.7), which is in particular due to the low thermal resistance between the cells and the heat carrier fluid. Prototypes of covered PVT collectors with similar η_0 -values have been constructed in a research project of Fraunhofer ISE (see Ref. [5]), where cells were directly laminated on a metal absorber. Ultimately, the goal of the development should be to reach a thermal efficiency in the range of good flat plate collectors, which have similar η_0 -values, but considerably lower heat loss coefficients (typical values would be $a_1=3.8 \text{ W}/(\text{m}^2\text{K})$ and $a_2=0.009 \text{ W}/(\text{m}^2\text{K}^2)$ at a wind speed of 3 m/s, see e.g. Ref. [6]). To this aim, several improvements of the design can be envisaged in future developments:

1) Improvement of the spectral selectivity of the absorber

The absorber with BiSoN PV cells without protective cover has an emissivity around 70 %. A solution should be found for reducing the emissivity of the absorber by a low-e coating and thereby reducing the radiative heat losses of the collector.

2) Antireflective coatings on front glass

In the case of the prototype the front glass didn't have an AR coating. Such a coating would allow to increase the transmission-absorption-product and hence the optical efficiency η_0 by around 2 % or 4 % if applied to one or both sides of the glass respectively.

3) Noble gas filling between absorber and front glass

The design of the prototype, with an insulating glass unit on the front side, would be particularly suited for replacing air by a noble gas between absorber and front glass. This would allow to reduce the convective heat transfer between the absorber and the front glass. This would mainly make sense in combination with a low-e coating, since in that case the convective heat transfer becomes more important compared to the radiative heat transfer.

The stagnation temperature of the prototype at conditions without wind, $T_a = 30 \text{ }^\circ\text{C}$ and $G = 1000 \text{ W}/\text{m}^2$ was calculated to be $142 \text{ }^\circ\text{C}$. Hence, already without improvements of the design, the stagnation temperature lies in the range of the lamination temperature used for EVA. This indicates that standard EVA materials clearly are no option for a final product that is not endowed with a stagnation prevention mechanism.

2.3.3 Exposure Testing

After performance testing, the prototype was mounted outdoor with an inclination angle of 45° , oriented south, without back-side insulation and without connection to a hydraulic loop (see Figure 17). The PU adhesive was protected from UV radiation by adding aluminium tape at the edges of the collector. A temperature sensor was placed at the top right corner of the air gap between cells and front glass. The exposure has lasted for 3.5 months, from mid-August to end of November. The goal was to gain first indications about its resistance to outdoor conditions.

On hot summer days, the temperature in the air gap rises to around $75 \text{ }^\circ\text{C}$ (a typical daily profile is shown in Figure 18). The temperature changes in the air gap induce pressure and volume changes that are considerably higher than in standard insulating glass units. At high temperatures a bulging of the front glass of estimated 2 mm could be observed. The strong temperature changes in the air gap will have to be considered for a future design of a collector. One will have to make sure that the edge sealing can support the associated stress, or opt for a design that is not air-tight.

With the help of thermography of the rear side of the collector (Figure 17 b), several hot spots were identified in the module. As mentioned above, the module was short-circuited due to insufficient insulation between cables and stainless steel frame, for which reason current could flow through the cells. Some of the cells that apparently had a considerably lower short-circuit current operated as resistances and hence showed much higher temperatures. The most serious hot spot is in the top right corner. This cell corresponds to the cell in the top left corner of Figure 14. The temperatures of the rear glass were measured on a summer day (18.8.2017) at 13:35 h (MEZ). In the lower part, temperatures were around $50 \text{ }^\circ\text{C}$, in the central part around $55 \text{ }^\circ\text{C}$ and in top part around $70 \text{ }^\circ\text{C}$. In the region of the mentioned hot

spot, the temperature was 105 °C. As a consequence of the frequently occurring high temperatures, the grid fingers on the front of this and the neighbouring cell loosened (Figure 17 c). The possibility of failure modes that lead to hot spots should be considered in the future design of the PVT collector, as this may impose yet stronger requirements on the materials.

In the relatively short time period of exposure no degradation of the EVA or other signs of degradation of the materials could be observed. It has to be mentioned, however, that the rear side of the collector was not insulated and hence stagnation temperatures were lower than the values indicated in the previous section.

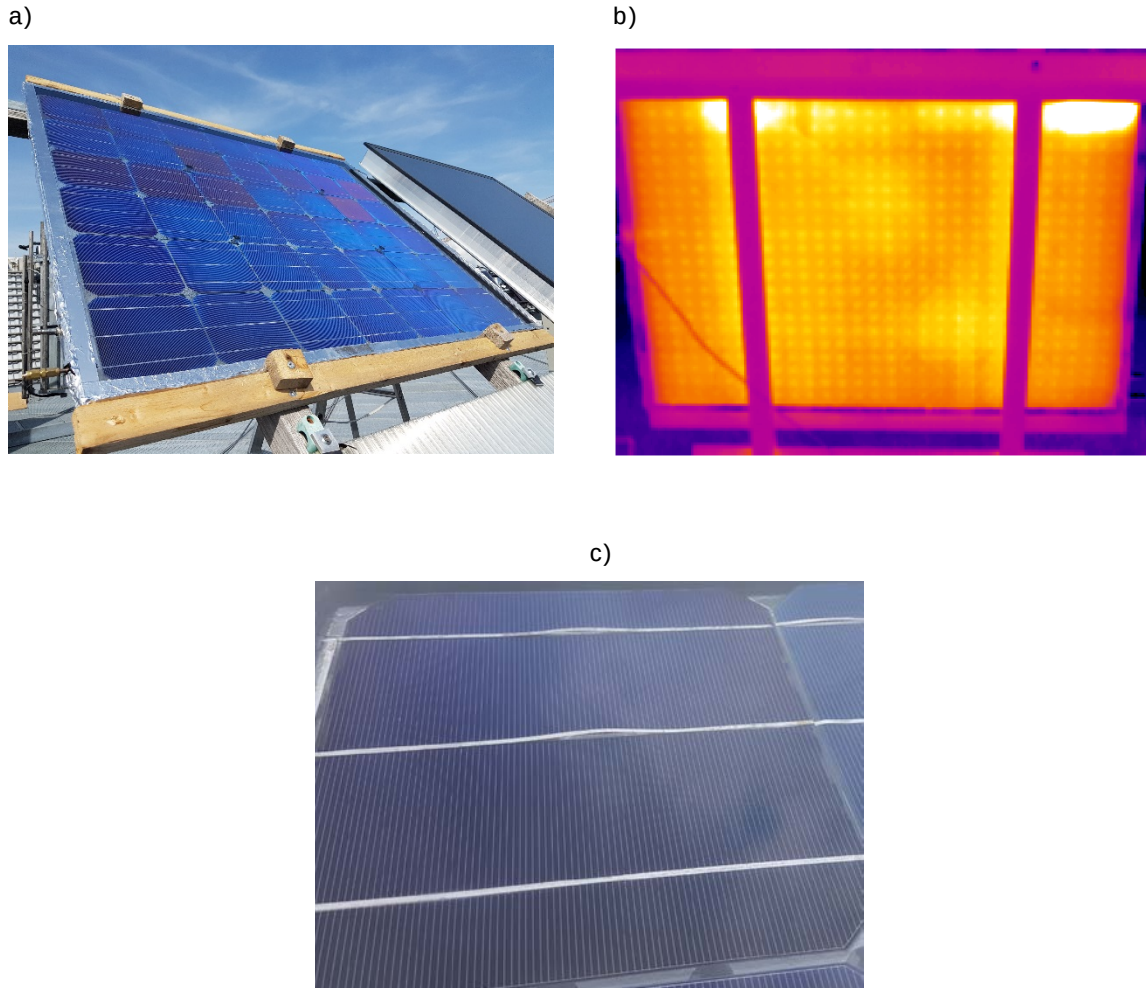


Figure 17: Outdoor exposure of full-scale prototype: a) prototype on outdoor exposure rig, b) thermography of backside of collector with hot spots visible as bright colours (the two cold vertical stripes appearing magenta are beams of the mounting rig), c) loose grid fingers on hot spot cell

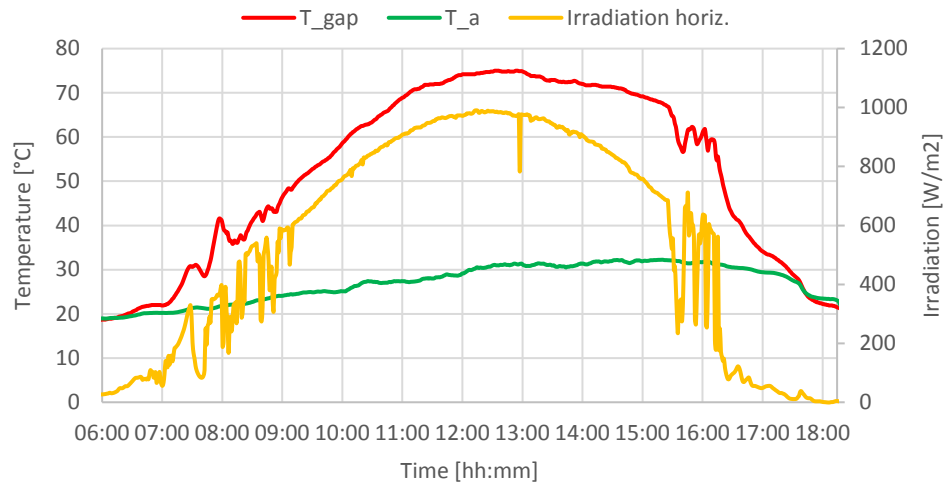


Figure 18: Evolution of the temperature in the air-gap of the full-scale prototype, the global irradiation on the horizontal and the ambient temperature on August 18th 2017.

2.4 Small-scale prototype (continuation of WPs 2 and 3)

2.4.1 Construction

A second, smaller prototype was built with the dimensions 0.4 m * 0.4 m with four BiSoN PV cells (see Figure 19). Unlike for the first prototype, where standard adhesives were used, for this second prototype, adhesives were chosen, which have a chance to be durable under the targeted conditions. In particular, instead of EVA, the silicone encapsulant Dow Corning PV 6212 (with properties similar to Momentive SilTRUST E110, which was tested in the climatic chamber, see Section 2.2) was used. Further, also for the edge sealing of the IGU, instead of the Polyurethane adhesive, the silicone based adhesive Sikasil SG-20 was used. The secondary sealing was, like for the first prototype, made with PIB.

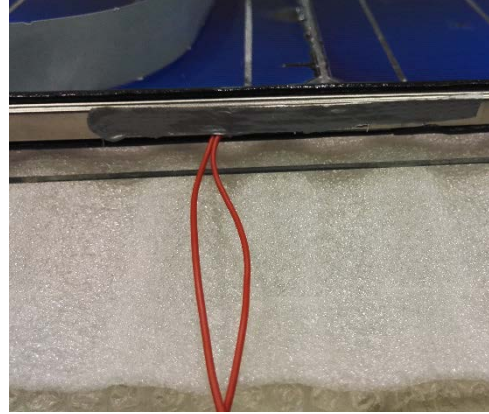
This second prototype was built in order to further evaluate the temperatures that occur in the different parts of the collector, in particular in stagnation conditions, and to test the IGU design with realistic materials, in particular with respect to possible moisture ingress. The design corresponded to the one of the first prototype (Figure 11), except that the collector was built without the Glasolo part, since no thermal performance tests needed to be done.

A temperature sensor was attached to the outer side of the metal frame (between frame and secondary sealing, Figure 19 b). A second temperature sensor was attached on the rear side of the PV glass at the position of a cell. Finally, a humidity sensor together with another temperature sensor were placed in the air gap between cells and front glass at the upper left corner of the module (Figure 19 c).

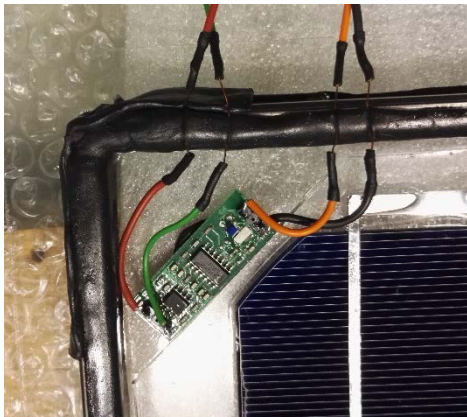
a)



b)



c)



d)



Figure 19: Construction details of the second prototype: a) collector before adding the front glass, b) temperature sensor on metal frame, c) temperature and humidity sensors in air gap, d) complete prototype.

2.4.2 Exposure testing

The small-scale prototype was placed on the outdoor exposure rig (south, 45°) from September 27th to November 13th (Figure 20). Like in the case of the first prototype, no heat insulation was put on the rear side of the collector. All three temperatures as well as the relative humidity inside the collector were logged (Figure 21 shows the profile of a sunny day).



Figure 20: Outdoor exposure of small-scale prototype

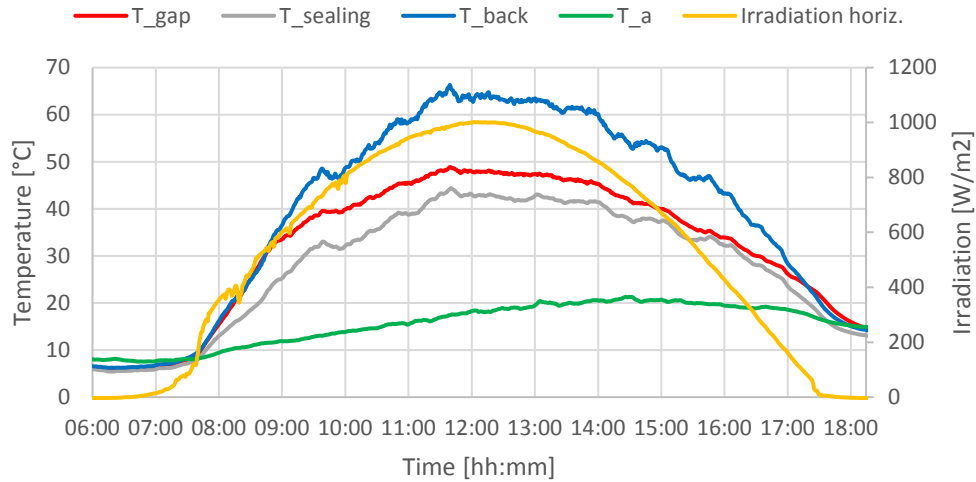


Figure 21: Evolution of the different temperatures of the small scale prototype and the global irradiation on the horizontal, on October 11th 2017.

The temperature at the back of the cells is clearly the highest with maxima around 70 °C. The temperatures in the air gap and in the edge seal are very similar, the air gap reaching temperature maxima around 50 °C and the sealing maxima that are a few degrees lower. The temperature in the air gap is lower than in the case of the large prototype, because in this case the sensor was not put in front of a cell and shielded from direct solar irradiation.

From the measurement of the relative humidity and the temperature in the air gap, the absolute humidity was calculated. The resulting curve, smoothed with a moving average, is shown together with the absolute humidity of the environment in Figure 22. If the edge sealings were tight, the two curves should be independent, and the absolute humidity should be roughly constant. However, the results show that the humidity in the collector follows the seasonal downward trend of the outside humidity, which indicates that the collector is not entirely tight. It is likely that the moisture exchange with the environment happened around the electric connectors, where presumable traces of moisture ingress were observed. However, no strong moisture ingress, like for instance condensation on the inner side of the front glass, was observed. Still, in a collector design with unprotected PV cells, the tightness of the edge sealings will be crucial. The observations made here show that the guiding of the connectors through the edge sealings will be a technical challenge to be solved by a future design.

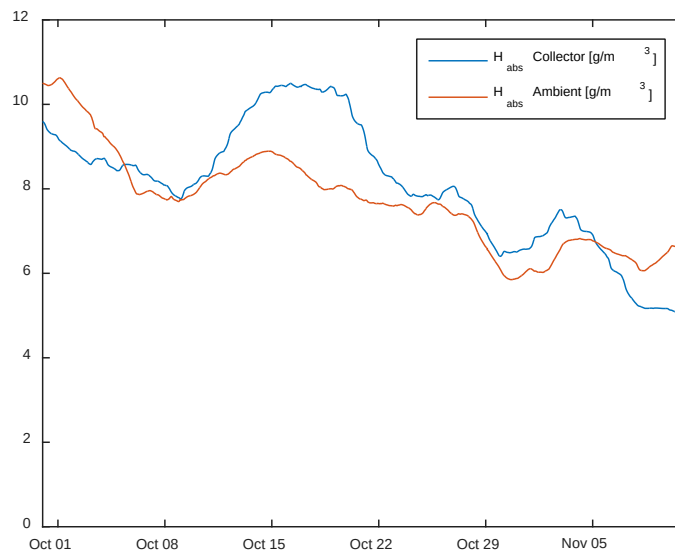


Figure 22: Absolute humidity of the collector air gap and the environment, calculated from measured relative humidity and temperature, and smoothed with a moving average with a window size of 5 days.

No other signs of degradation could be observed. It has to be kept in mind, however, that the exposure period was short and that temperatures would be considerably higher if the collector would be endowed with a backside heat insulation.

2.4.3 Stagnation test

In order to determine the temperatures at the different positions of the collector under steady-state stagnation conditions, the prototype was placed in the indoor solar simulator. Unlike during outdoor exposure, the backside was insulated with a 2 cm layer of EPDM foam (Aeroflex). The irradiation level during the test was 1020 W/m^2 and the ambient temperature around $25 \text{ }^\circ\text{C}$. The obtained values (averaged over 15 minutes) were: $T_{\text{back}} = 125.4 \text{ }^\circ\text{C}$, $T_{\text{gap}} = 88.9 \text{ }^\circ\text{C}$ and $T_{\text{sealing}} = 90.8 \text{ }^\circ\text{C}$. Like in the outdoor test, the temperatures in the air gap and in the edge sealing are similar to each other and are clearly lower than the temperature behind the PV cells.

The value of T_{back} can be compared to the results obtained for the large prototype. Calculating the stagnation temperature for an ambient temperature of $25 \text{ }^\circ\text{C}$ based on the performance coefficients of the first prototype, one obtains a value of $137 \text{ }^\circ\text{C}$. Given the higher boundary effects that occur in the case of the small collector and the somewhat thinner backside heat insulation, the measurement of T_{back} can be considered to confirm the results for stagnation temperatures that were obtained in the case of the large collector by extrapolation of measurements of the thermal performance at lower temperatures.

This confirms that in a full-size collector with the present design, and under stagnation conditions with $T_a=30^\circ\text{C}$ and $G=1000 \text{ W/m}^2$, the temperature in the region of the cells will reach values $> 140 \text{ }^\circ\text{C}$. The temperatures in the air gap and in the edge sealing can, based on the arguments mentioned above, be expected to reach temperatures in the range of $100 \text{ }^\circ\text{C}$.

3 Evaluation

The project has shown that the proposed new design allows to build a PVT collector with an efficiency clearly beyond the one of products available on the market. The achieved thermal efficiency lies in the range of non-selective flat plate collectors. In order to further increase the performance towards values comparable to state-of-the-art flat plate collectors, the greatest potential of improvement would lie in a reduction of the emissivity of the absorber, which should therefore be an objective of further research.

A key challenge that remains to be solved is the design of the Glasolo part. The solution chosen in this project allowed to produce a functional prototype. It is, however, not a solution that permits to build a product with long-term stability. In fact, the connection of the two glass panes must be able to resist high temperatures (up to stagnation temperatures $\sim 150 \text{ }^\circ\text{C}$) and high temperature gradients (shocks) that may in particular occur when a system is turned on after a stagnation period. This temperature resistance is needed both in terms of temperature stability of the adhesive and in terms of mechanical stress appearing as a consequence of the different thermal expansion of glass and adhesive. Further, the connection must have a high hydrolysis resistance and be able to support internal pressure (for practical applications at least 3 bar). Several approaches for building the Glasolo part, e.g. based on glass frits, had been investigated in a previous project [4]. However, as of today, no satisfactory solution has been found that fulfils the numerous requirements. The development of the Glasolo part hence remains the greatest technological hurdle for the proposed collector design.

The technology of insulating glass units was successfully applied to the construction of an efficient PVT collector. For the secondary sealing, products with the necessary specifications were identified. PIB materials, which are commonly used as primary sealing, have melting temperatures around $110 \text{ }^\circ\text{C}$. Hence, if the efficiency of the collector is further increased, these materials could no longer be used. And so far, after consulting several specialized companies, no alternative could be found. Therefore, an air-tight design of the IGU is likely not to be feasible in the projected manner. A related additional point that needs to be solved, as the project has shown, is the guiding of the electric connectors through the edge sealing. This, however, is expected to be a minor challenge.

The handling of silicone encapsulants for PV cells is, in comparison to EVA, more difficult and less standard. The manual handling resulted in a non-optimal result in the case of the small-scale prototype (inhomogeneous silicone layer, entrapped air). However, these difficulties are expected to be easily overcome if the collector is manufactured in an industrial manner.

Finally, it should be mentioned, that an overheating protection mechanism for the collector, which would for instance limit stagnation temperatures to 100 °C, would relax a number of the constraints. In particular, it would allow for the use of standard adhesives and encapsulants, which would for instance permit to maintain the air-tight design of the IGU and the option of a noble gas filling. In addition, lower stagnation temperatures would greatly reduce the requirements on the Glasolo part.

National Cooperation

- Evaluation of solutions for the IGU unit with the companies SIKA CH and Glas Trösch
- Discussions with the company Glass2Energy regarding possible collaborations for the further development of the Glasolo unit
- Evaluation of a possible collaboration with the Swiss Welding Institute in the context of the development of the Glasolo unit

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