Energetic performance analysis of a commercial water-based photovoltaic thermal system (PV/T) under summer conditions

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Abstract. In the last years, the importance of integrating the production of electricity with the production of sanitary hot water led to the development of new solutions, i.e. PV/T systems. It is well known that hybrid photovoltaic-thermal systems, able to produce electricity and thermal energy at the same time with better energetic performance in comparison with two separate systems, present many advantages for application in a residential building. A PV/T is constituted generally by a common PV panel with a metallic pipe, in which fluid flows. Pipe accomplishes two roles: it absorbs the heat from the PV panel, thus increasing, or at least maintaining its efficiency; furthermore, it stores the heat for sanitary uses. In this work, the thermal and electrical efficiencies of a commercial PV/T panel have been evaluated during the summer season in different days, to assess the effect of environmental conditions on the system total efficiency. Moreover, infrared thermographic diagnosis in real time has been effected during the operating mode in two conditions: with cooling and without cooling; cooling was obtained by natural flowing water. This analysis gave information about the impact of a non-uniform temperature distribution on the thermal and electrical performance. Furthermore, measurements have been performed in two different operating modes: 1) production of solely electrical energy and 2) simultaneous production of thermal and electrical energy. Finally, total efficiency is largely increased by using a simple solar concentrator nearby the panel.

1. Introduction

The ever-growing buildings’ energy consumption is a relevant issue for the civil sector. It is evident that the spread of electric appliances for domestic uses leads to an increase of electric energy consumption. It is also clear that, in the last decades, the living standards are getting higher, and people are reluctant to reduce them. For instance, we’re getting used to have televisions in several rooms, to have cooling devices for the hottest seasons, and to have multiple electric devices and lights simultaneously switched on. Simple hacks (like installing occupancy sensors) help to significantly reduce energy needs [1]. Besides these concerns, domestic hot water must be provided, too. On the whole, in a building, whatever is its intended use, there is the need to face requirement for electric energy and domestic hot water. In some special cases, situations may be even more complex [2]. Fortunately, the civil sector itself can provide the possibility of supply such requirements. In fact, the installation of photovoltaic systems and solar heating collectors on rooftops can help to provide the self-production of the supplies. The technological solution that can match both requirements is the PV-Thermal (PV/T or PVT) collector. It consists of a PV module that simultaneously serves as electricity producer and thermal absorber, thus it uses solar energy for producing hot water and electricity at the same time. There are many benefits in the use of PV/T. In fact, the rooftop area used is lower than the equivalent needed for...
the separate production of hot water and electricity, and such solution is better integrated in the architectural feature of a building, also due to the several available shapes and layout of PV/T collectors.

Different PV/T typologies are commercially available, and several research and review studies have been carried out on these systems.

The PV/T collector concept was firstly introduced in the ‘70s, as one of the responses to the oil crisis of such period. Although the PV/T technology is quite mature, the effort of the scientific community is to fully characterize its behavior, in terms of electrical and thermal efficiency, and to improve its capabilities.

In the study of Huang [3], an integrated photovoltaic and thermal solar system is proposed, and its performances are compared to a conventional solar water heater. In the paper, the primary-energy saving efficiency is also proposed. Results show that PV/T efficiency is increased if the heat collecting plate constituted the base plate of PV cells, and if it is directly in thermal contact with them.

An experimental prototype was employed in [4], and different numerical models (dynamic 3D or steady-state with 1D, 2D and 3D) for the thermal yield definition were also employed, proving reliable results, but with different calculation times.

The development of the thermal model of the integrated photovoltaic and thermal solar system mentioned before is proposed in [5], and results agree with those proposed in [3].

A review on PV/T collectors is proposed in [6], where different outcomes provided by research studies are compared.

In 2008, the study of [7] gives a review focused on flat-plate PV/T collectors, and the history of PV/T systems is also outlined, together with the main findings from a literature review that covers 30 years of publications.

In 2009, a study [8] compared the results of the total efficiency obtained from simulations carried out on seven design configurations for the absorber collectors of PV/T. Several parameters, like flow rate, solar radiation and ambient temperature, were also considered. As result, the design that performs the highest thermal efficiency is the one having spiral flow, which is one of the simplest investigated.

A work by Kostic et al [9] deals with the influence of a flat aluminum concentrator on energy efficiency of PV/T. The addition of a reflective foil, laid at specific angles in respect of horizontal and vertical plane, ensures the increase of the thermal and electrical energy given by the PV/T. The study proves that both the thermal and electrical efficiency, and the total daily thermal and electrical efficiency decrease with the solar radiation intensity concentration factor.

In 2011, Ibrahim at al [10] proposed a paper on recent advances in PV/T collectors, showing different design configurations and the future development of such systems, with attention to the building integrated photovoltaic systems. A similar approach was followed by Zhang et al [11].

The theme of building integrated photovoltaic and thermal system was deepened in a recent work [12], where an extensive review on the subject is presented.

Another recent review on PV/T systems is given by Al-Waeli et al [13], where thermal and electrical efficiency of PV/T systems assessed in literature are also compared in respect of the different cooling media.

A work authored by Vittorini et al [14] aims at developing a Matlab model that reproduces the thermal balance of modules, calibrated on experimental data.

It is evident that the interest of the scientific community on PV/T is high, because of the great potentiality of such system, and the possibility of integrating this technology in the building skin. This, of course, is an advantage and, possibly, a push to the wider installation of such systems in new buildings.

In this paper, a commercial PV/T collector consisting of a plane PV module of polycrystalline silicon, cooled by water, was investigated. Tests were performed during summer season, under real solar radiation conditions. The employed set up is quite simple, but it allowed to characterize the thermal and electrical efficiency of the collector under different weather conditions. Results are compared with
a commercial PV panel, having the same characteristics (displayed in Table 1), showing the better performance of the PV/T system.

2. Materials and methodology

2.1. PV/T and PV setup

Tests and measurements were carried out on a PV/T collector and on a frameless PV mounted on aluminum supports, needed for comparison. Panels were mounted on a flat roof of the Faculty of Engineering in L’Aquila (42°20’ N, 13°22’E); they were tilted of 41.5° in respect to the horizontal plane, and were south oriented.

The employed PV/T collector, shown in Figure 1, is certified by IEC EN 61215, IEC EN 61730-2, IEC EN 61730-3 and EN 12975-2. Its technical features are summarized in Table 1.

![Figure 1. Drawing of the employed PV/T module, with its sizes. Right side shows the absorber layout.](image)

| Table 1. PV/T and PV module technical specifications. |
|------------------------------------------------------|
| **PV/T panel**                                      | **PV panel**                                   |
| Number of solar cells                               | 60 polycrystalline cells                       | 72 polycrystalline cells                       |
| Cell sizes                                          | 156 x 156 mm                                   | 156 x 156 mm                                   |
| Module sizes (H x L x W)                            | 1666 x 992 x 40 mm                             | 1985 x 1005 x 4 mm                             |
| Pp *                                                | 250 W                                          | 300 W                                          |
| Pt**                                                | 785 W                                          | -                                              |
| Gross surface                                       | 1.63 m²                                        | 1.99 m²                                        |
| Net surface                                         | 1.48 m²                                        | 1.99 m²                                        |
| Weight                                              | 22 kg                                          | 27 kg                                          |
| Liquid content                                      | 1.15 l                                        | -                                              |
| Absorber                                            | Copper harp laser welded on aluminum plate     |                                                 |

* peak power
** maximum producible thermal power

A simple way to install a PV/T collector is shown in Figure 2.
In our case, it wasn’t possible to realize such layout, because of the lack of a boiler tank and of the possibility of net connection. Therefore, it has been decided to employ the configuration displayed in Figure 3.

In fact, given the electrical characteristics of the two modules (detailed in Table 2), a proper external electrical load was needed in the set-up, to measure the current and voltage on the load itself, thus having the possibility to measure the electrical power instantaneously produced by the module. The same load was applied to the two modules (PV/T and PV), and it was sized according to the maximum power current that could circulate in them (which is quite the same). In fact, hypothesizing electrical power \( P \) of about 200 W for each module, the required load, in terms of resistance, can be calculated as the ratio between the power and the square of the maximum current, that is:

\[
R = \frac{P}{I_{mp}^2} = \frac{200}{(8.33)^2} \approx 3 \Omega
\]
Table 2. Electrical characteristics of employed modules (from products datasheet).

|                  | PV/T module | PV module |
|------------------|-------------|-----------|
| Module Efficiency| 15%         | 15.04%    |
| Maximum Voltage  | 30.03 V     | 36.10 V   |
| Maximum Current  | 8.33 A      | 8.31 A    |
| Open Circuit Voltage | 37.68 V   | 45.10 V   |
| Short Circuit Current | 8.81 A   | 8.98 A    |

Due to the unavailability of a hot water storage tank, it has been decided to have a continuous water flow in the PV/T absorber, directly taken from the aqueduct. This, of course, causes a great penalty on the evaluation of the thermal efficiency of the module, since the module is always cooled by a new water rate. This choice may affect the electrical efficiency, too. In fact, as known, the electrical efficiency increases with the decrease of module temperature. The continuous heat exchange from module to water ensures the cooling of the module, whose temperature is lowered and whose electrical performances might be, in a closed circuit, lower.

2.2. Performance evaluation

The performance evaluation of a PV/T collector is expressed by its capability to convert solar energy into thermal and electrical energy.

The thermal efficiency $\eta_{th}$ of the system can be defined [9,13] as the capability of the device to convert the solar radiation into thermal energy, that is the ratio between solar irradiance on the surface and the thermal energy gained by water, that is:

$$\eta_{th} = \frac{\dot{m} \cdot c \cdot (T_{out} - T_{in})}{G \cdot A}$$

(2)

where $\dot{m}$ is the water mass flow rate, $c$ is water specific heat, $T_{out}$ and $T_{in}$ are respectively the outlet and inlet water temperatures, $G$ is the solar radiation on the module whose area is $A$.

The electrical efficiency $\eta_{el}$ can be defined as the amount of electric power generated by the PV module in respect of the solar radiation on the module surface. This parameter can be expressed as:

$$\eta_{el} = \frac{I \cdot V}{G \cdot A}$$

(3)

where $I$ and $V$ are the current and the voltage, whilst $G$ and $A$ have the meaning expressed before.

The total performance $\eta_{tot}$ of a PV/T panel can be expressed as the sum of the thermal and electrical efficiencies [13]:

$$\eta_{tot} = \eta_{th} + \eta_{el}$$

(4)

To evaluate thermal and electrical efficiency, data regarding ambient air temperature, relative humidity and wind speed were acquired through a weather station placed nearby the modules. Solar radiation $G$ was measured by a pyranometer included in the weather station, whose working principle is a thermopile. Weather station specifications are listed in Table 3. Alternatively, another equipment, already introduced in literature [15], which is based on the voltage difference on PV cell, can be used.
The following evaluations, however, are carried out with respect to the solar radiation.

**Table 3. Weather station technical specifications.**

|                      | Operating range | Accuracy     |
|----------------------|-----------------|--------------|
| Pyranometer          | 0~2000 W/m²     | ISO 9060 - 2nd class |
| Temperature          | -50~+150 °C     | ±0.5 °C      |
| Relative humidity    | 0~100 %         | ±2%          |
| Cup anemometer       | 0~50 m/s        | ±0.1 m/s     |

Thermocouples were employed for the measurement of inlet and outlet water temperatures. All quantities were acquired every 15 minutes during the morning. Different tests were carried out during the summer season; tests differ for the weather conditions that occurred, water mass flow rate set, and for the absence or presence of a flat reflector in front of the modules. This feature allows to increase the solar radiation on the module surface, that, in turn, implies an increase in the generated power. The flat reflector was realized with a cardboard covered with aluminum foil. Tests overview is shown in Table 4.

**Table 4. Tests matrix.**

| Weather condition | Water mass flow rate in the PV/T [kg/s] | Flat reflector | Thermographic inspection |
|-------------------|----------------------------------------|----------------|--------------------------|
| Test 1            | Overcast                               | 0.212          | -                        |
| Test 2            | Clear sky                              | 0.212          | -                        |
| Test 3            | Overcast                               | 0.106          | -                        |
| Test 4            | Clear sky                              | 0.106          | -                        |
| Test 5            | Clear sky                              | -              | ✓                        |
| Test 6            | Clear sky                              | 0.106          | ✓                        |
| Test 7            | Clear sky                              | -              | ✓                        |

3. Results and discussion

PV and PV/T panels efficiencies are shown in Figure 4 from (a) to (e), together with the recorded solar radiation, against the hour, for the tests carried out. For the PV/T panel, thermal, electrical and total efficiencies are shown. As foreseen, the thermal efficiency has always low values, due to the employed set-up. In literature, high values (order of 60 % to 90 %) of thermal efficiency are assessed for water cooled PV/T systems [13]. This, of course, affects the total efficiency.

Measured electrical efficiency of both the PV and the PV/T panel agree with those expected from manufacturers and available from previous studies. As a general remark, PV/T electrical efficiency is always slightly higher than the PV panel one. Such efficiencies have swinging values when the measured solar radiation varies rapidly. Such variations are, sometimes, due to clouds passing through. It’s the case of Test 2: the weather condition was favorable, in fact as a whole the sky was clear, and solar radiation reaches a peak of about 1067 W/m² (the highest value of all campaigns); nevertheless, moving clouds significantly reduced the solar radiation in the middle of the test, thus affecting the efficiencies, whose trends recall the one of G.

Test 3 and Test 4 were carried out by halving the water mass flow rate. The heat exchange was therefore enhanced, causing the increase of Tout, and, therefore, the (low) increase of $\eta_{th}$.

The indirect effect due to this is that electrical efficiency of Test 3 and Test 4 follows the solar radiation behavior. Instead, in Test 1 and Test 2, the electrical efficiency is less influenced by solar
radiation, unless the spikes already discussed for Test 2. Then, it has been decided to assess the electrical efficiency of the PV/T module when it is employed as a simple electricity producer, that is, without the cooling effects due to water circulation, which means it is employed as a simple PV panel (Test 5).

![Figure 4](image)

**Figure 4.** Thermal and/or electrical efficiency of the PV/T and PV panel, and solar radiation against hour. Results of: (a) Test 1; (b) Test 2; (c) Test 3; (d) Test 4; (e) Test 5.

Then, in order to enhance the solar radiation on panels, it has been decided to install a flat reflector in front of them. The conceived system wasn’t equipped with a solar tracking device, therefore its position remained fixed for all the measurement duration. Two tests (Test 6 and Test 7) were performed by using this feature, both of them under clear sky. Due to the fixed position of the flat concentrator, the concentrating factor (that is, the ratio between total solar radiation that reaches the panel - sum of reflected and solar radiation- and the solar radiation) was variable along the hours, therefore this parameter has not been measured.
Electrical efficiency obtained in Test 5 are lower than the ones of Test 6 and Test 7, carried out with the employment of a flat reflector. This implies that, despite the ease of the adopted reflector, its benefits on the efficiency are remarkable. In fact, $\eta_{el}$ increases of some percentage points (depending on the hour) in Test 6 and Test 7 in respect of results of Test 5.

By observing results of Test 5 and Test 7, it can be seen that, unless a few values, PV/T electrical efficiencies stand upon the PV ones. The difference between these values is higher when a reflector is employed (Test 7). However, when the solar radiation is high (at noon), electrical efficiency of both PV and PV/T module converge in asymptotical way to the module efficiency declared by manufacturers.

By comparing results from Test 6 and Test 7, it can be noted that, in case of water cooling, electrical efficiency gets higher. In this case, for instance, the PV/T electrical efficiency measured at 12:45 a.m. increases from 14% (Test 7) to 18% (Test 6), that is a difference of 28%.

Analogous considerations can be drawn by comparing results from Test 4 and Test 6 (that differ for the reflector absence or presence, respectively), showing the reflector influence on both thermal and electrical efficiency.

These encouraging results might be due to the thermal uniformity of panels, due to cooling. During Test 5, Test 6 and Test 7, thermographic inspection was carried out to visualize panels’ thermal field. Figure 6 shows thermal images taken at 12:30 a.m., i.e. in condition of maximum solar radiation (as deducible from plots of Figure 4 and Figure 5).

Temperature scale is the same for all images. Edge effects are clearly visible on both moduls, while squared contours reveal the positioning of superficial temperature probes (whose results are not subject of the present work).

Temperatures shown in Figure 6(c) are the highest, due to the severe working conditions (absence of water cooling and adoption of flat reflector) whilst in case of absence of both water circulation and reflector, temperatures are lower. The lowest temperatures, averaged on the surface, are obtained in case of moderate mass flow rate and in presence of reflector. Particularly, image of Figure 6(b) clearly displays cells layout.
4. Conclusions

In this study, a PV and a PV/T module were investigated during the morning of some summer days, in 7 different conditions. Electrical and total efficiency of the systems were assessed, by using a set-up specifically conceived for the purpose. Due to the simplicity of the set-up, the PV/T thermal efficiency was significantly underestimated, and its total efficiency, too. Nevertheless, some relevant outcomes can be drawn from tests:

- Electrical efficiency of both PV and PV/T modules obtained on field agrees with manufacturer expectations;
- PV/T electrical efficiency is always higher than the PV one, whatever the operative conditions are;
- When water flow rate is high, energy efficiency is quite constant against hours, although it seems deeply influenced by rapid solar radiation variation (Test 2);
- By lowering cooling fluid mass flow rate, electrical efficiency trend recalls solar radiation increase (due to its mathematical definition);
- If the PV/T module is employed without cooling (i.e. as a simple PV module), its efficiency is higher than the one of the comparison PV panel, especially in the early hours of the morning. Such difference decreases in the more irradiated hours (Test 5);
- Thermal images, besides the identification of possible damaged or inoperative cells, allow to visually sketch the benefits of different operative conditions;
- Highest temperatures are reached in the set-up with reflector without cooling, followed by the configuration without reflector. The cooling effect due to a moderate water mass flow rate decreases panel temperature, whose distribution, however, is uneven: the central area of the panel shows higher temperatures;
- The employment of simple reflector can significantly (+28%) increase electrical efficiency;
- Panel cooling is therefore advisable to enhance the electrical energy capability of panels.

Future development of this work will deal with the analysis of temperature trends on the centre and on edge of panels, and on the influence of thermal field uniformity on PV and PV/T panels efficiency.

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