Water flat plate PV–thermal collectors: A review

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Received 8 August 2013; received in revised form 17 January 2014; accepted 21 January 2014

1. Introduction

Currently, commercial solar cells typically have an electrical efficiency ranging from 5% to 25%, meaning that a significant part of the incident solar energy can be harvested in the form of heat and used for low-temperature heating. For this reason, much research effort has been spent on the development of hybrid photovoltaic–thermal (PVT) collectors technology (water or air) (Aste et al., 2008; Chow, 2010). Two are the main benefits related to PVT technology: first, the efficiency of PV cells can be increased by actively cooling the PV laminate and the removed heat can be subsequently used. Second, incorporating a PV and a thermal system into a single unit, the total area dedicated to solar energy devices can be reduced. For these reasons, many studies concur that a well-designed hybrid system can achieve better performances compared to two separated systems (Zondag et al., 2003; Van Helden et al., 2004; Fraisse et al., 2007; He et al., 2011).

In this sense, the PVT technology most investigated in recent times is based on systems which use water as heat transfer fluid, because they achieve higher overall efficiencies than air systems (Ibrahim et al., 2011), due to greater heat capacity of water. This paper will focus on flat plate solar water PVT collector, according to their technological components.

2. Basic concepts

PVT technology allows to produce electrical and thermal energy at the same time, through the direct conversion of solar radiation.

The operating principle of PVT collectors is the generation of electricity and, at the same time, the transfer of the thermal energy absorbed by the photovoltaic cells to a fluid (liquid or gaseous), enabling its subsequent use. The hybrid PVT water system allows to remove a part of the thermal fraction of solar radiation collected by photovoltaic cells and not converted into electricity, and to use it, for example to heat domestic hot water by means of a suitable storage tank.

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Nomenclature

A_c	area of the collector, m^2
AM	air mass
C_{el}	electricity energy cost, domestic currency
C_{th}	thermal energy cost, domestic currency
C_t	economic benefit generated by the system, domestic currency
C_0	capital cost, domestic currency
D	channels' diameter, m
E_{el}	electrical energy, W h
E_{th}	thermal energy, W h
$\dot{E}_{el}$	photovoltaic energy rate output per unit area, W/m^2
$\dot{E}_{th}$	thermal energy rate output per unit area, W/m^2
$\dot{E}_{\chi_{el}}$	photovoltaic exergy rate output per unit area, W/m^2
$\dot{E}_{\chi_{th}}$	thermal exergy rate output per unit area, W/m^2
$\dot{E}_{\chi_{sun}}$	solar radiation exergy rate input per unit area, W/m^2
f	solar fraction
G	solar irradiance on the module plane, W/m^2
G_{STC}	solar irradiance on the module plane at standard test conditions, W/m^2
H	solar irradiation on the module plane, W h/m^2
I_{STC}	current measured in standard test conditions, A
n	working life, years
NPV	net present value, domestic currency
Q_u	useful heat of the thermal component, W
r	number of years
k	discount rate
t_{amb}	ambient temperature, °C
t_m	mean fluid temperature of the collector, °C
t_{cell}	PV module temperature, °C
t_r	reduced temperature, $°Cm^2/W$
T_{amb}	ambient temperature, K
T_m	mean fluid temperature of the collector, K
T_{out}	outlet fluid temperature from the collector, K
T_{sun}	solar radiation temperature, K
P_{STC}	nominal power of the PV measured in standard test conditions, W
STC	standard test conditions: $G_{STC} = 1000\ W/m^2$, $t_{cell} = 25$ °C, AM = 1.5
V_{STC}	voltage measured in standard test conditions, V
W	distance between channels, m
α	temperature current coefficient of the PV cells, %/°C
β	temperature power coefficient of the PV cells, %/°C
γ	temperature voltage coefficient of the PV cells, %/°C
k_ϑ	optical reflection correction factor
η_{el}	electrical efficiency
$\eta_{el,n}$	nominal efficiency at standard test conditions
η_{PES}	primary energy saving efficiency
η_{th}	thermal efficiency
η_{Tpower}	average efficiency of power plants at national level
η_{tot}	overall efficiency
$\eta_{€}$	economic efficiency, economic value of the energy produced, W h
τ_θ	trasmittance at angle of incidence ϑ
τ_n	trasmittance at normal incidence

Generally, the thermal fraction is transferred from PV cells to the fluid through a channeled plate (heat exchanger), connected to the cells.

The total conversion efficiency of solar energy into electricity and heat is the main parameter that characterizes the performance of a hybrid PVT collector. In many researches (Lalović et al., 1986; Garg et al., 1990; Hayakashi et al., 1990; Sharan and Kandpal, 1992; Bergene and Løvvik, 1995; Sopian et al., 1996; Fujisawa and Tani, 1997; Hegazy, 2000), it is simply defined as the total amount of thermal and electrical efficiency, according to the following formula:

$$\eta_{tot} = \eta_{th} + \eta_{el} \tag{1}$$

In particular, n_{th} can be calculated by the widely-known formula defined for solar thermal collectors (Duffie and Beckman, 2006):

$$\eta_{th} = \frac{Q_u}{G_{STC} \cdot A_c} \tag{2}$$

where Q_u is the usable heat collected, G is the irradiance on module plane and A_c is the collector area.

However, thermal efficiency is a function of the conditions at which it is calculated. For this reason, it is expressed as a relation of the reduced temperature (t_r), defined according to the following formula:

$$t_r = \frac{t_m - t_{amb}}{G} \tag{3}$$

where t_m is the mean fluid temperature and t_{amb}, is the ambient temperature.

In order to obtain a single value of thermal efficiency, it is therefore preferable to refer to the maximum value of the efficiency curve, which is in correspondence of a reduced temperature equal to zero.

The electrical efficiency ($\eta_{el,n}$) at STC of the PV section is obtained from:

$$\eta_{el,n} = \frac{P_{STC}}{G_{STC} \cdot A_c} \tag{4}$$

where P_{STC} is the nominal power of the PV module, which can be expressed as the product of voltage (V_{STC}) and current (I_{STC}) at the maximum power point in standard test conditions (STC), according to the following formula:

$$P_{STC} = V_{STC} \cdot I_{STC} \tag{5}$$

As already known, while the dependence of the current on the thermal level is generally neglected, the effect of temperature on voltage is not to be underestimated. For this reason, the electrical efficiency at STC is to be corrected according to the module temperature coefficients for I, V, and P_{max} (α, γ and β, respectively). In particular, the actual module efficiency can be rewritten as follows (Evans, 1981; Charalambous et al., 2007):

$$\eta_{el} = \eta_{el,n} \cdot (1 - \beta \cdot [t_{cell} - 25°]) \tag{6}$$

where t_{cell} is the module temperature and β is the temperature coefficient on power, expressed in%/°C.

However, the overall efficiency parameter described above may be misleading as for the performance evaluation of the hybrid PVT component. From a thermodynamic point of view, in fact, a kW h of electricity cannot be directly compared with a kW h of heat, because it is not equally valuable (Coventry and Lovegrove, 2003). It is therefore more accurate to compare the two quantities in terms of primary energy, by introducing another efficiency parameter called Primary Energy Saving efficiency (η_{PES}) (Huang et al., 2001):

$$\eta_{PES} = \eta_{th} + \frac{\eta_{el}}{\eta_{Tpower}} \tag{7}$$

where η_{Tpower} is the average efficiency of power plants at national level. It depends on the manner whereby electric energy is generated in every reference context. For example, a value of 0.46 (AEEG, 2008) corresponds to the typical mixed fuel system used for electricity production in Italy, while an average value may be assumed to be equal to 0.4, considering the efficiency of electricity production from all fossil fuels in public power plants in OECD countries (Huang et al., 2001; Coventry and Lovegrove, 2003; Trudeau and Francoeur, 2008).

The above described efficiency η_{PES} is based on quantitative criteria, rather than qualitative. Thermal energy in fact does not take into account the output temperature of the fluid from the collector, which is an important parameter in order to evaluate the application potential. Therefore it is useful to define the exergetic efficiency, which represents the ratio of the rate of exergy output to the rate of exergy input of a given system. Exergy is the portion of the total energy of a system that is available for conversion to useful work; in particular, it is the quantity of work that can be performed in relation to a reference condition, usually the surrounding environment condition (Chow et al., 2009; Mishra and Tiwari, 2013). In a hybrid PVT collector, electricity can be easily and univocally converted into work, while the amount of thermal energy transformable into work is related to the Carnot efficiency.

Exergetic efficiency (ε) in a PVT system is thus the ratio of total exergy output (solar and thermal exergy) to total exergy input (solar radiation) and can be defined as (Chow et al., 2009):

$$\varepsilon_{PVT} = \frac{\int_{t_1}^{t_2} (A_c \cdot \dot{E}_{\chi el} + A_c \cdot \dot{E}_{\chi th}) \cdot dt}{A_c \cdot \int_{t_1}^{t_2} \dot{E}_{\chi sun} \cdot dt} \tag{8}$$

where A_c is the collector area, $\dot{E}_{\chi el}$ is the photovoltaic exergy output per unit PV area, $\dot{E}_{\chi th}$ is the thermal exergy output per unit area, and $\dot{E}_{\chi sun}$ is the exergy input of solar radiation. Since the original nomenclature of the authors was maintained, just in Eq. (8) t is the time of the calculation interval. Exergy outputs are related to energy outputs as follows:

$$\dot{E}_{\chi th} = \dot{E}_{th} \cdot \left(1 - \frac{T_{amb}}{T_{out}}\right) \tag{9}$$

$$\dot{E}_{\chi el} = \dot{E}_{el} \tag{10}$$

where $\dot{E}_{el}$ and $\dot{E}_{th}$ represent respectively the electrical and thermal energy rate produced by the PVT system and T_{out} is the output temperature of the fluid from the collector.

The most simplified formula to evaluate the exergy input was proposed by Jeter (1981)

$$\dot{E}_{\chi sun} = \left(1 - \frac{T_{amb}}{T_{sun}}\right) \cdot G \tag{11}$$

where T_{sun} is the solar radiation temperature, equal to 6000 K.

Another method to evaluate the performance of a PVT collector can be based on the evaluation of the economic benefit related to the energy produced. The economic efficiency can thus be defined as follows:

$$\eta_E = \frac{E_{th} \cdot C_{th} + E_{el} \cdot C_{el}}{H \cdot A_c} \tag{12}$$

where E_{el} and E_{th} represent respectively the electrical and thermal energy produced by the PVT system, C_{el} and C_{th} are the costs related to the two forms of energy.

It is important to note that E_{th} must be calculated as the useful fraction of the thermal requirements of the user covered by PVT collectors, and is thus dependent on the specific installation context of the PVT system. Similarly, C_{th} cannot be defined in general terms, since it is function of the efficiency and the fuel/energy source of the main thermal system that is integrated by the PVT plant. Therefore the product ($E_{th} \cdot C_{th}$) represents the solar saving generated by the thermal part of the PVT system. Similarly, E_{el} is also to be calculated considering the system localization and configuration, because in a PVT system electrical performance is strictly related to the thermal one. On the other hand, C_{el} is the average cost of electricity, which can be easily defined in advance, by considering the average market prices. The economic efficiency thus represents the total benefit generated by the PVT system, expressed in the domestic currency, divided by the solar energy available on the PVT collectors. The higher is η_E, the greater is the economic benefit generated by each kW h of solar radiation.

3. Water flat plate PVT collector classification

PVT collectors are generally classified depending on their components, and how the fluid flows inside them. The widest classification adopted in literature comes from Zondag et al. (2003) and distinguishes four main types of PVT, shown in Fig. 1, according to the water flow pattern and the heat exchange method: *sheet and tube* (1), *channel* (2), *free-flow* (3) and *two-absorber types* (4).

The *sheet and tub*e (1) type consists of a channeled plate, made of metal or rarely of polymeric material, overlaid by a photovoltaic sandwich or, in order to obtain a greater efficiency, laminated photovoltaic cells. The heat exchanger consists of a flat plate to which circular cross-section channels are generally soldered and arranged in parallel.

The *channel* type (2) differs from the first because the fluid channel is located *above* the photovoltaic component. Such channel is realized by interposing a glass over the photovoltaic cells. In this case, the analysis of solar radiation transmittance through the fluid must be performed carefully, because the presence of this layer could reduce the performance of the component. In addition, the presence of fluid in the channels below the electrical component, as is the case of types 3 and 4 as well, requires special attention, in order to ensure electrical safety.

In the *free-flow* collectors (3) the fluid flows unrestrained above the photovoltaic module. This configuration still remains purely theoretical, due to the difficulty to realize a free surface, which could lead to the formation of condensation in the cover, with a consequent reduction of solar energy throughout the module.

The last type (4), characterized by dual-channels, uses a semitransparent photovoltaic module as the primary absorber. The heat transfer fluid flows above it, but below it, spaced by a layer of air, there is a black metal plate, with the role of secondary channeled absorber. This system is composed of many elements which make the construction more complex, increasing the weight and the final cost.

In this paper the main components that constitute the *sheet and tube* type (1) are analyzed in detail. In particular, recent researches (Chow, 2010) have shown that many variants of the *sheet and tube* type were developed, all having in common the presence of channels below the PV cells, but being characterized by different configurations of the channels pattern.

For this reason, in this paper the term *sheet and tube* will be used only to refer to the classical configuration (1) explained above. Different configurations, similar to the classical one (such as the *roll bond* and the *box channel* designs), will be introduced, explained and defined in different ways.

PVT modules can also be classified depending on the presence or absence of the air gap formed by the transparent frontal cover, as shown in Fig. 2. The two types of PVT collector are called “covered” and “uncovered” (Eicker and Dalibard, 2011; Kim and Kim, 2012a). However, it is important to note that a protective layer for the photovoltaic cells is always required.

4. Transparent frontal cover

Part of the heat absorbed by the collector is lost through radiation and convection to the environment. When the absorber is in direct contact with the environment, as in the case of uncovered collectors, the heat losses are considerable and the fluid temperatures that can be reached are more influenced by the ambient temperature.

For these reasons, it is generally convenient to interpose between the photovoltaic laminate and the external environment a transparent cover, whose goal is to transmit the greatest part of the incident solar radiation to the absorber surface, restricting convection and radiation losses.

The air gap between the PV laminate and the cover material must be thin enough to benefit from the insulating

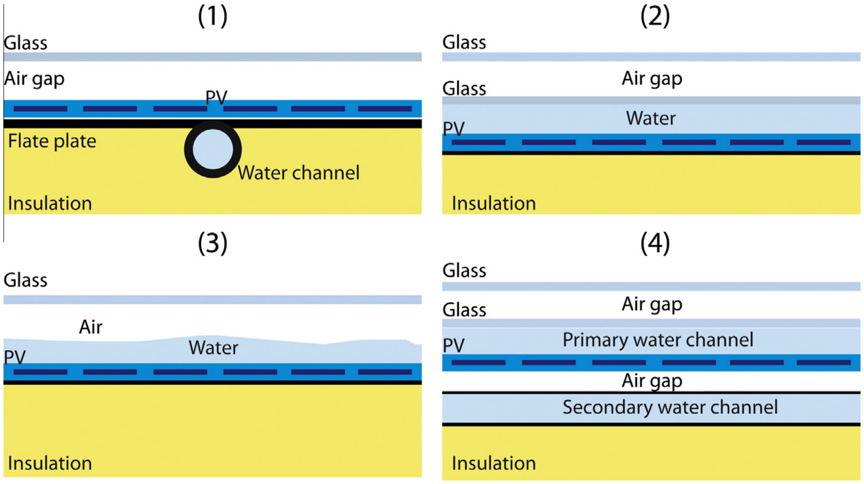

Fig. 1. PVT classification.

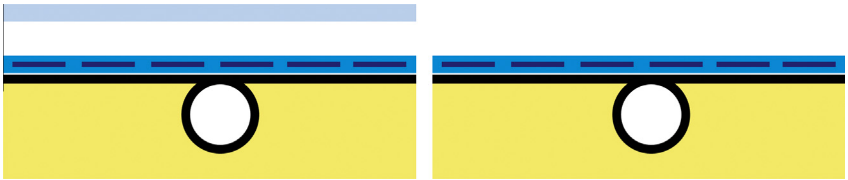

Fig. 2. Covered and uncovered PVT collector.

properties of air, preventing at the same time convective flows, which are the main cause of thermal losses, similarly to the traditional thermal collectors.

Generally the gap depth is between 15 and 40 mm (Gordon, 2001); a thicknesses greater than 40 mm could facilitate the creation of micro turbulences in the gap, which increase the convective heat transfer between the thermal absorber and the front cover.

The most widely used material is glass, due to its optical and mechanical properties, which make it ideal for this type of application (Deubener et al., 2009).

From the radiation point of view, the glass behaves as a unidirectional filter, since it is characterized by high transparency values in the visible and near infrared spectrum, and at the same time has an opaque behavior for far infrared wavelengths, which characterize the radiation emitted by the hot plate. In detail, the glass presents a selective radiative performance, which means that its transmittance properties, which are reflectance, absorptance and emittance, change according to the incidence angle of the radiation and the wavelengths which characterize it.

In particular, the smaller is the angle between incident radiation and the perpendicular to the glass surface, the lower is the reflected fraction. During the day, in fact, incident solar radiation forms with the modules a wide range of angles, causing a considerable variation of the transmittance coefficient and, consequently, of the absorptance and reflectance coefficients.

The reduction of the optical coefficient (Aste and Del Pero, 2006) through the front cover of a module is therefore a function of the incidence angle, according to the Fresnel law, which can be expressed through the following formula:

$$k_\theta = \frac{\tau_\theta}{\tau_n} \tag{13}$$

where k_θ is the optical reflection correction factor; τ_θ is transmittance at angle of incidence θ; τ_n is transmittance at normal incidence.

Generally k_θ has values close to 1 for angles of incidence up to 60°; after that the value decreases by about half for angles up to 70°, until reaching values close to 0 for angles of incidence greater than 80° (Duffie and Beckman, 2006).

The most widely used glass is characterized by a low content of iron oxide, a thickness of about 3–4 mm (Bai et al., 2012; Tiwari and Sodha, 2006; Chow et al., 2006; Sandnes and Rekstad, 2002), and a transmission coefficient for perpendicular angle of incidence greater than 90%. Note that the presence of the front cover glass in a hybrid PVT collector will cause a double transmission loss of solar energy, due to the glazed protection layer already present in the photovoltaic laminate.

Although it decreases the electrical performance of the module proportionally to the reduction of the transmittance coefficient, the presence of the cover significantly increases the thermal efficiency. Some researches (Sandnes and Rekstad, 2002; Zondag et al., 2003; Van Helden et al., 2004; Tripanagnostopoulos et al., 2005; Fraisse et al., 2007; Santbergen, 2008) estimate that the overall efficiency of covered PVT collectors is higher compared with the efficiency of uncovered collectors, as explained in Section 4.1. However, as already mentioned above, the overall efficiency of a PVT component is not a satisfactory indicator for the purpose of describing the global performances, which should rather be expressed in terms of primary energy or economic saving.

PVT collectors covered by glass usually have a maximum aperture area of 3 m^2, due to the wind and structural loads on the front cover (Gordon, 2001).

Instead of glass, other lighter and stronger materials, that provide a greater aperture area, such as polycarbonate, polymethylmethacrylate, polyvinyl fluoride, can be adopted, as described in Table 1. The advantages of synthetic materials consist in costs and weight lower than glass, while the disadvantages are represented by the degradation of the optical and mechanical properties over time, mainly caused by the exposure to ultraviolet radiation and to temperatures up to 130 °C (Affolter et al., 2000; Zondag and Van Helden, 2002) that can be reached in covered PVT collectors (Mark, 2006).

These negative aspects will probably limit the use of these materials for future applications in the hybrid PVT modules (Zondag et al., 2003).

In order to increase the thermal efficiency of covered collectors, some other measures can be adopted to reduce convective losses through the gap, such as the replacement of the air between PV module and coverage with a rarefied gas or the vacuum, as already suggested by (Zondag, 2008).

4.1. Comparison between covered and uncovered PVT collectors

As already mentioned, from an energy point of view covered collectors have a higher thermal performance than the uncovered components, due to lower convection and radiation losses (Fraisse et al., 2007; Chow et al., 2009,).

Table 1
Main covering material used in PVT collectors.

Glass	Polymer
Float glass	Polycarbonate (PC) – *Lexan*, *Qualex*
Low iron glass	Polyethylene terephthalate (PET) – *Mylar*
	Polymethylmethacrylate (PMMA) – *Perspex*, *Plexiglas*
	Polytetrafluoroethylene (PTFE) – *Teflon*
	Polyvinyl chloride (PVC) – *Nouvolux*
	Polyvinyl fluoride (PVF) – *Tedlar*
	Cellulose acetate-butyrate (CAB) – *Butyrate or Uvex*

Specifically, the increase of thermal production provided by the presence of the cover can be estimated between 10% and 30% (Tripanagnostopoulos et al., 2002; Nualboonrueng et al., 2012; Fujisawa and Tani, 1997), depending on the type of collector, insulation and material considered; at the same time, however, electrical output decreases by 1–10%, since it is a function of the transmission factor of the cover, type of cells and heat exchange with the fluid (Fujisawa and Tani, 1997; Zondag et al., 2003; Nualboonrueng et al., 2012); higher decrease values are sometimes reported in literature, referred to sites in which the influence of ambient temperature is predominant (Tripanagnostopoulos et al., 2002).

It is therefore crucial to study the performance of PVT components as a function of technological and environmental parameters. In fact, as shown Chow et al. (2009), the variation of some parameters such as PV cell efficiency, ratio of water mass to collector area, packing factor (ratio of the total solar cell area to the total collector area), average wind velocity, radiation and mean ambient temperature, has a different influence on energy efficiency with respect to exergetic efficiency. For example, according to the PVT configuration studied by the authors just mentioned, if the incident solar radiation strongly increases, both energetic and exergetic PV efficiencies of the PVT collector decrease. However solar radiation is a favorable factor for the thermal exergy efficiency, because it increases the output water temperature. Thus in covered PVT collectors the favorable factor outweighs the unfavorable factor and consequently the overall PVT exergy efficiency increases according to solar radiation.

For these reasons, a careful analysis of the above mentioned parameters can lead to the decision to adopt a covered collectors rather than an uncovered one.

5. Photovoltaic section

The photovoltaic technology implemented in the PVT collectors is based on the conversion of solar radiation into electrical energy by means of semiconductor materials which, as is well known, are able to release electrical charges in function of the solar radiation intensity. The photovoltaic cell is typically composed by a thin layer of semiconductor material with variable thickness, depending on the specific technology (Duffie and Beckman, 2006; Aste, 2002).

One of the main parameters used to assess the performance of a photovoltaic component is represented by the Performance Ratio (PR), which is a dimensionless quantity that measures the deviation between the actual performances of a PV system and those measured at Standard Test Conditions (Jahn et al., 2004).

The main loss mechanisms that affect the PR (Aste and Del Pero, 2006) of the photovoltaic part of a PV component and hence of the electrical section of a hybrid collector can be summarized as follows:

- optical losses, induced by the glass;
- spectral radiation losses, depending on the spectrum composition of the incident solar radiation and on PV cells' quantum efficiency;
- temperature losses, caused by the fact that the cell electrical power decreases when the cell temperature increases, according to the temperature coefficient on power (β).

It is important to note that the temperature coefficient on power (β) is influenced by the temperature coefficient on voltage (γ) and by the temperature coefficient on current (α). γ takes into account the decrease of the voltage value when the temperature increases, while α considers the slight increase of current according to the temperature increase.

The most widespread technology on the market used to make PVT modules is the crystalline silicon (c-Si), which, in spite of the high thickness of the cells, approximately equal to 0.2–0.5 mm, provides higher electrical efficiencies than thin-film technologies. The c-Si commercial modules are characterized by an efficiency typically in the range of 13–22% and a temperature coefficient on power between 0.3% and 0.5%/K (Kalogirou and Tripanagnostopoulos, 2006; Tiwari et al., 2011). Crystalline technology is separated in multiple categories according to crystallinity and crystal size in the resulting wafer. The most used categories are monocrystalline silicon cells (sc-Si) and polycrystalline silicon cells (mc-Si), which have very similar characteristics, although the conversion efficiency of the mocrystalline cells is slightly higher.

To overcome the high temperature coefficient that is sometimes decisive in the characterization of the electrical performance of a PVT module, the behavior of amorphous silicon cells applied to hybrid components has been studied in various researches. The a-Si technology in fact is characterized by lower temperature coefficients, typically equal to 0.2–0.3%/K (Pratish et al., 2007) and a thickness of the silicon deposit between 200 and 600 nm (Monokroussos et al., 2011).

Although amorphous silicon usually has a lower cost per watt peak (pvXchange, 2013), if compared to other technologies, it is generally characterized by a poorer electrical efficiency that requires more surface with respect to the same nominal power (Tiwari et al., 2011).

Anyway, subject to high temperatures (from 50 °C to 100 °C), amorphous silicon undergoes a sort of regeneration

Table 2
Main features of photovoltaic technologies used in PVT collectors.

	Crystalline Silicon	Amorphous silicon
Module efficiency (%)	13–22%	7–13%
Temperature coef. (%/K)	0.3–0.5	0.2–0.3
Cell thickness (mm)	0.2–0.5	0.0002–0.0006
Cost (€/W_p)	0.55–0.85	0.35–0.45

process, which increases the electrical efficiency (initially lost due to the Staebler-Wronski effect). That effect, known as *thermal annealing*, can increase the electrical production of the PVT component up to 10.6% compared to modules that do not receive high temperatures cycles. In particular, to achieve that result, the a-Si PV cells were annealed for 1 h at 100 °C on a 12 h cycle and for the remaining time the cells were degraded at 50 °C (Pathak et al., 2012).

Thermal annealing, combined with low temperature coefficients, makes amorphous silicon an interesting technology for the future development of PVT components.

In many researches (Kalogirou and Tripanagnostopoulos, 2006; Kalogirou and Tripanagnostopoulos, 2007; Nualboonrueng et al., 2012,) however, the authors concluded that the electrical performance of PVT collectors made with amorphous silicon technology is lower if compared with that of PVT modules with crystalline cells. This conclusion is not totally correct, since a real comparison between the two technologies should be done with the same power installed and not, as often happens, in function of the PVT active surface.

In order to assess the best technology to be adopted for each application, a technical and economic analysis should be carried out. In general, amorphous silicon cells are particularly suitable in covered PVT modules, in which cells surface can reach high temperatures. Crystalline silicon technology, on the other hand, is usually more appropriate for uncovered hybrid modules in which the PV laminate does not reach excessively high temperatures and takes the most advantage from the high efficiencies of crystalline silicon. In Table 2 the main features of the c-Si and a-Si photovoltaic technologies are reported.

In recent years a new type of photovoltaic cells with intermediate properties between the two above photovoltaic technologies has been developed. The photovoltaic sandwich, made with this technology, called HIT (Heterojunction with Intrinsic Thin layer), is in fact constituted by c-Si cells, coated with a thin layer of a-Si. The sandwich obtained allows to use a wide spectrum of solar radiation, with conversion efficiencies of the cell up to 22.5% (Tsunomura et al., 2009) and temperature coefficients in the order of 0.26%/K (Tanaka et al., 1992; Sawada et al., 1994; Green, 2004; Kanevce and Metzger, 2009; Nikolaeva-Dimitrova et al., 2010).

Currently, in literature there are no trials concerning the application of this type of PV technology to the PVT collectors.

5.1. Absorptance coefficient

The absorptance of solar radiation by the photovoltaic section and its subsequent emittance at different wavelengths is an additional parameter that characterize a PVT module.

The photovoltaic cells are in fact optimized for electrical performance: cells are able to convert solar energy into electricity according to the quantum efficiency of the adopted technology.

In particular, an amorphous silicon cell responds to a spectrum between 300 and 820 nm, as shown in Fig. 3 (Sirisamphanwong and Ketjoy, 2012). It converts much energy in the visible wavelengths, thus reflecting the wavelengths tending to infrared. On the contrary, the crystalline technology responds to a wider spectrum, between 300 and 1200 nm (as shown in Fig. 3), in order to convert more energy in the near infrared band (Minemoto et al., 2007; Ishii et al., 2011; Sirisamphanwong and Ketjoy, 2012).

In order to improve the conversion efficiency of a solar cell, an Anti Reflective Coating (ARC) is adopted. It allows to absorb solar energy mainly in the wavelengths useful for cells and minimize the amount of reflected energy. For example, according to the quantum efficiency of the c-Si, ARC absorbs more energy in the wavelengths of red, which determines the characteristic dark blue/black color of the cells.

Currently, referring to average values of absorptance of the photovoltaic cells, it is possible to report value between 85% and 90% for the crystalline technology (Dupeyrat et al., 2011a) and between 88.5% and 93.5% for the thin film technology (Santbergen, 2008).

In order to increase the thermal performance of PVT modules, a low emissivity layer, which limits the radiative losses, can be applied on the PV laminate. For such purposes metal coatings, such as tin oxide, indium oxide and tin oxide and zinc, are the most used (Löffler, 2005; Platz et al., 1997). However, the low emissivity layer on the surface of the photovoltaic laminate increases both the reflection losses and the temperature of the cells.

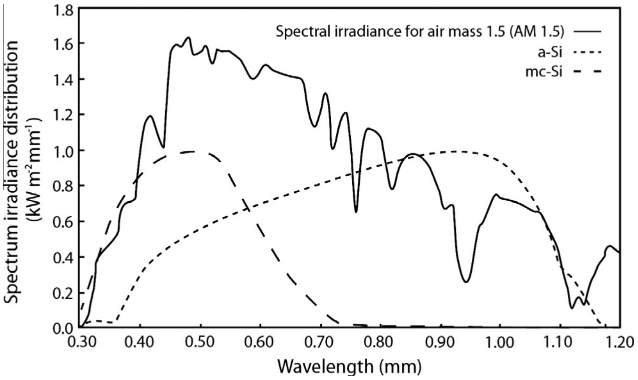

Fig. 3. Spectrum irradiance distribution (adapted from: Sirisamphanwong and Ketjoy, 2012).

Studies carried out by Santbergen (2008); Santbergen et al. (2010) on a glass covered PVT collector show that the addition of a low-emissivity layer increases by up to 3%, depending on the plant type, the thermal performance of the PVT module, but the electrical efficiency decreases by about 1%.

Moreover, it is important to note that in a PV module a rear white sheet is generally used to reflect the light in the non-active area. This can lead to a slight increase in the electrical efficiency. However, in the case of PVT collectors, this leads to larger reflection losses and therefore to a reduction of usable heat (Shimokawa et al., 1986).

According to the results presented, further comparative researches should be conducted to evaluate the most appropriate selective behavior of photovoltaic technology, in order to increase both the electrical and thermal performances of the PVT component.

5.2. Electrical configuration of the cells

In a photovoltaic module, cells are generally connected in series, in order to have higher output voltages and, consequently, lower ohmic losses.

In facts, in in-series connections the voltage increases, whereas in parallel circuits the current value increases. This means that a group of solar cells connected in series has the current of a single cell, but has an output voltage that is the sum of the voltages of each PV cell. It should be noted that, in high power modules, in some cases there are two series connected in parallel.

Moreover, the voltage of a single PV cell is affected by its working temperature: as the temperature increases, voltage decreases according to the temperature coefficient on voltage, while the current slightly increases according to the temperature coefficient on current.

Since in the PVT collectors the temperature distribution is not uniform across the plate, not all the cells will operate at the same voltage/current, therefore the overall electrical power of the module is affected by the electrical configuration. In order to analyze the effect of temperature distribution in function of the electrical configuration, several authors (Smith et al., 1978; De Vries, 1998) carried out theoretical and experimental analyses of in-series and parallel connection, at different temperature gradients.

The temperature effect was examined by Lambarski (Lambarski, 1984), who found a very small dependency on temperature in the case of in-series connections (1%), but a large effect in the case of all cells connected in parallel, with a loss of about 17%. Parallel connection, however, is a scarcely adopted configuration in photovoltaic technology, due to the greater section needed for wires.

Recently, CFD analysis and simulations were carried out by (Aste et al. (2012b), with the aim to identify the optimal electrical configuration of the cells, in two different flat plates.

The research shows that, considering ohmic and temperature losses, the modules with cells connected only in series are to be preferred, since they assure a higher output power. In particular the examined PVT collector with cells connected in series has a power greater by 3% than the same PVT module with two series of cells connected in parallel.

6. Thermal absorber

In a PVT solar collector, the flat plate is the main functional element, since it transfers the solar energy collected by the photovoltaic laminate to the fluid. Its main properties are its thermal conductivity and specific heat capacity, reported in Table 3. The first should be as high as possible, to allow the passage of the heat flux from the cells to the fluid. The specific heat capacity of the plate should instead have a low value, in order to allow fast reaction times according to the different meteorological conditions (for example in the presence of fluctuating conditions) and to optimize the management of the available heat energy, even in low quantities (Aste and Groppi, 2007).

For this reasons, PVT plates are generally made of metallic material, such as copper, aluminum or more rarely steel or polymers. The upper flat side of the plate allows the perfect adhesion of the cells or the PV laminate, thus increasing the removal of heat from the photovoltaic component.

The various types of plates differ according to manufacturing techniques, which also determine the choice of the material to adopt and the channel configuration as shown in Table 4. In the following paragraphs the most commonly adopted flat plates will be analyzed: they are *sheet and tube*, *roll bond* and *box channel* (Fig. 4).

6.1. Sheet and tube design

The *sheet and tube* configuration consists of a flat plate to which are generally welded, soldered or glued circular cross section channels.

The *sheet and tube* flat plate is generally made of copper, which presents as a main advantages ease of manufacturing, high conductivity (about 380 W/m K) and low specific heat capacity (350 J/kg K) of the material adopted. The bonding technique of the circular channels involves a small and not perfect contact surface between plate and pipes, which consequently inhibits the thermal exchange. Despite that, copper enables the use of very thin plates, about 0.2 mm, which improves the heat exchange between the fluid and the PV section, as well as allowing the use of less material.

Depending on the increasing cost of copper, observed from 2004 to 2012, by more than 400% (International Cablemakers Federation, January 2013), various technical and economical optimization measures were considered for the application of copper plates in PVT collectors, like the appropriate number of channels to apply to the plate, the adequate size and thickness of the channels' diameter and in general all the features which affect the amount of

Table 3
Main features of absorber materials.

Absorber material	Thickness (mm)	Density (kg/m^3)	Thermal conductivity (W/m K)	Heat capacity (J/kg K)
Copper	~0.3	8920	380	350
Aluminum	~1	2700	160	900
Steel	~2	7860	50	450
Polymer	~2–3	900–1500	0.2–0.8	1200–1800

Table 4
Main features of the thermal absorber type.

	Material	Channel arrangement	Advantage	Disadvantage
Sheet and tube	• Copper • Aluminum	• Serpentine • Harp	• Easy manufacturing • Low thickness permitted	• Small surface contact between plate and pipe • Variation in costs, depending on the number of channels
Roll bond	• Aluminum	• Any	• Flexibility of channel pattern design • High contact surface area between plate and channel	• Minimum thickness of 1 mm
Box channel	• Aluminum • Polymer	• Harp	• Wider contact surface area between plate and channel	• Special connecting components are required

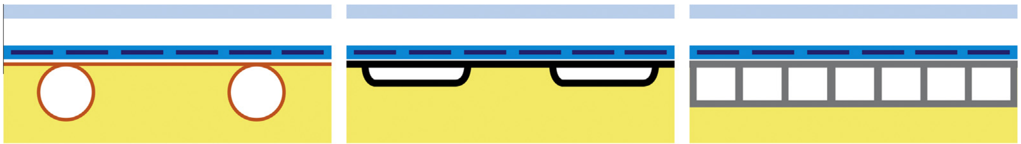

Fig. 4. Thermal absorber classification (sheet and tube, roll bond and box channel).

material used, and thus the overall cost (Charalambous et al., 2011).

Despite the high cost of the material, as shown by Charalambous et al. (2007), the *sheet and tube* design is still convenient if properly configured, according to the good thermal performance of the material and ease of construction.

For such reasons, until few years ago the *sheet and tube* configuration was the most widely used plate for the production of low cost PVT collectors (Bergene and Løvvik, 1995; Bakker et al., 2004; Chow, 2010; Santbergen et al., 2010; Nualboonrueng et al., 2012).

6.2. Roll Bond design

The conventional production of solar absorbers has the disadvantage that only simple pipe channel geometries are possible.

On the contrary the channeled plate made according to the *roll bond* process allows to configure the channels pattern with maximum flexibility, according to various design configurations, maintaining at the same time low production costs; in detail, in the *roll bond* manufacturing technique a sandwich of two aluminum sheets is formed by means of a special hot or cold rolling process. Before bonding together the aluminum sheets, on the inner surface of one sheet the desired pattern of channels is printed with a serigraphic process, using a special ink, which prevents the subsequent welding of the coupling surface along such pattern. Finally, the unbounded pattern of channels has to be lifted up by inflating air at high pressure. As a consequence, a roll-bond solar collector displays the channels integrated in the absorber plate.

Roll-bond technology is already widely used in the manufacturing of heat exchangers, such as evaporators for domestic refrigeration or radiant panels. It has also been investigated in various studies on solar thermal application (Anon, 1984; Joshi, 1986; Hufnagel, 1976; Orlando et al., 1979; Tekkaya et al., 2012) and in the recent past roll-bond exchanger are being introduced in PVT collectors (Boddaert and Caccavelli, 2006), due to the recent technological improvements which allow the PV lamination on the absorber plate (Dupeyrat et al., 2009; Dupeyrat et al., 2011a).

In spite of thermal properties slightly lower than copper (conductivity of about 160 W/m K and specific heat capacity of 900 J/kg K), aluminum has a market price 4 times lower than copper (International Cablemakers Federation, January 2013). Moreover, as already mentioned, the *roll bond* technology allows the making of channel arrangements of any shapes, for example with biomorphic configuration, as it will be shown later, and with any number of ducts per square meters without any change in the final cost of the plate.

Despite the impossibility of the manufacturing process to create aluminum plates with thicknesses lower than

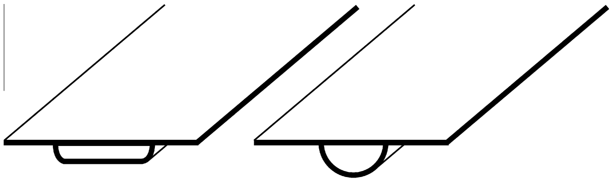

Fig. 5. Sin^2 section and semicircular section.

1 mm (the thickness of a typical copper plate is 0.2 mm), which restricts the thermal conduction transfer from the PV section to the fluid, the *roll bond* absorbers have ducts with semicircular section or, more commonly, with sections called Sin^2 (Pieper and Klein, 2011), as shown in Fig. 5, with a significantly higher contact surface between fluid and absorber, which ensure a high heat transfer coefficient.

6.3. Box channel design

The type called *box channel* is made of parallel ducts with a rectangular cross section which forms the plate. It can be made from an extruded or pultruded profile, in which almost the entire surface is in contact with the fluid in order to significantly increase the convective exchange (Ji et al., 2006b). However, special components are required to connect the inlet and the outlet manifolds to the rectangular channel. This feature greatly increases the costs and the manufacturing issues.

The *box channel* type is generally made of aluminum (Chow et al., 2006; Chow et al., 2007) or, more rarely, can be made of highly ultraviolet-rays-resistant polymeric materials, such as rubber or fiberglass (Cristofari et al., 2002, 2012, Mintsa Do Ango et al., 2013). Polymeric materials are low cost, easy to manufacture and light, but at the same time have several disadvantages, such as a thermal conductivity lower than copper and aluminum and a high thermal expansion coefficient, that could create problems in correspondence of the interface between the thermal and the photovoltaic components (Mark, 2006). In addition, polymeric materials have low resistance to the high temperatures that can be easily reached in PVT modules (Mark, 2006). For such reasons, polymeric materials are only slightly suitable for designing and manufacturing thermal absorbers (Tsilingiris, 2002).

Until now the combination of productive disadvantages and manufacturing high cost have limited the spread of *box channel* plates on the market.

6.4. Channels arrangement

Channels arrangement and configuration, as well as the connection between plate and pipes, have to be designed in order to obtain the best thermal transfer coefficient, at the same time containing the related production cost.

Of course, the possible geometric/morphologic configurations that the channels may assume is also depending on the technology adopted to produce the flat plate. In fact, according to some researches (Van Niekerk et al., 1996; Cristofari et al., 2012), the configuration of the flat plate collector is one of the most important parameter which affects the collector performance.

In general, serpentine and harp arrangements are the most used configurations in combination with the *sheet and tube* design. The first consists of a single continuous channel, created by bending a pipe; it is characterized by high pressure drops and high temperature gradient between input and output. In addition, the high fluid temperature reached by the serpentine arrangement could affect the PV efficiency. For this reasons the serpentine configuration is typically not suitable for hot climates (Al Harbi et al., 1998).

The harp configuration consists instead of several parallel ducts connected together by two transversal channels, as shown in Fig. 6. This channel arrangement ensures low temperature gradients between input and output and a good temperature distribution on the whole surface (Pieper and Klein, 2011), with electrical and thermal benefits on the PVT collector efficiency (Weitbrecht et al., 2002).

Although all channels have generally the same cross section area, a ratio between the area of the header manifolds and the area of the parallel channels equal to 0.2 is suggested in several studies, in order to improve PVT efficiencies (Fan et al., 2005, 2007; Fan and Furbo, 2008).

The comparison between parallel and serpentine configurations under the same boundary conditions shows that the harp collector has a thermal efficiency 4% greater than the serpentine collector (Matrawy and Farkas, 1997).

It is important to note that the comparison between different flat plate configurations is often inadequate, due to the different geometric characteristics of the channels.

Sometimes, in order to obtain a uniform flow distribution in the channels, a geometric variation of the layout, limited to the header manifolds, can be introduced. For example, the so-called *plenum*, shown in Fig. 7, is a manifold configuration that introduces larger pressure drop in the channels; it

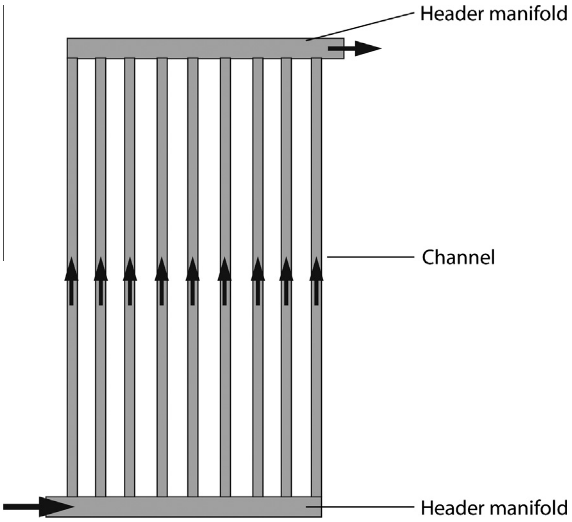

Fig. 6. Harp configuration.

is characterized by high fluid velocity, and smaller pressure drop where the fluid velocity is lower. This system is able to maintain the same flow rate in all channels and consequently an homogeneous temperature distribution.

One of the most innovative channel design is the configuration applied to the so called *Bionical collector* (Hermann, 2008, 2011; Pieper and Klein, 2011,). The plate replicates the structure and morphology of the blood vessels: small size parallels channels are connected together in pairs by bigger channels and then all are collected in the manifold. This configuration thus guarantees high thermal efficiencies, good temperature distribution over the entire plate and very small pressure drops.

The previously described three types are illustrated in Fig. 8.

Previous studies performed by Ibrahim (Ibrahim et al., 2009a) compare theoretically seven types of channel configurations, (direct flow design, oscillatory flow design, serpentine flow design, web flow design, spiral flow design, parallel-serpentine flow design, modified serpentine flow) applied to PVT collectors. Taking into account the overall efficiency of the modules, the authors point out the low efficiency of the serpentine configuration, equal to only 40%. Better results are obtained with the harp configuration, which reaches an overall efficiency of 44%, and with the spiral flow design, which reaches a maximum efficiency of 45%. Further experimental analyses about spiral flow have confirmed the good results obtained with the simulations (Ibrahim et al., 2009b).

6.5. Pressure drop

Pressure drop is an important feature that affects the global efficiency of the system. A greater pressure drop in fact corresponds to a greater energy demand of the pump to set the desired level of mass flow rate. If a PVT collector uses natural circulation, a large pressure drop corresponds to a lower flow rate.

The Fraunhofer Institute – Solar Energy Systems ISE (Hermann, 2011) carried out tests comparing the pressure drop of the *Bionical* configuration with the harp and serpentine configurations. Experimental results show that even at small values of flow rate, in the order of 20 l/m^2 h, the pressure drop of the serpentine is higher by over 400% compared to the *Bionical* configuration. Comparing instead the harp configuration with the *Bionical* one, the increase of pressure drop occurs only at high flow rate values, almost equal to 50% for flow rate values higher than 140 l/m^2 h.

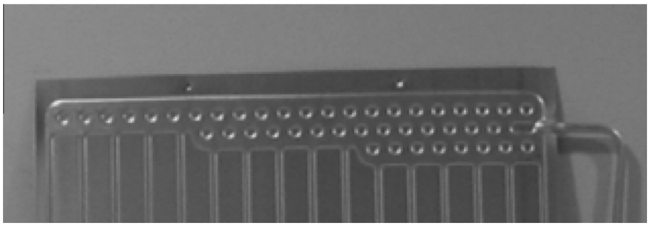

Fig. 7. Plenum manifold configuration (source: Hermann, M., FracTherm – Sonnenkollektoren und Wärmetauscher mit optimierten Strömungskanälen).

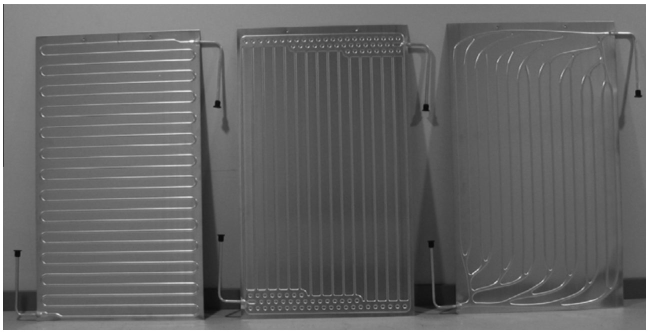

Fig. 8. Serpentine, harp and Bionical configurations (source: Hermann, M., FracTherm – Sonnenkollektoren und Wärmetauscher mit optimierten Strömungskanälen).

6.6. Connection system (PV-Absorber)

The most common connection to couple the photovoltaic part to the thermal absorber is the *gluing* technique. In this way the entire PV laminate is bonded to the flat plate, by means of thermo-conductive glues, which are resistant to high temperatures (Fig. 9a). The *gluing* method has been widely applied in several research projects in the past (Suzuki and Kitamura, 1979; De Vries, 1998; Sandnes and Rekstad, 2002,). However, this technique presents several problems, such as the risk of condensation between the two parts or an increase in thermal resistance. In fact with the gluing technique, some air bubbles trapped between the PV laminate and the plate decrease the thermal exchange coefficient and do not allow any homogeneity in the cells temperature distribution (Zondag, 2008; Dupeyrat et al., 2011b; Charalambous et al., 2011). Van Helden et al. (2004) reports a theoretical value of thermal exchange coefficient between photovoltaic laminate and copper plate, glued with an epoxy aluminum oxide adhesive with a thermal conductivity of 0.85 W/m K, of 100 W/m^2 K.

The same material was analyzed experimentally in a c-Si PV laminate glued onto the surface of a standard thermal absorber. The measured thermal exchange coefficient is equal to 45 W/m^2 K, a lower value with respect to the theoretical one provided by the previous research (Van Helden et al., 2004). This effect, according to the authors, is due to the air bubbles trapped between the two parts (Zondag et al., 2003).

A more advanced technique is the lamination of the whole package (Glass, PV cells, electrical insulation and absorber) in one step, as shown in Fig. 9b (Dupeyrat et al., 2009).

The aim of the *package lamination* is to minimize the thermal resistance between the PV-cells and the metal absorber. In fact, instead of the three different layers (encapsulant, polyvinyl fluoride film and adhesive) normally used in the

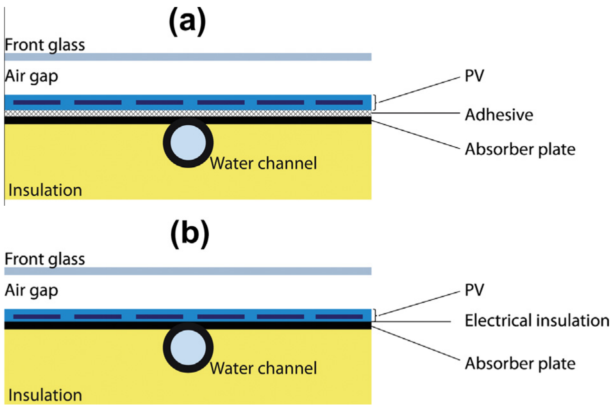

Fig. 9. Flat plate PV–T collector. (a) Gluing of pre-laminated PV module on metal absorber. (b) Direct lamination of PV module component on a metal absorber.

gluing method, in the whole package lamination only one layer is necessary.

If a metal absorber is used, particular care should be taken about the distance between the PV cells and the metal absorber. Therefore, normally an additional electrically insulating foil of ethylene–vinyl acetate (EVA) or polyvinyl butyral (PVB) is laminated between the cells and the absorber, but also an electrically insulating coating may be applied directly to the absorber (Zondag, 2008).

Van Helden shows a heat transfer coefficient of 125 W/m^2 K for the two elements coupled by lamination, compared with the value of 100 W/m^2 K reported for simple elements bonding (Van Helden et al., 2004).

Dupeyrat et al. (2011a) analyzes the electrical and thermal efficiencies of two PVT modules, which differ only for the coupling method (gluing and lamination). Lamination ensures a thermal efficiency greater than 10% with respect to the glued module, due to a higher heat exchange coefficient, and an improvement of the electrical performance due to the decreases of cells temperature.

However, the lamination coupling system is also affected by some technical issues, such as:

- the plate may be subject to deformations, caused by the different thermal expansion coefficients of the plate and the photovoltaic section;
- in the *sheet and tube* configuration, the tubes must be welded to the plate after the lamination of photovoltaic cells, to avoid any deformation that the channels may cause. This operation, however, may cause problems to the photovoltaic cells, due to the high temperatures required for welding (Zondag, 2008). This problem does not arise in the case of *roll bond* absorbers.

6.7. Flat Plate performances comparison

In literature only few researches compare PVT collectors with different absorber types in the same operating conditions. Among these, the results of experimental works carried out by Kim and numerically by Zondag about two hybrid modules with the *sheet and tube* and *box channel* absorber are described below.

In detail, the experimental results carried out by Kim on the uncovered PVT collectors (Kim and Kim, 2012a,b), with irradiance over 790 W/m^2, show that the maximum thermal and electrical efficiencies of a *sheet and tube* PVT with a flow rate of 0.02 kg/s m^2 are 66% and 14%, respectively, while the box channel PVT collector efficiencies are 70% and 15%.

Zondag et al. (2003) compares numerically the same two types of PVT collector with a cover glass, with an irradiance of 800 W/m^2, an ambient temperature of 20 °C and a wind speed of 1 m/s. The results of the covered collectors show that the maximum thermal efficiency of the *sheet and tube* is lower than the *box channel* collectors (58% and 60%, respectively), and also the electrical efficiency is slightly lower (8.9% and 9%).

Further experimental researches for each main type of absorber described in section 6 are shown below and summarized in Table 5. The reported efficiency values are referred to zero reduced temperature, except where otherwise indicated.

Over the recent years the *roll bond* technology has been widely spread in PVT researches, due to its promising performance. In particular, the indoor performance measurement carried out by Dupeyrat et al. (2011b) according to EN12975-2 (Standard, 2006) on a covered PVT with a roll bond absorber shows an excellent performance: the thermal efficiency when the fluid mean temperature is equal to ambient temperature (zero reduced temperature) was of 79%, with a corresponding electrical efficiency of 8.7%.

The PVT module developed by Chow et al., 2006, 2009 and studied by Ji is one of the most significant experimental products realized with the *box channel* absorber. It is built from the multiple extruded aluminum alloy box-structure modules shown in Fig. 10, which are assembled to produce a flat smooth absorber top surface, on which are glued polycrystalline cells with an efficiency of 14% and a temperature coefficient of 0.5%/K. Such PVT, simulated with a flow rate of 0.02 kg/s m^2 connected to a 95 kg tank, has a thermal efficiency at zero reduced temperature of 57% and an electrical efficiency of 12%, with irradiance of 800 W/m^2, ambient temperature of 20 °C and wind speed of 2.5 m/s. The same PVT collector was studied experimentally by Ji et al. (2007) in natural circulation with different water masses and different initial water temperatures in an outdoor environment. Since the hot-water load per unit heat-collecting area exceeded 80 kg/m^2, the daily electrical efficiency was about 10.15%, and the average daily thermal efficiency exceeded 45%.

One of the most innovative research about polymeric absorber was carried out by Sandnes and Rekstad (2002), who tested both numerically and experimentally a PVT collector made of a *box channel* plate of polyphenylenoxid (PPO) plastics material. In the component examined, the

Table 5
Main analyzed features.

Plate type	PVT Type	Flow rate (kg/s m^2)	Thermal efficiency	Electrical efficiency	Analysis type	Refs.
Sheet and tube	Uncovered	0.02	66%	14%	Experimental	Kim and Kim (2012a,b)
Box channel	Uncovered	0.02	70%	15%	Experimental	
Box channel	Covered	0.02	57%	12%	Numerical	Chow et al. (2006)
Box channel	Covered	n/a	45% daily	10.15% daily	Experimental	Ji et al. (2007)
Sheet and tube	Covered	0.02	58%	8.9%	Numerical	Zondag et al. (2003)
Box channel	Covered	0.02	60%	9%	Numerical	
Sheet and tube	Uncovered	0.02	52%	9.7%	Numerical	
Roll bond	Covered	0.01	49.3% yearly	10.3% yearly	Numerical	Bai et al. (2012)
Roll bond	Covered	0.02	79%	8.7%	Experimental	Dupeyrat et al. (2011b)
Box channel	Covered	n/a	71%	n/a	Experimental	Sandnes and Rekstad (2002)
Box channel	Uncovered	n/a	76%	n/a	Experimental	

Fig. 10. Box channel design (source: Chow et al., 2006).

channels through which the fluid flows are filled with ceramic granules, which ensure the uniformity of temperature on the plate.

As already mentioned, the PVT with the *sheet and tube* design has electrical and thermal efficiencies lower than the *box channel* design, although made with the same material. The comparison between the classical *sheet and tube* and the *roll bond* design is more challenging, due to the very different geometric characteristics of the channels.

6.8. Performance parameters

6.8.1. Tube spacing to tube diameter ratio (W/D)

Although the increase of the diameter section of the ducts could benefit the overall efficiency of the collector, it is necessary to analyze the relationship between the reciprocal distance and the diameter of the channels, as illustrated in Fig. 11.

In literature several researches (Bergene and Løvvik, 1995; Van Niekerk et al., 1996; Anderson et al., 2009; Najafi and Najafi, 2011) provide guidelines regarding the optimization of the width/diameter ratio (W/D), related to PVT collectors with serpentine and parallel configuration plates. The indications provided below cannot be referred to the plates with no parallel channel configuration, as in the case of the *Bionical* plate, on which experimental tests or advanced software analysis must be performed.

The main indications are listed below:

- The thermal efficiency is approximately halved when the fin width to tube diameter ratio, W/D, increases from 1 to 10, by keeping W constant.
- Increasing W/D from 1 to 10, the outlet fluid temperature decreases.
- The thermal efficiency of the PVT collector increases in a non-linear way with the decrease of the W/D ratio.
- The decrease of the W/D ratio affects the thermal efficiency of the PVT collector more than the electrical efficiency. Therefore there is not much point in increasing the cost of a system by decreasing the W/D ratio if the main issue is the cooling of the cells. On the contrary, if the thermal efficiency is more important, the fin's dependence on the relevant tube diameter should be weighed against the cost of the tubes.
- The calculations for the decrease of the W/D ratio should be carried out considering the cost of the plate material.

6.8.2. Mass flow rate

Water PVT collectors can work with natural circulation (Chow et al., 2006) or with forced circulation, using pumps to move the heat transfer fluid (Tonui and Tripanagnostopoulos, 2007). A number of authors investigated the influence of mass flow rate on PVT performance (Charalambous et al., 2007); the conclusion reached was that the PVT efficiency is a function of the flow rate (mass flux). In fact, when the water velocity in the tubes increases, the heat transfer coefficient also increases. However, in PVT water systems designed for forced circulation, higher flow rates may generate turbulences which do not allow the stratification in the storage tank, due to the marked mixing. This may result in a temperature of the water leaving the tank higher than that in the stratified condition, and

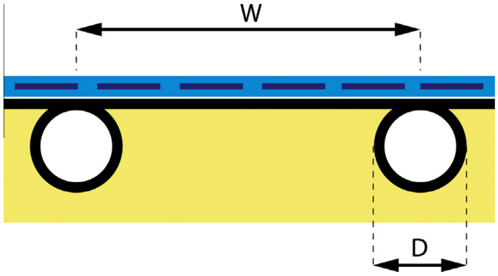

Fig. 11. Width (W) and diameter (D) diagram.

Table 6
Suggested optimal flow rate.

Channel type	PVT type	Flow rate (kg/s m^2)	Refs.
Parallel channel	Covered	0.0027	Nualboonrueng et al. (2012)
Parallel channel	Covered	0.0014	Kalogirou (2001)
Roll bond	Covered	0.0014–0.0049	Morita et al. (2000)
Parallel channel	Covered	0.005	Chow (2003)
Parallel channel (square)	–	0.0054–0.0064	Gao et al. (2011)
Parallel channel	Covered	0.015	Garg and Agarwal (1995)
Box channel	Covered BiPVT	0.025–0.04	Ji et al. (2006a)

leads to the decrease of the collector instantaneous efficiencies (Ji et al., 2006a). In addition, a technical–economic analysis is necessary to avoid additional costs due to the circulation pump consumption (Bergene and Løvvik, 1995).

In literature several authors do not agree on the optimum flow rate, since the most commonly reported values are in the range of 0.001–0.008 kg/s m^2 (Morita et al., 2000; Kalogirou, 2001; Chow, 2003; Gao et al., 2011; Nualboonrueng et al., 2012), whereas higher values such as 0.015 kg/s m^2 are also considered (Garg and Agarwal, 1995). Even higher values, in the range of 0.025–0.04 kg/s m^2, are in some cases recommended for PVT modules integrated in the building roof (BiOPVT – Building Integrated Opaque Photovoltaic Thermal), in which the photovoltaic cells may reach very high temperatures due to the poor heat dissipation caused by the building integration, which generally requires the rear insulation of the modules (Ji et al., 2006a). The wide spectrum of the values described above is due to two main reasons: first, each author analyzes PVT collectors linked to different systems and configurations; second, some authors define the optimal flow rate as the value that maximize the thermal and electrical energy production, while others, according to the Eq. (7) of Section 2, as a function of primary energy saving.

It is important to note that in most cases the PVT systems analyzed have different size and thus the optimal flow rates are not referred to unit areas. In order to make that parameter comparable, the flow rate data were converted in kg/s m^2 and are reported in Table 6.

7. Thermal insulation

In order to reduce thermal losses and increase the output fluid temperature from the collector, thermal insulation is generally applied in the rear side of the absorber. Usually it consists of materials such as fiberglass covered with a reflective foil layer or mineral fiber mat which does not allow the release of gas at elevated temperature, which may condense in the collector cover, reducing the efficiency. In addition, insulation materials should endure over time and should not change their physical proprieties at the high temperatures that may be reached in stagnation conditions. In recent years the use of polyester fiber materials is widely spreading, due to health and safety concerns with regard to the handling of the fiberglass during assembly. Injected foam insulation is not normally used, due to expansion problems under stagnation conditions, although slabs of foam that are free to move relatively to the frame can be used (Gordon, 2001; Aste and Groppi, 2007).

8. PVT systems

The overall efficiency of a liquid-based PVT system is not only determined by the quality of the collector, but it also depends on many design factors, explained below, that determine the total production of usable primary energy. Once the specific system technology has been defined (e.g. PVT collector characteristic and plant configuration), the climatic conditions and the solar fraction are two key factors to assess system performance.

In solar thermal collectors the optimal value of solar fraction *f*, which is the percentage of thermal energy demand that is covered by the solar system, typically ranges from 40% to 90% (Cardinale et al., 2003; The German Solar Energy Society, 2005; Trust, 2006; Allen et al., 2010,) of the total yearly energy demand, depending on the climatic conditions and the thermal load, while the remaining fraction is covered by an auxiliary heat generator. This dimensioning criteria allow to satisfy the whole DHW demand in summer and a smaller part in winter. Therefore, values of solar fraction higher than 60–70% would provide more energy saving in winter but also a surplus production in summer that, if not used, could affect the cost effectiveness of the system during its lifetime and could cause problems like overheating.

Differently from traditional solar thermal collectors, in the PVT collectors the optimal value of f varies between 40 and 60%, depending on latitude and climate (Aste et al., 2012a); higher values would negatively affect the electrical performance of the hybrid component.

In addition, the optimal size of the storage tank, that depends on the number of PVT modules installed, is a further parameter that determines the performance of a PVT system.

Depending on the surface of the PVT installed, a larger storage tank provides lower fluid temperature in the inlet manifold of the collector, with considerable benefits for the electrical efficiency. However, if the outlet fluid temperature decreases, a greater consumption of the auxiliary heating system is needed to achieve the temperature required by the specific application.

At the Indian Institute of Technology, a comparative research was carried out on the same PVT collector ($2\ \mathrm{m}^2$) connected to two tanks of different size, with a 100 kg and 200 kg capacity.

The first system could heat water from 31 °C up to 71 °C (average daily thermal efficiency of 38% and electrical efficiency of 7%) versus a final value equal to 57 °C for the second system (average daily thermal efficiency of 48% and electrical efficiency of 8%) (Agarwal and Garg, 1994; Garg et al., 1994; Garg and Agarwal, 1995).

The design of the entire system and that of the profiles of thermal energy need of the users are thus critical elements that affect the overall efficiency of PVT collectors.

A comprehensive review about PVT liquid systems is contained in the research proposed by Daghigh et al. (2011).

In addition, when a whole PVT system is analyzed, also a complete economic assessment should be carried out, in order to compare overall energy performances and costs (Tselepis and Tripanagnostopoulos, 2002; Van Helden et al., 2004). In this sense, beside the afore-mentioned economic efficiency, the overall capital cost should also be considered, including any supplementary costs such as the connection to the grid, the cost of the thermal storage tank and the cost of the auxiliary equipment.

The benefit generated by the PVT system every year, equal to $(E_{th} \cdot C_{th}) + (E_{el} \cdot C_{el})$, should be taken into account by applying the *discounted cash flow* method. The net present value (NPV) of the system is thus equal to the difference between the present value of the net cash flows generated by the system and the initial capital cost. This can be expressed as:

$$NPV = \sum_{r=1}^{n} \frac{C_t}{(1+k)^2} - C_0 \tag{14}$$

where C_0 is the capital cost, $C_t = (E_{th} \cdot C_{th}) + (E_{el} \cdot C_{el})$ is the net cash flow generated in the year r, n is the working-life of the project, k is the discount rate.

9. Conclusions

The possibility to effectively cogenerate electricity and thermal energy from solar PVT collectors has been demonstrated by several researches. PVT systems can contribute in the near future to replace fossil fuels energy consumption above all in building applications, where available surfaces for the installation of solar plants are often limited and electricity needs as well as hot water demands are considerable. This paper present a comprehensive analysis of the researches carried out on flat plate PVT water collectors and their components, highlighting the pro and cons.

In detail, thanks to the analysis, it was possible to conclude that several types of PVT flat plate collectors exist, but the most commonly type manufactured is the so called *sheet and tube*. In order to improve thermal energy, in the range of 10–30%, a top cover may be adopted; at the same time, however, such cover decreases the electrical output in the range of 1–10%, depending on the transmission factor of the cover.

Different PV technologies can be used in PVT collectors: a-Si seems to be an interesting technology for the future development of PVT components, due to thermal annealing effect combined with low power temperature coefficients. In addition, it can be noted that the in-series connection of PV cells is more efficient than the parallel configuration, due to lower thermal and ohmic losses.

With regard to the thermal absorber, which is one of the main functional element of a PVT collector, it is possible to conclude that it can be made in different ways, according to various manufacturing techniques, which also determine the choice of materials; the paper analyzes the most widely adopted flat plates, that can be classified as *sheet and tube*, *roll bond* and *box channel*. The type of absorber affects the channel arrangement: *serpentine* and *harp* are the most used configurations, but with the *roll bond* type any channel patterns is allowed. In addition, an optimized channel configuration allows to reduce the pressure drop and consequently the energy demand of the circulating pump. Generally the most adopted configurations are the so called serpentine and harp arrangements, but also different morphologies are allowed with *roll bond* technology.

The PVT efficiency also depends on the tube spacing to tube diameter (W/D) ratio and on the mass flow rate. In particular, when the W/D decreases, the efficiency of the collector increases, while different values of optimal flow rate are suggested, depending on the system. The most commonly reported values are in the range of 0.001–0.008 $\mathrm{kg/s\ m^2}$.

The connection between the PV section and the absorber can be carried out in two different ways: by gluing the PV laminate over the absorber or by laminating all the components in one single step. Compared to the glue technique, lamination ensures a thermal efficiency greater than 10%. In order to reduce thermal losses, insulation material such us fiberglass or mineral fiber are commonly applied to the back side of the collectors.

The research allowed also to summarize few suggestions which can be useful for further improvements of PVT systems; in detail, the performance evaluation of thin-films PV cells and the effect of thermal annealing, even in hot climates, should be carefully analyzed. In addition, a deeper research on the evaluation of the performance of building-integrated PVT modules should be carried out, as well as experimental performance evaluations of the lamination of the PV section with the absorber. In addiction it is considered useful to develop reference terms for the characterization of the components performance, simplifying the technical and economical comparison, and to study, with a systemic approach, the relationship between system configurations, climate and users.

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