Life cycle analysis of thermosyphon solar water heaters

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ABSTRACT

In this paper, a life cycle analysis of thermosyphon solar water heating systems is presented. This includes the performance, economics and environmental benefits offered by the system investigated which is of the domestic size, suitable to satisfy most of the hot water needs of a four-person family. The results presented in this paper show that the solar contribution is 79%, the pay back time is 2.4 years and life cycle savings are €3014 with electricity backup and 3.1 years and €2010 with diesel backup respectively. Additionally, by using solar energy considerable amounts of greenhouse polluting gasses are avoided. The energy spent for the manufacture and installation of the solar systems is recouped in about 13 months. It can therefore be concluded that thermosyphon solar water hearting systems offer significant protection to the environment and should be employed whenever possible in order to achieve a sustainable future.

1. INTRODUCTION

In this paper, a life cycle analysis of the thermosyphon solar water heating systems is presented. This includes the thermal performance, economics and environmental benefits resulting from the use of the system. Additionally, the amount of pollution saved because of the use of solar energy against the pollution caused for the manufacture of the systems is examined.

In literature, there are numerous studies on the environmental life cycle analysis of thermal systems. Some of them deal with solar water heating systems [1,2]. The latter study examined the life cycle environmental impact of a thermosyphon solar hot water system in comparison with electrical and gas heating in Greece.

Renewable energy technologies produce marketable energy by converting natural phenomena into useful forms of energy. Today, significant progress is made by improving the collection and conversion efficiencies, lowering the initial and maintenance costs and increasing the reliability and applicability of renewable energy systems [3]. The benefits arising from the installation and operation of renewable energy systems can be distinguished into three categories; energy saving, generation of new working posts and the decrease of environmental pollution [4].

This paper deals with thermosyphon solar water heating systems, which are very popular systems, used extensively in many countries with good sunshine potential such as the Mediterranean countries. A domestic size system is considered, which is analysed with respect to its energy performance, economics and environmental impact.

2. THERMOSYPHON WATER HEATING SYSTEMS

Thermosyphon, or natural circulation, solar water heating systems (also called passive systems) are the simplest and most widely used solar energy collection and utilization devices. They are intended to supply hot water for domestic use, and are based on natural circulation or thermosyphon principle. They supply hot water at a temperature of about 60°C and consist of a collector, storage tank, and connecting pipes as shown in Fig. 1. A typical unit operating in a good environment (Mediterranean area) usually consists of two flat-plate solar collectors having an absorber area between 2.5 to 4 m^2 and a storage tank with capacity between 150 to 180 litres. An auxiliary electric immersion heater and/or a heat exchanger, for central heating assisted hot water production, are used in winter during periods of low solar insolation. The flat plate collector is generally fixed permanently in position. Usually the tilt is equal to latitude of the location plus 5° [5].

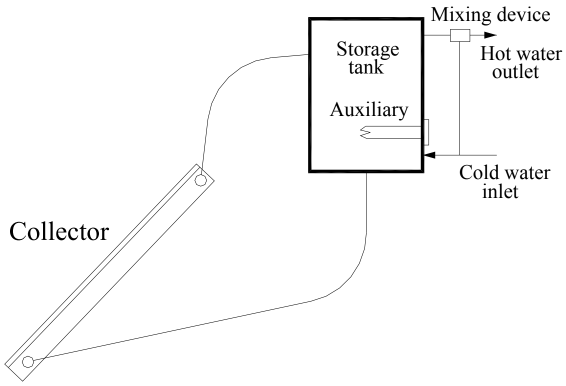

Fig. 1 Schematic diagram of a thermosyphon solar water heater

The unit considered in this work employs flat plate collectors which are by far the most used type of collector. The instantaneous efficiency of the collector considered is given by the following equation obtained by testing the collector at the Applied Energy Centre of the Ministry of Commerce, Nicosia, Cyprus:

$$\eta = 0.792 - 6.65\left(\frac{\Delta T}{G_t}\right) - 0.06\left(\frac{\Delta T^2}{G_t}\right) \quad (1)$$

where ΔT is temperature difference between the collector inlet (T_i) and ambient (T_a) temperatures, i.e., ΔT= (T_i-T_a), and G_t is the global solar radiation.

To evaluate the system long-term performance a TRNSYS model was used, running with the typical meteorological year (TMY) of Nicosia, Cyprus [6].

The storage tank is well insulated to reduce thermal loses to the environment and is equipped with a heat exchanger for heating the water with auxiliary energy. The auxiliary can be either electricity or diesel. In the case where diesel is considered this is used in a central heating boiler, which supplies the energy for the heating needs of a house and is not used only as the solar system backup. What is of interest to note is that if the temperature of the water in the storage tank is more than the desired temperature this is mixed with the make-up water to obtain the required temperature. This is done at the tap by the user but in the simulation, it is done with the mixing devise shown in Fig. 1. The specifications of the various components of the solar system are shown in Table 1.

Table 1. Specifications of the thermosyphon solar water system considered

Parameter	Domestic hot water system
Collector area (m^2)	2.7 (2-panels)
Collector slope (°)	40
Storage capacity (l)	150
Auxiliary (kW)	3
Heat exchanger	Internal
Heat exchange area (m^2)	3.6
Hot water demand (l)	120 (4 persons)

Traditional hot water systems comprise a hot water cylinder powered either by electricity or by diesel oil through the central heating boiler. Therefore, the extra equipment required for the solar system are the solar collectors and the piping to connect the collectors with the storage tank.

With regard to the thermal load, although the hot water demand is subject to a high degree of variation from day to day and from consumer to consumer it is impractical to use anything but a repetitive load profile. For the present simulation, the hot water consumption profile illustrated in Fig. 2 is employed, which assumes a daily hot water consumption of 120 litres at 50°C for a family of four (30 litres/person).

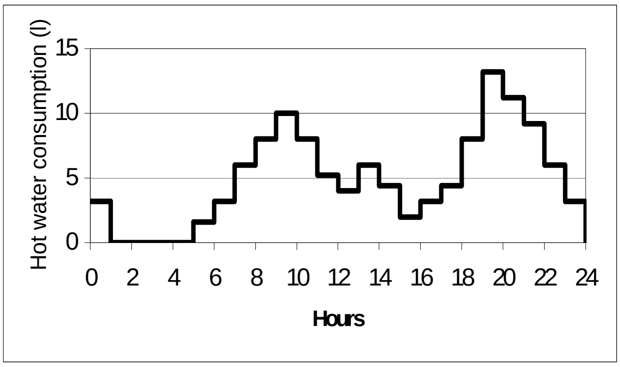

Fig. 2 Hot water daily consumption profile

3. THERMAL AND ECONOMIC ANALYSIS

Figure 3 illustrates the monthly energy flows, obtained by running the TRNSYS model of the system with a TMY data. These include the total radiation incident on the collector (Q_{ins}), the useful energy supplied from the collectors (Q_u), the hot water energy requirements (Q_{load}), the auxiliary energy demand (Q_{aux}) and the heat losses from the storage tank (Q_{env}).

As it can be seen from the graph, there is a reduction in the incident solar radiation and consequently the useful energy collected during the month of May. This is a characteristic of the climatic conditions of Nicosia and is due to the development of clouds as a result of excessive heating of the ground and thus excessive convection, especially in the afternoon hours. The annual value of the useful energy supplied by solar energy (Q_u) is equal to 6480 MJ.

The variation of the solar contribution, f, is also shown in Fig. 3. As can be seen the solar contribution is lower in winter months and higher, reaching 100%, in summer months. The annual solar contribution is determined to be 79%. It should be noted that by adjusting slightly the consumption, contributions of 100% could be obtained from May to October, which is what usually happens in practice.

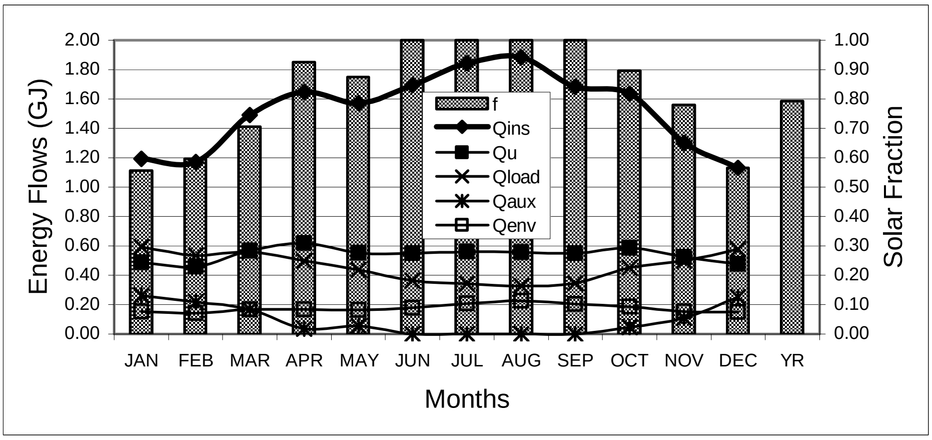

Fig. 3 Energy flows of the thermosyphon solar water heater

The economic scenario used in this project is that the cost of the solar system is paid at the beginning (i.e., no credit payments are assumed). The thermal performance degradation of the system is assumed to be 1% per year, the period of economic analysis is taken as 20 years (average life of locally produced systems), whereas all the other percentage figures are mean values of the previous decade [7]. Electricity at a price of 0.189 €/kWh and diesel at 1.161 €/l (current prices) are assumed to be used for auxiliary. Table 2 gives a summary of economic figures calculated by TRNSYS.

The results of the economic analysis shown in Table 2 were obtained by using the above fuel and electricity rates, a twenty years period a market discount rate of 6% and interest rate of 8%. No subsidies were considered. As can be seen the solar system gives much lower specific energy cost than the conventional system for both types of auxiliary energy considered.

Table 2. Results of economic analysis.

OUTPUT PARAMETER	Electricity backup	Diesel backup
Initial cost of the system	€373	€373
Resale or salvage value	€75	€75
Rate of return of solar investment	64.1%	45.9%
Pay back time	2.4 years	3.2 years
Undiscounted cumulative net cash flow	€5931	€4068
Present worth of total costs with solar	€1218	€981
Present worth of total costs without solar	€4232	€2990
Annualized total cost with solar	19.1 €/GJ	15.3 €/GJ
Annualized total cost without solar	66.9 €/GJ	47.1 €/GJ
Present worth of cumulative cash flow	€3014	€2010
Fuel price considered in the analysis	0.189 €/kWh	1.161 €/l

The pay back time is very low and is equal to 2 years and 5 months for electricity backup and 3 years and one month for diesel backup. Life cycle savings represent the money that the owner will save by installing the solar system instead of buying electricity/fuel to satisfy his hot water needs and is equal to €3014 for electricity and €2010 for diesel backup.

4. ENVIRONMENTAL BENEFITS

To investigate the environmental benefit of utilising solar energy instead of conventional sources of energy, the different emissions resulting from the solar system operation are estimated and compared to those of a conventional electricity/fuel system. These are obtained by correlations derived by using Polysun program given in [3]. The environmental interventions are expressed in physical units of the emitted substances per year.

The quantities of the emissions depend on the solar collector size and the required auxiliary energy and are compared to a non-solar system which is using conventional electricity/fuel. The environmental analysis of the system which includes the different pollutants as calculated by the program is tabulated in Tables 3 and 4 for electricity and diesel backup respectively. In the tables the seven most important greenhouse gasses are considered. For the case of electricity backup (Table 3), Polysun considers a mixture of European power stations (coal-based, nuclear, hydroelectric, etc.) in order to estimate the emissions of the conventional system [8]. As can be seen in both cases by using solar energy instead of conventional fuel very large amount of pollutants are avoided. The amount of emissions depends on the type of fuel used as auxiliary.

The percentage saving obtained in the cases where electricity or diesel backup is used is about 70%. It should be noted however that the quantities of emissions in the various substances emitted are completely different and the proximity of the total percentage numbers obtained is due to the generation efficiency of each system. Electrical energy is produced at a maximum efficiency of about 35% whereas in the case of diesel backup a boiler efficiency of 85% is considered.

Table 3. Environmental impact of the thermosyphon solar water heater with electricity backup

Emissions	Units	Conventional	Solar system	Savings (%)
Carbon dioxide (CO_2)	Tons/year	1.546	0.449	70.1
Carbon monoxide (CO)	g/year	374.6	109.7	70.7
Nitrogen oxides (NO_x)	g/year	56.3	16.3	71.1
Nitrous oxide (N_2O)	g/year	6.3	2.1	66.7
Methane (CH_4)	g/year	9.3	2.7	71.0
Hydrocarbons	g/year	37.7	11.0	70.8
Sulphur dioxide (SO_2)	g/year	562.7	164.5	70.8
Savings in GHG	%	-	-	70.3

Table 4. Environmental impact of the thermosyphon solar water heater with diesel backup

Emissions	Units	Conventional	Solar system	Savings (%)
Carbon dioxide (CO_2)	Tons/year	0.889	0.293	67.1
Carbon monoxide (CO)	g/year	1688	581.3	65.6
Nitrogen oxides (NO_x)	g/year	1636	544.8	66.7
Nitrous oxide (N_2O)	g/year	6.1	1.2	80.0
Methane (CH_4)	g/year	13.6	3.3	75.7
Hydrocarbons	g/year	52.7	12.9	75.5
Sulphur dioxide (SO_2)	g/year	651.4	169.9	73.9
Savings in GHG	%	-	-	70.5

5. POLLUTION CREATED FROM THE SYSTEM

The pollution created for the manufacture of the solar collectors is estimated by calculating the embodied energy invested in the manufacture and assembly of the collectors and estimating the pollution produced by this energy. Initially the embodied energy of one solar collector panel, 1.35m^2 in area is determined. This is the same collector considered in the performance analysis of the system. The analysis is based on the primary and intermediate embodied energy of the components and materials.

The total embodied energy required to produce a complete flat-plate collector is calculated using primary and intermediate production stages. The primary stage is established from an assessment of the various materials used and their corresponding mass. Using the embodied energy index (MJ/kg) defined by Alcorn [9] the material embodied energy content within the unit is determined. Table 5 summarizes the unit materials used and lists their corresponding mass and embodied energy content. The total embodied energy content for the production of one flat-plate collector panel is calculated at 2663 MJ.

An analysis of the embodied energy content of a complete thermosyphon solar water heating system is shown in Table 6. It should be noted that only the extra components of the solar system are considered in this analysis as the other components are standard and are also present in conventional systems. Here the objective is to compare the pollution created for the manufacture and installation of the solar system against its benefits due to the lower emissions realized during the operation of the system. As can be seen the total embodied energy for the complete system is 6946 MJ.

Table 5. Embodied energy content of one flat-plate collector 1.35m^2 in area

Description	Mass (kg)	Embodied energy index (MJ/kg)	Embodied energy content (MJ)
1.6x0.85x0.05m insulation	4.3	117	503.1
1.6x0.85x0.005m glass	9.5	15.9	151.1
1.8m, 22mm copper pipe	2.16	70.6	152.5
16m, 15mm copper pipe	9.9	70.6	698.8
2x1.05x0.005m galvanized steel sheet	8.2	34.8	285.4
5m rubber sealant	0.5	110	55
Black paint	0.3	44	13.2
Casing paint	0.9	44	39.6
169x0.85x0.003m copper absorber	3.6	70.6	254.2
Total			2,153
Add 10% for contingencies			215
Unit manufacture using a net to gross value of conversion rate of 27%			295
Grant Total			**2,663**

Table 6. Embodied energy content for the construction and installation of the complete system

Description	Mass (kg)	Embodied energy index (MJ/kg)	Embodied energy content (MJ)
2 No solar panels	-	-	5326
4m, 22mm copper pipe	3.8	70.6	268.3
4m, pipe insulation	1	120	120
Steel frame	30	34.8	1044
Total			6758.3
Installation			187.7
Grant Total			**6,946**

For the life cycle assessment of the system considered the useful energy supplied by solar energy per year, shown in Fig. 3 (6480 MJ) is compared with the total embodied energy of the system shown in Table 6. As can be easily deduced the total energy used in the manufacture and installation of the system is recouped in about 13 months, which is considered as very satisfactory.

The size of thermosyphon solar water heater considered is the usual type encountered in Cyprus. Today more than 93% of all houses have solar water heating systems installed and operating. The total number of systems is equal to 190,000 units, which corresponds to one heater for every 3.7 people in the island, which is a world record [10]. If we consider that all systems are of the same size as the one investigated here and that 50% of the systems are using electricity and 50% diesel as backup then the amount of pollutants avoided per year are as shown in Table 7, i.e., considerable reduction in environmental pollution occurs each year.

6. CONCLUSIONS

In this study, the performance, economics and environmental protection offered by thermosyphon solar water heating systems is presented. The results show that by using solar energy considerable amounts of greenhouse polluting gasses are avoided (about

70%). Additionally, the annual solar contribution is 79% whereas the pay back time of the system is 2.4 year and the life cycle savings are €3014 for electricity backup and 3.1 years and €2010 for diesel backup respectively.

Table 7. Annual environmental pollution reduction from using thermosyphon systems in Cyprus

Emission	Saving
Carbon dioxide (CO_2)	160,835 tons
Carbon monoxide (CO)	130.3 tons
Nitrogen oxides (NO_x)	107.5 tons
Nitrous oxide (N_2O)	864.5 kg
Methane (CH_4)	1605.5 kg
Hydrocarbons	6317.5 kg
Sulphur dioxide (SO_2)	83.6 tons

Additionally, as it was proved in this paper, the energy spent for the manufacture and installation of the solar systems is recouped in about 13 months, which is very satisfactory and, as the average life of the locally produced systems is 20 years, means that for the rest 19 years the system is able to provide pollution free energy. If the total number of systems currently installed and operating in Cyprus is considered then considerable quantities of pollution reduction is experienced. The pollution saved, just for CO_2, because solar energy is used instead of using electricity and diesel to produce the same quantity of hot water is more than 160,000 tons.

It can therefore be concluded that solar energy systems are efficient, cost effective and friendlier to the environment and should be employed whenever possible in order to achieve a sustainable future.

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