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Electrical energy saving in a passive-solar-heated residence using a direct gain attached sunspace

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Abstract

This paper deals with the thermal analysis and the auxiliary electrical energy saving in a passive-solar-heated residence. The particular residence is using an attached sunspace of inclined walls and roof and an electrically heated thermal storage floor as backup to satisfy the heating requirements. The thermal analysis and the corresponding electrical energy saving are determined using three different methods which are applied for thermostatically controlled temperature regime. The first is a simplified method based on three parameters: (1) the solar/load ratio (SLR), (2) the building thermal inertia and (3) the monthly unutilizability (UU). The other methods are, namely: the UU method and the SLR method.

Keywords: Electrical energy saving; Solar gain; Renewable energy; Solar energy conversion

1. Introduction

It is well documented that space heating dominates the energy consumption in residential sector and consumes the largest amount of electricity [1,2]. In order to reduce this consumption, it would be essential first to reduce the energy demand, which is associated with our life style and then to apply alternative technologies. It is strongly believed that the residential sector will initiate its retrofitting applications and energy reduction programs, particularly through the use of 'solar technology', supported by coherent 'incentives policy' [3].

Simplified methods provide a quantification of the thermal performance of a building. They usually also allow the identification of parameter groups that influence the building behavior and their significant end result is the annual auxiliary energy required.

This article describes the characteristics of the attached sunspace and considers the accuracy of three different thermal analysis methods. The residence uses an electrically heated thermal storage floor as backup and the corresponding electrical energy saving, resulted from the sunspace application, is calculated.

2. Description of the attached sunspace

The main building covers an area of 120 m^2, the net glazing surface is 15 m^2 and the slope of the windows is 50°. The single glazing thickness is 5 mm and it was chosen due to the mild climate of the region since double or triple glazing is recommended only for cold climates. The attached sunspace has inclined walls and inclined roof and faces to the south. In this case the sunspace can be considered as a direct gain space [4]. The geometry of the modified greenhouse with the tilted glazing was selected because it maximizes the transmitted radiation since it receives the sun rays in late winter at a more optimal angle and, thus, the passive system efficiency is increased. Also, the glazed roof increases the total solar energy collecting area of the sunspace. However, this design is subject to higher heat loss in winter during periods without sunshine, particularly by longwave radiation to the night sky. This is minimized with the use of operable night insulation. The passive-solar-heating system parameters are given in Table 1.

The sunspace area can be effectively cross ventilated and, thus, the likelihood of summer overheating is minimized. This is very important, particularly in the Mediterranean countries, since the ambient temperature in summer can sometimes exceed 40 °C. The residence is situated in the city of Xanthi in Northern Greece (Fig. 1).

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Nomenclature

A_f	enclosure floor area (m^2)
A_{glaz}	net glazing area (m^2)
C_e	thermal capacitance of the enclosure (J/C)
C_f	thermal capacitance of the floor (J/C)
C_p	specific heat (kJ/kg C)
C_s	thermal capacitance of the sunspace (J/C)
m	mass flow rate (kg/h)
UA	overall loss coefficient of the glazing (W/m^2 C)
UA_e	overall enclosure heat-transfer coefficient, area product (W/C)
U_{sa}	overall heat-transfer coefficient, sunspace to ambient (W/m^2 C)

Table 1
Parameters of the passive-solar system

A_{glaz} (m^2)	15 (160 ft^2)
A_f (m^2)	120 (1295 ft^2)
C_s (kJ/C)	5000 (2632 Btu/F)
C_f (kJ/C)	38000 (20000 Btu/F)
C_e (kJ/C)	19000 (10000 Btu/F)
U_{sa} (W/m^2 C)	10 (1.76 Btu/h ft^2 F)
m (kg/h)	50
C_p (kJ/kg C)	0.83
UA (W/m^2 C)	3 (1.056 Btu/h ft^2 F)
UA_e (W/C)	204 (388 Btu/h F)

3. Consideration of thermal analysis methods

In spite of the increasing facilities concerning the use of more powerful computers and software related to building energy simulations, the importance of simplified evaluation tools is still untouched. In fact, it is a general opinion that detailed simulations, hourly simulation programs, are not suitable for most of the possible users: they are time consuming and require a certain degree of specialization.

A simplified method, proposed by Oliveira and De Oliveira Fernandes [5], is intended as a low-use cost method that can he applied either by manual or small computational means.

For a building with an auxiliary heating system activated when the air temperature reaches a minimum value or setpoint, the solar gains (Q_{sol}) are equal to the solar energy transmitted through the glazing(s) and absorbed by the internal surfaces. The losses through the building envelope can be expressed as the sum of the reference heating load (Q_{ref}), which is the energy that the building would require if there were no solar gains, and the excess energy (Q_{exc}) which corresponds to the increase in the temperatures inside the building due to the solar gains.

In a real building, the instantaneous solar gains are either used to supply part of the losses, or stored in the building structure for later use. Some part of the solar gains are not useful, since they overheat the air. The fraction of solar gains

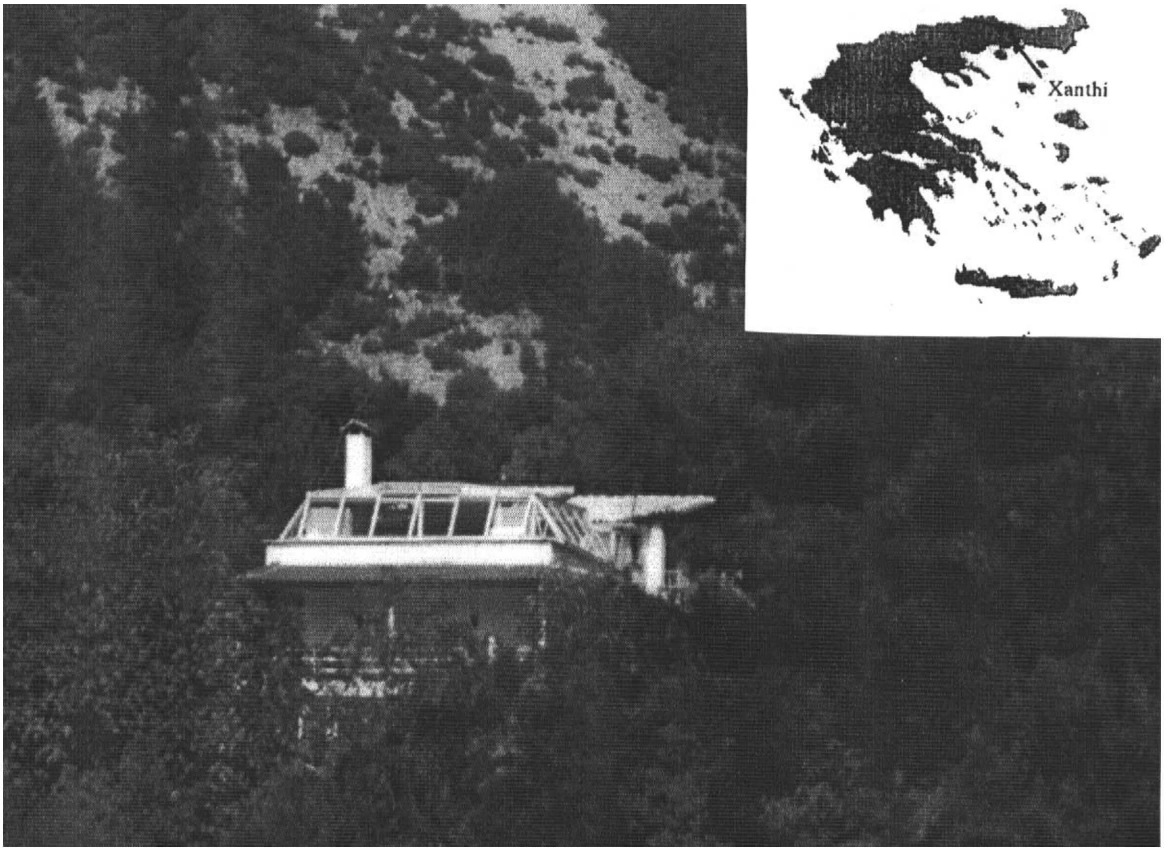

Fig. 1. Attached sunspace layout

($Q_{\mathrm{sol,us}}$) that are useful to the reference load, divided by the load, is called the solar fraction:

$$f = \frac{Q_{\mathrm{sol,us}}}{Q_{\mathrm{ref}}} \qquad (1)$$

where

$$Q_{\mathrm{sol,us}} = Q_{\mathrm{sol}} - Q_{\mathrm{exc}} \qquad (2)$$

The solar fraction f is a measure of the passive-solar performance of a building, thus, quantifying its thermal behavior.

For a building with infinite storage capacity, all the solar gains that are not instantaneously useful can be stored and used at a later time. Therefore, $Q_{\mathrm{exc}} = 0$, and

$$f = \frac{Q_{\mathrm{sol}}}{Q_{\mathrm{ref}}} = \mathrm{SLR} \qquad (3)$$

For a building with zero thermal capacity, whenever the incoming solar gains are greater than the load there is excess energy:

$$Q_{\mathrm{exc,0}} = (Q_{\mathrm{sol}} - Q_{\mathrm{ref}})^{+} \qquad (4)$$

where the symbol '+' means that only positive values of the difference are considered.

The monthly energy excess can be written as

$$Q_{\mathrm{exc,0}} = Q_{\mathrm{sol}}\varphi \qquad (5)$$

where φ is the monthly unutilizability (UU), that is, the fraction of the solar gains that are not useful.

The solar fraction for the zero thermal capacity case, using Eqs. (1), (2) and (5), can be written as

$$f_0 = (1 - \varphi)\mathrm{SLR} \qquad (6)$$

For a real building with the same characteristics and operating conditions, except for the thermal capacity, the solar fraction is

$$f = n\mathrm{SLR} \qquad (7)$$

where n is the utilization efficiency of the solar gains – percentage of the solar gains that are useful.

By using dimensional analysis, it can be shown that the dimensionless relationship for the solar fraction is [5]:

$$f = n(\varphi, I_{\mathrm{T}})\mathrm{SLR} \qquad (8)$$

where φ is the monthly UU for the zero thermal inertia case and I_{T} is the dimensionless thermal inertia calculated from the following equation:

$$I_{\mathrm{T}} = \frac{C_{\mathrm{ef}}}{UAt_{\mathrm{ef}}} \qquad (9)$$

where C_{ef} is the effective thermal capacity and t_{ef} a reference time. C_{ef} is calculated as follows [6]:

$$C_{\mathrm{ef}} = 0.75C_{\mathrm{d}} + 0.25C_{\mathrm{w}} \qquad (10)$$

where C_{d} is the daily heat capacity and C_{w} is the weekly heat capacity. The latter can be calculated as the response of the building massive elements to a week-period solicitation.

The effective thermal capacity differs from the heat capacity (product mass-specific heat) and varies with the location of the building element. Elements located in rooms with direct sunlight have a higher effective thermal capacity.

The proposed simplified method is characterized by the functional relationship of Eq. (8), which is more complete than the ones from other methods. In the solar/load ratio (SLR) method is $f = f(\mathrm{SLR})$ and in the UU method is $f = f(X, Y)$, where X is equal to SLR and

Table 2
Range of parameters used in the simulation

Glazing type	Double glazing, without night insulation; $\tau_n = 0.72$; $U = 3$–4 W/m^2 C
Thermal inertia	
I_{T}	5–95
$T_{\min}$	18–22
φ	0.1–0.9

Table 3
Solar radiation data for the city of Xanthi in Northern Greece

Month	$\bar{H}_{\mathrm{d}}/\bar{H}$	$\bar{H}$ (MJ/m^2)	$\bar{K}_{\mathrm{T}}$	$\bar{R}$	$\bar{H}_{\mathrm{T}}$ (MJ/m^2)	Degree–day data (DD; W/C)	$\bar{T}$ (C)
January	0.54	4.87	0.34	1.635	7.96	260	8
February	0.41	8.72	0.45	1.511	13.18	234	8
March	0.45	10.9	0.41	1.176	12.82	231	9
April	0.41	15.9	0.46	0.965	15.34	114	13
May	0.41	17.69	0.45	0.839	14.84	25	18
June	0.41	21.20	0.51	0.788	16.71	1	23
July	0.36	21.67	0.54	0.808	17.51	0	26
August	0.34	19.49	0.54	0.900	17.54	0	26
September	0.34	15.63	0.54	1.111	17.36	5	21
October	0.41	10.00	0.46	1.401	14.01	37	17
November	0.48	5.96	0.39	1.657	9.88	140	12
December	0.55	4.23	0.33	1.719	7.27	231	9

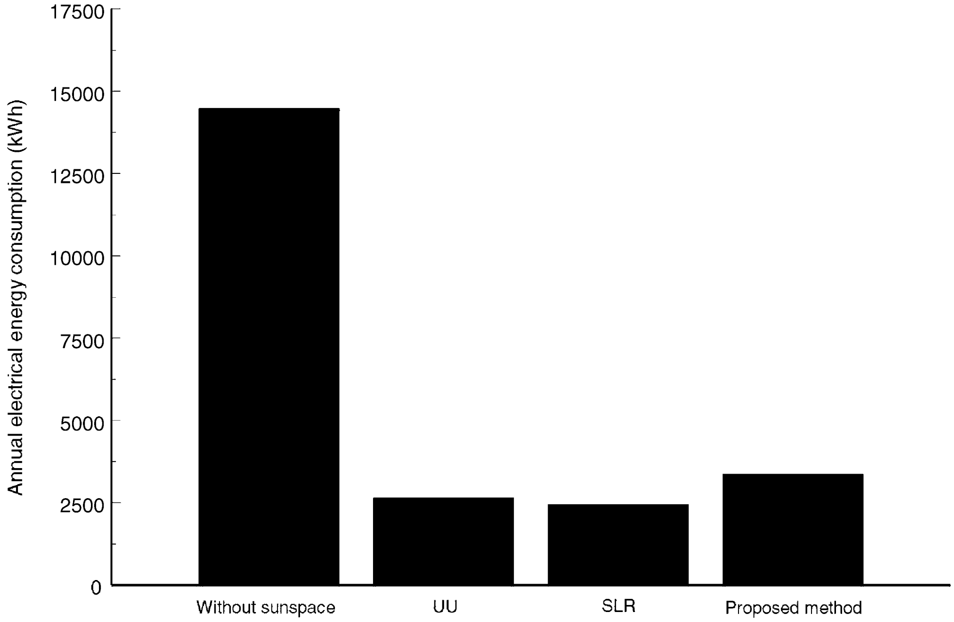

Fig. 2. Annual electrical energy consumption before and after the use of the passive-solar system.

the dimensionless parameter Y includes two different effects: φ and $I_T(C_{ef})$.

4. Results and conclusions

Several simulations have been performed with the ESP computer program [7], in order to obtain the $n(\varphi, I_T)$ correlations. Table 2 lists the range of parameters considered.

The operating conditions were typical of residential buildings: for instance, no mechanical ventilation and no control on the maximum temperature (no cooling system). The monthly solar radiation data in Xanthi are given in Table 3. It should be noticed that the use of only one climatic dataset does not restrict the applicability of the

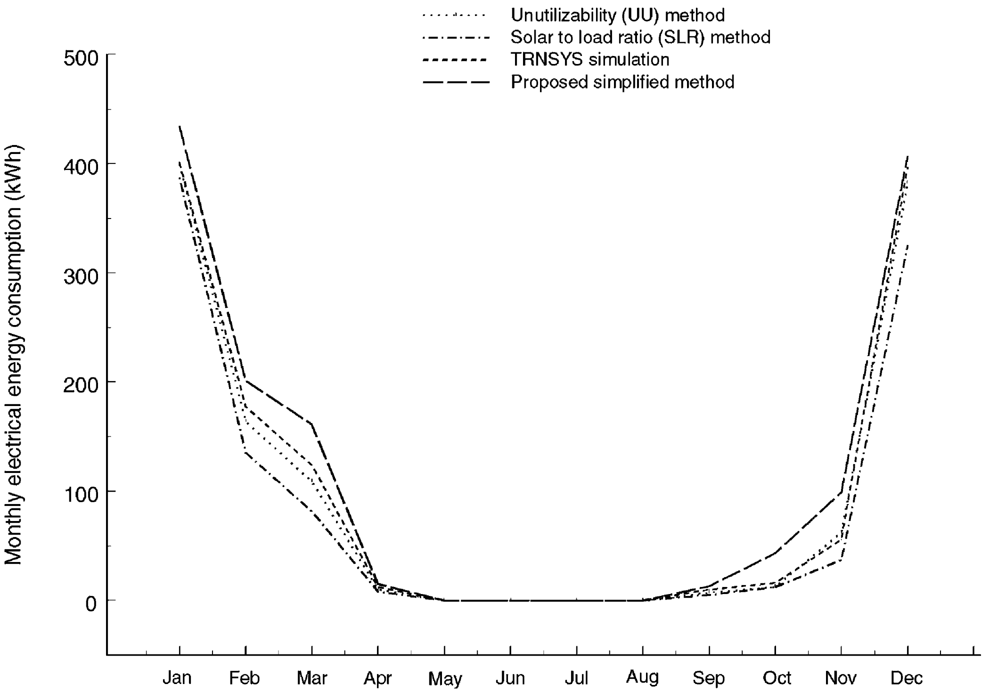

Fig. 3. Variation of monthly electrical energy consumption after the application of passive-solar system.

simplified method, since the climate is represented by the variable φ.

The results of the application of the thermal analysis methods are shown in Figs. 2 and 3. Fig. 2 shows the auxiliary electrical energy demand before and after the application of the attached sunspace. It can be seen that approximately 80% auxiliary electrical energy saving is achieved after the use of the passive-solar-heating system. Fig. 3 shows the monthly auxiliary electrical energy variation calculated from different thermal analysis methods including results produced from the application of TRNSYS simulation package. It can be noticed a considerable agreement between the results produced from different methods and this is due to the fact that the thickness of thermal mass was low, for which case C_{ef} is almost equal to the heat capacity. For higher thickness, errors should be expected in SLR and UU methods compared to the simplified method where a more complete functional relationship between the parameters was used and the thermal inertia of the building is adequately taken into account.

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