Photovoltaic-thermal (PVT) technology: Review and case study

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Abstract. Nowadays, solar technology converts solar energy into electricity and heat separately. For electricity generation, the main obstacle is the fact that the photovoltaic cells produce less energy as the temperature increases. To overcome this, cooling techniques can be used to raise the efficiency of solar cells, in order to obtain greater power generation. The photovoltaic-thermal hybrid solar collector (or PVT) is an equipment that integrates a photovoltaic (PV) module, for the conversion of solar energy into electrical energy, and a module with high thermal conversion efficiency (T), which employs a thermal fluid. This optimization of solar conversion technology has the main objective of cooling the photovoltaic cells, for increased generation of electricity, while also resulting in useful thermal energy from the working fluid, therefore constituting a cogeneration equipment. The present work reviews the development and global panorama of PVT technology. Afterwards, a case study of a PVT system is presented, together with a theoretical and experimental study. A thermography analysis performed in this PVT system is also examined, which allows for a real-time study of its operating regimes in different conditions, mainly of its thermal behaviour, and for the diagnosis of hot spots that signal potential defects in the cells.

1. Introduction

After the oil crisis of the 1970s, a greater awareness arose for the intensification of the development of renewable energies as an alternative to fossil fuels. This situation has resulted in impactful advancements on solar energy equipment, among other renewable energies, and in the increased efficiency of these technologies, as well as discoveries of new solutions.

As the global energy consumption increases daily, the projected energy demand is expected to grow about 25% by the year 2040 [1]. In the medium term, a new reality will take place in the worldwide energy sector, where consumption in countries belonging to the Organization for Economic Cooperation and Development (OECD) will stabilize and even decline, whereas growth will continue to be noticeable in other countries.

Although only a small fraction of the energy coming from the sun reaches the earth's crust, the incident radiation represents the largest energy transfer volume on Earth, when compared to fossil energy. If it were possible to use all incident solar energy throughout a year, a fraction of 0.01% would be enough to fulfill the global annual energy needs. However, even with the increasing interest in renewable energies in previous decades, the global production of electricity by conversion of solar
energy is still low, less than 2% at the end of 2017 [2].

However, in the medium term, it is predictable that renewable sources, which solar energy belongs to, will show the greatest growth in global electricity supply [1], with the solar photovoltaic having the most growth until 2040. The reason for such relies in the necessity to supply access to energy with reduced impact on the environment.

The climate challenge requires the evolution of technological solutions, in order to reduce the cost of inhibiting global greenhouse gas (GHG) emissions whilst meeting energy needs.

The conversion of solar energy into electricity is done through photovoltaic (PV) solar cells. However, solar radiation that is absorbed but not converted into electricity promotes the temperature increase of the solar cells, thus reducing their conversion efficiency. To counteract this phenomenon, the cells may be cooled by a working fluid (thermal fluid) in order to maintain a high level of conversion efficiency. In this setup, the thermal fluid - water or air - extracts the heat from the cells to be used elsewhere, resulting in a hybrid solar equipment with simultaneous generation of electric energy and thermal energy: this is called a Photovoltaic-Thermal collector or simply PVT. Thus, a PVT hybrid solar collector is a device formed by a PV module with an attached thermal unit on its back, being thus considered a cogeneration equipment. The importance of this equipment is that it can generate energy, electric and thermal simultaneously, with a good level of efficiency and in a smaller area than current thermal collectors and photovoltaic panels operating separately.

The present article presents a review of the development and global panorama of PVT technology. Afterwards, a case study of a PVT system is reported, along with a theoretical and experimental study. A thermographic analysis performed on said PVT collector is also examined, allowing for a real-time study of its operating regimes under different conditions, especially its thermal behavior, and for the diagnosis of hot spots that signal potential defects in the cells. Finally, the performance of the PVT system will be analyzed under real-life conditions.

2. Solar energy and PVT technology

Solar energy can be converted, by natural and technological processes, into other useful forms of energy, namely by the chemical process, through photosynthesis, by the electric process, using photovoltaic equipment to produce electricity, by the thermal process, to produce heat, and by the conversion of solar radiation into mechanical energy, as is the case with wind.

While solar cells are devices that convert sunlight directly into electricity through the photovoltaic and photovoltaic effects, a solar thermal collector collects heat by absorbing solar radiation. The conversion of solar energy into electricity and heat, simultaneously, with a single device, is done with a PVT system. Through PV cells, this equipment resources to a fraction of the incident solar radiation to generate electricity. This is verified to result in a rise in temperature, resulting in a decrease of the efficiency of the cells. However, with PV cooling, it is possible to maintain a sustained electrical efficiency at a satisfactory level [3].

Figure 1 illustrates different types of solar technologies where PV, Thermal, and PVT technologies are represented. The PV cells can be classified by the generation of technology, namely the first generation (crystalline silicon), which is the case of monocrystalline and polycrystalline cells (globally the silicon technology is the one that predominates in the production of solar cells); second generation (thin films), such as amorphous silicon cells, Cadmium Telluride cells (CdTe), Copper Indium Gallium Selenide cells (CIGS) and Gallium Arsenide cells (GaAs); and third generation (multi junction) cells as GaAs multi-junction, the sensitized dye cells, organic (which use organic materials, e.g. polymers) and inorganic (which use inorganic substances) cells. Thermal solar collectors are fluid heaters (liquid and/or gaseous) and are classified into concentrator collectors and flat collectors, according to the existence or lack of solar radiation concentration devices. There is also the evacuated tube collector that takes advantage of vacuum to receive solar radiation and at the same time act as a highly efficient insulation for heat losses from the collector to the outside. PVT collectors are classified according to the work fluid used, and the existence or lack of reflectors for the concentration of solar radiation. Thus, these collectors are divided into liquid PVT collectors, air PVT collectors and...
PVT concentrators.

![Diagram](image)

**Figure 1.** Types of solar technologies.

Figure 2 shows a typical solar radiation spectrum and the spectral response of a silicon solar cell. This spectral response or spectral sensitivity defines the range of the radiation at which the cell functions most effectively and influences its efficiency under different radiation conditions. It should be noted that these cells respond primarily in the visible spectrum and the near infrared.

![Solar radiation spectrum and spectral response of a silicon solar cell](image)

**Figure 2.** Solar radiation spectrum and spectral response of a silicon solar cell.

Note that figure 2 shows not only the spectral distribution of the extraterrestrial solar radiation, with AM0 (AM is the Air Mass coefficient), but also the radiation at sea level with sun directly overhead (0°), with AM1 and a 5250°C blackbody spectrum. It should be noted that the emission spectrum of the sun can be considered like that of a blackbody with a temperature of approximately
5800 Kelvin. The yellow areas in figure 2 show the energy absorbed by gases present in air, including water vapor, carbon dioxide, ozone and other greenhouse gases.

3. Review on PVT technology

The research and development of PVT technology has been done since the 1970s. In contrast to the individual photovoltaic panels and thermal collectors, PVT collectors have not yet reached a technological maturity and are still under development. In this section, a review of research on PVT collectors will be presented, according to, among others, their type, performance and application in heat and electricity production. Their modelling and simulation will also be considered.

The International Energy Agency (IEA), by recognizing their potentialities, created a task, “Task 35 - Solar PV/Thermal Systems”, which had its period of operation between 2005 and 2009, the goals of which were to increase the knowledge on PVT solar systems, promote their development, contribute to the standardization of functional tests, and to introduce these solar systems into the global market with quality products and commercial competitiveness. In the context of this task, some publications have been presented [4-6] with the goal of concentrating all information regarding PVT solar systems. This integration of the PV and thermal modules into a single device results not only in improved PV efficiency [7], but also generates more energy per unit area than an independent PV panel or thermal collector. After these studies on the technology, the IEA created the “Task 60 - PVT Systems”, which has an expected period of operation between 2018 and 2020. Its objectives are to provide an overview on the present state-of-the-art of the PVT technology, to improve the testing, modelling and technical characterization of PVT collectors and to find best PVT solutions for all kind of applications.

The PVT collectors can be classified primarily according to the existence, or not, of auxiliary mechanisms for concentration of the solar radiation [8]. The concentrators in collectors use reflective devices in order to increase the amount of solar radiation in a small area (in the PV face) [9-11]. Collectors without concentrators are of the flat type and the solar radiation reaches directly the area of the collector.

The collectors are also classified in accordance with the existence or lack of a solar tracking system, and the type of thermal fluid, which can either be gas (air) [12,13] or liquid, (water with antifreezing characteristics) [14-17]. These authors consider the choice of the thermal fluid as one of the most important selections to make, with the liquid-based PVT collectors (water) having a better performance than the air-based ones.

The assessment of PVT systems and their application areas have been analyzed in [18] and in [19], where the goal of these studies was the optimization of the water flow in the system. The authors considered that, comparing to PVT collectors, there are several practical and technical improvements over the installation of PV and thermal systems separately. These include: a lesser installation area, reduced installation costs and the fact that PV and thermal modules use different parts of the solar spectrum (PV - essentially wavelength of visible light, and Thermal - wavelength of infrared light), making the flat PVT hybrid technology the better fit to explore both radiation ranges.

There are several factors that interfere with the performance of PVT systems, namely the thermal fluid temperature, the mass flow rate of said fluid, the number of glass covers, the thermal flat plate module configuration and the monitoring and control system. In [20], it was reported that, in the analysis of a PVT collector, the temperature reduction verified in the photovoltaic module, due to the thermal fluid, was higher than 10 °C, resulting in an increase of about 5% in the photovoltaic efficiency. In a PVT flat-plate collector, it was found that the absence of a glass cover results in a greater electrical efficiency than with the presence of one. In the latter case, the glass cover must be highly transparent to solar radiation [21] in order to reduce its reflection. On the other hand, the thermal efficiency in PVT collectors rises with the increase of the coefficients of heat transfer, i.e. with the reduction of the thermal resistance. With glass covers, the thermal efficiency of PVT panels is higher. In [22], it is mentioned that an increase of 1°C in the temperature of photovoltaic cells results in a reduction of the electrical efficiency of around 0.4-0.5% for the crystalline silicon, and of around
0.25% for amorphous silicon.

The modelling of a PVT system can be based on known base models of the photovoltaic and thermal modules, with an additional path between them. In most studies, the analysis is performed through the energy balance and may use a steady or dynamic state. Although 3D and 2D models can be used to predict the behavior of PVT collectors, the one-dimensional model (1D) presents rather satisfactory results [23].

Most of the PVT system studies used the TRNSYS or the MATLAB/SIMULINK software. TRNSYS is used especially when the simulation is focused on the thermal part, although the simulation environment also allows for the inclusion of PV models, [24,25]. MATLAB/SIMULINK was used in the study of PVT systems with good agreement when comparing the simulation with experimental results [26].

In terms of market potential, PVT technology is ranked significantly higher than individual PV or solar thermal, and the PVT collector concept will boost solar energy application in line with future development trends of photovoltaic and solar thermal technologies [27].

4. PVT collector modelling
A PVT collector usually combines a photovoltaic module in the incident face, which converts solar radiation into electricity, with a solar thermal absorption module placed behind it, which absorbs and removes excessive heat from the solar cells, thus contributing to its cooling.

Figure 3 shows the basic principle of the PVT energy balance. The performance of the PVT collector can be obtained by combining the efficiencies (electrical and thermal).

![Figure 3. Basic principle of the PVT energy balance.](image)

As shown in figure 3, the electrical efficiency ($\eta_e$) and the thermal efficiency ($\eta_{th}$) of a PVT collector are described, respectively, by the following equations:

$$\eta_e = \frac{Qe}{GA}$$  \hspace{1cm} (1)

$$\eta_{th} = \frac{Qth}{GA}$$  \hspace{1cm} (2)

where $Qe$ and $Qth$ are, respectively, the electric power (electricity gain) and thermal power (heat gain), $G$ the incident solar radiation normal to surface, and $A$ the collector aperture area.

To evaluate the global performance and considering the first law of thermodynamics, the overall efficiency ($\eta_0$) of the PVT is the direct sum of the efficiencies of the electric and thermal modules.

$$\eta_0 = \eta_e + \eta_{th}$$  \hspace{1cm} (3)

The PVT system modelling presented in this work considers these equations and the reference [28], with the appropriate adaptation. To simulate the PVT system, the MATLAB/Simulink software was
5. Case study of a PVT system

The study of the PVT system was carried out at GIRS-RES (Guarda International Research Station on Renewable Energies) of CISE (Electromechatronic Systems Research Center) at the Polytechnic of Guarda, in Portugal (latitude 40.54254791, longitude -7.28117437).

5.1. Details of the system

The PVT collector studied in this work is composed of a PV module – which contains 72 monocrystalline silicon solar cells, 1.4 m² of collector aperture area, and nominal electric power of 200 W – a thermal module with pipes and copper plate, and an insulative material. Figure 4 depicts the complete structure.

![Figure 4. Structure of the PVT collector.](image)

The PVT system generates both electricity and thermal energy in the form of hot water. Figure 5 shows the circuit described, where the other components are also represented, such as the stabilization tank (temperature and system pressure) and the radiator with cooling fan. The latter functions as a thermal resistance, in order to cool the working fluid and, thus, to force a temperature gradient between the outlet and inlet of the PVT.

![Figure 5. Scheme of the PVT system.](image)

The working pressure of PVT system did not exceed the local water supply pressure value, which was of around 1.5 bar.
5.2. Analysis of the PVT data
The results herein presented were observed throughout a typical cloudless summer day in July, at Guarda, Portugal. Figure 6 shows the variation of the solar power ($G$) and PVT electrical power over time. The experimental results ($Q_{e_{exp}}$) are compared to the simulation data ($Q_{e_{sim}}$). The results show a good agreement between the experimental and simulation values for the PVT electrical power, which evidences the validity of the model used.

![Figure 6. Solar radiation ($G$), experimental ($Q_{e_{exp}}$) and simulation ($Q_{e_{sim}}$) results of PVT electrical power.](image)

For the same time frame, the PVT electrical power ($Q_{e_{exp} \text{ PVT}}$) was experimentally compared to the electrical power of a regular PV panel ($Q_{e_{exp} \text{ PV}}$) with the same electrical characteristics of the former. Figure 7 displays the correspondent results. The results show that both electric powers reach their maximum in the same time interval, although the PVT is able to output significantly more power than the PV during the apogee of solar power. This difference can reach up to around 40 W.

![Figure 7. Experimental results of solar radiation ($G$), of PVT electrical power ($Q_{e_{exp} \text{ PVT}}$) and PV electrical power ($Q_{e_{exp} \text{ PV}}$).](image)

Regarding the PV panel, it can be confirmed that an increase in the temperature of the solar cells – strictly linked to solar radiation – results in a negative influence. Thus, it can be verified that, in the period from 12:00 to 16:00 (the time interval of highest solar radiation and temperature in the solar cells), there is no increase of generated power; instead, this value stays roughly the same, with a slight
decreasing monotony.

As for the PVT, for the same time interval, it can be observed that the effect of the temperature in the solar cells is significantly less, since the generated power curve, $Q_{eexpPVT}$, follows the solar radiation trend. This is due to the cooling of the solar cells resourcing to the thermal fluid: this situation reveals the importance of solar cell cooling for electric power gains.

Figure 8 shows the variation of the electrical efficiency throughout the day, with simulation ($\eta_{e\text{sim}}$) and experimental ($\eta_{e\text{exp}}$) data. It can be verified that the two curves have the same trend and good agreement between them, which validates, once again, the modelling used in the PVT system.

![Figure 8. Electrical efficiency of PVT: simulation ($\eta_{e\text{sim}}$) and experimental ($\eta_{e\text{exp}}$) results.](image)

As can be seen in figure 8, the experimental results indicate that the higher electrical efficiency of the PVT is about 15%, which is confirmed by the theoretical analysis.

The maximum thermal efficiency of the PVT was determined to be about 60% and this value depend mainly on crucial parameters, such as an appropriate mass flow rate and a good thermal conduction between PV cells and the absorber plate. Thus, and taking into account the experimental data, the maximum total efficiency of the PVT is 75%, which is in agreement with other related works [29,30].

5.3. Thermography analysis of the PVT

Infrared thermography is a method of non-destructive analysis that is applied in several areas, namely thermal energy systems and various areas of preventive maintenance, where it is used to identify faults and defects. It is already a consolidated technique in this regard [31]. In the case of PV evaluation, thermography is a rapid analytic technique that has demonstrated great reliability, being relevant not only for preventive maintenance and early problem detection, but also for quality analysis of photovoltaic modules. The monitoring of temperature values allows for the detection of anomalies before they become faults, and diagnosis can be achieved without interrupting the operation of the monitored equipment [32].

Bearing in mind that PV analysis using thermography is already a matured concept [33], the same techniques were used in the present PVT case. In this context, and considering that the literature on PVTs infrared analysis is scarce, the objective herein is to present some information about hot-spots (localized heating in the cell or module, with temperatures much higher than in neighbouring regions), which testify to the presence of defective solar cells. Reference [34] can be consulted for issues related to the detection of hot spots in PVTs and to the investigation of the correlation between the PV component temperatures of PVT collectors, regarding their electrical and thermal behaviour.

Figure 9 shows the difference in temperature between two points of the same PVT. The value of 39.9°C represents the temperature of the entire front area, with the exception of a cell area that displays a temperature of 48.9°C. The cell with the temperature of 48.9°C is considered a hot-spot.
The cooling fluid in (indirect) contact with the cell is insufficient to provide enough cooling to eliminate the hot-spot. Thus, if such situation persists, it may cause overheating in that zone, thus leading to cell failure over time.

![Figure 9. Higher temperature point in a PVT cell.](image)

6. Conclusions
The various PVT collector types have been studied theoretically, numerically and experimentally for more than four decades. In this article a critical review of solar PVT technologies has been presented. Afterwards, a system of a flat plate PVT collector with water as a working fluid was analyzed. The study was conducted at CISE | GIRS-RES, at the Polytechnic of Guarda, Portugal.

A PVT collector has been modelled and validated with experimental data, showing good agreement between datasets. The results show that the electrical power of the PVT collector can easily be increased by simply cooling the solar cells. The PVT collectors are considered rather useful when it is necessary to generate thermal and electric energy simultaneously, and all the more so when there is a commitment to use renewable energies with space limitations.

In relation to hot-spots that may occur in solar cells, thermography was used with the same PV analysis techniques. In the present case, a situation has been detected in one of the cells of the PV module, where overheating is observed when comparing to the rest of the PVT cells. If such situations are not resolved over time, the solar cells may become defective, and the damage might extend to the entire PV module.

Although not yet widespread, PVT collectors are expected to have great market potential in the near future.

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