OPTIMISATION OF DESIGN CRITERIA FOR SOLAR SPACE HEATING SYSTEMS THROUGH MODELLING AND SIMULATION

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ABSTRACT

This paper is concerned with the optimisation of some design criteria for water based active solar space heating systems intended for residential applications in Cyprus. For this purpose, a system model based on the TRNSYS simulation programme has been used to correlate the performance and cost effectiveness of the system with a number of key design criteria.

Two design criteria are investigated in the present study, namely the collector to floor area criterion (CAF), which relates the collector area to the building floor area, and the collector to load criterion (CAL) which relates the collector area to the building thermal load.

The simulation results showed that the system is not viable when compared with a diesel oil alternative. The system is cost effective when compared with electricity. In that case the system solar fraction is maximised for CAF value of 0.3 m^2 of solar collector per m^2 of building floor area while the optimum CAL value is about 0.5 m^2 of collector per annual GJ of building thermal load.

INTRODUCTION

The sizing of a solar space heating system (SSH) for a building is a complex problem involving a number of interrelated factors and parameters which include, among others, the building thermal characteristics, the collector size and slope, the storage tank size, the heat exchangers size, the solar radiation, and a good number of economic parameters. The components of a SSH system must be well selected, properly sized, and carefully assembled in order to ensure that the system will function properly and cost-effectively. Oversizing of the system is not advisable because of high initial cost, while undersizing may not provide significant savings of conventional fuels. The optimisation of the design factors can be achieved either through experimental investigations which, however, are time consuming, expensive and not repeatable, or through modelling and simulations which can provide much of the same thermal performance information as physical experiments with less time, effort and expense.

Lunde (1979) correlated the performance of solar heating systems with the ratio of the collector area to the heating load (m^2/GJ). He simulated the performance of a solar heating system under the weather conditions of six different locations in the United States, at collector to load ratios ranging from 0 to 1.32 m^2/GJ. He demonstrated that this ratio is a good design parameter for predicting the performance of a solar heating system but he did not investigate the optimum design values for such applications.

Barley (1979) derived an algorithm for choosing insulation levels, as well as solar collection area, so as to minimize the overall cost of constructing and heating a building. The general algorithm is applicable with any solar performance prediction method and with economic criteria where the cost is a linear function of collection area and of auxiliary energy consumption. It has been shown that the ratio of solar collector area to the annual space heating load has an economically optimal value, corresponding to an optimal solar heating fraction, which is independent of the magnitude of the load.

The present study is dealt with the optimisation of two design criteria for solar space heating systems intended for residential houses in Cyprus, using the TRNSYS (Klein S.A. *et al.,* 1990) Simulation Programme. These are the collector to floor area criterion, CAF, defined as the ratio of the collector area A_c to the floor area A_f of the building heated rooms, and the collector to load criterion, CAL, which is defined as the ratio of the collector surface area A_c to the annual space heating load. The CAF criterion is expressed in m^2 of collector per m^2 of floor area, and CAL is expressed in m^2 of collector per annual GJ of heating load.

THE SYSTEM

The schematic diagram of the solar heating system under investigation is illustrated in fig. 1. It is a water-

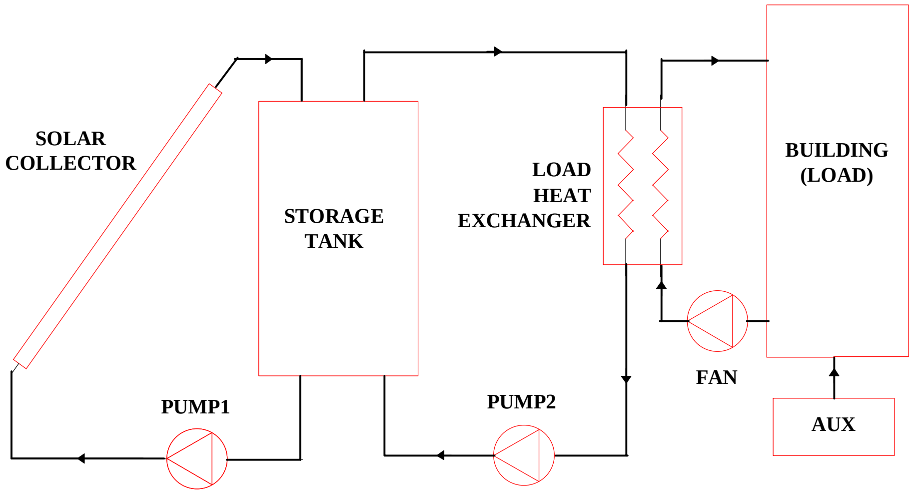

Fig. 1. Schematic diagram of the solar space heating system

based active system which comprises a number of flat-plate solar collectors coupled to a water storage tank. In addition, there is a load heat exchanger and two circulating pumps which are used to maintain the required water flow rate through the collector-storage and the storage-load heat exchanger sub-circuits. Auxiliary heating is provided by using conventional heaters to supply any shortfall in the heat energy that is supplied by the storage.

Two scenarios are investigated, the first one assuming diesel oil as backup energy source, and the second one with electricity as backup energy source. The above approach has been adopted for the present study because there is a significant difference in the cost of energy provided by the said sources (see Table 2).

THE SIMULATION MODEL

According to Klein *et al.* (1990), there are three possibilities for modelling the building energy loads with TRNSYS. However, for relatively quick estimates of heating requirements, the space heating load model of TRNSYS known as Energy/(degree-day) TYPE 12 model, may be used. In this case, the building is modelled through the use of a single conductance (UA) for heat loss. A single energy balance on the structure is performed each simulation timestep.

The energy/(degree-day) concept has been shown by ASHRAE (1981) to be useful in estimating the monthly heating load of a structure. In this space heating load model, the energy/(degree-day), or more appropriately the energy/(degree-hour), concept is extended to estimate the hour by hour heating load of a structure. According to Klein *et al* (1990), the hour by hour space heating load estimated in this manner may be significantly in error, but over a period of time, the model may provide reasonable estimates of overall energy quantities. Furthermore, the model does provide an estimation of the space heating load with minimal computational effort.

The simulation of the system requires hourly weather data, representative of the location under investigation. In the absence of TMY for Cyprus, the monthly average values of the daily solar radiation and air temperatures for the years 1984-1987, have been used in the simulation. The TRNSYS programme, through its Weather Data Generator has the capability of producing hourly data from monthly averages.

Given a certain load that is some function of time through a year, a type of collector and a system configuration, the primary design variable is the collector size. System performance is much more sensitive to collector area than to any other variable (Duffie and Beckman, 1980). To this effect the economics of the system are very essential and need to be treated in conjunction with the thermal performance of the system. For this purpose, the Economic Analysis subroutine of TRNSYS has been included in the system model.

The performance of the system will be expressed in terms of its solar fraction, f, which is defined as the fraction of the space heating load provided by solar energy and can be calculated from the following relationship:

$$f = \frac{Q_{load} - Q_{aux}}{Q_{load}}$$

where Q_{load} is the space heating load and Q_{aux} is the auxiliary energy supplied to the system.
The costs of solar heating equipment include purchase and installation of all collectors, storage tank, pumps, controls, ductwork, piping, heat exchangers, etc., and are considered as the incremental costs, that is, the difference in cost between the solar heating system and a conventional heating system.

Operating costs include costs of auxiliary energy, parasitic power, maintenance, etc. It is assumed that the costs of components which are common to both, conventional and solar heating systems, e.g. the furnace, load heat exchanger, ductwork, fans, controls, and the maintenance costs of this equipment are identical. As a result of the above, all references to solar heating system costs, or conventional system costs, refer to the cost increment above the common costs.

For the simulations of the present study, it has been necessary to use a number of parameters which concern the building, the solar system and the economic scenario, some of which are listed in Tables 1 and 2.

Table 1. System simulation parameters

Parameter	Value *
$F_R U_L$	24.4 kJ h^{-1} K^{-1} m^{-2}
$F_R(\alpha\tau)_n$	0.78
G	50 kg h^{-1} m^{-2}
G_{test}	54 kg h^{-1} m^{-2}
U_s	1.2 kJ h^{-1} K^{-1} m^{-2}
UA (building)	4000 kJ h^{-1} K^{-1}
β	50^o from horizontal
$\varepsilon_L C_{min}/UA$	2
* Taken from experimental tests	

Table 2. Economic parameters

Parameter	Value	Parameter	Value
C_{EE}	36 US$/GJ	d	9%
C_{ED}	7.4 US$/GJ	M_s	1%
N_E	20 yrs	i	5%
D	50%	t	9%
m	9%	N_D	20 yrs
N_L	15 yrs	i_{FCF}	5%
DEG	1%/yr	i_{FBUP}	5%/yr

One of the parameters which concern the building is the dimensionless parameter $\varepsilon_L C_{min}/UA$, where ε_L is the effectiveness of the load heat exchanger, C_{min} is the minimum capacitance rate of the heat exchanger and UA is the total building energy loss coefficient. This parameter has been found to provide a measure of the size of the heat exchanger needed to supply solar energy to a specified building (Klein *et al*. 1976). Klein *et al.* suggest that reasonable values of $\varepsilon_L C_{min}/UA$ for solar space heating systems are between 1 and 3. Based on the above and the findings of Michaelides (1993), in the present study $\varepsilon_L C_{min}/UA$ is taken as 2.

ANALYSIS OF SIMULATION RESULTS

A number of simulations were run for different collector areas, assuming a collector slope of 50^o from horizontal, a storage factor of 50 l/m^2 and a water flow rate through the collector equal to 50 kg/h per m^2 of collector. The results of the simulations were used to plot graphs relating the annual solar fraction and the life cycle savings of the system to the design criteria CAF and CAL. These are shown in figs. 2 and 3. This approach is considered useful because it offers the flexibility to the designer to base his design on either of the parameters and do some kind of cross-checking in determining the optimum collector area of a solar space heating system.

It is seen from the graphs that the system solar fraction, f, which is an indication of the what proportion of the building thermal load is met by solar, increases with an increase in both the CAF and the CAL criteria. The increase is more dinstict at low values, but the rate of increase is reduced as CAF and CAL increase to higher values. This can be explained by the fact that an increase in the collector area will result to higher temperatures in the collector system, thus increased heat losses which in effect will bring about lower collector efficiencies and therefore reduced contribution to the building heating load.

The situation is not the same for the life cycle savings. In the case of diesel oil backup it is seen that as the CAF criterion increases, the LCS decrease. It is interesting to note that for CAF values up to 0.1 the LCS are positive while for CAF higher than 0.1 the LCS get negative. At the same time, it is seen from the simulation results that the payback period varies from 9 years to values which exceed the expected lifetime of the system, i.e. higher than 20 years (see Table 3). It is, therefore, evident that solar space heating in Cyprus, under the socio-economic and weather conditions prevailing in the island, is not cost effective and in fact cannot compete with conventional heating systems which use diesel oil fired boilers.

The situation is however different if the comparison is made with electricity. The life cycle savings are positive for the ranges of CAF and CAL values investigated in this study and much higher than those experienced in the case of diesel oil. At low values of CAF and CAL, the life cycle savings are low; as CAF and CAL increase, the life cycle savings increase until they reach a maximum value corresponding to approximately 0.3 m^2/GJ and then declines to reach a value lower than that corresponding to the low values of CAF and CAL. Therefore, the optimum value for the CAF criterion is 0.3 m^2 of collector per m^2 of building floor area but any value within the range of 0.25 and 0.4 seem to represent optimal design values.

In the same way, from fig. 3 it is found that the life cycle savings maximise at a CAL value of approximately 0.5 m^2/GJ but it is also remarkable that any value within the range of 0.4 and 0.7 m^2/GJ would represent optimal design values.

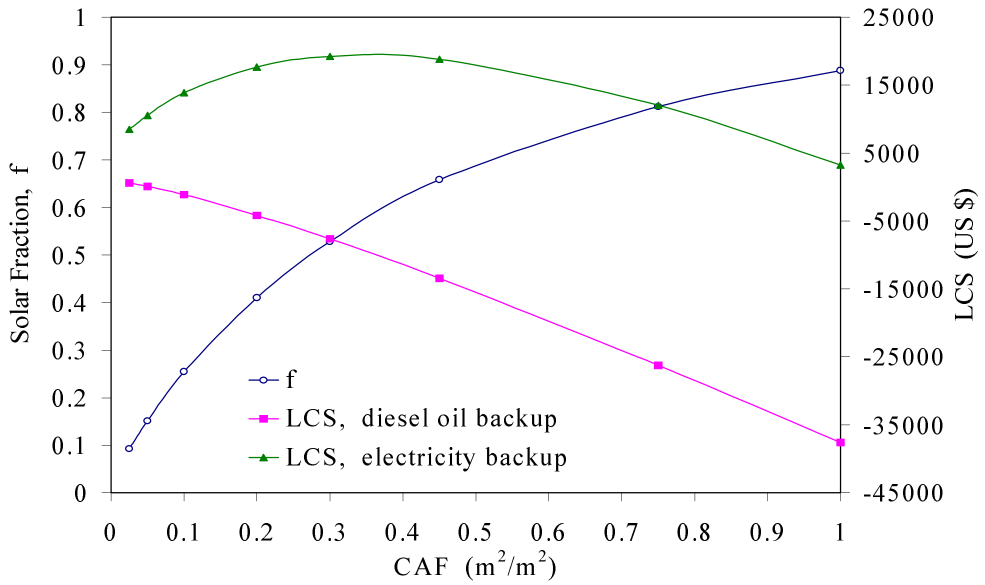

Fig. 2. Annual solar fraction and life cycle savings as a function of the collector to building floor area criterion (CAF).

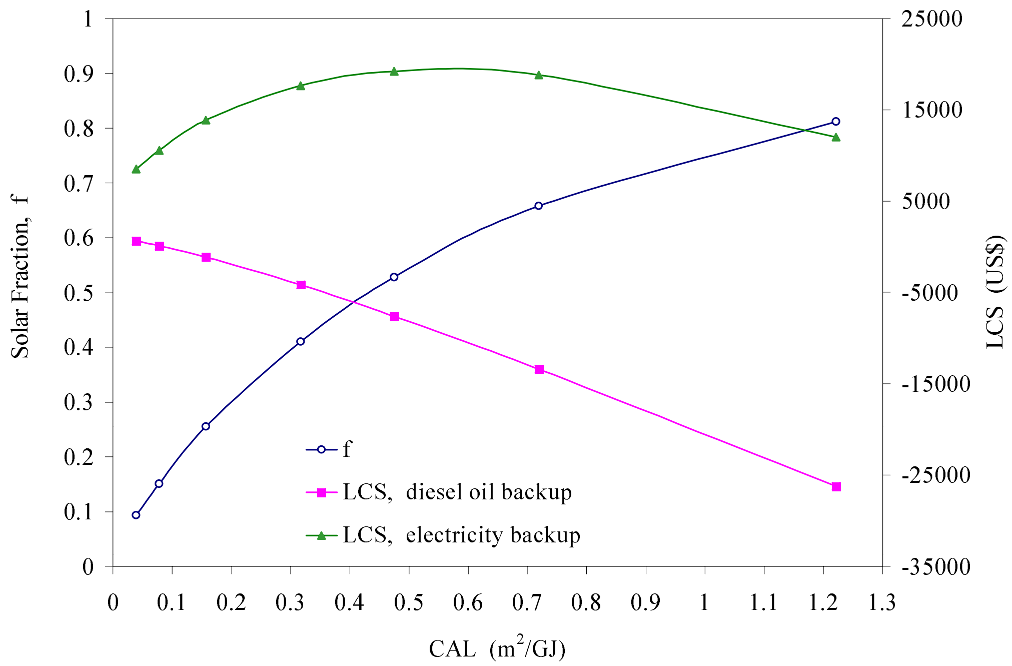

Fig. 3. Annual solar fraction and life cycle savings as a function of the collector to building thermal load criterion (CAL).

The situation is however different if the comparison is made with electricity. The life cycle savings are positive for the ranges of CAF and CAL values investigated in this study and much higher than those experienced in the case of diesel oil. At low values of CAF and CAL, the life cycle savings are low; as CAF and CAL increase, the life cycle savings increase until they reach a maximum value corresponding to approximately 0.3 m^2/GJ and then declines to reach a value lower than that corresponding to the low values of CAF and CAL. Therefore, the optimum value for the CAF criterion is 0.3 m^2 of collector per m^2 of building floor area but any value within the range of 0.25 and 0.4 seem to represent optimal design values.

In the same way, from fig. 2 it is found that the life cycle savings maximise at a CAL value of approximately 0.5 m^2/GJ but it is also remarkable that any value within the range of 0.4 and 0.7 m^2/GJ would represent optimal design values.

Table 3. Payback period and system solar fraction for diesel oil and electricity backup

CAF (m^2/m^2)	Diesel oil backup		Electricity backup	
	f	Payback (years)	f	Payback (years)
0.025	0.093	9	0.093	3
0.050	0.151	11	0.151	4
0.100	0.255	13	0.255	4
0.200	0.410	15	0.410	5
0.300	0.528	17	0.528	5
0.450	0.658	20	0.658	6
0.750	0.812	>20	0.812	8
1.000	0.888	>20	0.888	10

At optimal values of CAF and CAL criteria, the solar fraction is approximately 0.53, which means that 53% of the space heating load of the building is met by solar while the rest is supplied by the auxiliary heating unit. Simulation results revealed that under the above optimal conditions, the payback period for the solar system is around 5 years which is a very attractive figure.

The curves of figs. 2 and 3 could be used for the prediction of the annual solar fraction of a solar space heating system at any imposed collector size. They can also serve as a quick estimate of the expected yearly contribution of a solar heating system to the building's heating requirements.

CONCLUSIONS

It has been found that solar space heating in Cyprus, under the socio-economic and weather conditions prevailing in the island, is not cost effective and in fact cannot compete with conventional heating systems which use diesel oil fired boilers.

The situation is different if electricity is the competitor. In such a case, a designer could use either the CAF criterion or the CAL criterion to size the solar heating system. Solar heating is cost effective for a size of 0.3 m^2 of collector per m^2 of building floor area. For a cross check calculation, the designer could use the CAL criterion which is 0.5 m^2 of collector per GJ of building heating load. The above criteria are valid for ground floor residential houses in Cyprus.

REFERENCES

ASHRAE, 1981. *Handbook of Fundamentals.* New York: American Society of Heating Refrigeration and Air conditioning Engineers.

Barley, C.D. 1979. Load optimisation in solar space heating systems. *Solar Energy* **23**, 149-156.

Duffie, J.A. and Beckman, W.A, 1980. *Solar Engineering of Thermal Processes.* John Wiley, New York.

Klein, S.A., Beckman, W.A., and Duffie, J.A., 1976. A design procedure for solar heating systems. *Solar Energy* **18**, 113-127.

Klein, S.A. *et al*. 1990. *TRNSYS, a Transient Simulation Program*. Solar Energy Laboratory, University of Wisconsin.

Lunde, P.J., 1979. Prediction of the performance of solar heating systems over a range of storage capacities. *Solar Energy* **23**, 115-121.

Michaelides, I.M, 1993. Computer simulation and optimisation of solar heating systems for Cyprus. PhD thesis, University of Westminster, London, UK.

NOMENCLATURE

A_c	Collector area, m^2
A_f	Building floor area, m^2
CAF	Collector to floor area factor, m^2 of collector per m^2 floor area
CAL	Collector to load factor, m^2 per annual GJ
C_{EE}	Cost of electric energy, US$/GJ
C_{ED}	Cost of diesel oil energy, US$/GJ
C_{min}	Minimum capacitance rate in a heat exchanger, kJ h^{-1} K^{-1}
d	Market discount rate, %
D	Down payment, % of original investment
DEG	Thermal performance degradation, %/yr
f	Solar fraction (fraction of the load that is met by solar)
F_RU_L	Slope of the collector efficiency curve, kJ $h^{-1}K^{-1}$ m^{-2}
$F_R(\alpha\tau)_n$	Intercept of the collector efficiency curve
G	Collector mass flux, kg h^{-1} m^{-2}
G_{test}	Collector mass flux at test conditions, kg h^{-1} m^{-2}
i	Inflation rate, %
i_{FBUP}	Backup (auxiliary) fuel inflation rate, %
i_{FCF}	Conventional fuel inflation rate, %
m	Mortgage, %/yr
M_S	Extra insurance, maintenance in year 1, % of initial investment
N_D	Useful life for depreciation purposes, yrs
N_E	Period of economic analysis, yrs
N_L	Term of loan, yrs
Q_{aux}	Auxiliary energy, kJ
Q_{load}	Space heating load, kJ
t	Effective income tax rate (%), time
U_L	Collector heat loss coefficient, kJ h^{-1} K^{-1} m^{-2}
U_L	Collector heat loss coefficient, kJ h^{-1} K^{-1} m^{-2}
U_s	Heat loss coefficient of storage tank, kJ h^{-1} K^{-1} m^{-2}
UA	Constant characterising the building, kJ h^{-1} K^{-1}
β	Collector tilt angle, degrees from horizontal
ε_L	Effectiveness of the space heating load heat exchanger.