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A simple procedure to size active solar heating schemes for low-energy building design

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Abstract

The energy consumption of a building depends on the thermal demand and on the mean performance of the system. Apart from passive solar indoor climate control techniques, it is also possible to reduce conventional energy consumption of a building, even bringing it close to zero by installing solar heating. Hence, better knowledge of these techniques and of how they can be implemented in a simple but effective way will further progress towards more energy efficient buildings.

The present work describes a straightforward procedure – applicable in any part of the world – to estimate the climate variables, to compare the efficiencies of solar heat collectors, and to size certain installations for domestic hot water, radiant flooring, or heating of buildings. The values of the climate variables – the monthly means of the daily values of solar radiation, maximum and minimum temperatures, and number of hours of sun – are determined from data available in the FAO's CLIMWAT database.

Even though the calculation process uses approximate values for the variables involved rather than taking their dynamic evolution into account, it is fairly precise, giving results that are comparable to other more sophisticated and less easy to handle procedures such as the worldwide known f-CHART, TRNSYS, ISOFOTON and CENSOLAR computation programs. The predictive validity of the procedure has also been tested by comparing the results with those obtained experimentally via a solar heat collector installed on the roof of a building in the city of Badajoz.

We believe that the procedure together with the computation program, will be of great use to builders and architects, since it allows a solar installation to be rapidly sized for applications in active solar heating schemes for building design.

Keywords: Low-energy building; Active solar heating; Simple sizing procedure

1. Introduction

In the energy structure of all European Union countries, the principal end users of energy in absolute terms are households and the service sector. There has been a constant rise in the intensity of energy use, reflected in a year-to-year increase in consumption per inhabitant, mainly in the form of electricity. It is estimated that the residential and services sector, most of which is buildings, accounts for more than 40% of the final energy consumption in the European Union, a percentage comparable to that of the transport sector and more than twice that of the industrial sector [1–3]. The methodology of calculating the energy efficiency of buildings may differ on a regional scale, but must have in common not only the consideration of thermal insulation, but also other ever more important factors, such as the efficiency of heating and air conditioning installations, the use of renewable energy sources, and building design [4].

It is also important to stress that the end energy consumption of a building is the quotient between the energy demand and the mean efficiency of the indoor climate (heating and cooling) systems. Once a building has been constructed it is difficult to reduce its energy demand since it depends on the building's envelope, occupants, and functional characteristics, as well as on the outdoor climate. But one could act, for example, to cut the cost of the energy used in maintaining the indoor climate of the building by introducing renewable energies. The cost-effectiveness of a passive building – understood as a standard construction that ensures a comfortable indoor climate during summer and winter without the need for any conventional heating or cooling system – can and should be improved by partially covering the demand with renewable energy heating and cooling systems [5].

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The technology of solar heating energy is well established, and has an extensive literature. For practical applications, however, there is a need for comparative studies of the different commercially available makes and models of solar collectors to aid potential installers and end users in assessing which device best suits their needs for a specific application in a specific location.

Also, the diverse variables that affect solar system efficiencies make it difficult to determine whether, for a given application and characteristic climate conditions, the output of a collector with a complex design, and hence more expensive, will be higher or lower than that of another, simpler collector. Therefore, a tool that makes it possible to size a solar installation for a building in a simple and rapid manner would be extremely useful at both the design level for engineers and architects and the construction level for installers and builders.

The procedure to be described will allow one to determine simply and rapidly what percentage of the mean monthly domestic hot water or heating requirement can be covered by current technology both in residential buildings, in which the heating system works efficiently in a temperature range of 50–70 °C, and in commercial buildings with extensive glazing, and hence high heat loss, with the system working in the temperature range 70–90 °C.

One knows that the type of solar collector to use will depend on the application. For low temperature applications (below 100 °C), as in the case being considered here, the commonest systems use flat collectors, including flat-plate and evacuated-tube collectors. We shall include in the study neither transpired air collectors, as these systems use pre-heating, nor those manufactured with other technologies and used in applications that require higher temperatures.

2. Antecedents, and existing calculation procedures

As was indicated above, renewable energies, and in particular solar energy, reduce a building's ultimate consumption of conventional energy, so that better knowledge of the solar heating and cooling techniques involved, and of how they can be implemented in a simple but effective form will further progress towards greater energy efficiency. Thus, for instance, nowadays it is possible to determine with great accuracy the front or parts in a building which are exposed to maximum solar radiation via procedures based on computation programs and GIS (geographic information systems) [6], and the energetic behaviour of a front or a single wall when an active or passive solar heating collector is installed on it, and the energy loss through walls or through window glasses [7].

There currently exist various procedures, computer programs, and simulation methods for evaluating on the one hand a building's annual heating energy demand, and on the other the performance and efficiency of solar energy collecting processes and devices in their various applications to heating and domestic hot water supply. They can be classified in terms of the levels of complexity and precision that they involve.

The simplest programs do not require the user to have any extensive knowledge of the operation of the installation. They generally provide results that are adequate for the normally required level of accuracy and the input data that are readily available. When one needs to evaluate the detailed behaviour of the installation, or the results have to be more precise, then one can use specific simulation programs which need a greater quantity of input data and a notable level of technical know-how on the part of the user.

There exist effective methods to predict the final annual energy demand of a building, which have achieved a broad-based acceptance and are very much in use [8,9].

In relation to the computation programs to perform the caltulations involved in the installation design, ISOFOTON [10] has great relevance. This program was created by one of the most important manufacturers of photovoltaic panels and thermal solar energy collectors in the European Union, and uses algorithms from the program f-CHART [12]. ISOFOTON allows calculations for several types of solar installations (including heating and radiant flooring) and, even though it is not based on a dynamic simulation process, it gives satisfactory results and is used quite successfully by Spanish and South American engineers.

Another computation program is CENSOLAR [11], which includes a vast solar radiation database, and is also widely used to design several types of solar installations in Spain.

At the global scale, there exist several programs of outstanding rigour which are used by most researchers and professionals in the sector. One is the f-CHART [12]—a computer program for the analysis and design of active and passive solar heating systems. Developed in the University of Wisconsin's solar energy laboratory, its fundamental algorithm is based on obtaining the solar factor—the ratio between the instantaneous solar power and the required heat load, where the latter is the sum at each instant of the solar and the auxiliary source powers.

Lastly, there exist other less-frequently used programs and methods at the international level. Examples are NREL [13] and Garrison [14], which have characteristics similar to those of the present work, and which evaluate the performance of fixed or sun-tracking collectors. All these procedures for determining a building's solar heating needs have the drawbacks of complexity of use, and the difficulty in obtaining the input data. This makes their use impractical for builders, users, and installers who do not generally have an extensive knowledge of the operation of solar installations.

Programs that simulate the operation of a conventional heating installation connected to a solar heating system are currently well accepted. They are increasingly used in research centres, universities, industrial R&D departments, etc., to determine the energy behaviour of a building with a mixed (conventional plus solar) heating system. Examples are ESP [15], DOE-2 [16], BLAST [17], CODYRUN [18], and TRNSYS [19]. With respect to TRNSYS (Transient Simulation System), this is a dynamic simulation program for energy systems, of recognized prestige worldwide for the simulation of solar heating systems in the fields of research, teaching, and applied engineering. Like all dynamic simulations, it is a very complex program since it takes into account the reciprocal influence of solar radiation, temperature, and consumption on the system's operation.

In this work we present a procedure that allows one to compare simply and rapidly the efficiencies of flat collectors presently available on the market, and also to size different solar installations according to the degree of substitution of conventional sources. Its usefulness extends to both the users of this clean energy source, and to installers, constructors, architects, and engineers. It is applicable in any part of the world, since one has available – either commercially or on the Web – such databases as the FAO's CLIMWAT [20], from which one can obtain the monthly mean daily solar radiation, the monthly mean daily maximum and minimum temperatures, and the monthly mean daily number of hours of sun, which are needed as input to the computation program.

3. Fit to the climatic variables

One part of the procedure consists of fitting simple mathematical expressions (cosines) to the climate variable data as a function of a standard day of each month of the year [21]. Naturally, the fitting parameters will vary from place to place. Despite its simplicity, the model yields excellent fits. The absolute mean deviation of the fits of cosines to the aforementioned climate data for more than 50 sites worldwide was in all cases less than 10%.

These fitting functions are then used for the daily comparison of the collector efficiencies, thereby also providing a very clear vision of the climate and mean daily solar radiation over the course of the year at the site of the application. A further advantage is that this fit avoids the need to maintain a large data file for all the regions of the world in order to predict the climatology and solar radiation when one uses a simulation program.

To fit the monthly mean daily temperatures, we shall use an expression of the type:

$$T(t) = A_0 \pm B_0 \cos \omega(t + \lambda_1), \tag{1}$$

where $T(t)$ is the temperature of an average day of each month of the year, A_0 is a coefficient equal to the semi-sum of the mean maximum and minimum temperatures corresponding to each month of the year, $(T_{\max} + T_{\min})/2$, B_0 is the semi-difference of these same temperatures, $(T_{\max} - T_{\min})/2$, and will have a negative or positive sign according to whether the observatory is located in the northern or the southern hemispheres, respectively, and λ_1 is the phase difference due to the location of the meteorological observatory providing the data, and may be evaluated by the expression:

$$\lambda_1 = 15 + (n - 1)30 \quad \forall n \Rightarrow 1 \leq n \leq 6, \tag{2}$$

where n will take the value of the integer corresponding to the month of the year in which the minimum temperature occurs in the northern hemisphere, or the maximum in the southern hemisphere if this is in the first 6 months of the year; otherwise $\lambda_1 = 0$.

The solar radiation incident on the surface of the solar collector influences its behaviour. It is therefore necessary to know the value of the mean overall daily solar radiation on a horizontal surface during each month of the year. The function used to fit these data is similar to that for the temperatures:

$$E(t) = A_1 \pm B_1 \cos(\omega t), \tag{3}$$

where $E(t)$ is the overall horizontal radiation during a mean day of a month of the year, A_1 and B_1 have the same meanings as do A_0 and B_0 in Eq. (1) except that now they refer to the radiation, i.e., $A_1 = (E_{\max} + E_{\min})/2$, and $B_1 = (E_{\max} - E_{\min})/2$ with a negative or positive sign according to whether the observatory is located in the northern or the southern hemispheres, respectively.

Lastly, to calculate the mean daily overall horizontal solar power during each month of the year, one needs an analytical expression for the hours of sun as a function of the day of the year. We suggest using the same mathematical model as before, i.e., the hours of sun are fitted by the expression:

$$H(t) = A_2 \pm B_2 \cos \omega(t + \lambda_2), \tag{4}$$

where A_2 and B_2 have the same meanings as in Eq. (1), but now referring to the hours of sun, and λ_2 will be the phase difference, analogous to that considered in Eq. (2). Dividing Eq. (3) by (4), one obtains the mean daily overall horizontal solar power during a mean day of each month of the year. With the conversion factor between units ($1\ \mathrm{kJ\ m^{-2}\ day^{-1}} = 0.278\ \mathrm{Wh\ m^{-2}\ day^{-1}}$), this leads to the expression:

$$P(t) = 0.278\frac{E(t)}{H(t)}, \tag{5}$$

where $P(t)$ is mean overall horizontal solar power of a mean day of each month of the year, in $\mathrm{W\ m^{-2}\ day^{-1}}$.

The application that we shall use as an example is for the city of Badajoz, located in SW Spain in the European Union, at latitude 38.9°N and longitude 6.58°W. It receives some 6120 $\mathrm{MJ\ m^{-2}}$ of solar energy per annum. The climate data taken from the CLIMWAT database corresponding to the city of Badajoz are given in Table 1.

Using data from the FAO's CLIMWAT database, one could fit the mathematical models of Eqs. (1)–(5) to the climate variables of any place in the world. Naturally, the values of the coefficients A_i and B_i ($i = 0, 1, 2$) that appear in Eqs. (1)–(4) will vary from one location to another, but there is no question that with these parameters one may characterize climatically any point on the planet, at least for an application of this type. Table 2 gives the values of these coefficients for different cities.

Fig. 1 shows the overall horizontal solar power during the year, corresponding to the city of Badajoz calculated with Eq. (5).

4. Methods

4.1. Comparison of efficiencies

The collector efficiency is defined as the ratio of usable heat energy extracted from a collector by the heat transfer fluid during any time period to the solar energy striking the cover

Table 1
Mean monthly climate data for the city of Badajoz (Spain), taken from the FAO CLIMWAT database

Month	Max. daily temp. (°C)	Min. daily temp. (°C)	Mean daily temp. (°C)	Mean daily hours of sun, H (h)	Mean daily radiation, E (MJ m^{-2})
January	13.1	4.4	8.75	4.9	7.9
February	15.2	5.1	10.15	5.7	11.2
March	17.9	7.5	12.7	6	14.3
April	21.1	9.6	15.35	8.6	20.4
May	24.3	11.9	18.1	9.5	23.4
June	30.2	15.7	22.95	11.6	27.0
July	34.1	17.8	25.95	12.6	27.9
August	33.3	17.9	25.6	11.5	24.8
September	29.7	16.2	22.95	8.9	18.7
October	23.5	12.3	17.9	6.9	13.0
November	17.5	8.0	12.75	5.2	8.7
December	13.5	5.1	9.3	4.5	7.0

during that same time period:

$$\eta = \frac{Q_u}{PA}, \tag{6}$$

where Q_u is the usable energy transferred to the fluid, P the mean daily solar power, and A is the collector area. Eq. (6) is finally transformed into

$$\eta = \eta_0 - \frac{U_L(T_e - T_a)}{P} = \eta_0 - \frac{U_L\,\Delta T}{P}, \tag{7}$$

where η_0 is the collector's optical efficiency, U_L the collector's overall heat loss coefficient, T_e the collector fluid input temperature, T_a the ambient temperature, and $\Delta T = T_e - T_a$ the difference between the fluid input temperature and the ambient temperature.

The collector's efficiency can also be approximated by a quadratic equation of the form:

$$\eta = \eta_0 - k_1\frac{\Delta T}{P} - k_2\frac{\Delta T^2}{P}, \tag{8}$$

where k_1 and k_2 are the collector's heat loss coefficients given in units of W m^{-2} K^{-1} and W m^{-2} K^{-2}, respectively. There are manufacturers who express the collector's efficiency using the linear formula (Eq. (7)), and others who use the quadratic formula (Eq. (8)), although this latter form is customarily more appropriately used for evacuated-tube collectors. There are also manufacturers who provide for the same collector both a linear and a quadratic expression together with their corresponding loss coefficients.

Our procedure uses the manufacturers' values of η_0, k_1, and k_2 of Eq. (8), and ΔT is obtained as the difference between the collector fluid input temperature, which depends on the application involved, and the mean monthly ambient temperature, thereby giving a mean monthly ΔT.

Lastly the collected daily mean overall solar power over each month of the year (P in Eq. (8)) is the ratio of the corrected solar radiation and the hours of sun measured on a mean day of that month. The values of the horizontal radiation, $E(t)$, and the hours of sun, $H(t)$, of a mean day of each month are obtained from the climate database, and the radiation is corrected for latitude, tilt angle of the collector, and climate, using correction factors that are given in various publications [11,12,22–24].

The procedure lies in a computation program implemented in an Excel spreadsheet, which allows to compare the efficiency of different collectors for a given application, to size a new installation, and also to calculate the percentage of substitution of conventional energy support.

4.2. Implementation of applications

As a first result, values of the mean efficiency of a concrete solar energy collector for each day of the year were obtained, which as well can be fitted to a simple cosinoidal function.

Table 2
Fitting coefficients for the mathematical models given by Eqs. (1)–(4) to the climate data corresponding to Badajoz, Rome, Paris, Tokyo, and Seoul

Coefficients	Badajoz	Rome	Paris	Tokyo	Seoul
A_0	17.35	11.50	11.50	15.87	11.22
B_0	−8.60	−8.60	−8.05	−11.37	−14.57
A_1	17450	15150	11850	13650	14800
B_1	−10450	−9650	−9050	−4950	−700
A_2	8.55	7.05	4.75	5.2	6.70
B_2	−4.05	−3.55	−3.25	−0.90	−1.60
λ_1	15	15	15	15	15
λ_2	0	0	0	0	0

The last columns give the values of λ_1 and λ_2. In all cases, $\omega = 2\pi/365$.

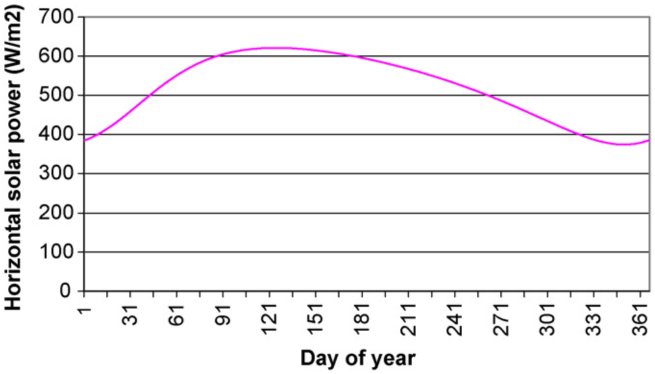


Fig. 1. Mean daily solar power of each month for the city of Badajoz (Eq. (5)).

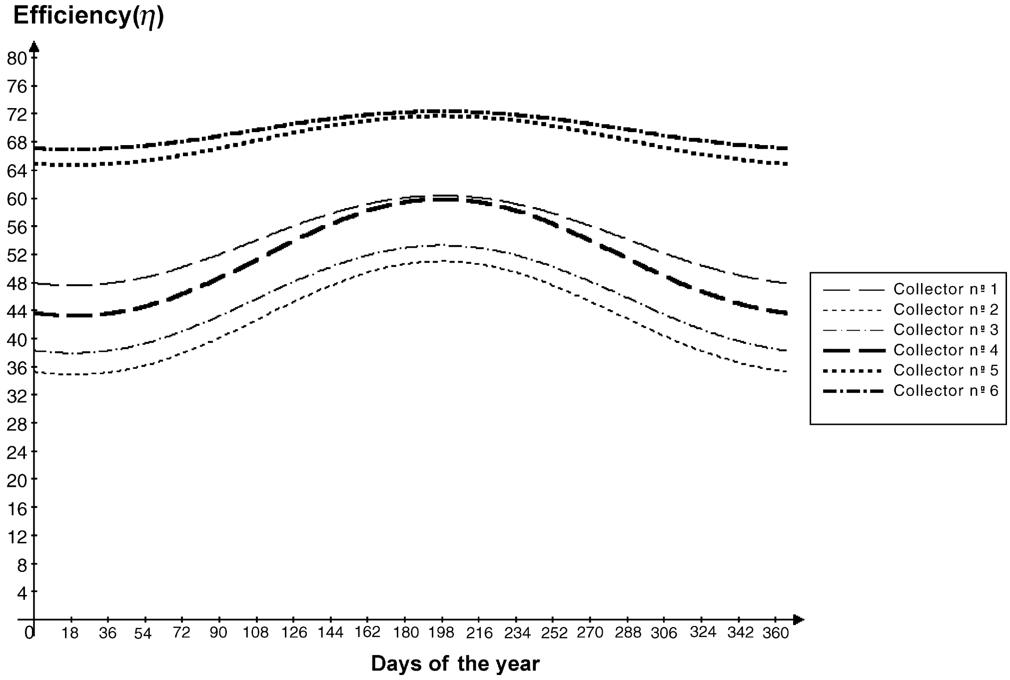


Fig. 2. Comparison of the efficiencies of the collectors used, for a temperature of the heat transfer fluid at the entrance to the collector of 45 °C.

Fig. 2 shows the efficiency curves for several commercial collectors whose loss coefficients (k_1 and k_2) and optical efficiencies (η_0) are listed in Table 3. The comparison amongst the collectors was performed by considering the production of domestic hot water in buildings, assuming the temperature of the heat transfer fluid at the entrance of the collector as being 45 °C. As can be observed, the best efficiencies in domestic hot water production correspond to those of collector no. 6, which is a vacuum pipe device.

It is as well possible to size a concrete type of installation in terms of the percentage of coverage or the percentage of substitution of conventional sources. The computation program also allows to try different solar installation's coverage percentages, varying the number of collectors that should be installed.

The data input to the spreadsheet program are the monthly maximum and minimum temperatures, mean monthly daily radiation, and mean monthly daily number of hours of sun, either obtained directly from the CLIMWAT database, or by choosing the meteorological observatory in the database that is closest to the site of the application. At the same time, one inputs the values η_0, k_1, and k_2 provided by the manufacturer of each collector (see Table 3).

Next one enters the collector fluid input temperature according to the type of application under study (45 °C is the usual temperature for domestic hot water in buildings), or one takes an average value once the stationary regime has been attained, which is estimated or obtained by some other means, such as the application of a program simulating the installation (conventional heating, radiant flooring, etc.). We are currently developing a new program that will provide the various collector input temperatures according to the heating load and coverage requirements for different heating installations in building designs.

Lastly, in order for our sizing procedure to be as simple as possible, the solar heating installation will have to be characterized by means of another energy loss coefficient. This coefficient will depend on the distance from the solar heat collector to either the heat exchanger or the heating storage, according to the type of installation (see Fig. 3). Table 4 lists the values of this coefficient in terms of that distance.

The program first needs to calculate the building's heat requirements whether for domestic hot water or for heating. In the hot water case, the heat requirement is obtained from the number of potential occupants of the building (40 l person^{-1} day^{-1}), taking the level of temporal occupation into account. For other

Table 3
Loss coefficients, k_1 and k_2, optical efficiencies, η_0, and areas of different commercially available collectors

Collector no.	η_0	k_1	k_2	Area (m^2)	Characteristics
1	0.85	5.25	–	2	Flat plate
2	0.75	5.1	–	1.9	Flat plate
3	0.73	3.6	0.022	1.85	Flat plate
4	0.78	3.07	0.017	1.85	Flat plate
5	0.84	1.75	0.008	1.95	Evacuated tubes
6	0.825	1.19	0.009	2	Heat pipe

Table 4
Heating loss coefficients, η_s (Eq. (9)), according to the distance to either the heat exchanger or the heating storage, and the correction coefficient, η_c, due to the collector tilt angle, dirt build-up, and decline in solar radiation at dawn and dusk [21,22]

Distance to heat exchanger or to heating storage (m)	Loss coefficient (%)
<15	5
15–25	8
>25	12

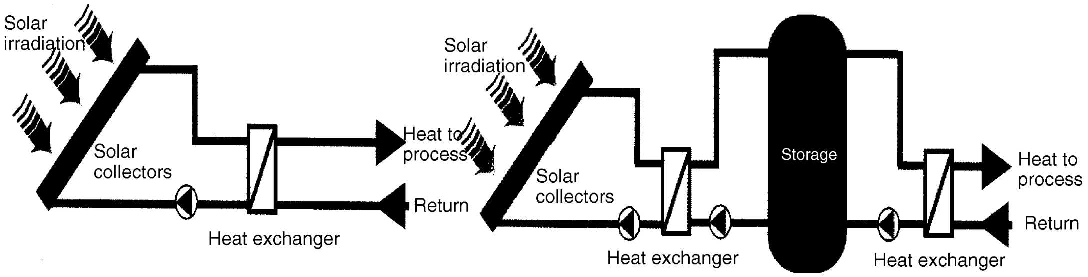


Fig. 3. Configuration of the two heat storage and distribution systems considered.

types of application, the required heat energy must be estimated by some appropriate procedure.

The solar installation's percentage of coverage is obtained from the following expression:

$$C = \frac{\sum_1^{365} E(t)\eta(t)\eta_c\eta_s}{\sum_1^{365} Q(t)}, \tag{9}$$

where C is the energy coverage per m^2 of panel surface; $E(t)$ the overall horizontal radiation over a day of the year; $\eta(t)$ the collectors' efficiency for each day of the year; η_c the coefficient to correct for the tilt angle, dirt build-up on the cover plate, and the decline in radiation for times of day when the sun is very low in the sky [22]; η_s the coefficient of heat losses in the exchanger, storage, and tubing (given in Table 4); and $Q(t)$ the daily heat requirement, which in the case of domestic hot water will be the product of the daily consumption per person by the potential number of occupants of the building and by its level of occupation.

The percentage of coverage of the overall solar heating scheme, G, will be given by

$$G = CAn, \tag{10}$$

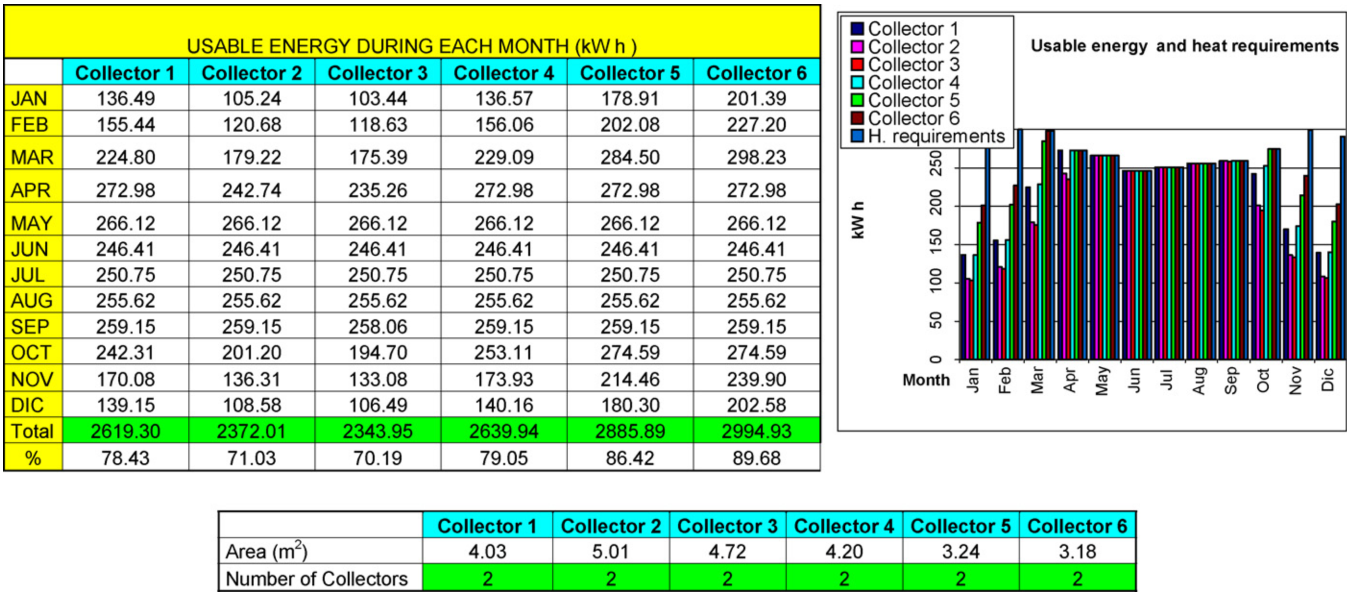
where A is the area of the collector used in m^2, and n is the number of collectors. The result that one obtains is a solar collector area in m^2, or a certain number of collectors of the chosen technical characteristics, for a solar heating system coverage given by Eq. (10).

5. Results and discussion

The results obtained for a variety of solar collectors, solar installation's percentages of coverage, usable energies and efficiencies analyzed in this work are shown in Fig. 4. Such information constitutes the graphical output of our program, which obviously can also be arranged to give the corresponding numerical values.

Comparisons with other well-known computation programs, as well as measurements with a solar heat collector for domestic hot water installed in a building were carried out as a validity test for our results. For such purpose, programs ISOFOTON, CENSOLAR, f-CHART and TRNSYS were used, the two first of which must be regarded as being calculation programs and the rest simulation programs, whereas only TRNSYS is based on a dynamic simulation procedure.

Provided the variety of the input data and of the final results, we decided to compare buildings in order of increasing thermal energy demand, according to domestic hot water consumed by an increasing number of inhabitants (40 l day^{-1} person^{-1}),



USABLE ENERGY DURING EACH MONTH (kW h)

	Collector 1	Collector 2	Collector 3	Collector 4	Collector 5	Collector 6
JAN	136.49	105.24	103.44	136.57	178.91	201.39
FEB	155.44	120.68	118.63	156.06	202.08	227.20
MAR	224.80	179.22	175.39	229.09	284.50	298.23
APR	272.98	242.74	235.26	272.98	272.98	272.98
MAY	266.12	266.12	266.12	266.12	266.12	266.12
JUN	246.41	246.41	246.41	246.41	246.41	246.41
JUL	250.75	250.75	250.75	250.75	250.75	250.75
AUG	255.62	255.62	255.62	255.62	255.62	255.62
SEP	259.15	259.15	258.06	259.15	259.15	259.15
OCT	242.31	201.20	194.70	253.11	274.59	274.59
NOV	170.08	136.31	133.08	173.93	214.46	239.90
DIC	139.15	108.58	106.49	140.16	180.30	202.58
Total	2619.30	2372.01	2343.95	2639.94	2885.89	2994.93
%	78.43	71.03	70.19	79.05	86.42	89.68

	Collector 1	Collector 2	Collector 3	Collector 4	Collector 5	Collector 6
Area (m^2)	4.03	5.01	4.72	4.20	3.24	3.18
Number of Collectors	2	2	2	2	2	2

Fig. 4. Graphical output given by the spreadsheet program based on our procedure.

Table 5
Comparison of the percentage of coverage obtained when sizing several flat-plate collector (a) or vacuum pipe collector (b) solar installations in Badajoz, using different computation programs (ISOFOTON, CENSOLAR, f-CHART and TRNSYS)

Daily hot water usage (l)	Isofoton method (%)	f-Chart program (%)	This work (%)	TRANSYS (%)	Censolar method (%)	Number of collector panel (%)
(a) No. 2. Flat-plate collector						
100	84.30	64.40	74.04	36.40	73.40	1
300	84.30	78.30	74.04	52.50	73.40	3
500	84.30	81.60	74.04	57.10	73.40	5
1000	86.30	85.20	76.80	68.80	75.70	11
2500	85.90	85.70	76.25	70.50	75.40	27
5000	85.90	86.00	76.25	71.90	75.40	54
10000	85.70	85.90	75.97	72.30	75.20	107
25000	85.80	90.00	76.03	73.20	75.20	268
(b) No. 6. Vacuum pipe collector						
100	96.20	82.60	95.25	49.80	89.50	1
300	85.60	79.40	81.94	60.60	77.90	2
500	91.10	89.50	88.52	67.60	83.60	4
1000	91.10	91.30	88.52	71.40	83.60	8
2500	89.60	91.10	86.83	74.00	82.20	19
5000	89.60	91.50	86.83	75.70	82.20	38
10000	89.40	91.50	86.83	76.30	82.20	76
25000	86.60	91.60	86.66	77.70	82.10	189

which will consequently correspond to buildings of increasing size. In all cases the same pipe-line insulation was assumed, using higher capacity water supply tanks as the domestic hot water demand increased. Also, higher loss coefficients were set as the size of the building increased, since longer pipe-lines should be required in such case.

A study of the solar energy coverage was performed for every building with the four abovementioned computation programs, considering the number of collector panels provided by our procedure. Results obtained for each program with two types of collectors (flat plate and vacuum pipe) are shown in Table 5.

Fig. 5a presents the solar installation's percentage of coverage for the production of domestic hot water in a building obtained with a flat-plate collector, whereas data in Fig. 5b correspond to a vacuum pipe collector. All results are referred to the city of Badajoz, which has a high level of solar radiation. The discrepancies of our values with respect to those obtained with the other programs (ISOFOTON, CENSOLAR, f-CHART and TRNSYS) reach a maximum of 10%, which characterizes our procedure as being quite accurate as well as very easy to handle. Such deviations decrease (and hence curves become closer) as domestic hot water demand (i.e., the size of the building) increases (see Fig. 5a and b).

Real measurements with flat-plate collectors installed in a building were also performed in order to establish a comparison with the results yielded by the computation program described in the present work. In particular, the experiment was set in a

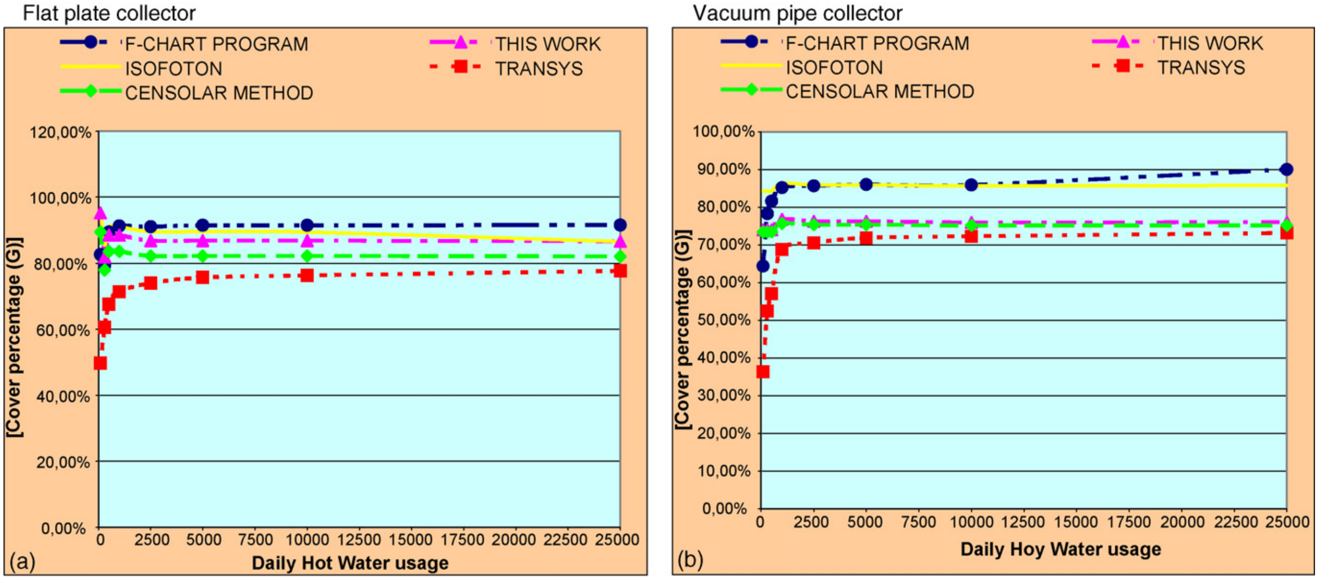


Fig. 5. Comparison of the procedure described in this work for the calculation of the solar energy coverage percentage of a domestic hot water installation, with that of several well-known computation programs. Flat-plate (a) and vacuum pipe (b) collectors were considered.

$250\ m^2$ two-plant building in Badajoz, with three bathrooms with domestic hot water supply, and a constant occupation during the whole year equivalent to four adults, which corresponds to a mean hot water demand of $160\ l\ day^{-1}$. The pipe-lines were insulated with glass wool jackets, and the energy support system was a natural gas modulating boiler. Temperature probes were installed in the inlet/outlet openings of the accumulation tank, as well as in the outlet of the collectors.

The panels were set on the roof of the building, facing south at an inclination angle of 45°. Considering the parameters provided by the manufacturer, the efficiency (Eq. (8)) of these collectors can be fitted to the following expression:

$$\eta = 0.83 - 8.8\frac{\Delta T}{P}. \tag{11}$$

The climate variables corresponded to 8 months validated data supplied by a weather station of the Spanish National Institute of Meteorology located in Badajoz.

Results are shown in Fig. 6, which compares for certain months of the year the energy coverage percentages yielded by our procedure with those obtained directly from experiment. Note that discrepancies are very small, which proves that our procedure can be regarded as being quite accurate, since it meets not only other more sophisticated and complex methods, but also the experimental values.

Finally, we wish to note that we have also applied this procedure to sizing solar heat installations for heating residential and commercial buildings [21,24]. The first results have compared excellently with those given by other computer and simulation programs. In this first study, we used approximate values for the variables, since the calculation of a building's heating installation requires a process of temporal simulation to determine the variability of heating loads with time, and thereby allow a greater level of detail and precision.

Application of the procedure to the city of Badajoz, with relatively high levels of solar radiation and mild temperatures during the heating season, showed that the most efficient flat-plate collectors for use in heating presented relatively low efficiencies—between 35 and 40%. To heat buildings in Badajoz, therefore, it would only be possible to use evacuated-tube collectors. These are more costly, however, and their massive installation in residential buildings would be unprofitable [21,24]. The systematization of the generalized use of the procedure described in the present work for the solar heating of buildings is currently under study, and we hope to be able to publish it shortly.

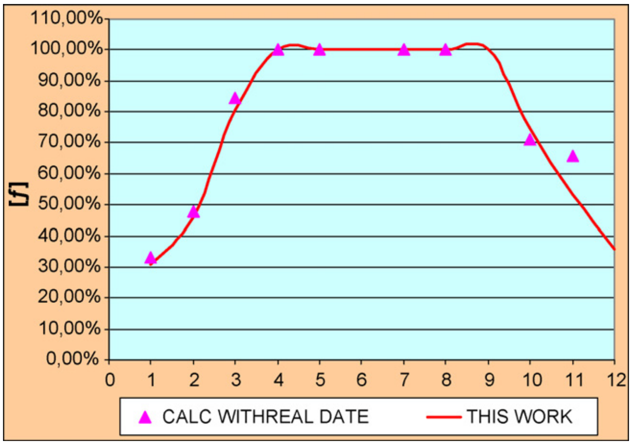


Fig. 6. Comparison of output data yielded by the procedure described in this work with those obtained in a real experimental installation.

6. Conclusions

A program has been implemented of simple, practical, and universal calculation that allows one to display the daily values of climate and solar radiation variables, and to make a rapid comparison of the efficiencies of the various collectors available on the market. Then an installation for heating of domestic hot water in a building can be sized for any given solar energy coverage.

As a consequence of disposing of the same final available energy using less conventional primary energy, the energetic efficiency of the building is higher. It also leads to a decrease of the energy consumption and hence to a positive energetic characterization of the building, if compared with a reference one. Moreover, this helps towards the reduction of emission of CO_2 and other greenhouse effect gases into the atmosphere.

The validation of the program was carried out by a comparison with other well-known and worldwide accepted ones (ISOFOTON, CENSOLAR, f-CHART and TRNSYS), and also with experimental values obtained from a flat-plate heat collector set in the city of Badajoz. Results are coherent in all cases, with small deviations, in high solar radiation regions.

Given that the CLIMWAT database (or some other commercial or Web-based database) is used, one defines rules and norms that make it possible to apply the program for any part of the world where the average ambient temperature reaches values that make water heating advisable, or where there are high levels of solar radiation.

Lastly, the calculation process was found to be very accuracy, even though it uses approximate values for the variables of the heating load to which the installation is subjected, rather than taking their dynamic evolution into account. It is especially simple to apply, giving a rapid comparison of the efficiencies of collectors currently available on the market, and sizing heating installations for buildings. It usefulness extends both to users who have little technical knowledge of this clean source of energy, and to installers, builders, architects, and engineers. Note other methods which are massively used are much more sophisticated and complex, and hence are suitable to be handled only by qualified users.

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