EXPERIMENTAL AND NUMERICAL ASSESSMENT OF PV-T COLLECTOR FOR COMBINED PRODUCTION OF ELECTRICITY AND DOMESTIC HOT WATER IN THE FRAME OF THE PROJECT “PVTCOL“

Patrick Dupeyrat[1], Gérald Kwiatkowski[2], Christophe Ménézo[3], Matthias Rommel[4], Gerhard Stryi-Hipp[1]

[1] Fraunhofer-Institut für Solare Energiesysteme ISE, Freiburg, Germany

[2] EDF R&D – Enerbat Department, Moret sur Loing, France

[3] Chaire EDF/INSA “Habitats et Innovations Energétiques”- CETHIL, UMR CNRS 5008/INSA Lyon/UCB Lyon1, France

[4] SPF, University of Applied Sciences Rapperswil, Switzerland

1. Introduction

A photovoltaic/thermal hybrid solar collector (or PV-T collector) is a combination of photovoltaic (PV) panels and solar thermal components (Zondag 2008). The aim of these components is to enhance the heat collected and generated by the PV panel. Therefore a PV-T device generates not only electrical, but also thermal energy and represents in principle the most efficient way to use solar energy (see Fig. 1).

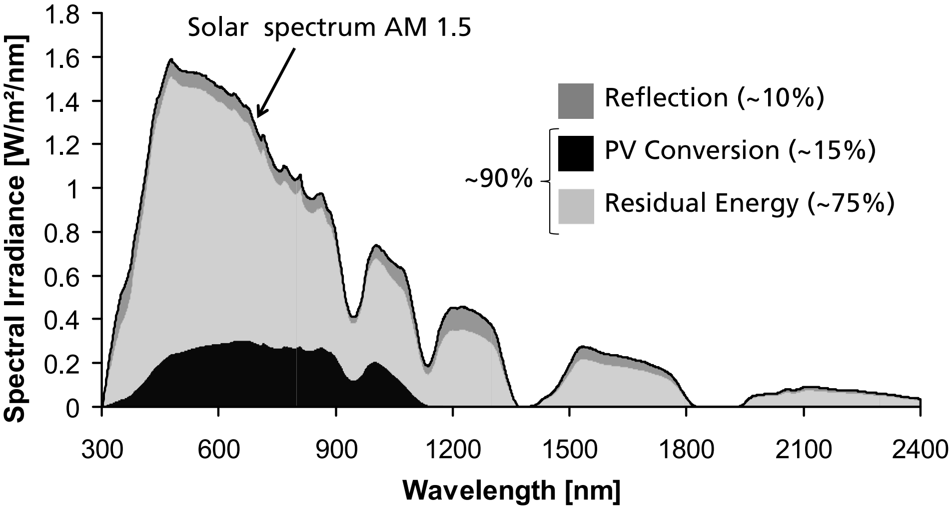

Fig. 1: Spectral representation of the absorption, reflection and PV conversion of a real c-Si solar cell. The share of absorbed radiation not converted to electricity, and therefore wasted as heat in a c-Si cell corresponds approximately to 75 % of the incoming radiation.

Some of the advantages to this approach include:

- A high combined (electric and thermal) efficiency and yield (per m²), especially where only a limited collector area with good solar radiation is available.
- The integration of both technologies into one type of collector may provide for a better aesthetic and a better architectural uniformity
- A single type of collectors may simultaneously cover parts of the demand for electricity and heat
- The potential other synergistic effects (e.g. cost reduction) from obtaining both outputs in one device.

However, the concept of PV-T is not new and in spite of the continuously interest for this field, PV-T is still a controversial technology which has not been able to enter the solar market successfully yet.

Therefore, in 2008, a research project led in collaboration with the R&D section of EDF, the CETHIL Lyon and the Fraunhofer ISE has started to develop an improved PV-T collector by using new technology approaches. In a first place, the objective of the project was to analyze the feasibility and the complexity of the concept of water PV-T collectors. One of the imposed major constraints was to directly achieve a water temperature level that is suitable for Domestic Hot Water use (DHW). This aim is strong and quite challenging. It indeed differs from the majority of studies that are targeting at pre-heating systems due to photo-conversion operating temperature dependency. Then under this constraint, the aim of this project was to understand the performance limitations and to investigate innovative solutions based on recent material improvements in order to increase their performance. Finally, the target of the project was to present a general assessment on the global performance of PV-T collectors.

2. Design of an experimental PV-T prototype

2.1. Covered vs. uncovered PV-T collector

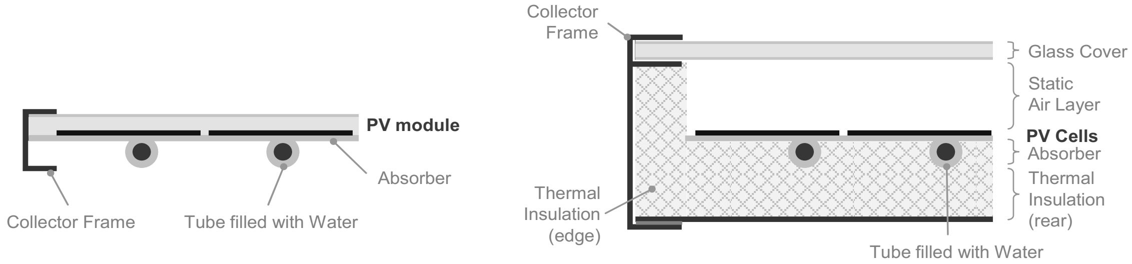

Fig. 2: Description of a liquid flat plate PV-T collector in uncovered (left) and covered (right) configuration.

As it can be seen in the Fig. 2, a flat plate PV-T collector consists of a PV module or PV cells attached to a flat heat exchanger (absorber), a heat transport medium (fluid, i.e. water-glycol) to remove the heat from the heat exchanger, and back thermal insulation. In this configuration (uncovered PV-T), the absorber plate is directly exposed to the surroundings. Due to the high thermal losses on the front side, mainly due to the wind convection and the radiation losses, these uncovered collectors are mostly suitable for low temperature applications (pre-heating, swimming pool heating or coupling with heat pump). From a component point of view, the solution is simpler and less constraining for the PV function. However, from a system point of view, it makes the solution more complicated and far from a short or medium term application. It is the reason why we decided to focus on PV-T collector operating in a domestic hot water system (DHWS). To reach the targeted temperature, the thermal losses of the PV-T collector must be sufficiently low.

In order to reduce the thermal losses, a collector glass cover can be placed between the absorber and the ambient air. On one hand it reduces the amount of light reaching the PV cells (optical losses due to the limited transmission of the cover). However on the other hand, it reduces much of the convection losses on the front side. Due to the lower thermal losses on the front side compared to uncovered PV-T collectors, covered PV-T collectors can be suitable for medium temperature level applications (domestic hot water systems, for example). It is the reason why we decided to develop a covered flat plate PV-T collector.

2.2. Prototype description

The development of a covered flat plate PV-T component is at the edge of both PV and solar thermal technologies. A broad, multi-scale and multi-competence approach has been aggregated in this project in order to improve not only the PV and the thermal components separately, but also to find synergetic and specific solutions for the PV-T collector as a whole. Based on detailed numerical models made in this study, changes were made to material characteristics and constructions with the aim of improving both PV and thermal performance (Dupeyrat et al. 2011a).

Four strings of eight pseudo square sc-Si PV cells (156 x 156 x 0.2 mm) were prepared and connected in series. Those interconnected PV cells were inserted between two EVA films and deposited on the flat surface of the 1350 x 750 mm one-side-extra-flat aluminium Rollbond heat exchanger with fractal channel structure (Hermann 2006). To improve the electrical isolation of the solar cells from the metal absorber through EVA, a coating was applied on the surface of the absorber. The same coating serves as the radiation absorbing surface for those areas which are not covered by PV cells. Then, a 0.13 mm thick low refractive index film was used as front layer. All those layers were laminated together in a vacuum laminator using standard PV lamination conditions in terms of pressure load, vacuum and temperature, in order to obtain a functional PV-T laminate (see Fig. 3).

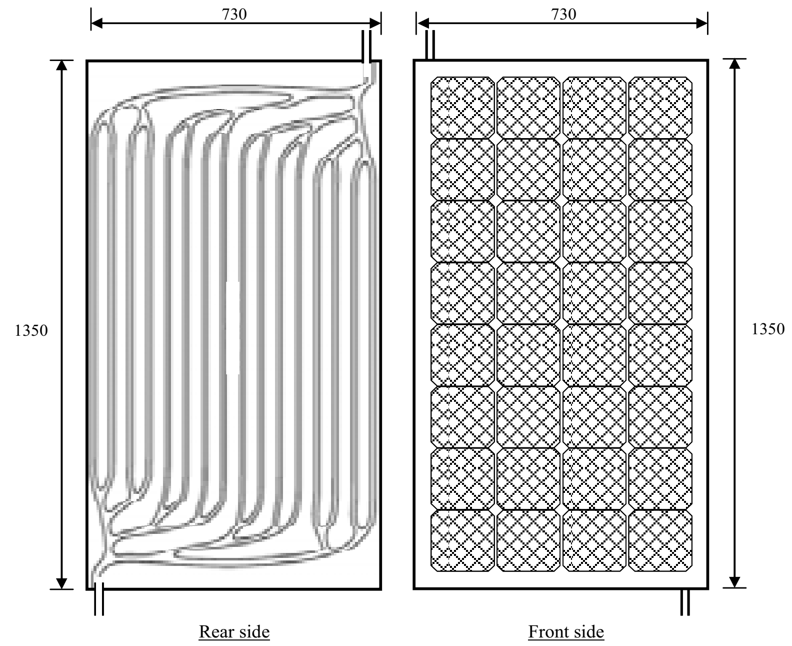

Fig. 3: Description of the PV-T absorber plate rear side (left) and front side (right).

This new PV-T lamination process showed significant improvements of solar thermal properties: an increase of the PV plate absorption coefficient (from 0.85 to 0.93) and a tenfold improvement of the heat transfer coefficient between the PV cell and the heat exchanger in relation to the reference PV-T collector. This new process showed also that the losses in terms of electrical efficiency due to the presence of the glass collector cover can be compensated by the combined effects of both improved PV lamination structure (i.e. an increase of current density above 2 mA/cm²) and anti-reflective coatings on glass cover (Dupeyrat et al. 2011b).

Then, a single glazed flat plate PV-T collector was built using the PV-T laminate and inserted in a special frame. The outer dimensions of the experimental collector were 1390 x 770 x 60 mm and the aperture area was A_{col} = 1.01 m². The front cover was a low-iron glass pane with an anti-reflective coating. The thickness of the glass cover was 4 mm and the measured solar transmission was $\tau_{cover} = 0.936 \pm 0.005$. An air layer thickness of δair = 20 mm was set up to insure a good thermal performance. The thickness of the whole collector was reduced in comparison with standard collectors (8-10 mm) in order to achieve a better potential building integration while checking thermal performances were not affected. The thermal insulation on the edge of the collector was a polyurethane foam insulation panel with a thickness of δ_{iso} = 20 mm and a thermal conductivity of k_{iso} = 0.035 W/(m.K). The thermal insulation on the bottom of the absorber was a filament reinforced silica high performance micro-porous insulation panel in a glass cloth outer envelope with a thickness of δ_{iso} = 20 mm and a thermal conductivity of k_{iso} = 0.022 W/(m.K).

2.3. Thermal and electrical measurements evaluation

To succeed in the evaluation of both thermal and electrical performance of the prototype, an appropriate test procedure to estimate correctly both thermal and electrical performance of the developed PV-T prototype has been selected. In spite of a recent and growing interest in this field of PV-T, there is still no specific dedicated test procedure for PV-T collectors available yet. For the measurements presented here, the test procedure developed was based on the standards for solar thermal collectors and for photovoltaic modules.

Measurements on the developed PV-T collector have been carried out according to EN12975. The collector was tilted with an angle of 45° and exposed to a constant average global irradiation using an artificial sun simulator. In order to take into account the radiation losses from the collector to the surroundings, the simulator has an artificial sky. This is made of two highly transparent glass covers cooled by the circulation of air between both panes. The collector was exposed to artificial wind in a parallel direction to the collector in order to simulate the convection losses from the collector to the surroundings as required by the EN12975 standards. A picture of the developed prototype during the measurements in indoor sun simulator is presented in the Fig. 4.

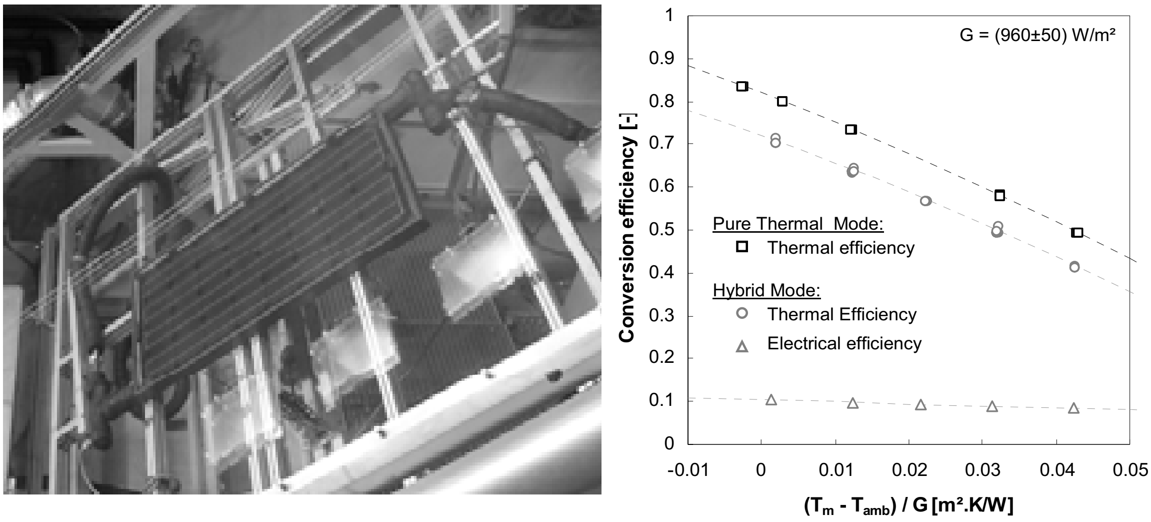

Fig. 4: Left: picture of the developed prototype during the measurements in indoor sun simulator. Right: Thermal efficiency curve based on the collector aperture area (1.01 m²) in open-circuit mode (black) and in maximal power point mode (grey) as a function of the reduced temperature.

In a first set of measurements, the PV-T collector operated in open circuit "oc" mode. The electric cables coming out of the collector were not connected to an electrical load. The collector behaved like a pure thermal collector and the solar radiation was converted into heat only. In a second set of measurements, the PV-T collector has been connected to an electrical load in order to determine both the electrical and thermal performance of the prototype. The electrical load was at the same time a Maximum Power Point Tracker and MPP Scanner. Results are presented in the Fig. 4.

In a pure thermal mode (open-circuit), the thermal efficiency at η_0 based on the aperture area was 0.82. In a hybrid mode, the thermal efficiency at η_0 was 0.72 under PV operation with a corresponding electrical efficiency of 0.105. As a consequence, it results in a high overall reference efficiency of 0.825. The results indicated a significant improvement of both thermal and electrical performance in comparison to previous work on PV-T collector concepts, validating our experimental approach in terms of improvements.

3. Assessment of PV-T collector for combined production of electricity and hot water

In the context of the global approach regarding the development of PV-T collectors, the achievement of a more efficient PV-T collector is not a sufficient step. It must be evaluated, based on the experimental measurements as a part of a system.

3.1. Simulation of Domestic Hot Water System with PV-T in TRNSYS

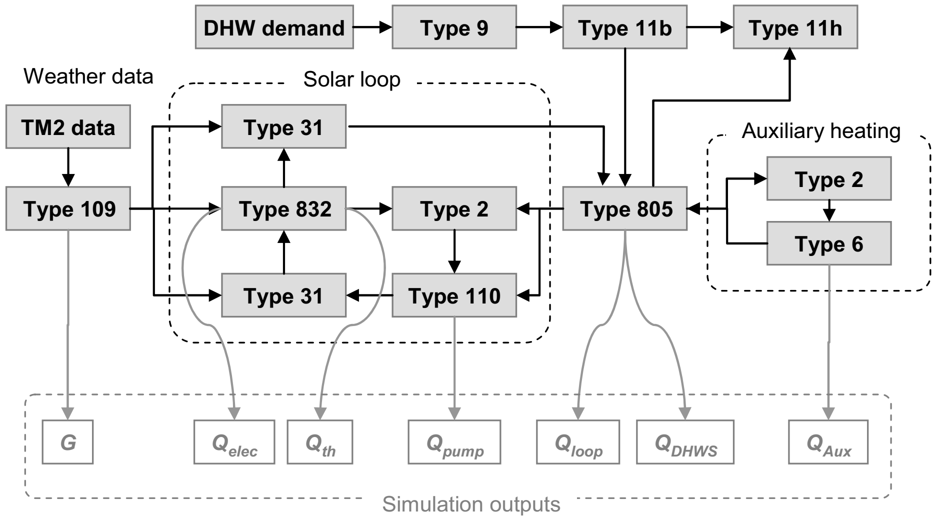

Fig. 5 DHWS description in TRNSYS

The parameters required for the simulation of the DHW deck presented in Figure 5 are listed below.

- Collector (Type 832 modified): South orientation, inclination 45°. Parameters extracted from the tests. Type 832 modified to take in to account the production of electrical energy.
- Pump (Type 110): flow rate of 45 kg/(hr.m²), collector to tank piping : 10 m, ΔT controller with hysteresis 7 °C (on) and 4 °C (off), mix of 60 % water and 40 % glycol
- Water storage (Type 805): volume of 300 L, auxiliary heated volume of the storage: 130 L with set temperature of 52.5 °C, cold water inlet temperature : 10 °C plus/minus 3.5 °C (summer/winter)
- DHW consumption: 200 L of 45°C heated water per day (4 persons)
- Simulation time step : 180 s
- Weather files: Nice, Lyon, Paris (France) and Essen (Germany). These weather types were selected for giving a large range of climate type in Central Europe.

3.2. Evaluation criteria

As was often described in the scientific literature dedicated to PV-T collectors, the evaluation of the performance of PV-T systems is complex and the comparison of energy productions ($Q_{thermal}$ and Q_{elec}) is not a sufficient criterion to assess the performance.

Several different comparison criteria taking into account the "value" of the energy produced through thermodynamic and environmental considerations were already suggested (Coventry and Lovegrove 2003, Fraisse et al. 2007). In this paper, we focus mainly on the following criteria:

- Energy production and consumption

$$\left(Q_{Energy}\right)_{yearly} = \sum_{i=1}^{8760}\left[\left(Q_{th}\right)_{hourly}^{i} + \left(Q_{elec}\right)_{hourly}^{i}\right] \quad \text{(eq. 1)}$$

- Fractional thermal energy saving, defined as the saved auxiliary heating energy consumption of the DHW system Q_{Aux} compared to the total energy consumption of a DHWS where no solar collector is integrated

$$f_{sav} = 1 - \frac{\sum_{i=1}^{8760}\left(Q_{Aux}\right)_{hourly}^{i}}{\sum_{i=1}^{8760}\left(Q_{DHW} + Q_{Losses(tank)}\right)_{hourly}^{i}} \quad \text{(eq. 2)}$$

- Primary energy saving, takes into account the consumption of the pump Q_{pump} and of the auxiliary heating Q_{Aux} (η_{TPP} is the efficiency of a thermal power plant, assumed to be 0.40).

$$\left(Q_{PES}\right)_{yearly} = \sum_{i=1}^{8760}\left[\frac{\left(Q_{elec}\right)_{hourly}^{i} - \left(Q_{pump}\right)_{hourly}^{i}}{\eta_{TPP}} + \left(Q_{DHWS}\right)_{hourly}^{i} - \left(Q_{Aux}\right)_{hourly}^{i}\right] \quad \text{(eq. 3)}$$

- Exergy production, part of the energy that could theoretically be converted to work in an ideal Carnot process. The results are calculated from the second law of thermodynamics.

$$\left(Q_{Exergy}\right)_{yearly} = \sum_{i=1}^{8760}\left[\left(1 - \frac{T_{amb} + 273.15}{T_m + 273.15}\right)\cdot\left(Q_{th}\right)_{hourly}^{i} + \left(Q_{elec}\right)_{hourly}^{i}\right] \quad \text{(eq. 4)}$$

3.3. Side-by-side installations

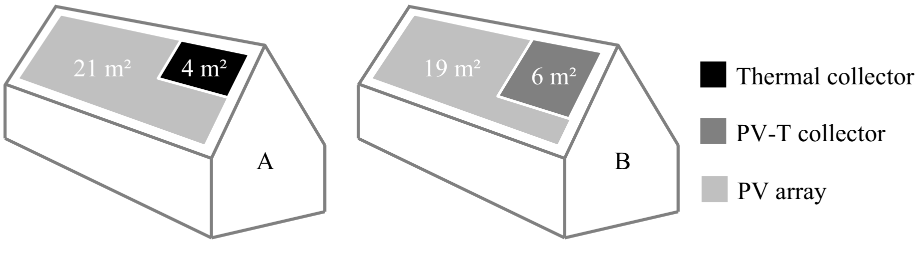

Fig. 6: DHWS description in TRNSYS (typical values indicated).

In many cases, the installation of thermal collectors on a roof is jointly done with the installation of PV panels. The aim of this part is to evaluate the global performance of a solar roof either covered with PV panels and thermal collectors (reference) or covered with PV panels and PV-T collectors. It is obvious that a larger PV-T collector area is required to obtain the same fractional thermal energy savings than for a standard thermal collector installation. The PV-T area will therefore be increased until the same thermal output as a standard thermal collector installation is reached (see Fig. 6).

In fact, as the size of the roof is limited (25 m² for this simulation), only the ratio between the area covered by PV module and thermal collector (i.e. PV-T) will change. As both thermal and PV-T collector installations will be assumed to have exactly the same thermal output, a clear statement will be done simply by comparing the total PV output of both roofs. Results are presented in the Table 1.

Table 1 shows that for equivalent thermal performance (in terms of fractional thermal energy saving as well as thermal output), side-by-side installation with PV-T collectors have higher total PV output and exergy than side-by-side installation with conventional thermal collectors. This is valid for Nice, Lyon, Paris and Essen weather data. In fact, the increase of PV output for equivalent roof surface area between the systems A and B is around 12.4 % for Essen, 12.7 % in Paris, 12.6 % in Lyon and 10.7 % in Nice. This result is a quite obvious proof of interest for PV-T versus conventional thermal collectors.

Tab. 1: Results side-by-side solar roof (25 m²).

	ESSEN		PARIS		LYON		NICE	
	A	B	A	B	A	B	A	B
Total surface area [m²]	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0
PV surface area [m²]	21.2	18.5	21.2	18.9	21.3	19.2	21.8	20.2
Th. Coll.surface area [m²]	3.8	-	3.8	-	3.7	-	3.2	-
PV-T surface area [m²]	-	6.5	-	6.1	-	5.8	-	4.8
Q_{elec} PV [kWh/year]	2112	1843	2334	2075	2626	2367	3414	3163
Q_{elec} PV-T [kWh/year]	-	530	-	556	-	591	-	617
Q_{elec} total [kWh/year]	2112	2373	2334	2631	2626	2958	3414	3780
$Q_{thermal}$ [kWh/year]	1643	1643	1846	1819	2070	2042	2467	2479
F_{sav}	0.50	0.50	0.55	0.55	0.60	0.60	0.70	0.70
Exergy [kWh/year]	2265	2523	2510	2796	2833	3149	3650	4006

4. Conclusion

Photovoltaic-Thermal (PV-T) hybrid solar collectors represent, in principle, one of the most efficient ways to convert solar radiation into useful energy. The objective of the "PVTCol" project was to explore the different ways induced by this concept, to identify one of the most relevant solutions, to check its feasibility and to concretize by realization of a prototype.

Based on the experimental results of tests on a prototype developed within the project, TRNSYS simulation were carried out to asses the overall system performance of a system using this improved collector. The results showed that the integration of PV and thermal energy collection on a limited roof area can provide higher energy and exergy output than side-by-side installation with conventional components.

The findings of this project combined with current market developments indicate that PV-thermal collectors have a future that is not yet fully defined. However we are convinced that it will certainly gain in interest and potential applications, in the fields of research and in the market.

5. References

Coventry, J.S., Lovegrove, K., 2003, Development of an approach to compare the "value" of electrical and thermal output from a domestic PV/thermal system. Solar Energy, 75, 63-72.

Dupeyrat, P., Ménézo, C., Rommel, M., Henning, H-M., 2011, Efficient single glazed flat plate photovoltaic–thermal hybrid collector for domestic hot water system, Solar Energy, 85, 1457-1468.

Dupeyrat, P., Ménézo, C., Wirth, H., Rommel, M., 2011, Improvement of PV module optical properties for PV-thermal hybrid collector application, Solar Energy Materials and Solar Cells, 95, 2028-2036.

Fraisse, G., Ménézo, C., Johannes, K., 2007, Energy performance of water hybrid PV/T collectors applied to combi-systems of Direct Solar Floor type. Solar Energy, 81, 1426-1438.

Zondag, H.A., 2008, Flat-plate PV-Thermal collectors and systems: A review. Renewable and Sustainable Energy Reviews, 12, 891-959.