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Applications of hybrid photovoltaic modules with thermoelectric cooling

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Abstract

Among the energy sources with low efficiency, thermoelectric systems are used for hybrid systems with improved performance. This paper provides a review of recent literature concerning the integration of ThermoElectric Cooling (TEC) devices into PhotoVoltaic (PV) generators to constitute PV-TEC systems. The role of TEC is to reduce the temperature of the PV cells, to increase the efficiency of the system, its power capacity and lifetime. The paper also contains a formulation of thermoelectric module equations referring to cooling capacity, rate of heat rejected to the ambient and input power, together with the electrical model of the PV generator.

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1. Introduction

The current trends concerning High Energy Efficiency and High Renewable energy sources are set up in documents such as the Energy Roadmap 2050 of the European Commission [1], as well as in other sources addressing the promotion of better environmental impact and more green building applications [2].

Among the most effective renewable energy technologies, photovoltaic (PV) systems are emerging because of the possibility of high diffusion in different types of climates, increasing possibility of integration into the building architectures in building-integrated photovoltaic (BIPV) solutions, and widespread experience of design and installations gained by a number of operators in recent years. These characteristics make PV systems a very

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interesting asset in the integration of energy sources in nearly-zero energy buildings (NZEB). In order to further improve the situation, the effectiveness of PV technologies has to make further progress in order to reach, in a systematic way, the grid parity [3-9]. This condition occurs when the price of the self-consumed energy produced by PV is equal to the price of the energy purchased from the electrical grid [10].

In order to become more attractive, the PV systems have to become more and more efficient. For this purpose, the parameters affecting the PV production have to be modified in the direction of enabling higher productivity and efficiency. Among these parameters, the PV cell temperature plays a key role in determining the PV cell efficiency: when the other conditions (e.g., solar irradiance, wind, humidity, etc.) are constant, the higher the temperature, the lower the PV cell production. Hence, one of the techniques used to improve the PV cell efficiency is to insert a cooling system able to reduce the cell temperature during operation. For this purpose, this paper addresses the use of thermoelectric materials, considered to be a viable solution for electrical and thermal energy harvesting, as well as to implement easily controllable solutions to condition the temperature even in small-size applications [11,12].

From the technology viewpoint, a thermoelectric module is a bi-directional device, which operates in two ways:

- as a thermoelectric generator (TEG), exploiting the Seebeck effect, when the module is subject to a temperature difference and generates an output voltage in direct current (DC) [13];
- as a thermoelectric cooler (TEC), exploiting the Peltier effect, when the module is supplied by the electrical system with a DC current and a temperature difference is created between its hot and cold sides [14].

This paper addresses only the TEC devices, providing a review of recent literature concerning the integration of these devices into PV generators to constitute hybrid PV-TEC systems. The TEC devices transfer heat from one zone to another by the utilization of an amount of the electrical energy produced by the PV system. Integrating the TEC device with the PV cells may have two positive consequences:

- enhancement of the *power capacity* of the PV modules, that is, the maximum power output under given operating conditions.
- increase of the *electrical efficiency* of the PV system, including the following causes of losses [15].

In practice, additional input power is necessary for supplying the TEC module. The technical effectiveness of the hybrid PV-TEC solution exists when power and energy output from the system with TEC is higher than power and energy output of the corresponding solution without TEC. Establishing the limit conditions for this effectiveness under different ambient situations is one of the current open fields of research.

The hybrid PV-TEC systems have been studied in a limited way until now, with interesting conversion efficiencies emerging mainly for concentrating photovoltaic (CPV) solutions [16]. However, thermoelectricity from TEG and TEC is a “green technology” and the related solutions are becoming more and more interesting under today’s higher concern on energy conservation and environment protection [2,17].

A TEC has compact construction, limited maintenance needs and long duration of use because of the absence of moving parts, leading to high reliability (over 200,000 life hours), and may operate in any working position. Hybrid PV-TEC systems are good candidates for thermal energy harvesting, reducing the PV modules temperature and improving their efficiency. Meanwhile, the temperature reduction implies the possibility of increasing the power capacity of the PV cells, as the power generated by the PV cells at a given solar irradiance is higher when the temperature is lower.

In recent years, a number of studies appeared in the literature about the incorporation of TEC into the different types of photovoltaic systems mentioned above. The main issues concerning different types of PV systems are:

- *Fixed rooftop PV systems*: the increased temperature of the PV cells can damage the PV modules, reducing both lifetime and energy conversion efficiency [18]. On the operational side, the system is fixed and does not need specific controls.
- *Sun-tracking PV systems*: the temperature reached by the PV cells is higher with respect to fixed ground mounted PV systems, since a sun-tracking system makes the PV cells receive more solar irradiance during time. The system is in motion and its position needs to be controlled.

- *CPV systems*: in these systems, the efficiency improvement due to the TEC effect may be remarkable, since the PV cells may reach significantly higher temperatures with respect to the two previous cases, making their efficiency decrease considerably; with the addition of TEC, the extra power generated by the PV cells due to the cooling effect is largely higher than the power needed to supply the TEC [19]. The system is in motion and needs also an accurate control system to track the correct incidence angle of the solar beam.
- *BIPV systems*: the air circulation on the back of the PV module is limited by the integration in the building structures, and the presence of TEC devices may interact with the ambient conditions in the structure itself or in the internal side of the building [18].

In all these systems, the efficiency improvement is obtained by cooling the back side of the PV module through the installation of TEC modules. The power utilized by the TEC modules is provided by the PV cells themselves, making the whole system compact.

The main aspects reviewed and discussed in this paper are:

- the analytical model of the hybrid PV-TEC system, taking into account the thermal and electrical characteristics;
- the indications on efficiency improvements and increase of the power capacity obtainable in hybrid PV-TEC solutions in different ambient and operating conditions, with respect to the operation of the systems without TEC;
- a systematic assessment of the advantages of incorporating TEC into PV technologies of different types. These advantages have been indicated in the recent international literature, in many cases through simulations [16,18-20], and in some cases with experimental testing performed in laboratory [21-23].

The next sections of the paper are organized as follows. Section 2 introduces the theoretical framework for the analysis of thermoelectric devices and modules and for the integration of these devices into PV systems. Section 3 discusses the efficiency aspects of hybrid PV-TEC systems. The last section contains the concluding remarks.

Nomenclature

Acronyms

BIPV	Building integrated photovoltaic
CPV	Concentrated photovoltaic
DC	Direct Current
NOCT	Nominal Operating Cell Temperature
NZEB	Nearly Zero Energy Buildings
PV	Photovoltaic
STC	Standard Test Conditions
TEC	Thermoelectric cooler
TEG	Thermoelectric generator
TEM	Thermoelectric module

Symbols

I_0	diode reverse saturation current [A]
I_D	diode current [A]
I_{max}	maximum input current which produce ΔT_{max} across a TEM [A]
I_{ph}	photo-generated current [A]
I_{PV}	output current [A]
I_{TEM}	input current across of TEM [A]
K_{TEM}	total thermal conductance of n thermocouples [$W \cdot K^{-1}$]
m	diode ideality factor
P_G	power gain [W]
P_{PV}	power produced by the PV module [W]
P_{TEM}	power input to the TEM [W]

q	electron charge ($1.60217646 \cdot 10^{-19}$ C)
$\dot{Q}_{c_{TEC}}$	cooling capacity of a TEC [W]
$\dot{Q}_{c_{TEM}}$	cooling capacity of n couples of legs [W]
$\dot{Q}_{c_{TEC}}$	rate of heat released by TEC at the hot junction [W]
$\dot{Q}_{h_{TEM}}$	rate of heat released by TEM at the hot junction [W]
R_{NP}	electrical resistance for a thermocouple [Ω]
R_{ser}	series resistance of PV module [Ω]
R_{sh}	shunt resistance of PV module [Ω]
R_t	thermal resistance for a thermocouple [$K \cdot W^{-1}$]
R_{ts}	thermal resistance of the heat sink at the back side of TEM [$K \cdot W^{-1}$]
$R_{t_{TEM}}$	thermal resistance for n thermocouples [$K \cdot W^{-1}$]
$R_{t_{c_{TEM}}}$	cold junction to TEM thermal resistance [$K \cdot W^{-1}$]
R_{TEM}	electrical resistance for n thermocouples [Ω]
S_{NP}	Seebeck coefficient of a thermocouple [$V \cdot K^{-1}$]
S_{TEM}	Seebeck coefficient of n thermocouples [$V \cdot K^{-1}$]
T_{amb}	ambient temperature [K]
T_{bs}	temperature at the interface between the backside of the PV cell and connection layer [K]
T_C	cell temperature [K]
T_c	cold side temperature of TEM [K]
T_h	hot side temperature of TEM [K]
ΔT	temperature difference between hot and cold side [K]
ΔT_{max}	the biggest temperature drop obtained between the hot and cold ceramic plates of TEM [K]
V_D	diode voltage [V]
V_{PV}	output voltage of PV module [V]
V_t	thermal voltage of the diode related to T_C [V]
V_{TEM}	input voltage to TEM [V]
V_{max}	maximum voltage, which gives ΔT_{max} at I_{max} [V]
Z	thermoelectric figure of merit [K^{-1}]
k	Boltzmann constant ($1.3806503 \cdot 10^{-23} \cdot J \cdot K^{-1}$)

2. Theoretical aspects and analytical model of the hybrid PV-TEC system

2.1. Thermoelectric devices: TEC and TEM

A TEC (thermoelectric cooler) is a device which converts a direct current into a temperature gradient. The TEC devices are generally used when the temperature of a device needs to be accurately controlled [24]. A TEC is composed of two legs or pellets which are Bismuth Telluride semiconductor materials (N-type and P-type semiconductors) connected at one end by a conducting metal strip (electrical connector, e.g., copper), in order to form a junction. A pair of pellets is called a thermocouple. The N-type and P-type semiconductors are electrically connected in series but operate thermally in parallel between two ceramic substrates used as a foundation. The other end of a TEC is connected to the next TEC device, and so on (Fig. 1). Such an arrangement of semiconductor legs is known as a thermoelectric module (TEM). The n couples of legs in a TEM determine the cooling capacity and the maximum electric current which flows in the module [25].

In a TEM, the positive terminal of the first TEC and negative terminal of the last TEC are connected to the external power supply. In cooling mode, a DC voltage generator supplies the N- and P-type legs of each device and the current flows in them. Therefore, the thermoelectric effects are developed when an input current I flows through

the TEM circuit. The current path has the same direction as the electrons flow (which are carriers in N-type semiconductor) and in the opposite direction for the holes flow (which are carriers in P-type semiconductor). During this process, the upper junction is cooled at a temperature T_c (for each device) and the heat is absorbed from the equipment to be cooled (in this case a PV module). In addition, the lower junction is heated at a temperature T_h (for each device) and releases heat to the heat sink, which dissipates it to the ambient. In other words, the direction of heat flux depends on the polarity of current. Consequently, inverting the current path, the direction of heat flux is changed. This direction at a junction depends on the thermoelectric material, the type of junction, as well as the path of the flowing current [25,26].

In this way, it is possible to form an active cooling system, in which the thermal energy is absorbed from the surface to be cooled and is released at the other side to the heat sink. The design of such a system is challenging, as there are many quantities to be considered, including the TEC parameters, the ambient air temperature, the thermal resistance of the heat sink, and the electrical current flowing in the TEC legs [24]. The cooling effect of TEM is enhanced, when the electrical current increases with the consequent reduction of PV cell temperature and increment of output power [27].

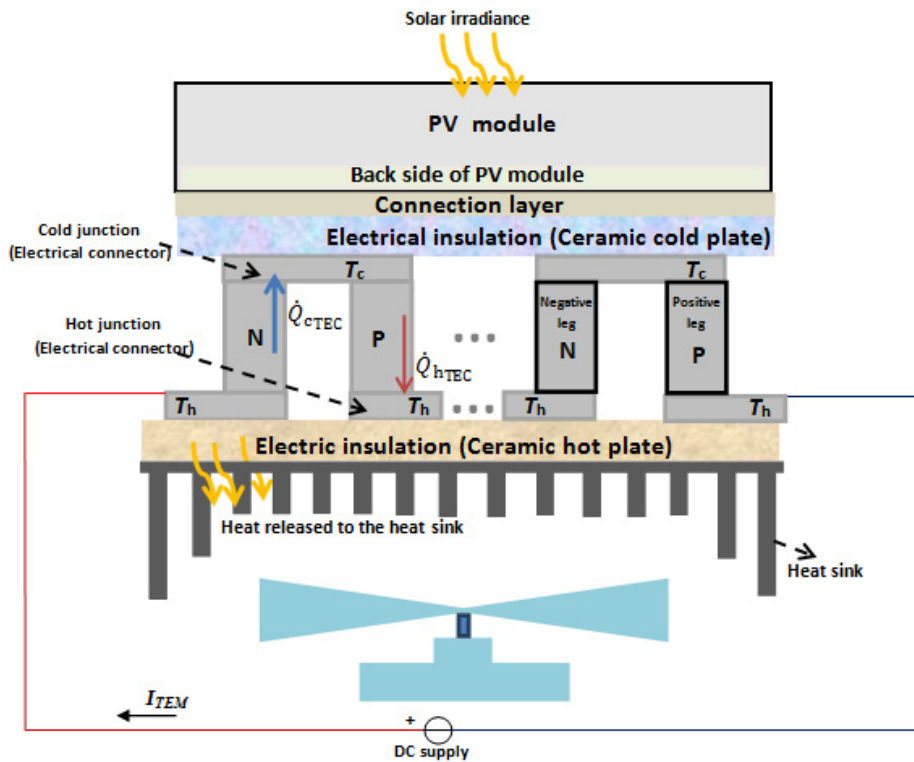


Fig. 1. The hybrid PV-TEC system.

Commercial TEMs contain a number n of thermoelectric couples of pellets. The pellets have the same structure in terms of length, thickness, thermal conductivity and electrical conductivity. The following thermal analysis is carried out in steady-state conditions, and the heat flow is assumed to be unidirectional. The behaviour of a TEC is determined by three basic parameters of the N-type and P-type thermocouple: the thermal resistance R_t , the electrical resistance R_{NP} , and the Seebeck coefficient S_{NP} [24].

For an entire TEM the thermal conductance of n thermocouples K_{TEM} is n times the thermal conductance of a thermocouple. Similarly, the electrical resistance R_{TEM} and the Seebeck coefficient S_{TEM} for n thermocouples in series are increased by the number of series connected thermocouples.

The analytical equations of TEM performance are presented below [27, 29, 30]. It is also considered that the temperature effect on the thermoelectric properties, the effects of ceramic plates, and electrical contact resistances are negligible in the thermal balance equations [28]. The energy balance equation at the cold side of the one TEC gives the cooling capacity (the rate of heat absorbed) $\dot{Q}_{c_{TEM}}$ at the cold junction:

$$\dot{Q}_{c_{TEM}} = S_{TEM} \cdot I_{TEM} \cdot T_c - K_{TEM} \cdot \Delta T - 0.5 \cdot R_{TEM} \cdot I_{TEM}^2 \quad (1)$$

where I_{TEM} is the input current of TEM; the temperature difference between hot temperature T_h and the cold temperature T_c is $\Delta T = T_h - T_c$; the TEM Seebeck coefficient is S_{TEM} ; the TEM thermal conductance is K_{TEM} the TEM electrical resistance the thermocouple is R_{NP} .

The energy balance equation at the hot side of TEM gives the rate of heat released $\dot{Q}_{h_{TEM}}$ at the cold junction:

$$\dot{Q}_{h_{TEM}} = S_{TEM} \cdot I_{TEM} \cdot T_h - K_{TEM} \cdot \Delta T + 0.5 \cdot R_{TEM} \cdot I_{TEM}^2 \quad (2)$$

The input voltage V_{TEM} to the TEM is given by [24, 27, 28]:

$$V_{TEM} = I_{TEM} \cdot R_{TEM} + R_{TEM} \cdot S_{TEM} \cdot \Delta T \quad (3)$$

The input power P_{TEM} to the TEM is given by:

$$P_{TEM} = I_{TEM} \cdot V_{TEM} \quad (4)$$

The temperature at the back side of the PV cells is obtained from the cooling capacity expression of TEM, at the interface between backside of the PV cells (e.g., tedlar or PET) and connection layer (e.g., aluminum plate or conductive film) [19, 24]:

$$T_{bs} = T_c - \dot{Q}_{c_{TEM}} \cdot R_{ic_{TEM}} \quad (5)$$

where the thermal resistance from the cold junction to TEM is $R_{ic_{TEM}}$, and the temperature at the interface between the backside of the PV cell and connection layer is T_{bs} . The temperature at the hot side T_h is obtained from the rate of heat released by TEM:

$$T_h = T_{amb} - \dot{Q}_{h_{TEM}} \cdot R_{ts} \quad (6)$$

where the thermal resistance of the heat sink at the back side of TEM is R_{ts} , and the ambient temperature is T_{amb} . The reduced value of R_{ts} increases TEM performance and enhances the heat transfer through the hybrid PV-TEM system. The analytical expressions of the thermal resistances $R_{ic_{TEM}}$ and R_{ts} reported in [28] show that these thermal resistances have a mutual dependence.

The TEM parameters K_{TEM} , R_{TEM} and S_{TEM} are computed according to the parameters specified by the manufacturers, that is, I_{max} , V_{max} , T_h and ΔT_{max} [19, 24, 28]:

$$K_{TEM} = I_{TEM}^{max} \cdot V_{TEM}^{max} \cdot (T_h - \Delta T_{max}) \cdot (2 \cdot T_h \cdot \Delta T_{max})^{-1} \quad (7)$$

$$R_{TEM} = V_{TEM}^{max} \cdot (T_h - \Delta T_{max}) \cdot I_{TEM}^{max-1} \cdot T_h^{-1} \quad (8)$$

$$S_{TEM} = V_{TEM}^{max} \cdot T_h^{-1} \quad (9)$$

where the maximum input current which produces ΔT_{max} across a TEM is I_{TEM}^{max} . This current is obtained when the cooling capacity is nil ($\dot{Q}_{c_{TEM}} = 0$); ΔT_{max} is the biggest temperature drop obtained between the hot and cold ceramic plates of TEM, and V_{TEM}^{max-1} is the maximum voltage which gives ΔT_{max} at current I_{TEM}^{max} . The effectiveness of the TEM is given by the thermoelectric figure of merit Z which specifies if a material is a good thermoelectric cooler [28, 29]:

$$Z = S_{TEM}^2 \cdot (R_{TEM} \cdot K_{TEM})^{-1} \quad (10)$$

2.2. PV module

The conversion efficiency of commercial PV modules in crystalline silicon (c-Si) is about 15% [18]. The operating temperature of the cells inside a PV module highly affects their current-voltage I - V characteristic curve and thus their efficiency. The major parameters of PV performance are light absorption, short-circuit current, open-circuit voltage, and fill factor [31-33]. An important factor for a solar cell is to control its operating cell temperature [34]. The energy not converted into electricity becomes heat that increases the temperature of the PV cells, reducing their electrical power production and reducing the PV module lifetime with ageing of the PV module encapsulation [35, 36]. Other cooling modes of PV cells under concentrated sunlight (with no thermoelectric component) have been reviewed in [37]. The complete thermal-electrical model used in this paper is based on single-exponential junction in order to simulate the cell temperature and the I - V curve of the PV module [15]. The one-diode model of a solar cell includes five parameters defining the behaviour of four components. A current source representing the photo-generated current I_{ph} and a diode with two parameters ($-I_0$ and m) are connected in parallel each other and with a shunt resistance R_{sh} . Finally, a resistance R_{ser} is connected in series with the previous components. The fundamental equations, obtained from the Kirchoff's laws, are presented below for a single solar cell:

$$I_{PV} = I_{ph} - I_D - \frac{V_D}{R_{sh}} \Rightarrow I_{PV} = I_{ph} - I_0 \left[\exp\left(\frac{q \cdot V_D}{m \cdot k \cdot T_c}\right) - 1 \right] - \frac{V_{PV} - R_{ser} \cdot I_{PV}}{R_{sh}} \quad (11)$$

where the output current is I_{PV} ; the diode current is I_D ; the diode reverse saturation current (strongly dependent on the cell temperature T_c and with negative sign to indicate a reverse bias) is $-I_0$; the diode voltage is V_D ; the electron charge is $q=1.60217646 \cdot 10^{-19}$ C; the diode ideality factor is m ; the Boltzmann constant is $k=1.3806503 \cdot 10^{-23} \cdot \text{J} \cdot \text{K}^{-1}$, the output voltage of PV module is V_{PV} .

3. Applications of hybrid PV-TEM systems

3.1. Power balance for the hybrid PV-TEC system

The hybrid PV systems with TEC addressed in this section take the electrical supply from the PV module for cooling the back side of the PV module (Fig. 2), by sending a controlled current to the TEM. The heat released by the hot surface of the TEM is not used for other purposes. TEC modules attached on the rear of PV modules use the waste heat of solar cells and for this reason the efficiency of the solar cells raises. Fig. 2 shows the PV-TEM control system block, representing both the individual controls of PV and TEM, as well as the circuits managing the TEM supply TEM from the PV output voltage.

One of the relevant aspects is the power needed to supply the TEC in different operating conditions. Paper [19] addresses the power balance for the hybrid PV-TEC system, carrying out simulations on a PV-TEC model for cooling the PV module surface. By using TEC, the PV module temperature is kept at a relatively low level (57°C) through TEC input control. The relevant quantity is the *power gain* P_G , given by the additional power that can be produced by reducing the cell temperature through cooling. Obviously, the power needed to supply the TEM is included in the calculation. The power gain expression is:

$$P_G = (P_{PV}^{(cooled)} \cdot P_{PV}^{(not\ cooled)}) - P_{TEM} \quad (12)$$

where $P_{PV}^{(cooled)}$ is the power produced by the PV module with cooling from TEM, $P_{PV}^{(not\ cooled)}$ is the power produced by the PV module without cooling from TEM, and P_{TEM} is calculated as in (4). The acceptable values for the power gain in order to have an efficient solution must be positive, i.e., $P_G > 0$. The explicit evaluation of the power gain requires the complete thermal model of the layers forming the PV module, with different possible solutions depending on the layer structure and materials.

The net output power from the hybrid PV-TEC system in operating conditions with cooling from TEM is:

$$P_{out} = P_{PV}^{(cooled)} - P_{TEM} \quad (13)$$

Starting from equation (12), paper [19] developed an optimization procedure to find the value of input current to TEM giving the maximum power gain.

A number of recent results have shown the effectiveness of using TEC. The study presented in [22] concerns the thermoelectric cooling of a PV module in order to improve its performance and to increase the electric conversion efficiency and its lifetime. The experimental results of PV module showed that the efficiency of the solar panel varied from 8.35% to 11.46% without cooling system and reached the values of 12.26% up to 13.27% with TEC cooling. Furthermore, the results from [20] indicate that the TEC improved the PV power capacity by 2%-20% and increased the efficiency of the PV module by 2.3%-3.4% with respect to a traditional PV system. The results of the experimental work developed in [23] on a hybrid PV-TEM system focus on the effect of temperature on the PV performance. The results show that the PV cell temperature decreased from 83 °C without cooling to 65 °C with TEC.

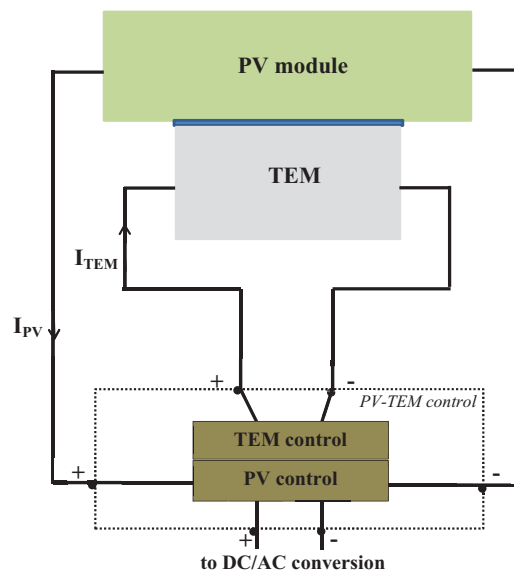


Fig. 2. Structure of the hybrid PV-TEM system with supply and control.

3.2. PV module cooling in other hybrid systems

The effect of cooling the PV module surface, with the corresponding benefits on the improvement of the PV cell efficiency, can be obtained also from TEM operating in electricity generation mode inside a composite multi-layered structure, providing multiple effects on the electrical and thermal side. For example, in the model [21], the TEM is

connected to the PV module on one side, and on the other side is incorporated into a structure with hot water tubes contained into a functionally graded material. The prototype solution tested enhances the PV cell efficiency and the power capacity with respect to the traditional PV module considered. At irradiance of 1000 W/m², the power density in the maximum power point grows passing from 91 to 103 W/m². In addition, further increase of the overall electrical output is due to the contribution of the TEM depending on the temperature difference between its hot and cold sides. The application presented in [18] proposes a PV-TEM hybrid system in order to increase its efficiency and lifetime. Results of the simulation showed that the temperature of the PV module without cooling is 63.5 °C and with cooling is 53 °C. Therefore, PV modules with a temperature gap of 10 °C enhanced the efficiency and the lifetime without power loss.

Further applications refer to BIPV systems. Paper [17] carried out a theoretical and experimental investigation about an active solar wall system integrating thermoelectric radiant cooling and photovoltaic (PV) technologies. The overall cooling efficiency of the system was about 3.3% and 7.1%. The system can transfer 1.9% and 5.5% of the solar energy into cooling capacity for indoor air conditioning. Paper [13] described the performance of hybrid PV–TEC module, attaching thermoelectric converters to the back of PV modules. With the new materials used the efficiency of roof integrated PV–TEC hybrid module raised up to 23%. The solution in [38] refers to the lack of air passage on the back of the PV modules mounted in BIPV applications. In this case, the PV module temperatures may be relatively high in normal conditions. The incorporation of thermoelectric cooling can provide an increase in the BIPV power. It is also shown that the use of thermoelectric cooling provides better results than using a ventilator with wide range solar irradiance. The use of thermoelectric devices in active building envelopes has been described in [38]. The characteristics of the thermoelectric devices of changing the thermal heat flow depending on the direction of the current is useful to provide cooling effect inside the building when the temperature is relatively warm, as well as warming the indoor part of the building when the external temperature is relatively cold.

4. Conclusions

From the analysis carried out on hybrid PV-TEC systems, the efficiency of a PV system may be enhanced by incorporating TEC devices on the back side of the PV module. The effect is to reduce the PV cell temperature, in turn increasing the efficiency and the power capacity of the PV system. The extent of this improvement can be expressed by the analytical formulation of the PV-TEC module equations. In particular, since the efficiency improvement is limited to some ambient temperature ranges, the exact quantification of these ranges for different technological solutions, such as rooftop PV systems, sun-tracking PV systems, concentrated PV systems and building integrated PV solutions, all incorporating TEC devices, is one of the open research topics. Indeed, it needs appropriate experimental verification. The easy controllability of TEC is a major asset for the development of the hybrid PV-TEC solutions and their inclusion into dedicated control systems to monitor the efficiency and set up the input power to the TEC. In a future work, the sustainability of hybrid PV-TEC solutions has to be established both on the technical point of view and on the assessment of the economic and environmental benefits. It is also necessary to highlight the TEC contribution to provide extra output power from renewable energy sources installed in different ways in conventional and green building applications.

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