Modeling and Simulation of Solar Systems Employing Collectors with Colored Absorber

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ABSTRACT: To avoid the monotony of the black colored flat plate solar collectors we can use absorbers of blue, red-brown, green or other color. Because of the lower collector absorptance these collectors have lower thermal efficiency than that of the usual black type collectors, they are however of more interest to architects for applications on traditional or modern buildings. In this paper applications of solar collectors with colored absorbers are presented and analyzed with respect to their performance, aiming to give guidelines for their wider use on buildings. These systems are simulated with TRNSYS on an annual basis at two different locations, Nicosia, Cyprus and Athens, Greece. The results show that the energy output depends on the absorber darkness. For a medium value of the coefficient of absorptance, the colored collectors give satisfactory results with respect to the drop of the amount of collected energy, compared to collectors with black absorbers. This implies the use of slightly larger collector aperture area to have the same energy output as that of typical black colored collectors.

1. INTRODUCTION

Flat plate solar collectors are of black appearance because of the color of the absorber, which is employed to maximize the absorption of solar spectrum. The black view of the solar collectors on building roofs and facades is not usually aesthetically attractive and in some applications, as for example in Mediterranean islands, they are not compatible with the color and the architecture of the buildings. In most of these installations the black color of the collectors is not effectively combined with the white color of buildings, the blue color of sea and sky and the color of the doors and windows. Considering that the aesthetic view is of priority for buildings of traditional or modern architecture we estimate that solar collectors with absorbers of different color than black could be an interesting solution for the building integration of solar energy systems.

Generally, to avoid the monotony of the black color, collectors with absorbers of blue, red-brown, green or other color can be used. These collectors are of lower thermal efficiency than that of the usual black type collectors, because of the lower collector absorptance, but they are of more interest to architects for applications on traditional or modern buildings. The application of solar collectors with colored absorber is a new concept and regarding the total solar system, we notice that the increase in cost (by using larger area of collectors to overcome the lower efficiency of the colored absorber) is balanced by the achieved aesthetic harmony with the building architecture.

An extensive study, including prototype testing and modeling, has been carried out at the University of Patras, Greece [1], and has shown that colored collectors can be of satisfactory efficiency, especially if a dark color absorber is used which have a better performance than the light tone ones. The constructed and tested flat plate collector prototypes were of blue and red-brown absorbers and the tests showed that the obtained efficiency can be considered acceptable compared to that of the usual collector type with black absorber. As part of the same work, lower cost collectors without cover (unglazed collectors) and colored absorbers are studied, aiming mainly to low temperature applications. The effective use of unglazed colored collectors was recently confirmed for swimming pool application [2], while a method to overcome the disadvantage of the lower optical efficiency was the development of colored selective absorbers [3] that increase the temperature range of collector efficient operation.

In this paper we present the application of solar collectors with colored absorbers in a house heating, multi-flat residential or office buildings, and industrial process heat applications. The collectors are analyzed with respect to their performance and practical applications, aiming to give guidelines for their wider use on buildings. These systems are simulated on an annual basis at two different locations at different latitudes, Nicosia, Cyprus (35°) and Athens, Greece (38°).

2. MODELING OF THE SYSTEM

The proper sizing of the components of a solar system is a complex problem, which includes both predictable (collector and other performance characteristics) and unpredictable (weather data) components. In this work the transient simulation program TRNSYS [4] is used.

The various systems investigated were simulated with TRNSYS using Typical Meteorological Year (TMY) data for Nicosia, Cyprus and Athens, Greece. TMY is defined as a year which sums up all the climatic information characterizing a period as long as the mean life of the system. Using this approach the long-term integrated system performance can be evaluated.

Petrakis *et al*. [5] have generated the TMY for Nicosia, Cyprus used in the present study from hourly measurements, of solar irradiance (global and diffuse) on horizontal surface, ambient temperature, wind speed and direction, and humidity ratio, for a seven-year period, from 1986 to 1992 using the Filkenstein – Schafer statistical method. The measurements were recorded by the Cyprus Meteorological Service at the Athalassa region, an area at the suburbs of the town of Nicosia. The TMY is considered as a representative year for the Cypriot environment. Using the same method Pissimanis *et al*. [6] have generated the TMY for Athens, Greece.

Two types of flat plate collectors are considered, collectors painted with normal black and color paints with an emittance value of 0.9 and collectors with selective coatings with an emittance value of 0.1. The absorptance of the black collectors is 0.95 whereas the value for light color collectors is 0.85. This value applies to light-colored collectors irrespective of the actual color. The performance equations of the collectors considered are [1]:

Type A - Black collector, $\alpha=0.95$ and $\varepsilon=0.1$: $n=0.8319 - 4.2629\ (\Delta\ /G)$ (1)
Type B - Color collector, $\alpha=0.85$ and $\varepsilon=0.1$: $n=0.7453 - 4.2648\ (\Delta\ /G)$ (2)
Type C - Black collector, $\alpha=0.95$ and $\varepsilon=0.9$: $n=0.7937 - 6.7128\ (\Delta\ /G)$ (3)
Type D - Color collector, $\alpha=0.85$ and $\varepsilon=0.9$: $n=0.7109 - 6.7316\ (\Delta\ /G)$ (4)

3. SYSTEMS DESCRIPTION

Three types of systems are investigated in this work. A large solar water heating system suitable for a block of 10 flats or similar use, a solar heating system for a house and an industrial process heat system. A generic schematic diagram of the systems considered is shown in Fig. 1. The same basic system applies to all cases with the options concerning location of auxiliary and house heating as shown.

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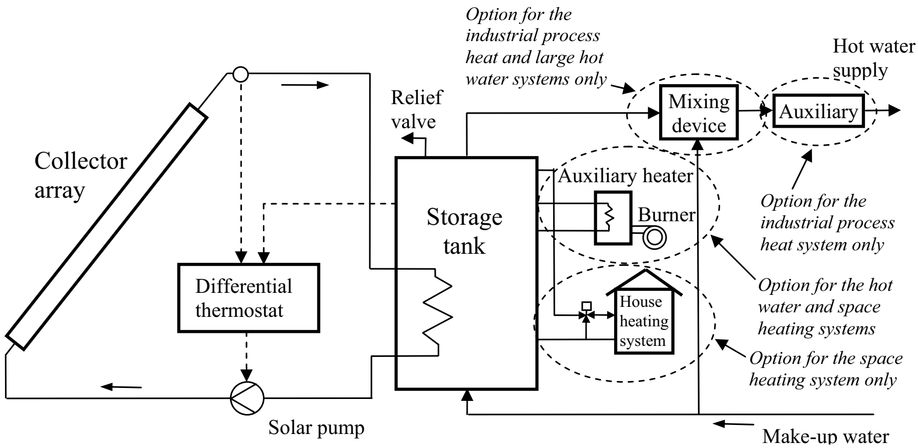

Fig. 1 Schematic diagram of the solar hot water and space heating system

3.1 Large hot water system

The system consists from a collector array, a storage tank, solar pump and auxiliary. A differential thermostat is used to compare the temperature at the exit of the collectors and the storage tank and give a signal to switch on the pump. The auxiliary energy considered in this case is diesel. The specifications of the system are shown in Table 1. Such a system can supply hot water to blocks of 10 flats or to any other similar size system.

Table 1. Large hot water system specifications

Parameter	Value
Collector area	40m^2
Storage tank volume	1.5m^3
Load temperature	50°C
Collector inclination	40°

3.2 Solar heating system

This is very similar to the hot water system with the difference that the hot water is supplied to the house radiators circuit. The specifications of the system are shown in Table 2.

Table 2. Space heating system specifications

Parameter	Value
Collector area	50m^2
Storage tank volume	3m^3
Collector inclination	40°
House UA value	1200 kJ/hr°C
Room temperature	21°C

3.3 Industrial Process Heat System

Such a system is suitable for supplying hot water or low temperature steam to various industrial applications (e.g. food industry). The system consists of an array of collectors, a circulating pump and a storage tank. It includes also the necessary controls and thermal relief valve, which relieves energy when storage tank temperature is above a preset value. The system is once through, thus the used hot water is replaced by mains water.

Mean monthly ground temperature values are used for the mains water temperature in simulations. When the temperature of the stored water is above the required process temperature, this is mixed with mains water to obtain the required temperature. If no water of adequate temperature is available in the storage tank its temperature is topped-up with an auxiliary heater before use. The system considered provides 1000 kg/hr of hot water at a temperature of 80°C (load). This is an average consumption of hot water for medium size food industries. The load is required for the first three quarters of each hour. The specifications of the system are shown in Table 3.

Table 3. Characteristics of the industrial process heat system

Parameter	Value/Type
Load temperature	80°C
Load flow rate	1000 kg/hr
Use pattern	5 days a week, 8.00-16.00 hours each day
Collector to storage distance	30m
Piping UA value	20 W/°C
Relief valve set temperature	100°C
Storage tank capacity	$14m^3$
Collector area	$300m^2$
Collector inclination	40°

4. RESULTS

TRNSYS can give results in an annual, monthly, daily or hourly basis. Here mainly annual results are presented together with some typical monthly ones.

4.1 Large hot water system

The annual results for this system are shown in Table 4. As can be seen the poorer the collector characteristics the poorer the system performance indicated by the useful energy delivered from the solar system (Qu) and consequently more auxiliary is required (Qaux). However the differences between ordinary painted collectors (type C & D, ε=0.9) with the corresponding selective coated collectors (type A & B, ε=0.1), is about 16% for Nicosia and 20% for Athens.

Table 4. Annual results for the large hot water system

Collector type	Collector characteristics	Nicosia		Athens	
		Qu (GJ)	Qaux (GJ)	Qu (GJ)	Qaux (GJ)
A	α=0.95, ε=0.1	150.5	8.006	154.9	14.06
B	α=0.85, ε=0.1	135.8 (9.8)	10.26	137.7 (11.1)	18.63
C	α=0.95, ε=0.9	125.9	10.77	125.1	20.93
D	α=0.85, ε=0.9	113.7 (9.7)	13.24	110.1 (12)	26.14
Note: Number in brackets represent percentage difference with respect to black absorber					

Typical monthly results for type A collectors for both Nicosia and Athens are shown in Table 5. As can be seen the solar system can satisfy almost all needs during the summer months represented by the small value of Qaux during these months. The column Qins in Table 5 refers to the radiation incident on the collector surface and the Qenv to the heat loses from the storage tank envelope.

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Table 5 Monthly performance of large hot water system for Nicosia and Athens for type A collector in (GJ).

Month	Results for Nicosia				Results for Athens			
	Qins	Qu	Qaux	Qenv	Qins	Qu	Qaux	Qenv
JAN	17.5	10.2	1.75	0.063	18.1	10.5	2.44	0.067
FEB	17.2	10.0	1.58	0.059	19.4	11.3	1.69	0.065
MAR	21.9	12.6	1.23	0.071	23.5	13.2	1.71	0.077
APR	24.1	13.8	0.209	0.079	23.7	13.0	1.37	0.078
MAY	23.0	12.7	0.448	0.077	26.1	13.9	1.03	0.085
JUN	24.8	13.4	0.009	0.088	27.5	13.9	0.431	0.091
JUL	26.9	14.5	0.006	0.100	29.6	15.0	0.162	0.100
AUG	27.5	14.9	0.006	0.106	29.5	15.4	0.099	0.106
SEP	24.7	13.4	0.027	0.100	28.6	15.2	0.129	0.104
OCT	24.1	13.8	0.326	0.088	23.9	13.2	1.15	0.086
NOV	19.1	11.2	0.669	0.071	17.4	10.1	1.96	0.067
DEC	16.6	10.0	1.80	0.059	16.9	10.4	1.91	0.058
SUM	**267.5**	**150.5**	**8.01**	**0.963**	**284.1**	**154.9**	**14.06**	**0.983**

Comparative graphs of the monthly useful energy (Qu) and auxiliary energy (Qaux) for the four types of collectors considered are shown in Figs 2 and 3 for Nicosia and Athens respectively. In all cases the performance of the color collectors is somewhat lower than that of the respective black absorber collectors.

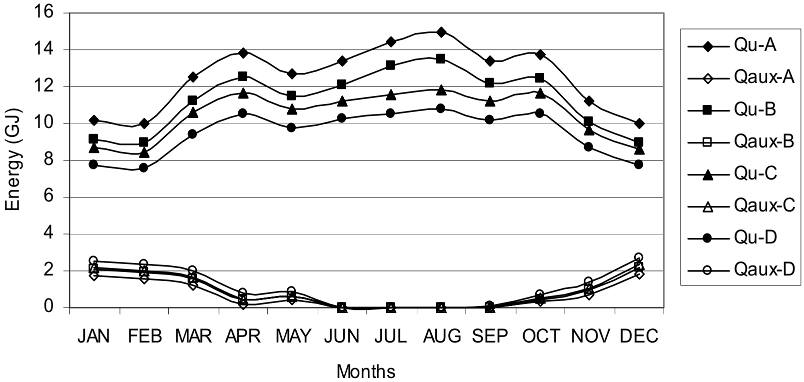

Fig. 2 Monthly useful and auxiliary energy of the large hot water system for the different collectors considered for Nicosia

4.2 Solar heating system

The annual results for this system are shown in Table 6. As the characteristics of all systems are the same, the inlet temperature depends on the heating load which affects the temperature of the stored water and thus the temperature of the water entering the solar collector (from the bottom of the storage tank).

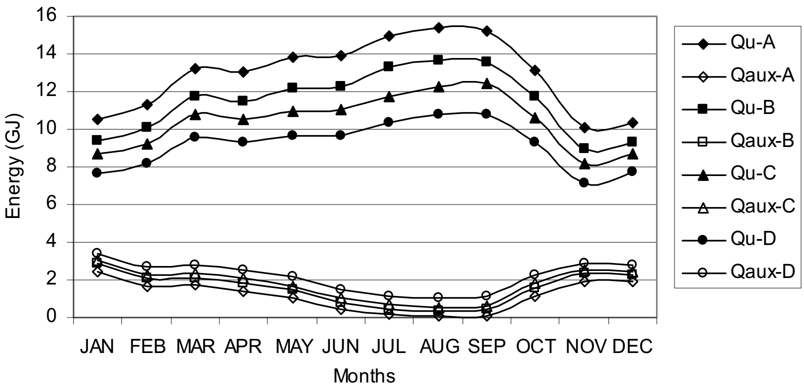

Fig. 3 Monthly useful and auxiliary energy of the large hot water system for the different collectors considered for Athens

This behaviour is illustrated in the comparative graphs of the monthly useful energy (Qu) and auxiliary energy (Qaux) for the four types of collectors considered shown in Figs 4 and 5 for Nicosia and Athens respectively. As can be seen in both cases the performance (Qu) of the collectors during summertime is lower than that of other mid-season months (March and October). No auxiliary is required during the period April to November.

Table 6 Annual results for solar heating system

Collector Type	Collector characteristics	Nicosia		Athens	
		Qu (GJ)	Qaux (GJ)	Qu (GJ)	Qaux (GJ)
A	α=0.95, ε=0.1	112.0	1.625	112.8	6.308
B	α=0.85, ε=0.1	94.33 (15.8)	3.026	94.47 (16.3)	8.228
C	α=0.95, ε=0.9	67.57	4.996	64.64	11.06
D	α=0.85, ε=0.9	57.58 (14.8)	7.106	53.29 (17.6)	13.44
Heating load (GJ)		52.05		51.58	
Note: Number in brackets represent percentage difference with respect to black absorber					

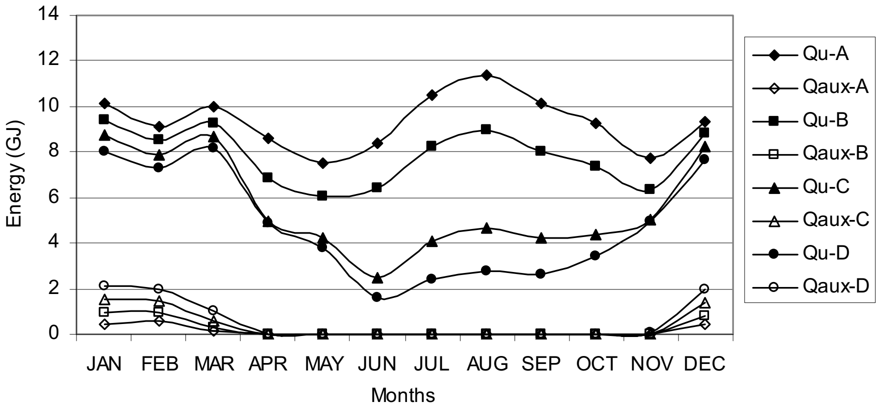

Fig. 4 Monthly useful and auxiliary energy of the solar heating system for the different collectors considered for Nicosia

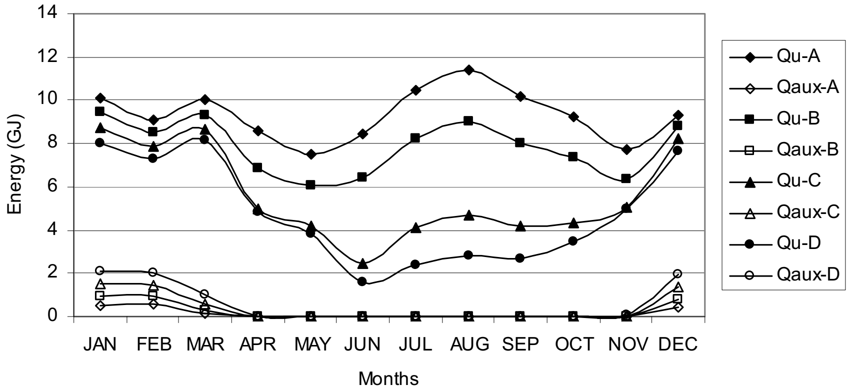

Fig. 5 Monthly useful and auxiliary energy of the solar heating system for the different collectors considered for Athens

4.3 Industrial Process Heat System

The annual results for this system are shown in Table 7. Typical monthly results for type A collectors for both Nicosia and Athens are shown in Table 8.

Table 7. Annual results for the industrial process heat system

Collector Type	Collector characteristics	Nicosia		Athens	
		Qu (GJ)	Qaux (GJ)	Qu (GJ)	Qaux (GJ)
A	α=0.95, ε=0.1	729.3	55.04	722.6	86.56
B	α=0.85, ε=0.1	671.9 (7.9)	79.36	653.6 (9.5)	123.0
C	α=0.95, ε=0.9	587.2	114.9	543.4	176.4
D	α=0.85, ε=0.9	537.3 (8.5)	143.5	488.6 (10)	208.8
Note: Number in brackets represent percentage difference with respect to black absorber					

Table 8 Monthly performance of the industrial process heat system for Nicosia and Athens for type A collector in (GJ).

Month	Results for Nicosia				Results for Athens			
	Qins	Qu	Qaux	Qenv	Qins	Qu	Qaux	Qenv
JAN	131.7	52.9	11.2	0.653	136.6	52.7	13.4	0.659
FEB	129.8	49.1	8.48	0.601	146.1	52.0	8.33	0.709
MAR	164.3	59.7	8.05	0.737	177.5	60.3	8.79	0.811
APR	180.1	60.8	1.86	0.827	178.5	59.0	5.79	0.835
MAY	171.8	61.7	5.30	0.697	196.7	63.8	6.62	0.829
JUN	185.4	64.6	1.52	0.735	206.8	64.7	4.80	0.837
JUL	201.5	68.5	0.48	0.827	222.7	67.7	3.23	0.926
AUG	205.8	71.0	0.48	0.874	222.5	73.2	2.84	0.927
SEP	184.7	65.7	1.03	0.828	216.4	68.8	2.18	0.952
OCT	181.2	65.7	2.68	0.816	180.0	61.3	7.64	0.832
NOV	152.2	56.8	5.17	0.750	131.6	48.4	11.9	0.686
DEC	125.2	52.9	8.80	0.653	127.8	50.8	11.1	0.655
SUM	**2013.7**	**729.3**	**55.04**	**8.998**	**2143.0**	**722.6**	**86.56**	**9.657**

Comparative graphs of the monthly useful energy (Qu) and auxiliary energy (Qaux) for the four types of collectors considered are shown in Figs 6 and 7 for Nicosia and Athens respectively. As can be seen again the performance of the color collectors is somewhat lower than that of the black colored collectors. The difference in performance between the respective cases is almost constant in all months of the year. The maximum useful energy collected occurs in both locations during the month of August and is about 71 GJ and 73 GJ (black selective absorber) for Nicosia and Athens respectively.

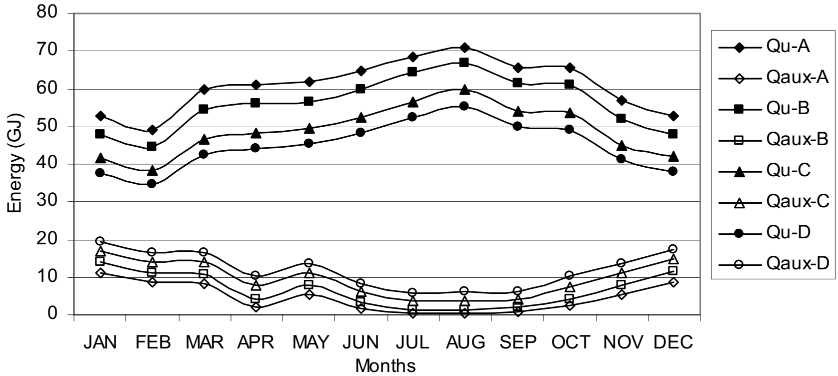

Fig. 6 Monthly useful and auxiliary energy of the industrial process heat system for the different collectors considered for Nicosia

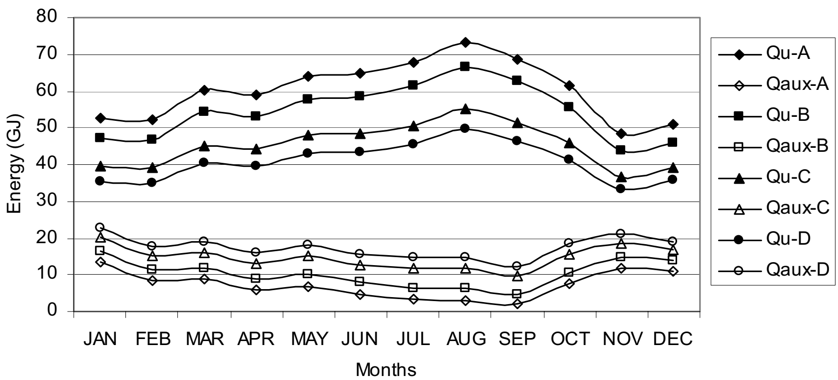

Fig. 7 Monthly useful and auxiliary energy of the industrial process heat system for the different collectors considered for Athens

It can be generally concluded from the results presented in this section that color collectors give in most of the cases about 10% lower performance than collectors painted with black paint either for the normal paint or selective. This means that 10% more collector area would be required to obtain the same performance as the black colored collectors, which is acceptable.

5. CONCLUSIONS

In this paper applications of solar collectors with colored absorbers in a house heating, multi-flat residential or office buildings, and industrial process heat applications are presented. These systems are simulated on an annual basis at two different locations at different latitudes, Nicosia, Cyprus (35°) and Athens, Greece (38°).

The results show that although the colored collectors present lower efficiency than the typical black type collectors, the difference in energy output depends on the absorber darkness. For a medium value of the coefficient of absorptance (α=0.85), the colored collectors give satisfactory results regarding the drop of the amount of collected energy for the two locations (about 10%), compared to collectors with black absorbers (α=0.95).

This implies the use of proportionate larger collector aperture area to have the same energy output as that of typical black colored collectors.

REFERENCES

[1] Tripanagnostopoulos Y., Souliotis M. and Nousia Th., Solar Collectors with Colored Absorbers, *Solar Energy*, 68: 343-356, 2000.
[2] Medved S., Arcar C., Cerne B. A large-panel unglazed roof-integrated liquid solar collector-energy and economic evaluation. *Solar Energy* **75**, 455-467, 2003.
[3] Crnjak Orel Z., Gunde Klanjsek M. and Hutchins M.G. Spectrally selective solar asorbers in different non-black colours. *In Proc. Int Conf. WREC VII (CD-ROM)*, Cologne, Germany, 29 June–5 July, 2002.
[4] TRNSYS program Manual, Solar Energy Laboratory, University of Wisconsin, Madison, USA, 1996.
[5] Petrakis M. Kambezides H.D, Lykoudis S, Adamopoulos A.D, Kassomenos P. Michaelides I.M, Kalogirou S.A., Roditis G., Chrysis I. and Hadjigianni A., Generation of a “Typical Meteorological Year” for Nicosia, Cyprus. *Renewable Energy*, **13**: 381-388, 1998.
[6] Pissimanis D., Karras G., Notaridou V. and Gavra K., The generation of a “Typical Meteorological year” for the city of Athens. *Solar Energy* **40:** 405-411, 1988.