Simulation of hybrid Photovoltaic-Thermal Collector (PV-TC) Systems for domestic Heating and Cooling – Case Study: Island of Rhodes

N. CHRISTANDONIS G.A VOKAS F. SKITTIDES
Department of Mechanical Engineering - Management of Energy Systems
Technological Institute of Education - TEI Peireaus
P. Ralli and Thivon 250, 12244 Aigaleo, Athens
GREECE

Abstract: The idea of hybrid photovoltaic-thermal collectors (PV-TCs) is based on the simultaneous operation of a photovoltaic laminate and a thermal collector attached as a thermal absorber. PV-TCs have improved electrical efficiency, due to the decrease of the photovoltaic panel temperature. The thermal efficiency of PV-TCs is also remarkable. This research aims to simulate and define PV-TCs electrical and thermal efficiency. After the theoretical simulation of a PV-TC, its electrical and thermal efficiency is calculated and compared respectively to the electrical efficiency of a photovoltaic panel and to the thermal efficiency of a conventional solar collector. This comparison leads to significant conclusions concerning the PV-TC overall efficiency in relation to its surface area. The theoretical study of a photovoltaic-thermal system for domestic heating and cooling in the region of Rhodes resulted that the system can cover a remarkable percentage of the domestic heating and cooling demands.

Key-words: Photovoltaic-thermal collector, Solar heating and cooling

1 Introduction

Solar radiation consists of photons and every photon has a specific quantity of energy, which is equal to the product of its mass and speed. The material normally used for the manufacture of photovoltaic panels is silicon. Each electron of the nucleus of the silicon atom possesses a quantity of energy in order to remain in the nucleus. Every photon, which has energy equal or higher than the above-mentioned energy, is absorbed by the silicon atom and activates the electron, while the rest of the photons convert their energy to heat. One very important element is that each photon can only activate and release one electron from the nucleus. The photons, which have more energy than the minimum energy required for the activation of an electron, convert it to heat on the photovoltaic cell [1]. The result is that a great part of solar radiation turns to heat on the photovoltaic cell. However, the electrical efficiency of the photovoltaic panel is reduced when the temperature increases. This is evident from equation (1), which shows how the efficiency of a photovoltaic cell is influenced by its temperature [2]:

$$n_{mp} = n_{mp,ref} + \mu_{P,mp} (T_c - T_{pv,ref}) \quad (1)$$

Equation (1) shows that each photovoltaic panel produces apart from electrical energy a remarkable amount of thermal energy as well, when solar radiation falls on its panel. The idea of improving the electrical efficiency, by reducing the photovoltaic collector's temperature, as well as taking advantage of the thermal energy produced, constitutes the basic idea in the development of hybrid PV-TCs.

2 Problem Formulation

It is well known and proved in several energy audits that the greatest part of energy consumption in houses and buildings is for heating and cooling. This part can reach almost 60% of the total energy [3]. Taking into account that all recent years show a rising trend of the average global temperature, the cooling of houses during summer has also become an important issue. The notable increase in the use of air-conditions especially at urban areas in European Union during the summer may cause problems overloading the electrical network leading consequently to blackouts. This problem is more evident in Greek islands, where the autonomous diesel stations are often unable to cover the increased electrical load during summer. A possible solution to this problem could be the extended use of the hybrid PV-TCs' in order to partially meet the needs for electrical energy and for domestic water heating and air cooling.

The subject of PV-TCs is quite new, so the existing bibliography consists of a few recently published articles. Wiebe [4] describes a procedure for designing a photovoltaic-thermal system using analytical equations. Sandnes and Rekstad [5] have also developed a hybrid PV-TC with several different absorbing surfaces. A sound paper on PV-TCs has been written by Tripanagnostopoulos et al [6], where the electrical and thermal efficiencies of four different settings of PV-TCs with air and water as an absorption medium are compared.

It is obvious that not many hybrid photovoltaic-thermal systems aiming at further usage of their produced thermal energy have been developed so far. So, there is much to investigate especially towards the co-operation of PV-TCs with other additional equipment (for example absorption chillers), their use instead of flat plate solar collectors and the application of complete hybrid systems in buildings.

In this research a PV-TC at NOCT conditions is simulated and then its electrical and thermal efficiency is calculated. Then the electrical efficiency of a conventional photovoltaic collector and the thermal efficiency of a conventional solar collector, with characteristics similar to that of the PV-TC, are also calculated. The results of the above calculations for the thermal and electrical efficiency of the PV-TC are compared respectively to the thermal efficiency of a conventional solar collector and to the electrical efficiency of a conventional photovoltaic collector.

In addition, in the present research the use of a system consisting of PV-TCs for the coverage of domestic heating and cooling load in the area of Rhodes is analysed. Furthermore, the solar coverage percentage of the photovoltaic-thermal system is calculated and then compared to the solar coverage percentage of a conventional solar collectors' system also installed in Rhodes. Moreover, the results of the above comparison are indicative of whether the PV-TCs can replace the conventional solar collectors for domestic heating and cooling applications.

3 Problem solution

3.1 Thermal efficiency

The instant thermal efficiency of the PV-TC is expressed by the following equation:

$$n_T = F_R(\tau\alpha)_n - F_R U_L \cdot \frac{T_i - T_\alpha}{G_T} \quad (2)$$

The characteristic parameters of the PV-TC $F_R(\tau\alpha)_n$ and $F_R U_L$ are calculated using the equations that refer to the flat plate collectors [2]. The equations are modified and adjusted properly in order to include the added section of the photovoltaic according to the research of Wiebe [4]. Using these equations the heat removal factor (F_R) and overall loss coefficient (U_L) of a PV-TC is calculated. The transmittance absorptance product of a PV-TC was equal to 0.74 according to Wiebe [4]. The calculated values of the PV-TC coefficients are presented in the Table 1, which also includes the results of the above calculations of the coefficients repeated for the same thermal collector, without taking into account the laminate of the photovoltaic.

Table 1. PV-TC and conventional solar collector characteristics parameters

Symbol	Pv-t	Solar collector
F_R	0.821	0.819
U_L	6.614	6.076
$(\tau\alpha)_n$	0.74	0.85

The temperature that is developed on the PV-TC is calculated using the following equation [4].

$$T_{pm} = T_{fi} + \frac{Q_u / A_c}{F_R U_L}(1 - F_R) \quad (3)$$

For Nominal Operating Cell Temperature (NOCT) conditions (irradiance level 800W/m^2, wind velocity 1m/sec, ambient temperature 20^o C) the temperature that is developed on the PV-TC is found to be equal to T_{pm} = 35.98^o C.

According to the equation (2) and the above values of $F_R U_L$ and $F_R(\tau\alpha)_n$, the thermal efficiency of the photovoltaic-thermal and of the thermal collector are presented in the Figure 1.

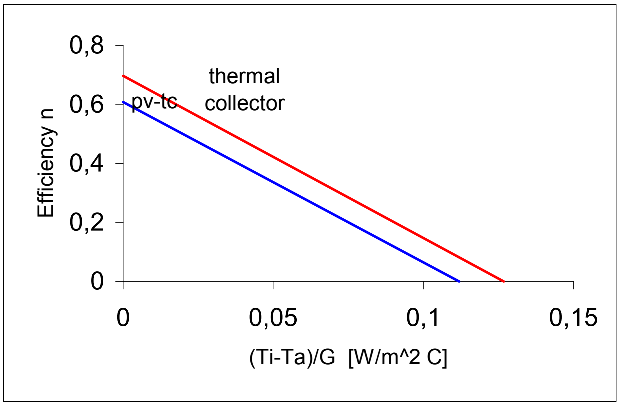

Fig. 1. Thermal efficiency of the photovoltaic-thermal and thermal collector

According to Wiebe [4], at NOCT conditions the inlet fluid temperature may be considered stable and equal to 20° C. Therefore, the PV-TC's thermal efficiency is:

$$n_{th} = 0.6078 \text{ or } 60.78\%$$

At NOCT conditions the conventional solar collector's thermal efficiency is:

$$n_{th} = 0.6968 \text{ or } 69.68\%$$

From these calculations it is concluded that the thermal efficiency of the PV-TC is about 8.9% less than the thermal efficiency of the thermal collector. This small difference is due to the insulation of the PV-TC.

3.2 Electrical efficiency

For the investigation of the PV-TC the characteristics of the SP150 photovoltaic collector of the 'Shell' company are used. All the details for this photovoltaic are included in the product information sheet of SP150 [7]. The collector is manufactured from 72 series of connected 125x125 (mm) mono-crystalline silicon solar cells. Its dimensions are 1.622 x 0.814 (m)= 1.32m^2 and its electrical characteristics at NOCT conditions are shown in Table 2.

Table 2. Electrical characteristics of the SP150 panel at NOCT conditions [7]

Temperature	$T_{(pv)NOCT}$	45° C
Peak power	P_{mp}	109 W
Peak power voltage	V_{mp}	31.2 Volts
Open circuit voltage	V_{oc}	39.9 Volts
Short circuit current	I_{sc}	3.9 A

The electrical efficiency of a PV-TC is represented at the equation (1). This equation describes the influence of the temperature T_c of the photovoltaic collector on the system's efficiency n_{mp}. The term $T_{pv,ref}$ refers to the temperature of the photovoltaic collector at reference conditions (25° C).

The maximum power point efficiency of the photovoltaic collector is calculated at NOCT conditions and panel temperature 45° C, according to the equation (4) as described in [2].

$$n_{mp,ref(pv)} = \frac{I_{mp} \cdot V_{mp}}{A_C \cdot G_T} = 0.1032 \qquad (4)$$

For irradiance level 800W/m^2 and ambient temperature 20° C, the PV-TC's temperature was found to be 35.98° C. The decrease of the PV-TC's temperature affects the collector's I_{mp} and V_{mp} and according to the product information sheet, the power (P_{mp}) is increased 0.45% per ° C [7]. Therefore, the reduction in temperature of 9.02° C (45-35.98), results to an increase of the PV-TC's power ($P_{mp(pv-t)}$) for 0.45 x 9.02 = 4.059%. Hence the photovoltaic panel power jumps from 109 W to 113.42W.

$$P_{mp(pv-t)} = I_{mp} V_{mp} = 113.42 \text{ W} \qquad (5)$$

The maximum power point efficiency of the PV-TC at NOCT conditions according to the following equation is:

$$n_{mp,ref(pv-t)} = \frac{I_{mp} \cdot V_{mp}}{A_C \cdot G_T} = 0.1074$$

The photovoltaic efficiency temperature coefficient is $\mu_{P,mp\ (pv-t)}$ = - 0.00046 (1/K) for both the PV-TC and conventional photovoltaic collector.

Finally, based on the above elements the electrical efficiency of the photovoltaic panel and of the PV-TC at NOCT conditions is:

$n_{mp,(pv)}$ = 0.1032 – 0.00046 (45 – 25) = 0.094 or 9.4%

$n_{mp,(pv-t)}$ = 0.1074 – 0.00046 (35.98 – 25) = 0.1023 or 10.23%

Hence, the hybrid PV-TC has 0.83% higher electrical efficiency in relation with the plain photovoltaic panel.

3.3 A Photovoltaic - Thermal system for domestic heating in Rhodes

The approximation method F-chart heating is used for the study of the photovoltaic-thermal system for the coverage of the domestic heating load. Moreover, the same methodology is used for the conventional solar system, which is compared to the photovoltaic-thermal system. This methodology has been extensively developed by Klein, Beckman and Duffie in their book 'Solar heating design by F-chart method' [8]. In the present research the analytical equations of the F-chart method that are put to use are those mentioned in the book 'Analysis of Energy Systems' [3]. According to this method the percentage of monthly thermal domestic load, which is covered by solar energy, is determined by the equation (6) for liquid system.

$$f_h = 1.029 \cdot Y_h - 0.065 \cdot X_h - 0.245 \cdot Y_h^2 + 0.0018 \cdot X_h^2 + 0.0215 \cdot Y_h^3 \qquad (6)$$

for $0<X_h<18$, $0<Y_h<3$

X_h and Y_h are two dimensionless parameters. X_h is related to the ratio of the collector's losses to heating load and Y_h is related to the ratio of absorbed solar radiation to heating load. Their values are defined from the equations (7) and (8).

$$X_h = \left(\frac{A_C}{L_h}\right) \cdot F_R U_L \cdot \left(\frac{F'_R}{F_R}\right) \cdot \left(T_{ref} - T_a\right) \cdot \Delta t \cdot k_1 \cdot k_2 \quad (7)$$

$$Y_h = \left(\frac{A_C}{L_h}\right) \cdot F_R (\tau\alpha)_n \cdot \left(\frac{F'_R}{F_R}\right) \cdot \left(\frac{\tau\alpha}{(\tau\alpha)_n}\right) \cdot \overline{H_\beta} \cdot k_3 \quad (8)$$

The monthly average incidence solar radiation (H_β) on the PV-TC surface for the region of Rhodes was calculated according to the equations that are presented in the book 'Conventional and mild forms of energy' [9]. The domestic heating consumption (L_h) is calculated by using the Degree-days method of Kreider and Rabl [10].

From the use of the above elements arises the percentage of the monthly thermal domestic load covered by a photovoltaic-thermal system (40 m^2) at the region of Rhodes. The same procedure was repeated for a system of solar collectors with total surface area equal to that of the PV-TCs' (40m^2). The results are presented in the Table 3.

Table 3. Monthly heating domestic load covered by photovoltaic-thermal system and conventional solar system during the winder for the region of Rhodes

Month	T_α [C]	H_β [kwh/m^2]	L_h [GJ]	$F_{(PV-T)H}$ (%)	$F_{(Solar)H}$ (%)
1	12.6°	91.531	10.08	31.24	38.19
2	13.1°	105.99	8.3	48.75	56.95
3	14.5°	144.58	7.08	72.94	81.38
4	17.7°	168.03	2.83	100	100
5	21.9°	194.27	-	-	-
6	26.3°	192.45	-	-	-
7	28.6°	198.52	-	-	-
8	28.9°	193.84	-	-	-
9	26.2°	171.81	-	-	-
10	21.8°	140.32	-	-	-
11	17.6°	109.3	2.93	87.36	92.68
12	14.2°	88.409	7.53	37.96	45.84
Average	20.28°	149.92		63.04	69.17
Total		1799.12	38.77		

The solar coverage percentage of the domestic heating load from a photovoltaic-thermal system and from a system of conventional solar collectors is presented in Fig.2.

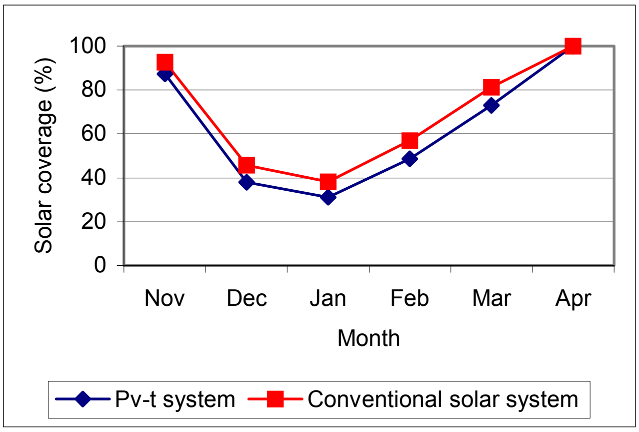

Fig. 2. Monthly solar coverage percentage of the domestic heating load from a photovoltaic-thermal system and from a system of conventional solar collectors

3.4 A Photovoltaic - Thermal system for domestic cooling in Rhodes

The analysis of the system during the summer season is completed by using the method F-chart cooling, which is thoroughly examined in the researches of Joudi and Abdul-Ghafour [11-12]. The coverage of the cooling load during the summer season is achieved by a low power absorption chiller. The coefficient of performance (COP) of this system is between 0.6 and 0.8 [13] and in the present investigation it is used COP = 0.6. According to this method the percentage of monthly cooling domestic load, which is covered by solar energy, is determined using the following equation.

$$f_c = (A_0 + A_1 \cdot X_c + A_2 \cdot X_c^2) + (B_0 + B_1 \cdot X_c + B_2 \cdot X_c^2) \cdot Y_c + (C_0 + C_1 \cdot X_c + C_2 \cdot X_c^2) \cdot Y_c^2 \quad (9)$$

Table 4. F-chart cooling parameters

$A_0 = 0.0663798$	$A_1 = -0.134709$	$A_2 = -0.00133054$
$B_0 = 0.624435$	$B_1 = 0.0187689$	$B_2 = 0.000195037$
$C_0 = 0.03755762$	$C_1 = 0.0062918$	$C_2 = 0.00041$

Where:

X_c is the ratio of the reference monthly energy loss to the monthly energy required for operating the absorption chiller,

Y_c is the ratio of the monthly energy absorbed on the PV-TCs' surface to the monthly energy required to operate the absorption chiller.

These values can be calculated by using the equations (10) and (11).

$$X_c = \frac{\overline{COP} \cdot A_C \cdot F_R U_L \cdot (T_{ref} - T_\alpha) \cdot \Delta t}{L_c} \cdot \frac{F_R'}{F_R} \quad (10)$$

$$Y_c = \frac{\overline{COP} \cdot A_C \cdot F_R (\tau\alpha)_n \cdot \overline{H_\beta}}{L_c} \cdot \frac{F_R'}{F_R} \quad (11)$$

The cooling domestic consumption (L_C) is calculated using the cooling Degree-days method of Kreider and Rabl [10]. From the use of the above elements arises the percentage of the monthly thermal domestic load covered by a photovoltaic-thermal system (40 m^2) at the region of Rhodes. The same procedure was repeated for a system of solar collectors with total surface area equal to that of the PV-TCs' (40m^2). The results are presented in the Table below.

Table 5. Monthly cooling domestic load covered by photovoltaic-thermal system and conventional solar system during the summer for the region of Rhodes

Month	T_α [C]	Hβ [kwh/m^2]	L_c [GJ]	$F_{(PV-T)C}$ (%)	$F_{(Solar)C}$ (%)
1	12.6°	91.531	-	-	-
2	13.1°	105.99	-	-	-
3	14.5°	144.58	-	-	-
4	17.7°	168.03	-	-	-
5	21.9°	194.27	7.42	62.64	80.07
6	26.3°	192.45	14.36	31.19	38.44
7	28.6°	198.52	18.93	25.53	30.98
8	28.9°	193.84	19.46	24.13	29.27
9	26.2°	171.81	14.19	26.02	32.48
10	21.8°	140.32	7.26	31.06	43.01
11	17.6°	109.3	-	-	-
12	14.2°	88.409	-	-	-
Average	20.28°	149.92		33.43	42.37
Total		1799.12	81.65		

The solar coverage percentage of the domestic cooling load from a photovoltaic-thermal system and from a system of conventional solar collectors is presented in Figure 3.

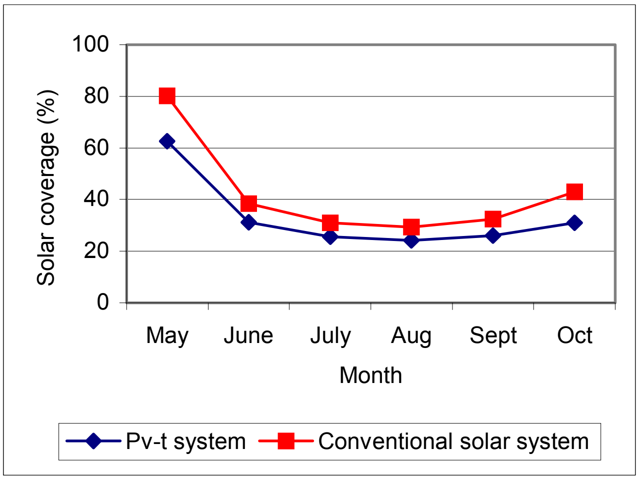

Fig. 3. Monthly solar coverage percentage of the domestic cooling load from a photovoltaic-thermal system and from a system of conventional solar collectors

4 Conclusions

The presented analysis and simulation led to the conclusion that the thermal efficiency of a PV-TC is about 9% lower than the efficiency of the conventional solar collector. A very important fact is that a PV-TC is operating at lower temperatures than plain photovoltaic panels leading to a higher electrical efficiency of about 0.9%. Gathering the results in Table 6 one can observe the differences in the thermal and electrical efficiency of a PV-TC and a system consisting of a solar collector and a conventional photovoltaic panel. Although a PV-TC has a lower total efficiency (by almost 8%), it demands only half of the total surface area.

Table 6. Total efficiency of a PV-TC (1.32m^2) and of a system consisting of a photovoltaic panel (1.32m^2) and a solar collector (1.32m^2)

Photovoltaic-thermal collector (PV-TC)		Photovoltaic panel and thermal collector	
$n_{thermal}$	$n_{electrical}$	$n_{thermal}$	$n_{electrical}$
60.78%	10.23%	69.68%	9.40%
71.01%		79.08%	

The case study worked out for a PV-TC system designed to cover part of the heating and cooling load of a typical house on the island of Rhodes. Using the F-chart and F-chart cooling methods it is proved that the above system can cover 63.04% of the domestic heating load and 33.43% of the domestic cooling load. In addition, a conventional solar system can cover 69.17% of the domestic heating load and 42.37% of the domestic cooling load. From the above comparison it is proved that a photovoltaic thermal system can replace conventional solar systems in domestic heating and cooling applications.

The use of photovoltaic-thermal systems in houses can contribute to the reduction of the energy consumption for heating, cooling and to the electrical energy consumption while at the same time it is achieved the reduction of the total surface area of the system.

Nomenclature:

A_c	:	The surface area of the PV-TC
A_c	:	The PV-TC's area
$\overline{COP}$	:	The average coefficient of performance of the absorption chiller
f_c	:	The monthly domestic cooling load covered by solar energy
f_h	:	The monthly domestic heating load covered by solar energy
F_R	:	The heat removal factor
$\left(\frac{F'_R}{F_R}\right)$	:	The collector-heat exchanger efficiency factor
G_T	:	The solar radiation at NOCT
$\overline{H_\beta}$	:	The monthly average daily radiation incident on the collector
I_{mp}	:	The peak power current
k_1	:	The correcting coefficient of the capacity for the storage
k_2	:	The correcting coefficient of warm water
k_3	:	The correcting coefficient of the heat load exchanger
L_c	:	The monthly domestic cooling load
L_h	:	The monthly domestic heating load
n_{mp}	:	The electrical efficiency of the photovoltaic collector
$n_{mp,ref}$	:	The maximum power point efficiency of the photovoltaic collector at reference conditions
P_{mp}	:	The peak power
Q_u	:	The useful energy gain
T_α	:	The ambient temperature
T_c	:	The photovoltaic collector temperature
T_{fi}	:	The inlet fluid temperature
T_i	:	The inlet fluid temperature
T_{pm}	:	The mean plate temperature
$T_{pv,ref}$	:	The photovoltaic collector temperature at reference conditions.
T_{ref}	:	The reference temperature (100° C)
U_L	:	The overall loss coefficient
V_{mp}	:	The peak power voltage
Δt	:	The duration of each month in (sec)
$\mu_{P,mp}$	:	The photovoltaic efficiency temperature coefficient (generally a negative number)
$(\tau\alpha)_n$	:	The transmittance absorptance product of the PV-TC

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