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Thermal and Electrical Modelling of a CPV/T System Varying Its Configuration

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Abstract: In this paper, the main aim is the performances modelling from the electrical and thermal point of view of a concentrating photovoltaic and thermal (CPV/T) system in order to evaluate the primary energy and economic savings respect to a traditional system, when the same energy loads are satisfied. This study is realized by both varying the CPV/T system configuration and considering two different users. In particular, the point-focus (PF), and linear focus (LF) configurations of the CPV/T system are considered in order to match the residential user and hotel energy loads. The CPV/T system is sized adopting as input data: the Direct Normal Irradiance (*DNI*) modelled by an artificial neural network and the users' energy demands. In these hypotheses, the performances of the PF and LF systems are evaluated and then compared for the two users located in Southern Italy, in terms of electrical and thermal energy production, cells number, space occupied, energy and economic savings and CO_2 emissions avoided. Finally, the PF system shows a lower simple pay-back and a higher primary energy saving, while the space occupied by a LF system results to be lower respect to the PF configuration.

Keywords: CPV/T system, point-focus configuration, linear focus configuration, thermal analysis, electrical analysis, primary energy saving, economic analysis

1. Introduction

The solar energy is the main highly available renewable source in the world and allows a reduction in terms of primary energy, CO_2 emissions and costs, above all referring to users characterized by high consumptions [1]. In particular, both the concentrating photovoltaic (CPV) systems and the concentrating photovoltaic and thermal (CPV/T) systems represent an interesting solution. In the CPV system, only the electrical energy is obtained, while in the CPV/T system both electric and thermal energy. The concentrating systems adopt an optics to concentrate the solar radiation on triple-junction (TJ) solar cells determining higher electrical performances and temperatures [2]. The basic parameter is the concentration factor (C) and, corresponding to different C values, the concentrating systems can be designed varying the system configuration in terms of solar cells, optics and tracking system. As for the optics, refractive solutions such as the Fresnel lens or reflective systems as the parabolic concentrators, are adopted [3].

In literature, the performances of different concentrating photovoltaic systems according to typology of optics, tracking system or application, are investigated. A long-term electrical performances evaluation of two types of CPV system, the mini dish and the Fresnel lens CPVs, has been realized in [4] under the outdoor tropical weather of Singapore. In [5] a parabolic dish solar receiver is experimentally tested in order to find the energy efficiency, exergy efficiency and exergy factor

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Nomenclature

A	Area/m^2	σ_t	temperature coefficient/%·°C^{-1}
AHP	Absorption Heat Pump	**Subscripts**	
ANN	Artificial Neural Network	b	boiler
C	concentration factor	c	cell
CPV	concentrating photovoltaic	ac	additional components
CPV/T	concentrating photovoltaic and thermal	co	cooling
DNI	Direct Normal Irradiance/W·m^{-2}	dir	direct
E	Energy/Wh	e	environment
FUC	Fuel Utilization Coefficient	el	electric
$\bar{h}_c$	convective heat transfer coefficient /W·m^{-2}·K^{-1}	f	fluid
InGaP/ InGaAs/Ge	indium-gallium-phosphide/indium-gallium-arsenide/germanium	inv	inverter
LCV	lower calorific value $\left(\frac{k_J}{m^3}\right)$	mod	module
SHW	Sanitary hot water	n	electrical network
T	Temperature/°C	oc	open-circuit
TJ	triple-junction	opt	optic
V	Voltage/V	out	outlet
x	suns	pr	primary
Greek symbol		ref	reference
β	tension thermal coefficient/V·°C^{-1}	sav	saving
ε_c	emissivity	th	thermal
η	efficiency	ts	tracking system
σ	Stefan-Boltzmann costant/W·m^{-2}·K^{-4}		

for the same solar intensity with water and SiC+water. In [6] the tracking strategy for small-scale double-axis parabolic trough collector, has been numerically investigated. A three dimensional numerical investigation of heat transfer in a parabolic trough collector receiver with longitudinal fins using different kinds of nanofluid, is presented in [7]. The design and techno-economic optimization with net CPV-Hydrogen system energy management for a stand-alone operation using micro genetic algorithm, is presented in [8]. The characteristics, performance and general position strategy of parabolic-trough direct steam generation loop in recirculation mode, have been numerically studied in [9]. An optimization strategy and performance simulation model with overall system energy management strategy, has been proposed in [10] and implemented for the stand-alone operation of CPV-hydrogen system. In [11] a novel concentrating assembly for CPV system that is designed to concentrate solar radiation onto four multi-junction solar cells with a single set of concentrators, is proposed; in particular, a multi-leg homogeniser CPV concentrating assembly is designed, developed and experimentally tested. In [12] the optimized value of C able to provide a fluid outlet temperature that satisfies the thermal demands and decreases the CPV/T system size, is evaluated. In [13] a CPV/T system able to recover thermal energy and to increase the electric performances, is studied. In [14], a dynamic simulation of a CPV/T system is determined. Moreover, the thermal recovery depends above all on the evaluation of the cell temperature whose value is not easy to determine theoretically in each working condition [15], because it is strongly linked to the concentration factor; hence, the mechanism of thermal recovery remains a problem not completely resolved. The CPV systems present only a passive cooling, while the CPV/T systems according to the typology of concentration (point-focus, linear focus, dense array) present different technologies able to recovery thermal energy.

Different concentrating systems have been above mentioned, but in the literature there is not a standard configuration of a CPV/T system. It depends on many factors such as the concentration factor, the type of optics, the typology of user, etc. Hence, in this paper the main aim is the performances evaluation of the CPV/T system in terms of electrical and thermal energy production, cells number, space occupied, energy and economic savings and CO_2 emissions avoided respect to a traditional system, by varying: the concentration factor, the configuration of the CPV/T system (point-focus (PF) and linear focus (LF)), and the typology of user (residential user and hotel).

2. Point-focus and linear focus configurations of a CPV/T system

A CPV/T system is a complex apparatus which mainly consists of three elements: optics, receiver and tracking system. The optics focuses the sunlight in order to maximize the incident radiation. The receiver is represented by the TJ cells that allow the electric energy conversion; in the CPV/T systems, the receiver presents also an active cooling system that allows to recover thermal energy [16]. The concentrating system can work only with the solar radiation direct component and the tracking system, usually biaxial, follows the sun during the day keeping the optics axis perpendicular respect to the sunrays. There are several configurations of a CPV system: point-focus, linear focus and dense array. In the point-focus system (Figure 1), each lens or mirror focuses the sunlight only on a cell. The optics is mainly refractive generally consisting of acrylic material lenses with transmission coefficient between 0.80 and 0.95. In the linear focus system (Figure 2) the concentration takes place along a line where TJ cells are usually arranged; these systems use refractive or reflective optics based on parabolic trough concentrators. Dense array systems adopt a reflective focusing optics that uses parabolic mirrors which concentrate solar radiation on a series of cells arranged side by side. In particular, in a PF configuration the incident radiation is focused only on the cells and not along the tube, and the distance between two cells is higher respect to the LF configuration. On the contrary, the LF configuration allows the concentration along a line that includes both the tube and the cells whose distance is reduced in comparison with the PF configuration.

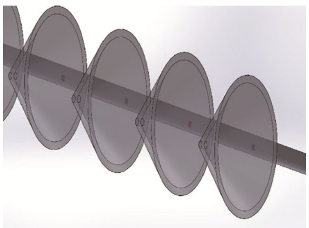

Fig. 1 Point-focus configuration

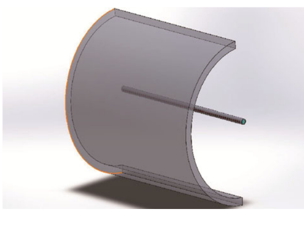

Fig. 2 Linear focus configuration

In this paper, the PF and LF configurations considered present the triple-junction solar cells (InGaP/InGaAs/Ge) with an area of 1.0×1.0 mm^2, whose characteristics are reported in Table 1 [17]. These cells are thermically coupled with the tube, where the cooling fluid (water and glycol) flows, and, in particular, they are arranged on its surface, as reported in Figure 3. As a consequence, the concentrated sunlight can be converted into electrical and thermal energy by means of a photovoltaic layer and the cooling fluid respectively. The PF and LF configurations can be repeated in series with more rows in parallel that constitute the overall module.

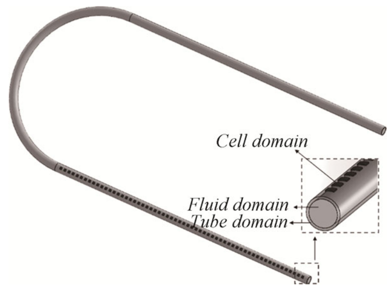

Fig. 3 Position of cell, tube and fluid in the CPV/T system

Table 1 Characteristics of the TJ solar cell

Triple-Junction cell	
parameter	*value*
material	InGaP/InGaAs/Ge
dimensions	1.0 cm × 1.0 cm
η_{ref} (at 25°C, 50 W/cm^2)	38.7%
temperature coefficient (σ_t)	-0.04%/°C

3. Thermal and electrical modelling of a CPV/T system and its sizing

3.1 The electrical model of the CPV/T system

An accurate evaluation of the CPV/T system performances depends on external and internal parameters. The main external variable is the Direct Normal Irradiance (*DNI*) evaluated in this paper by means of an Artificial Neural Network (ANN) determined in [18]. In order to evaluate the CPV/T system electric production in each condition, the *DNI* can assume hourly, daily or monthly values. The internal parameters are concentration factor, optical efficiency and TJ cell temperature that affect the cell and overall performances. The electrical performances of the CPV/T system can be analyzed starting from the cell behavior. Once the *DNI* temporal level is defined, the electrical energy of the TJ cell is equal to:

$$E_{\mathrm{e,c}} = DNI \cdot A_{\mathrm{c}} \cdot C \cdot \eta_{\mathrm{opt}} \cdot \eta_{\mathrm{c}} \tag{1}$$

where A_c is the cell area and the optical efficiency (η_{opt}) has been evaluated according to the results reported in [10].

The cell efficiency depends on the cell temperature and the concentration factor. The cell temperature determination is complex because of the illumination characteristics and the cell construction technology. Although there are not equations that uniquely express the cell temperature in terms of the concentration factor, it is possible to refer to some results reported in the literature [8,19]. Hence, the cell temperature (T_c) can be approximately evaluated as [19]:

$$T_{\mathrm{c}} = T_{\mathrm{ref}} + \frac{V_{\mathrm{oc}}\left(T_{\mathrm{c}}, C\right) - V_{\mathrm{oc}}\left(T_{\mathrm{ref}}, C_{\mathrm{o}}\right)}{\beta(C)} \tag{2}$$

where V_{oc} (T_c, C) is the open circuit voltage function of the cell temperature and C; V_{oc} (T_{ref}, C_o) is the open circuit voltage depending on the reference temperature and C equal to 1; $\beta(C)$ is the tension thermal coefficient [20]. It is possible then to linearize, by means of some experimental results, the variables as a function only of C [21]:

$$T_{\mathrm{c}} = T_{\mathrm{ref}} + \frac{V_{\mathrm{oc}}(C) - V_{\mathrm{oc}}(C_0)}{\left|\beta(C)\right|} \tag{3}$$

Once known the cell temperature, the cell efficiency can be determined. Also in this case it is not possible to define a theoretical equation between the quantities examined, but it is possible to use some experimental results [22] which show the efficiency decrease when the concentration factor increases at the same cell temperature. Hence, the cell efficiency (η_c), can be expressed as [22]:

$$\eta_{\mathrm{c}} - \eta_{\mathrm{ref}} = \sigma_{\mathrm{t}} \cdot \left(T_{\mathrm{c}} - T_{\mathrm{ref}}\right) \tag{4}$$

where T_{ref} is the reference temperature equal to 25°C and η_{ref} is the reference efficiency corresponding to the concentration value, according to the cell manufacturer indications reported in Table 1. The temperature coefficient σ_t represents the efficiency percentage reduction as function of the temperature increase; its value has been set at -0.04%/°C in a range of 10°C~100°C.

Hence, considering the CPV/T system composed by a variable number of cells subdivided into different modules, the CPV/T system electric energy can be estimated as:

$$E_{\mathrm{e,CPV/T}} = E_{\mathrm{c}} \cdot n_{\mathrm{c}} \cdot \eta_{\mathrm{mod}} \cdot \eta_{\mathrm{inv}} \tag{5}$$

where the module efficiency (η_{mod}) up to 100 cells is equal to 0.95; η_{inv} is the inverter efficiency and n_c the number of cells considered.

3.2 The thermal model of the CPV/T system

The thermal energy obtained by the CPV/T system is directly connected to the heat recovery from the TJ solar cells layer. This means that the thermal energy corresponds to the incident radiation not converted into electricity that is so expressed [23]:

$$E_{\mathrm{th,CPV/T}} = \left[\left(1 - \eta_{\mathrm{el,CPV/T}}\right) \cdot DNI \cdot A_{\mathrm{c}} \cdot n_{\mathrm{c}}\right] - E_{\mathrm{th,loss}} \tag{6}$$

where the electric efficiency of the CPV/T system considers the cells and module efficiency:

$$\eta_{\mathrm{el,CPV/T}} = \eta_{\mathrm{c}} \cdot \eta_{\mathrm{mod}} \tag{7}$$

In order to provide an effective evaluation of the thermal energy potential, the convective and radiative losses have to be considered. Hence, the thermal losses can be evaluated as:

$$E_{\mathrm{th,loss}} = \left[\overline{h_{\mathrm{c}}} \cdot \left(T_{\mathrm{c}} - T_{\mathrm{a}}\right) + \varepsilon_{\mathrm{c}} \cdot \sigma \cdot \left(T_{\mathrm{c}}^4 - T_{\mathrm{a}}^4\right)\right] A_{\mathrm{c}} \cdot n_{\mathrm{c}} \tag{8}$$

where ε_c is the cell emissivity equal to 0.85 [12].

3.3 The sizing of the CPV/T system

The starting point of the sizing has been the analysis of the annual electrical demands. The system proposed starts from the hypothesis that the electrical demands have to be totally satisfied, evaluating then what can be matched also in terms of thermal energy. Once known the user input data (electrical load, available space and installation site) and the necessary values of C and n_c, the CPV/T system performances in terms of thermal energy, number of modules and area occupied, are evaluated. If the CPV/T system satisfies the user in terms of electrical energy and available space, the system is well sized and then it is possible to evaluate the costs and the environmental impact, otherwise C and n_c have to be properly varied. The dimension of the CPV/T systems depends on the typology of concentration [11]: point-focus, linear focus and dense array. The sizing of the module depends not only on the arrangement of the cells, but also on the values of C and n_c used for each module. Hence, the calculation of the total size of the module takes into account: concentrator area, cell area, n_c and C. Modules of rectangular shape, where the cells are positioned along parallel rows, have been chosen. For a PF system modules containing 90 cells arranged in six parallel rows, each of which consists of 15 units, have been considered. As for the LF system, modules containing 150 cells arranged in two rows of 75 cells, have been considered. Once known the dimensions of the cell and considering a C value, it is possible to determine the concentrator dimensions multiplying the C value by the cell area and then to calculate the module dimensions imposing a proper distance among the single concentrators.

3.4 Energy savings, CO_2 emissions and costs analysis

The CPV/T system performances can be evaluated also in terms of primary energy by means of a Fuel Utilization Coefficient (FUC) that compares the CPV/T system with a traditional system matching the same energy demands:

$$FUC = \frac{E_{\mathrm{el}} + E_{\mathrm{th}} + E_{\mathrm{co}}}{\frac{E_{\mathrm{el}}}{\eta_{\mathrm{el,n}}} + \frac{E_{\mathrm{th}}}{\eta_{\mathrm{th,b}}} + \frac{E_{\mathrm{co}}}{\eta_{\mathrm{el,t}} \cdot COP}} \tag{9}$$

where $\eta_{\mathrm{el,n}}$ is the electric efficiency of the electric network; $\eta_{\mathrm{th,b}}$ is the thermal efficiency of a boiler and *COP* is the coefficient of performance of an electric heat pump adopted by a traditional system to obtain the cooling energy. The electric, thermal and cooling energy savings are determined evaluating the difference between the CPV/T system energy production and the user energy loads. Hence, the solar source use decreases the CO_2 emissions respect to a traditional solution corresponding to the same loads. Once determined the primary energy savings related to the electrical, heating and cooling demands, the CPV/T system environmental impact is evaluated in terms of emissions of CO_2 avoided, linked to the primary energy savings, by means of the equation:

$$kg\mathrm{CO}_2\,avoided = \frac{\left(E_{\mathrm{el,pr,sav}} + E_{\mathrm{th,pr,sav}} + E_{\mathrm{co,pr,sav}}\right)\cdot 3600}{LCV} \cdot \frac{1.94}{1.056} \tag{10}$$

which allows to evaluate the annual CO_2 emission savings. The total CO_2 emissions avoided are evaluated considering the overall system life cycle of about 20 years.

As for the economic analysis, the CPV/T system total cost is equal to:

$$C_{\mathrm{t}} = C_{\mathrm{c}} + C_{\mathrm{opt}} + C_{\mathrm{ts}} + C_{\mathrm{ac}} \tag{11}$$

where the costs of cell, optics, tracking system and additional components are considered. Hence, starting from the cost of the CPV/T system and its energy production, the Simple Pay-Back (SPB) can be evaluated determining the cash flows generated by the CPV/T system considering the electrical and thermal energy savings.

4. Results and discussion

In this paper, the main aim is the performances modelling of a CPV/T system in order to evaluate the primary energy and economic savings and the CO_2 emissions avoided in comparison with a traditional system, when the same energy loads of an user are considered. In Figure 4 the flow-chart of the model is reported. The *DNI* has been modelled by means of an ANN [18], considering the data reported in Figure 5 and compared with the actual *DNI* data presented in [4] with error included in the range 3%~5% in the less rainy months of Singapore.

The residential user presents a surface whose area is equal to 100 m^2 and is inhabited by 4 people. The electricity consumption is about 3000 kWh/year, the

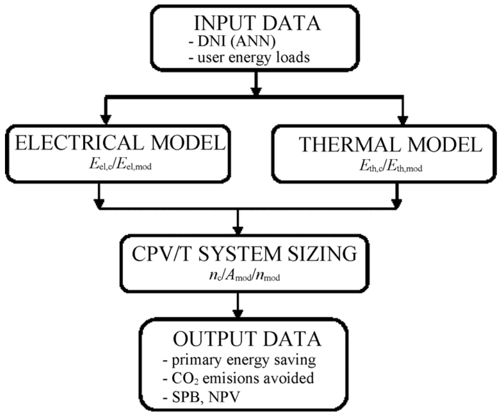

Fig. 4 Flow-chart of the model

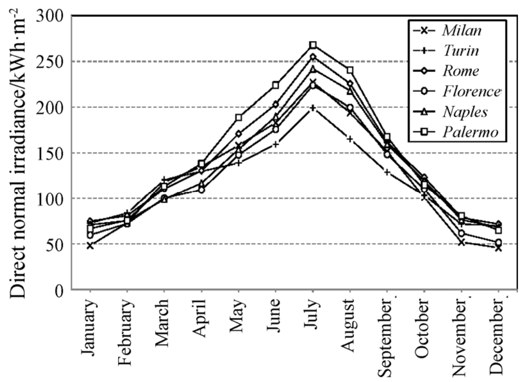

Fig. 5 Monthly values of direct normal irradiance related to Italy

energy needed for heating during the winter months is about 8600 kWh/year, while the cooling demand is about 3200 kWh/year [24]; the thermal energy for SHW is about 3000 kWh/year. The other user considered in this paper is a medium-sized hotel characterized by variable electrical and thermal demands during the year, but there are not periods of inactivity. The hotel allows the contemporaneity of the electrical and thermal demands respect to the residential user. The hotel consumptions data (space conditioning, steam production, production of domestic hot water, lighting, etc) have been collected and processed on the basis of data found in the literature for hotels in different areas of Italy [25], according to the size of the hotel and the number of rooms. In particular, in this paper three and four stars hotels that have a high level of customer service, have been considered. Moreover, in addition to the typical characteristics of a hotel (guest rooms, common areas, etc), also extra services are considered such as a restaurant, laundry service and conference room. It has been observed by the data analysis that a high part of the electrical demand is due to the air conditioning demands, in addition to the electricity consumption related to services such as elevator, kitchens and lighting. The thermal energy demand is related to the SHW and heating loads [25]. Figure 6(a) and 6(b) show for both the residential and hotel users, the trends of the monthly electric, thermal, cooling loads. The cooling load can be completely satisfied by a single-effect LiBr/H_2O absorption heat pump (AHP) with a *COP* equal to about 0.9 [26]. Moreover, in order to obtain thermal energy for SHW, heating and cooling from the CPV/T system, three fluid temperature values are set: 45°C (SHW), 65°C (winter heating) and 85°C (summer cooling).

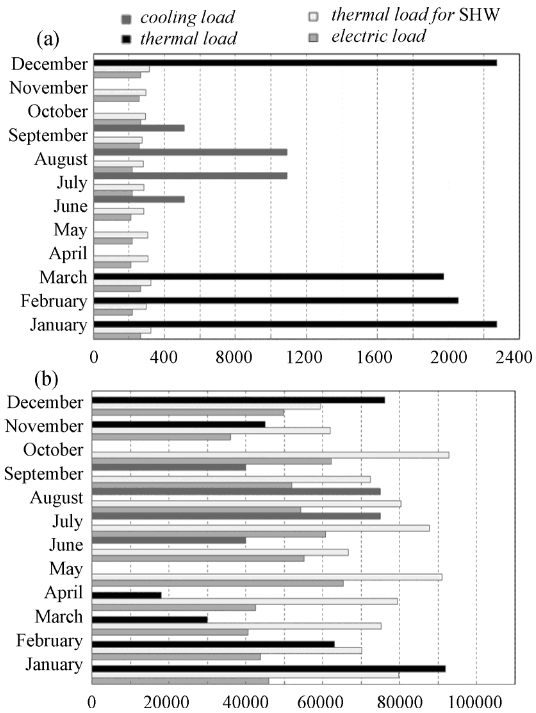

Fig. 6 Energy loads: residential user (a) and hotel (b)

Once known the energy loads of the users, a study on an annual basis has been carried out for both residential and hotel users, sizing the CPV/T system on the basis of the required electrical energy. Two types of concentration systems have been studied, linear focus and point-focus, varying the *C* values. It has been noted that in the winter months, when the days are shorter and the insolation is lower, it is necessary sometimes to integrate the electricity from the network. On the contrary, in the summer months, when the days are longer and the insolation is higher, the produced energy is greater than that required by the user and it is given to the network. As for the thermal loads, the PF and LF systems generally match, for both the residential and hotel users, during the year the SHW thermal and cooling loads, while an integration for the heating is necessary. Moreover, when the thermal energy produced is higher than that required, it can be stored in a thermal tank and integrated when necessary. In Figure 7(a) and 7(b) the electrical and thermal energy production for residential and hotel users are reported.

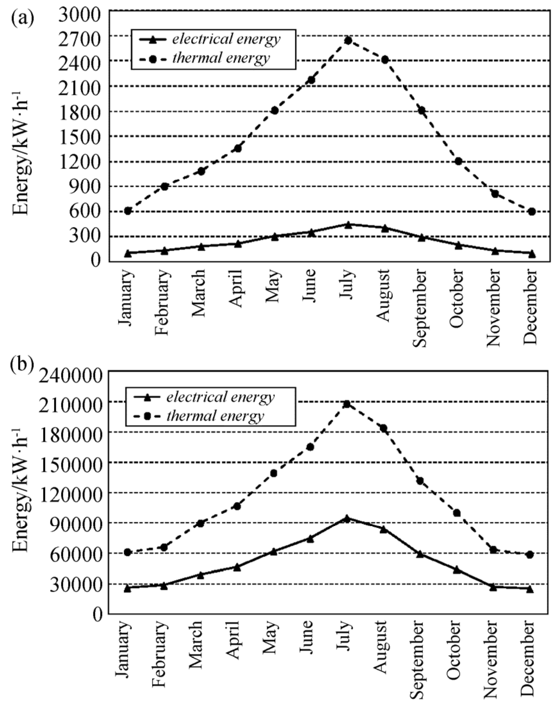

Fig. 7 Production of electrical and thermal energy: residential user (a) and hotel (b)

Moroever, in Figure 8 a comparison between thermal production and thermal loads for the residential user (Figure 8(a)) and the hotel (Figure 8(b)), is proposed.

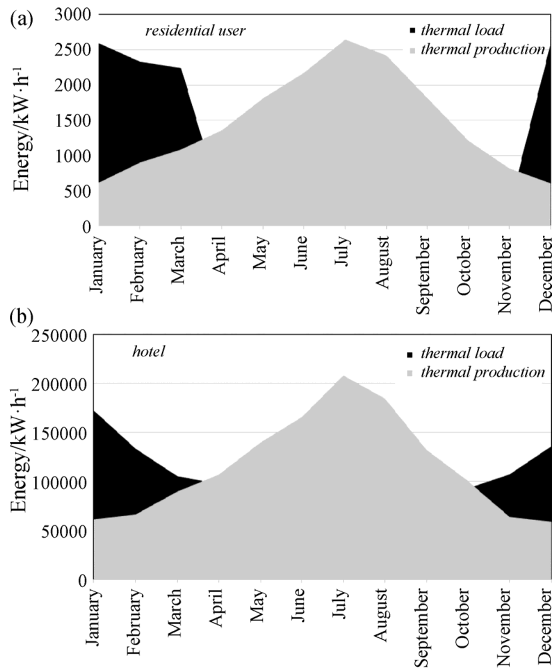

Fig. 8 Comparison between thermal production and thermal loads: residential user (a) and hotel (b)

A PF system with *C* values equal to 100×, 300×, 500×, 700× and 900×, has been analyzed for both users; as for the LF system the *C* values considered are 50×, 100×, 120× and 150×. The PF and LF systems, compared under the same conditions in terms of energy loads, have given significantly different results in terms of size, number of cells and costs. As for the residential user the configurations analyzed are with *C* equal to 300× in the PF case, and *C* equal to 100× in the LF case. As for the hotel the configurations are with *C* value equal to 500× in the PF case, and *C* equal to 100× in the LF case. For both the users considered in this paper, some specific configurations have been considered because they present the highest technical feasibility. In particular, referring to the PF configuration if the concentration factor increases, the accuracy of the acceptance angle gets worse and the precision of the solar radiation concentration could vary; hence, the *C* values chosen are more realistic and also experimentally tested [27]. On the contrary, as for the linear focus configuration, the theoretical limit is slightly above 200×, but a more realistic value is about 100×. In Tables 2 and 3 it is possible to observe for the residential and hotel users that the number of cells and the total dimension of the CPV/T system vary with *C* for both LF and PF configurations.

In particular, the number of cells and the total size of the CPV/T system decrease when *C* increases. Since the total area of the mirrors used is constant and the size of the cells is fixed, when *C* increases, the number of cells decreases considering that C is the ratio between the area of the concentrator and the area of the cell. Hence, the system total area decreases with *C* while the single module area increases (Tables 2 and 3). This is due to the fact that the use of a high *C* leads to a decrease of the total number of cells [27] and then of the modules that consitute the CPV/T system, but a higher *C* value also involves concentrators with larger surfaces and, therefore, a larger single module surface. Hence, the single module area increases but the modules number decreases when *C* increases.

Moreover, it is possible to note that the overall dimensions differ considerably for the LF and PF configurations. In fact, for example in the case of the hotel, when *C* is equal to 100×, the size of a PF system (about 8000 m^2) is about 5.5 times higher than a LF system (about 1500 m^2). In fact, the LF case presents modules of 150 cells respect to 90 cells of the PF modules, with less dead space thanks to the linear arrangement of the cells. On the contrary, for a LF system, the *C* values are lower than a PF system. Hence,

Table 2 Number of TJ cells and sizing of the point-focus and linear focus CPV/T systems as function of the concentration factor for the residential user.

	point-focus				*line-focus*			
	cells number	*module area (m^2)*	*modules number*	*total area (m^2)*	*cells number*	*module area (m^2)*	*modules number*	*total area (m^2)*
C=50	-	-	-	-	1800	0.69	12	8.3
C=100	900	3.7	10	36.6	900	1.07	6	6.4
C=150	-	-	-	-	600	1.46	4	5.8
C=300	270	6.9	3	20.6	-	-	-	-
C=500	180	9.6	2	19.3	-	-	-	-
C=700	90	12.2	1	12.2	-	-	-	-
C=900	90	14.7	1	14.7	-	-	-	-

Table 3 Number of TJ cells and sizing of the point-focus and linear focus CPV/T systems as function of the concentration factor for the hotel.

	point-focus				*line-focus*			
	cells number	*module area (m^2)*	*modules number*	*total area (m^2)*	*cells number*	*module area (m^2)*	*modules number*	*total area (m^2)*
C=50	-	-	-	-	405383	0.69	2702	1864
C=100	201236	3.7	2235	8180	201236	1.07	1341	1435
C=120	-	-	-	-	167375	1.2	1115	1338
C=150	-	-	-	-	133584	1.46	890	1299
C=300	66303	6.9	736	5042	-	-	-	-
C=500	39446	9.6	438	4218	-	-	-	-
C=700	28161	12.3	312	3822	-	-	-	-
C=900	21845	14.7	242	3567	-	-	-	-

the two systems present a considerable difference both in terms of overall dimensions and necessary cells. For example, referring to the residential user, a PF system with *C* equal to 300×, 270 cells corresponding to three modules are necessary. As for the LF system with a *C* equal to 100×, 900 cells and six modules are needed. The overall dimensions are 20.6 m^2 for the PF system and 6.44 m^2 for the LF system. Related to the hotel, the LF system with 100× presents a cells number five times greater than the PF system with 500× (Table 3). On the contrary, analyzing the results in terms of overall dimensions, it is possible to observe how the surface area required for the PF system is three times higher than that required for the LF system, with a surface area of about 1400 m^2 compared to about 4200 m^2 of the PF CPV/T system.

As for the environmental impact, an analysis in terms of CO_2 emissions avoided has been realized. The use of a CPV/T system allows a primary energy saving and, then, a reduction of CO_2 emissions compared to a traditional system. First of all, the primary energy savings corresponding to the energy demands of the user, have to be considered. Referring to the residential user, the electrical, thermal and cooling primary energy required by point-focus CPV/T and traditional systems, is evaluated in Table 4. The traditional system consists of the electric national grid ($\eta_{el,n}$=0.39), a traditional boiler ($\eta_{th,b}$=0.9) and an electric heat pump with a *COP* equal to 3, working under the same operating conditions. Table 4 shows that the primary energy required by a system that utilzes solar energy, is the only necessary energy for the integration. Hence, the CPV/T system allows high energy savings and its Fuel Utilization Coefficient (FCU) results higher than the traditional system. It is possible to evaluate the primary energy savings obtained by the CPV/T system (Table 4). In particular, referring to the user energy demands, the system allows a saving of 7396 kWh/year related to the electric demand, and an energy saving of 5271 kWh/year and 2737 kWh/year in terms of respectively thermal and cooling consumptions. So, considering a life cycle of 20 years, the system allows a high primary energy saving.

Table 4 Comparison between the traditional and CPV/T systems in terms of primary energy saving and CO_2 emissions avoided

Month	*traditional system*			*CPV/T system*			
	$E_{el,pr}$/kWh	$E_{th,pr}$/kWh	$E_{co,pr}$/kWh	$E_{el,pr}$/kWh	$E_{th,pr}$/kWh	$E_{co,pr}$/kWh	*kg* CO_2
January	685	2855	0	0	2270	0	265
February	563	2582	0	0	1920	0	256
March	685	2526	0	0	1610	0	334
April	542	336	0	0	0	0	184
May	561	335	0	0	0	0	187
June	542	311	438	0	0	0	270
July	561	312	931	0	0	0	377
August	561	309	931	0	0	0	376
September	663	302	438	0	0	0	293
October	685	322	0	0	0	0	210
November	663	324	0	0	0	0	206
December	685	2846	0	0	2290	0	259
Total	*7396*	*13360*	*2738*	*0*	*8090*	*0*	*3217*
		FUC=0.745			***FUC=2.265***		

Moreover, the primary energy saving determines also a decrease of the CO_2 emissions. The leakage of CO_2 avoided in a year is equal to 3217 kg and about 65 t during the system life cycle (Table 4). Finally, it is possible to realize a similar analysis for the hotel; in this case the CO_2 emissions avoided result to be equal to 628 t/year for a LF configuration.

In order to realize an economic analysis of the PF and LF CPV/T systems adopted for the residential and hotel users, it is necessary to consider the costs of cell, concentrator, cooling system, tracking system, inverter, thermal tank and AHP. Summing all these costs, it is possible to determine the total cost of the CPV/T system. The following costs have been considered: cell cost of 5 €/cm^2 [28], cooling system cost of 200 €/m^2, optics/concentrator cost of 10 € for a single concentrator related to the PF system and 900 €/m^2 related to the LF system, tracking system cost of 300 €/module, AHP cost of 200 €/kW_f [26]. In particular, the concentrators cost depends on the cell area and the number of cells for module. In order to calculate the cash flows, it is necessary to consider all the savings obtained thanks to the use of the CPV/T system. In particular, the electric energy consumed by the user, the cost of the gas used to obtain SHW and heating, the electrical energy to match the refrigeration load, and also the electricity surplus sold during the summer months to the public power grid. Referring to the residential user, the total cost of the point-focus CPV/T sytem with *C* equal to 300× is about 11.5 k€; on the contrary, the linear focus cost with *C* equal to 100× is about 14.9 k€. Figure 9 shows the Net Present Value (NPV) trend for the PF and LF configurations. The economic analysis shows that the values of the SPB for the PF and LF systems are respectively equal to about 9 years and 11 years. The PF system presents an economic advantage, but the LF system allows both the use of lenses without an image determining a greater acceptance angle and lower overall dimensions. As for the hotel, the PF configuration with *C* equal to 500× results more convenient than the LF configuration with SPB lower (Figure 10). In particular, the economic analysis shows that the values of the SPB for the PF and LF systems are respectively equal to about 8 years and 12 years. Finally, for both users and referring to the same electrical load satisfied, the PF configuration is an economically more advantageous solution, while the LF configuration is more convenient in terms of overall dimensions.

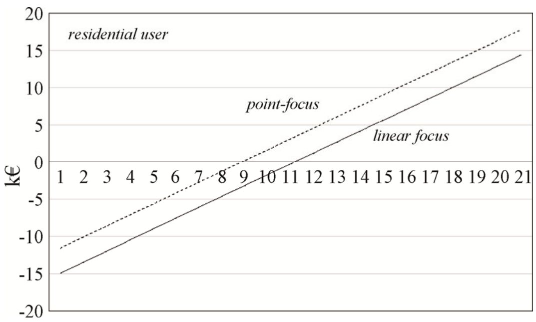

Fig. 9 NPV for the point-focus and linear focus CPV/T systems applied to the residential user referring to *C* values respectively equal to 300× and 100×

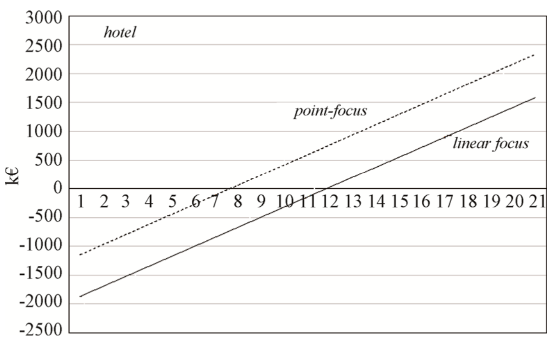

Fig. 10 NPV for the point-focus and linear focus CPV/T systems applied to the hotel referring to a concentration to *C* values respectively equal to 500× and 100×

5. Conclusions

In this paper the main aim has been the study of the CPV/T system used for two different types of users, residential and hotel, when *C* varies. Two specific configurations of the CPV/T system, point-focus and linear focus, are studied referring to different users. Different concentration levels for the PF configuration (150×, 300×, 500×, 700× and 900×) and the LF configuration (50×, 100×, 120× and 150×), have been adopted. The CPV/T system has been sized under different working conditions, adopting an ANN for the *DNI* evaluation and according to the energy loads of the users considered. In these hypotheses the PF and LF systems performances have been evaluated from the electrical and thermal point of view, and compared for both the users located in Southern Italy. In particular, the performances of the PF and LF configurations in terms of energy, economic and CO_2 emissions avoided, are evaluated; the comparison is realized also in terms of the cells number adopted and the space occupied. The CO_2 emissions avoided result to be equal to 3217 kg/year for the residential if a point-focus CPV/T system is adopted and 628 t/year for the hotel considering a linear focus CPV/T system. The PF system with 300× and the LF system with 100× for the residential user, the PF system with 500× and the LF system with 100× for the hotel, appear to be the highest technical feasibility solutions. It has been observed for the two users which the LF system shows a SPB higher and then a primary energy saving lower, but the space occupied by a LF system results to be lower, corresponding to the same energy needs. Future developments will have to take into account an optimization process, which evaluates the optimal *C* value able to guarantee the minimum size of the CPV/T system, further energy and economic savings and higher CO_2 emissions avoided.

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