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ENERGY PRODUCTION ANALYSIS OF A SOLAR PV-T COLLECTORS SYSTEM INTEGRATED IN A BUILDING FACADE

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The paper presents a comparative study concerning the thermal and electrical energy productions related to a system with PV-T type solar collectors, placed across a reference building facade. The method of analysis for the annual thermal and electrical energy production was the numerical simulation, performed via specialized software for this type of systems, under dynamic operating schedule and for 12 geographical locations. The results obtained from these simulations show similar behaviors of the energy production for a given city and a given parameter variation, but also some important differences among the three countries, especially concerning the investment payback times.

Keywords: PV-T collectors, energy yield, solar thermal fraction, payback time

1. Introduction

This paper is oriented to the analysis of the solar fraction and the electrical efficiency of Photo-Voltaic Thermal (PV-T) solar collectors installed on the façade of a building. The geometry of the building was considered identical in all the simulations, while the parameters being changed were: the tilt angle of the collectors (70º or 90°), their cardinal orientation (South East, South, South West), the destination of the building (hotel, residential and office) and the geographical location (12 cities from Romania, Bulgaria and France). The electrical energy load of the building and the daily domestic hot water consumption remained fixed for comparison reasons.

For a deeper understanding of the updated theoretical and practical research already done by different researchers in the field, the information can be found below.

Aste et al. [1] found an inverse proportionality relation between the temperature of the hybrid PV-T panels and the efficiency of the system. By knowing that, it is obvious that the overheating of the panels during strong

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sunshine periods of time will increase the heat transferred to the water circuit of the PV-T collector (figure 1).

By using the specialized software TRNSYS, the aim of the project was to observe the solar fractions in 3 different zones in Italy. It has been calculated that the solar fraction is strongly dependent on the solar radiation and DHW load variation. Moreover, the thermal panel system studied has an efficiency of 70%, while the corresponding PV-T system has a thermal efficiency of only 50-60%.

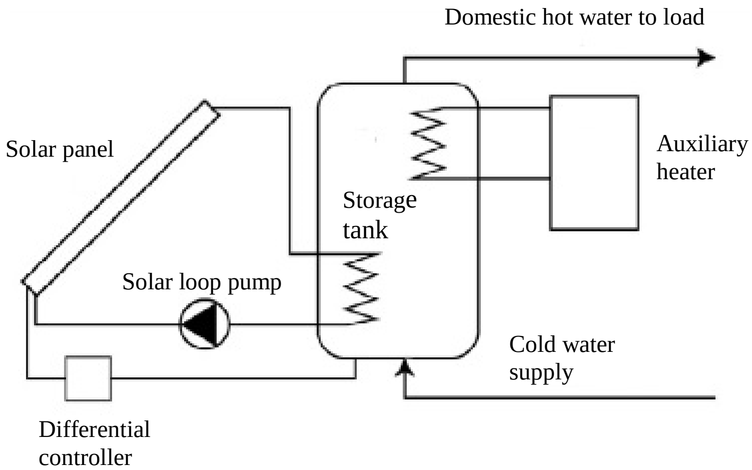


Fig.1 : Sketch-up of the system simulated [1]

Matuska [2] analyzed the performance of different constructive types of solar hybrid PV-T liquid collectors for a domestic hot water application in a block of flats. A comparison with conventional installation of photovoltaic (PV) and thermal (PT) solar collectors with the same total collector area 100 m^2 has been done for identical load conditions. Conventional solar system has been considered with different fractions of PV collector to PT collector area, for comparison with the PV-T system.

It is already known that unglazed PV-T collectors cannot be competitive with conventional PV-PT collectors in a given solar DHW system. Competitive price range has been assumed in advance for solar glazed PV-T collectors being under development with novel siloxane lamination: 290-410 €/m2 for nonselective type and 370-500 €/m2 for selective type.

Axaopoulos et al. [3] found that, for residential buildings, the idea of DHW supply systems that are connected by PV-T Panels is a real option (figure 3). The simulations were done with the same hourly specific water flow consumption – 45 l/h*m^2 that has the water pre-heated in a boiler from the PV-T system and has also an electrical heater and a gas heater to compensate the periods without sunshine. The research shows that the systems are a viable solution, with the system providing 60-80% of hot water to the building, with the advantage of delivering into the grid the electrical energy. Furthermore, it has been shown that it would be more advantageous for the difference of the water to be heated electrically than through gas systems. In Greece, this system is economically attractive as an investment.

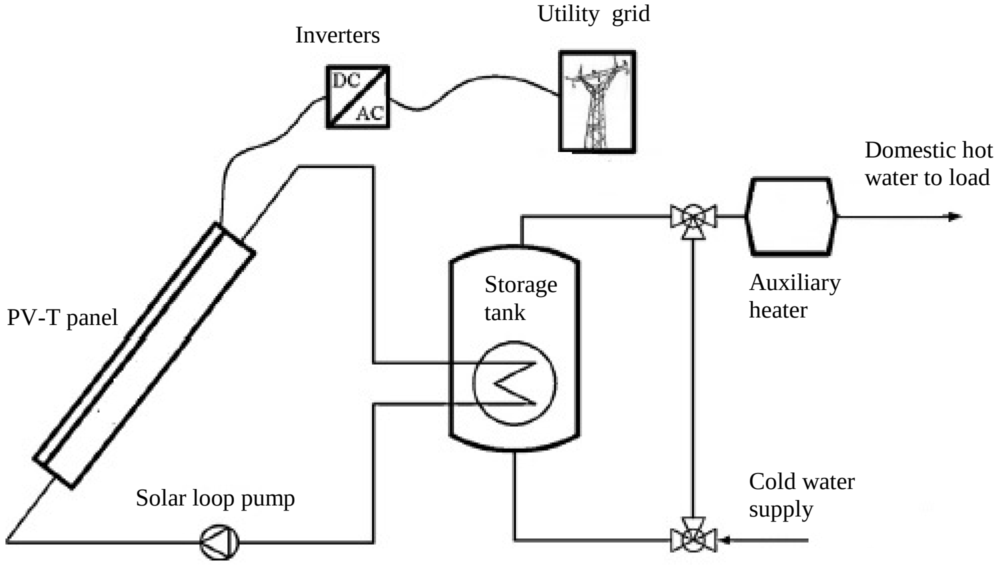


Fig.2 : Schematic representation of the PV/T system configuration [3]

More experimental work has been conducted to provide comparative results between classical PV panels and PV-T panels [4]. The research has shown that the temperature of the PV Panels is higher than the temperature of the PV-T panels, so the glazed PV-T system is shown to produce about 4% more electrical energy than the PV Panels, with the bonus of delivering heat for the pre-heating circuit of DHW.

While studying the PV-T loop heat exchanger (figure 3), Buker et al. [5] found that, in the United Kingdom, the cold water could be pre-heated by up to 16ºC, thus increasing the overall thermal efficiency of the collectors up to 20-25%. The discharging of the heat into the water will reduce the temperature of the panels, increasing the energy savings by 10.3 MWh/year. In the frame of a Life Cycle Cost analysis, for 25 years life span, the net present value was found to be equal to 19456 Euros.

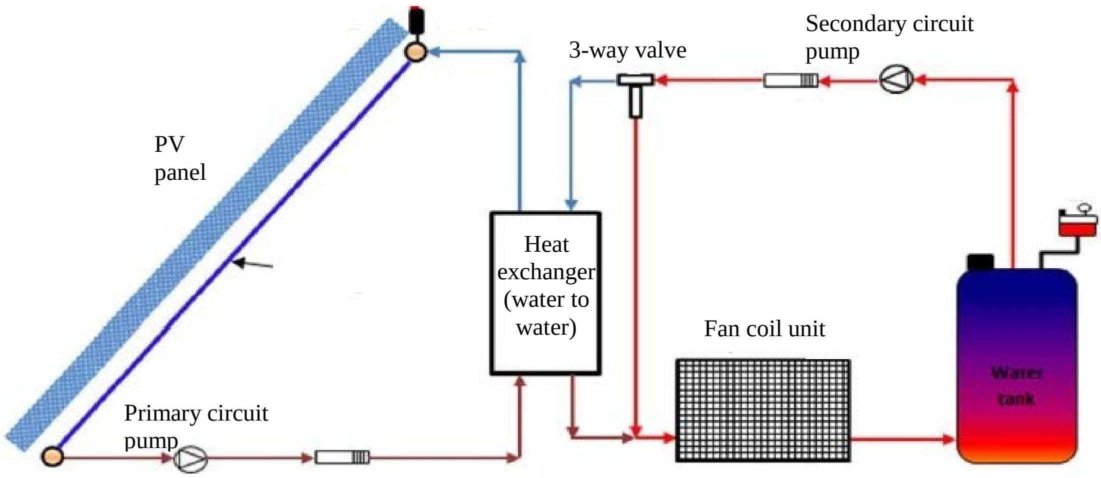


Fig.3 : The PV-T loop heat exchanger system considered for the numerical study [5]

Evola and Marletta [6] presented an analysis of the Second Law of Thermodynamics for a water-cooled PV-T glazed collector, by means of numerical simulations (figure 4). The study also discussed a crucial problem for the optimal exploitation of this technology: the electricity production from PV cells is supported by low temperatures, whereas the usability of the thermal energy increases at high temperatures.

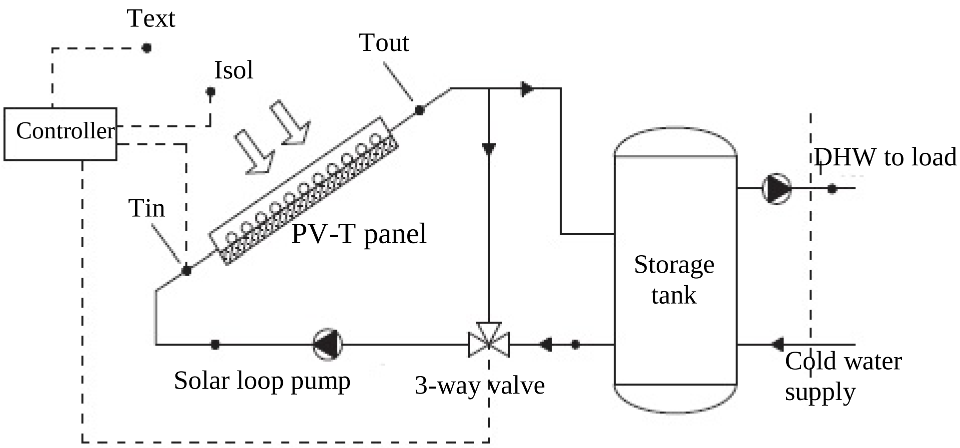


Fig.4 : Simplified sketch of the command-control system on the PV-T solar loop [6]

If speaking in terms of maximizing the amount of energy the system can absorb, the temperature of the inlet water should be around 20ºC, with a total yield of 3016 kWh/an, but this means the water temperature would be low and it could not be utilized properly. The optimal temperature of the inlet water should be around 35ºC for the system to be efficient electrically and thermally – with a global yield of 2460 kWh/year.

Rommel et al. [7] presented an experimental research conducted for two projects: a borehole heat exchanger with regeneration and pre-heating system of hot water for residential usage (figure 5). The focus was on the second experiment, that has shown an yearly thermal output of about 270 kWh/m^2, for an electricity production increased by 4% compared to classical PV modules case.

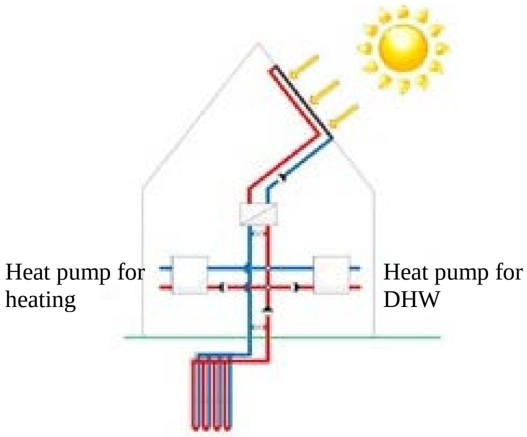


Fig.5 : Overview of the system using a borehole heat exchanger with regeneration [7]

Daghigh et al. [8] have demonstrated that the PV part of a PV-T system is dependent on the temperature of the solar panels. Their studies have shown that, in order to keep low the temperature of the solar cells, there can be used different types of cooling agents: air, water and refrigerant. If the heat that is generated from the solar radiation can be dealt with more easily, it is still a question on how to handle the air temperature around the PV-T panel. The research needs also to include a deeper analysis of the material composing the absorbent layer. Moreover, the type of refrigerant cooling PV-T is a future direction of research, in order increase the COP (Coefficient Of Performance) of the system.

Another interesting research has been performed for the case of family dwellings block of flats equipped with solar PV-T panels integrated on the building façade [9]. The paper is focused on a comparison between a commercial rectangular panel and a custom, trapeze-style panel. The study is oriented toward aesthetic architectural integration of the solar collectors, keeping also in mind their energy efficiency. In the simulations it is visible that, for the same area of 2 m^2, the commercial panel has a better efficiency (around 80%) than the trapeze one (around 65% or lower). The study also shows an analysis of the panel tilt angle influence, showing that, between 70º and 110º the collectors would absorb a bigger amount of solar energy.

2. Parametric studies

The parametric study presented in this paragraph was performed on a given building, with known architectural shape and building envelope composition, by installing a system for both hot water and electricity production, based on a special type of solar collectors. These collectors are already known in the technical literature as "PV-T collectors" or "PV-T panels" (PhotoVoltaic-Thermal), according to their dual objective in terms of types of energy delivery.

The system we will take note of is a Photovoltaic–Thermal collector system–referred as "PV-T collector system". It is connected as follows:

- **for the electricity production –** the panels are connected to the electrical grid with no energy storage (no batteries). At every moment of time, the surplus of electrical energy, calculated as the difference between the electricity production and the electricity consumption, is delivered into the grid. The installed power calculated for the supply of the lighting system for domestic and technical spaces is 5 kW.
- **for the domestic hot water (DHW) production –** the hot water from the PV-T system supplies a mono-valent storage tank used to preheat the hot water. If the water does not reach the desired consumption temperature of 45ºC, the water is then heated by a 30 kW gas boiler to the desired temperature. Further, if the water exceeds 45ºC, the system has a 3-way valve that mixes the cold water from the supply grid with the hot water.

We proposed a set of simulations that take into account a building with the same geometrical properties: levels, floor area, exterior dimensions and the same window layout. The simulations performed were based on the daily electrical load for lighting purposes, as well as on the daily domestic hot water (DHW) load for the occupants' needs. The daily profiles for electrical and DHW loads have been varied according to the building usage: residential, office or hotel. Thus, the parameters that will be varied are presented as follows:

1. <u>Building configuration and usage</u>

The building analyzed in this study has five floors (ground floor and four storeys), with a floor area of about 150 sqm. The daily domestic hot water (DHW) load is equal to 2400 litres/day, while the installed electric power for lighting appliances equals 5 kW. The architectural configuration of the building allows for three types of usage: office, hotel and residential.

Each of this usage types leads to different daily electrical and DHW load profiles. By switching between the types of buildings, these loads vary as follows:

- The office building will have the peak load for hot water in the day, and for electrical in the morning and in the afternoon ;

- The hotel has the peak water load in the morning and in the late evening, and the same for the electrical consumption ;
- The residential building has the hot water load peaks in the morning and evening and electrical peaks in the evening.

2. Geographical sites

For the simulations, in order to study various climatic conditions related to solar radiation and outdoor air temperature, we took into account 12 European cities corresponding to the three countries considered: Romania, Bulgaria and France, placed to close geographical latitudes (table 1):

Table 1

Geographical sites considered in simulations

Bulgaria	**France**	**Romania**
Plovdiv (42°9'**N**)	Ajaccio (41°55'N)	Bucuresti (44°30'**N**)
Rousse (43°51'**N**)	Lille (50°38'N)	Cluj Napoca (46°47'N)
Sofia (42°41'**N**)	Lyon (45°45'**N**)	Constanta (44°13'N)
Varna (43°12'N)	Paris (48°49'N)	Iasi (47°10'N)

3. Tilt angles of the solar panels mounted along the facade

According to the influence of the view factor between the Sun and the useful energy capture area of the solar collectors, we have taken into account 2 tilt angles of the PV-T solar panels: 90º and 70º, with respect to the horizontal plane.

4. Cardinal orientation of the panels placed on the facade

Due to the fact that we are studying the best incidence angle to the Sun for the system energy efficiency, we have positioned the panels towards three possible cardinal orientations: South, South-East and South-West.

In the parametric study we considered a PV-T collector containing monocrystalline PV cells and flat plate collector: PV-T Fototherm Monocrystalline FT260AL, with the electrical characteristics presented in table 2. In order to cover the electricity need of the building, 56 PV-T collectors of this type were installed on the building's facade.

Table 2

Electrical characteristics of the PV-T collector

Panel type	Mono-crystalline Si cells
Energy produced by panel [W]	260
Energy reduction at each 1K temperature difference [%/K]	0.4
Surface [m^2]	1.58
Dynamic capacity [J/K]	13 300
Price [€]	344.25

In order to perform annual simulation of the PV-T collectors' system operation, we decided to use specialized software–Polysun- released by the Swiss enterprise Vela Solaris [10]. This tool allows simulating various schemes of solar collectors systems, under lot of climatic conditions. The general sketch-up of the system with PV-T panels simulated with the Polysun software is illustrated in Fig. 6.

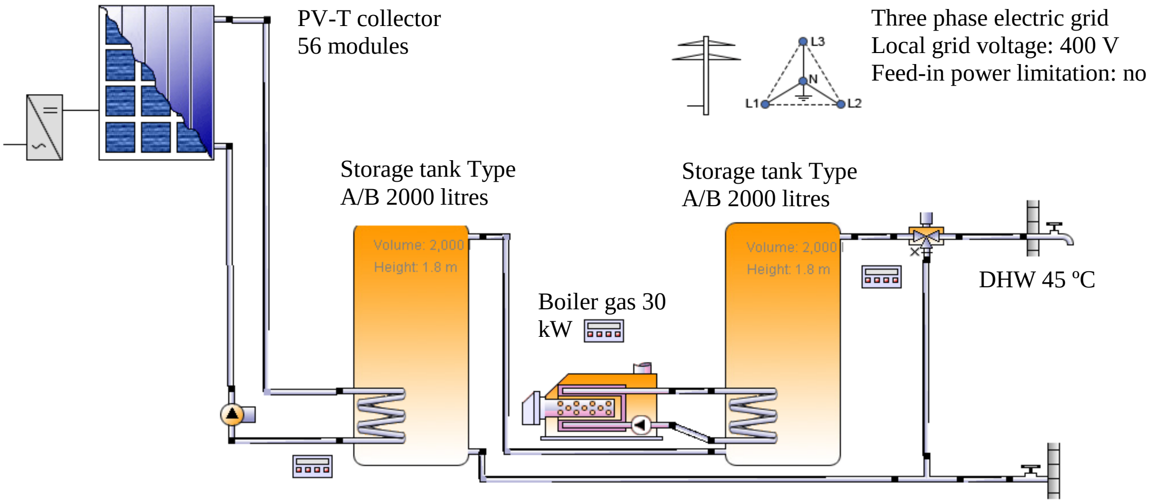


Fig. 6 : Sketch-up of the PV-T system on the Polysun graphical user interface [10]

For the determination of the payback time of the analyzed systems, we have estimated the selling price of the whole PV-T system to be around 5700 Euros.

The incentives allowed by each of the 3 countries Governments for the implementation of green energy potential were the following ones :

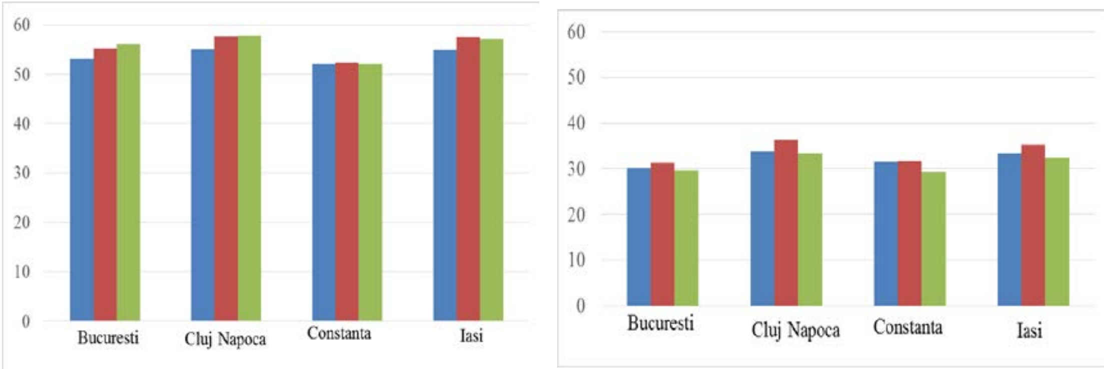
- Romania: 1300 €/project; France: 12000€/ project; Bulgaria: 90 €/year/project

The prices of the electrical energy "bought from/sold to" the National Grid were the following ones:

- Romania: 11 €cents per kW_e bought and 40 €cents per kW_e sold
- France: 17 €cents per kW_e bought and 60 €cents per kW_e sold
- Bulgaria: 10 €cents per kW_e bought and 30 €cents per kW_e sold

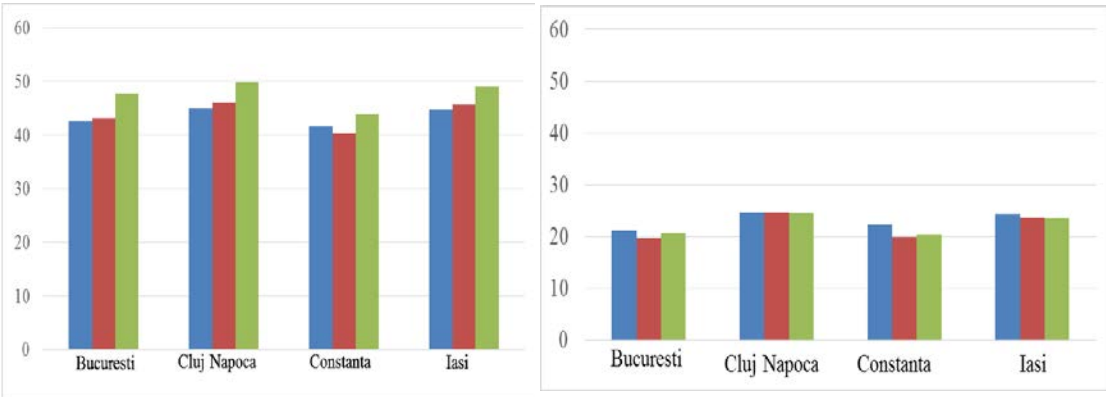
In addition, the thermal energy prices were found to be around ~ 2 Euro-cents/kW_{th} for all the three countries.

In the figures 7 and 8 are outlined the solar fraction and the electrical contribution of the analyzed system for the Romania case of residential building profiles (DHW and electrical need) and for two tilt angles of the PV-T collectors: 90º (figure 7) and 70º respectively (figure 8).



a. b.

Fig.7: Solar fraction (a) and electrical contribution (b) for 90° tilt angle for the residential building-the Romania case (blue: South-East, red: South, green: South-West)



a. b.

Fig.8: Solar fraction (a) and electrical contribution (b) for 70° tilt angle for the residential building-the Romania case (blue: South-East, red: South, green: South-West)

In tables 3 and 4 are represented the simulation results for the thermal and electrical contributions of the PV-T system (table 3-corresponding to the hotel case, 70°collectors tilt angle and orientation South), as well as a comparison between the thermal and electrical contribution obtained with the same system for three different consumption profiles (table 4 – residential, office and hotel cases, orientation South and 70°collectors tilt angle).

Table 3

Results of the PV-T system thermal and electrical contributions for the 12 cities, 70°collectors tilt angle and orientation South (hotel case study)

Country	City	Solar fraction thermal energy	Annual production of thermal energy	Annual solar contribution solar energy	Annual production of electrical energy	Internal consumption electrical energy	Electrical energy supplied to the grid	% of electrical energy supplied to the grid
		%	kWh	%	kWh	kWh	kWh	%
Romania	Bucuresti	53.3	19513	31.2	5052	4913	139	2.7
	Cluj	50.7	19366	30.5	5013	4847	166	3.3
	Constanta	46.9	16536	31.4	5037	4907	130	2.6
	Iasi	48.8	17820	31.8	5243	5048	195	3.7
Franta	Ajaccio	54.6	18144	29.0	5378	5281	97	1.8
	Lille	33.4	11525	43.0	3406	3364	42	1.2
	Lyon	32.6	11516	33.7	3564	3499	65	1.8
	Paris	40.7	14311	37.9	4029	3934	95	2.4
Bulgaria	Plovdiv	42.1	15423	28.8	3804	3690	114	3.0
	Rousse	44.9	16007	30.1	4331	4220	111	2.6
	Sofia	47	16479	29.4	4727	4611	116	2.5
	Varna	48.3	17165	29.2	4594	4475	119	2.6

Table 4

Comparison between the of the PV-T system thermal and electrical contributions for the 12 cities, 70°collectors tilt angle, orientation South and three building types

South orientation		Office case			Residential case			Hotel case		
Country	City	Annual solar fraction thermal energy	Annual solar contribution electrical energy	Payback time	Annual solar fraction thermal energy	Annual solar contribution electrical energy	Payback time	Annual solar fraction thermal energy	Annual solar contribution electrical energy	Payback time
		%	%	years	%	%	years	%	%	years
Romania	Bucuresti	56	37.2	7	55.3	31.3	9	53.3	31.2	10
	Cluj Napoca	58.3	41.5	6	57.7	36.3	8	50.7	30.5	10
	Constanta	53.1	37.8	7	52.4	31.6	9	46.9	31.4	10
	Iasi	58.3	41.1	6	57.5	35.3	8	48.8	31.8	9
Franta	Ajaccio	52.1	34.5	5	51.3	29.1	7	54.6	29.0	3
	Lille	62.4	47.6	4	61.6	43.1	4	33.4	43.0	2
	Lyon	55.2	38.3	5	54.6	33.7	5	32.6	33.7	3
	Paris	58.8	43.1	4	58.2	38.0	4	40.7	37.9	3
Bulgaria	Plovdiv	52.5	34.5	13	52.1	28.8	17	42.1	28.8	17
	Rousse	53.7	35.3	12	53.1	30.1	16	44.9	30.1	16
	Sofia	53.7	35.3	13	52.9	29.5	16	47	29.4	16
	Varna	53.3	35.7	13	52.7	29.2	17	48.3	29.2	17

Several conclusions could be outlined according to these results:

- for the thermal contribution, the solar fraction appears to be the biggest for the South-West orientation and the lowest for the South-East orientation;

- the 70º collectors tilt angle is always better than the 90º tilt angle, for both thermal solar fraction and electrical contribution (fig.7 and fig.8);

- for the electrical contribution, the orientation South-East seems to be the most favorable for a 70º collectors tilt angle (fig.8b); this trend was also observed for the France and Bulgaria cases;

- the best usage of the solar radiation is observed for the office case, for which the thermal solar fraction and electrical contribution show the biggest figures for all the 12 cities, while the hotel case appears to be the poorest beneficiary of this free-energy potential (table 4) ; this could be explained by the daily profile of the hotel consumption, which is not in phase with the daily solar radiation variation (high consumption during evening time) ;

-the smallest payback times are observed for the French case and the greatest for the Bulgaria case, where the Government incentives are the poorest; a payback time greater than the life duration of the system could mean an economic failure in the implementation of this type of system;

- the electrical contribution to the National Grids are small, around 3-4 % (maximum value) for all the cases, meaning that the PV-T system was designed to cover the internal electrical needs without overproduction; this could be a useful strategy in some cases, when the selling price of the kWh_e of electricity to the grid is of the same order with the corresponding buying price.

6. Conclusions

The paper outlines the influence of the climate type, collectors' tilt angle, cardinal orientation and domestic hot water (DHW) and electricity daily profiles on the thermal and electrical energy contribution that could provide a PV-T system installed on a given building. In order to outline the influence of these parameters, several sets of numerical simulations had been performed by using a dedicated software-Polysun, for one year-period of system operation.

The results are promising, showing that the 70º collectors tilt angle is always better than the 90º tilt angle, the South-West orientation is always the best in terms of solar thermal fraction and the South-East orientation for the electrical contribution and 70º tilt angle. In terms of payback times, the France case appears to be the best of all, with values smaller than 10 years, while the Bulgaria case is the worst, exceeding 15 years. This is due to the incentive amounts allowed for three countries.

More research work should be performed in order to assess the opportunity of implementation of this type of solar systems in other climatic conditions and architectural configurations.

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