SUCCESS STORY OF SOLAR THERMAL WATER HEATERS

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ABSTRACT

One of the most widely used systems for domestic water heating is the solar thermosyphon unit. Such a system consists of two flat-plate collector panels 1.35m^2 in aperture area each and a 150 lt hot water cylinder. No pump is required for this system as the hot water is transferred to storage because of the thermosyphon effect. The system is modeled and simulated with TRNSYS program for Nicosia and the results show that 6,394 MJ of energy can be provided per year and the solar contribution is 0.8. The life cycle savings is C£687 and C£485 for electricity and diesel backup respectively. The pollution created for the production of the system is estimated by calculating the embodied energy invested in the manufacture, assembly and installation of the collectors and other parts of the system. For the present system the embodied energy is found to be 7,260 MJ. By considering the useful energy collected by the system each year, the embodied energy is recouped in about 1.14 years.

1. INTRODUCTION

Energy is considered a prime agent in the generation of wealth and a significant factor in economic development. The importance of energy in economic development is recognised universally and historical data verify that there is a strong relationship between the availability of energy and economic activity. Although at the early seventies, after the oil crisis, the concern was on the cost of energy, during the past two decades the risk and reality of environmental degradation have become more apparent. The growing evidence of environmental problems is due to the increase of the world population, energy consumption and industrial activities. Achieving solutions to environmental problems that humanity faces today requires long-term potential actions for sustainable development. In this respect, renewable energy resources appear to be one of the most efficient and effective solutions.

One of the most widely accepted definitions of sustainable development is: "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*". There are many factors that can help to achieve sustainable development. Today, one of the main factors that must be considered in discussions of sustainable development is energy and one of the most important issues is the requirement for a supply of energy that is fully sustainable [1,2]. A secure supply of energy is a necessary but not a sufficient requirement for development within a society. Such a supply in the long term should be readily available at reasonable cost, be sustainable and be able to be utilized for all the required tasks without causing negative societal impacts. This is why there is a close connection between renewable sources of energy and sustainable development. Today the world daily oil consumption is 76 million barrels. Despite the well known consequences of fossil fuel combustion on the environment, this is expected to increase to 123 million barrels per day by the year 2025 [3].

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Pollution depends on energy consumption. There are a large number of factors which are significant in the determination of the future level of the energy consumption and production. Such factors include population growth, economic performance, consumer tastes and technological developments. Furthermore, governmental policies concerning energy and developments in the world energy markets will certainly play a key role in the future level and pattern of energy production and consumption.

Problems associated with energy supply and use are related not only to global warming, but also to other environmental impacts such as air pollution, acid precipitation, ozone depletion, forest destruction and emission of radioactive substances [4]. Today much evidence exists, which suggests that the future of our planet and of the generations to come will be negatively impacted if humans keep degrading the environment. The three major environmental problems that are internationally known are acid rain, ozone layer depletion and global climate change.

The principal objective of this paper is to present the performance characteristics of thermosyphon units and the environmental protection offered by the systems in terms of the return of embodied energy required for the manufacture and installation of the units.

2. RENEWABLE ENERGY TECHNOLOGIES

Renewable energy technologies produce marketable energy by converting natural phenomena such as sunshine and wind into useful forms of energy. Renewable energy sources have massive energy potential, however, they are generally diffused and not fully accessible, most of them are intermittent, and have distinct regional variabilities. These characteristics give rise to difficult, but solvable, technical and economical challenges. Nowadays, 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.

Several potential solutions to the current environmental problems associated with the harmful pollutant emissions from the burning of fossil fuels have evolved, including renewable energy and energy conservation technologies. Many countries consider today solar, wind and other renewable energy technologies as the key to a clean energy future. A worldwide research and development in the field of renewable energy resources and systems is carried out during the last two decades. Energy conversion systems that are based on renewable energy technologies appeared to be cost effective compared to the projected high cost of oil. Furthermore, renewable energy systems can have a beneficial impact on the environmental, economic, and political issues of the world.

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 [5]. The energy saving benefit derives from the reduction in consumption of the electricity and/or diesel which are used conventionally to provide the energy required for the production of hot water. This benefit can be directly translated into monetary units according to the corresponding production or avoiding capital expenditure for the purchase of imported fossil fuels.

One area which seems to be of considerable importance in many countries is the ability of renewable energy technologies to generate jobs as a means of economic development to a country. The penetration of a new technology leads to the development of new production activities contributing to the production, market distribution and operation of the pertinent equipment. Specifically in the case of solar energy collectors, job creation mainly relates to the construction and installation of the collectors. The latter is a decentralised process since it requires the installation of equipment in every building or every individual consumer.

The most important benefit of renewable energy systems is the decrease of environmental pollution. This is achieved by the reduction of air emissions due to the substitution of electricity and conventional fuels. The most important effects of air pollutants on the human and natural environment are their impact on the public health, agriculture, buildings and ecosystems [5].

3. THERMOSYPHON SOLAR WATER HEATERS

One of the most widely used systems for domestic water heating is the solar thermosyphon unit. Thermosyphon systems heat potable water or heat-transfer fluid and use natural convection to transport it from the collector to storage. The water in the collector expands becoming less dense as the sun heats it and rises through the collector into the top of the storage tank. There it is replaced by the cooler water that has sunk to the bottom of the tank, from which it flows down the collector. Circulation continuous as long as there is sunshine. Since the driving force is only a small density difference larger than normal pipe sizes must be used to minimise pipe friction. Connecting lines must be well insulated to prevent heat losses and sloped to prevent formation of air pockets which would stop circulation. At night, or whenever the collector is cooler than the water in the tank the direction of the thermosyphon flow will reverse, thus cooling the stored water. One way to prevent this is to place the top of the collector well below (about 30cm) the bottom of the storage tank. The usual type of collector employed in thermosyphon units is the flat-plate. Flat plate collectors are usually permanently fixed in position and require no tracking of the sun. The collectors should be oriented directly towards the equator, facing south (northern hemisphere). The optimum tilt angle of the collector is equal to the latitude of the location with angle variations of 10° to 15° more or less depending on the application [6]. The characteristics of the thermosyphon system are shown in Table 1.

Table 1 Characteristics of the thermosyphon system

Parameter	Characteristics of collector
Collector area	2.7 m^2 (2 panels)
Storage tank volume	150 lt
Efficiency mode	n v_s $(T_i - T_a)/G$
G_{test} – flow rate per unit area at test conditions (kg/s-m^2)	0.015
I – intercept efficiency	0.79
S – negative slope of the first-order coefficient of the efficiency (W/m^2 °C)	6.67
b_o – incidence angle modifier constant	0.1
Collector slope angle	40°

Cyprus began manufacturing solar water heaters in the early sixties. Today more than 93% of all houses have solar water heating systems installed and operating most of them of the thermosyphonic type. The total number of systems is equal to 190,000 units. In fact the number of units in operation today corresponds to one heater for every 3.7 people in the island, which is a world record. Therefore for the Cyprus case, it is of interest to know the energy and economic performance and the magnitude of the environmental protection offered by these systems.

4. PERFORMANCE CHARACTERISTICS OF SOLAR WATER HEATER

In order to evaluate its performance characteristics the system is modelled with TRNSYS program [7]. The program consists of many subroutines that model subsystem components. The mathematical models for the subsystem components are given in terms of their ordinary differential or algebraic equations. TRNSYS has the capability of interconnecting system components in any desired manner, solving differential equations and facilitating information output. Thermosyphon systems are modelled with Type 45 in which the collector characteristics shown in Table 1 are required together with various dimensions of the system.

TRNSYS is employing the standard collector performance equation in which the intercept (I) and slope (S) factors, shown in Eq. 1, are used to model the collector.

$$n = K_{\alpha\tau} I - S \frac{\Delta T}{G} \tag{1}$$

where G is the global solar radiation, $k_{\alpha\tau}$ is the incidence angle modifier and ΔT is equal to T_i-T_a, i.e. inlet temperature to the collector minus ambient temperature. For the present work the following model for the incidence angle modifier is used:

$$k_{\alpha\tau} = 1 - b_o \left(\frac{1}{\cos(\theta)} - 1 \right) \tag{2}$$

where b_o is a constant and θ is the angle of incidence. The useful energy extracted from the collectors is given by:

$$Q_u = F_R A \left[k_{\alpha\tau} (\tau\alpha) G - U_L (T_i - T_a) \right] \tag{3}$$

where F_R is the heat removal factor, A is the collector area, $\tau\alpha$ is the tranmsittance-absorptance product and U_L is the collector heat loss coefficient.

The total useful energy for the whole year is obtained from:

$$Q_{u,a} = \sum_{d=1}^{365} \sum_{h=1}^{24} Q_u \tag{4}$$

and the auxiliary energy required, Q_{aux} is:

$$Q_{aux} = Q_{load} - \left[Q_{u,a} - Q_{loss} \right] \tag{5}$$

where Q_{load} is the energy required by the load and Q_{loss} is the energy lost from the storage tank.

As can be seen from the above equations the energy obtained from the solar collector field depends on the inlet temperature to the collector T_i, which depends on the load pattern and the losses from the storage tank.

The systems were simulated with TRNSYS using Typical Meteorological Year (TMY) data for Nicosia, Cyprus. 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. The selection of typical weather conditions for a given location is very crucial in computer simulations for performance predictions and has led various investigators either to run long periods of observational data or to select a particular year, which appears to be typical from several years of data. The TMY for Cyprus was generated 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 [8]. 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 this approach the long-term integrated system performance can be evaluated and the dynamic system's behavior can be obtained.

4.1 Economic Analysis

A life cycle analysis is performed in order to obtain the total cost (or life cycle cost) and the life cycle savings (LCS) of the system. The economic scenario used in this project is that all the initial cost of the solar system is paid at the beginning. The period of economic analysis is taken as 20 years (life of the system). The economic analysis is performed within the TRNSYS environment.

In general, the present worth (or discounted cost) of an investment or cost C at the end of year N, at a discount rate of d and interest rate of i is obtained by:

$$PW_N = \frac{C(1+i)^{N-1}}{(1+d)^N} \tag{6}$$

In the case of this project, the various costs and savings are estimated annually. From the addition of fuel savings incurred because of the use of the system and the tax savings the mortgage, maintenance and parasitic costs are subtracted and thus the annual solar savings of the system are estimated which are converted into present worth values of the system. These are added up to obtain the life cycle savings according to the equation:

$$PW_{LCS} = \sum_{N=1}^{N} \frac{Solar\ \ Savings}{(1+d)^N} \tag{7}$$

The fuel savings are obtained by subtracting the annual cost of the conventional fuel used for the auxiliary energy from the fuel needs of a fuel only system. The integrated cost of the auxiliary energy use for the first year, i.e. solar back up, is given by the formula:

$$C_{aux} = \int_0^t C_{FA} Q_{aux}\, dt \tag{8}$$

The integrated cost of the total load for the first year i.e. cost of conventional fuel without solar, is:

$$C_{load} = \int_0^t C_{FL} Q_{load}\, dt \tag{9}$$

where C_{FA} and C_{FL} are the cost rates for auxiliary energy and conventional fuel respectively. If the same fuels are used for both then $C_{FA} = C_{FL}$. The investment cost of the stationary solar systems is estimated from:

$$C_s = C_f + C_a A \tag{10}$$

where C_f is the fixed cost and C_a is the area dependent cost. For the present work, C_f=C£ 100 and C_a=95 C£/m^2. The maintenance cost is considered to be 1% of the initial investment and are assumed to increase at a rate of 1% per year of the system operation.

4.2 Results

The results show that such a system, with 2.7m^2 of collectors and a 150 lt storage tank, can provide 6,394 MJ of energy per year. The monthly values of the various energy flows, which include the total radiation incident on the collector (Qins), the useful energy supplied to the tank (Qu-tank), the hot water energy requirements (HWload), the auxiliary energy demand (Qaux) and the solar contribution (f-solar) are shown in Table 2. As it can be seen from the column of total radiation incident on collector (Qins), the maximum value occurs in the month of August (1889 MJ). The useful energy supplied to tank (Qu-tank) is maximised in the month of April (610 MJ). Another important point is the reduced incident solar radiation and consequently the useful energy collected during the month of May. This is 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.

Table 2 Energy flow of the thermosyphon solar water heater.

MONTH	Qins	Qu-tank	HWload	Qaux	f-solar
JAN	1197	476	592	280	0.53
FEB	1177	447	535	235	0.56
MAR	1497	556	561	185	0.67
APR	1652	610	498	50	0.90
MAY	1577	547	437	66	0.85
JUN	1701	547	362	1	1.00
JUL	1849	558	343	0	1.00
AUG	1889	548	327	0	1.00
SEP	1691	548	347	1	1.00
OCT	1644	578	452	54	0.88
NOV	1306	516	498	128	0.74
DEC	1135	463	577	272	0.53
SUM	18320	6394	5529	1272	0.80

The solar contribution is also shown in the last column of Table 2. This is defined as:

$$f = \frac{HWload - Qaux}{HWload} \tag{11}$$

For the present system the mean monthly solar contribution is 0.80, i.e., 80% of the needs for hot water for a 4-persons family are satisfied with solar energy. As can be seen from Table 2 the system satisfies 100% the needs for hot water for four months (contribution=1, Qaux=0).

The financial characteristics of the system investigated give positive and very promising figures. By considering a rate for electricity equal to 0.05 C£/kWh, the pay back time is 5.6 years and the life cycle savings, representing the money saved because of the use of the system throughout its life (20 years) instead of using conventional energy (electricity), is C£687. By considering diesel as auxiliary at a rate equal to C£0.415/lt the pay back time is 7.5 years and the life cycle savings are C£485.

5. LIFE CYCLE ANALYSIS

The negative environmental impact of solar energy systems includes land displacement, and possible air and water pollution resulting from manufacturing, normal maintenance operations and demolition of the systems. However, land use is not a problem when collectors are mounted on the roof of a building, maintenance requirement is minimal and pollution caused by demolition is not greater than the pollution caused from demolishing a conventional system of the same capacity. Another advantage of the system is that, when it reaches the end of its life, almost all materials used in the construction of the system can be recycled which minimizes the pollution of the environment. 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 systems. The analysis is based on the primary and intermediate embodied energy of the components and materials as illustrated in Fig. 1. In the present analysis no allowance is made for the unit packing, transportation and maintenance as these have insignificant contribution compared to the total.

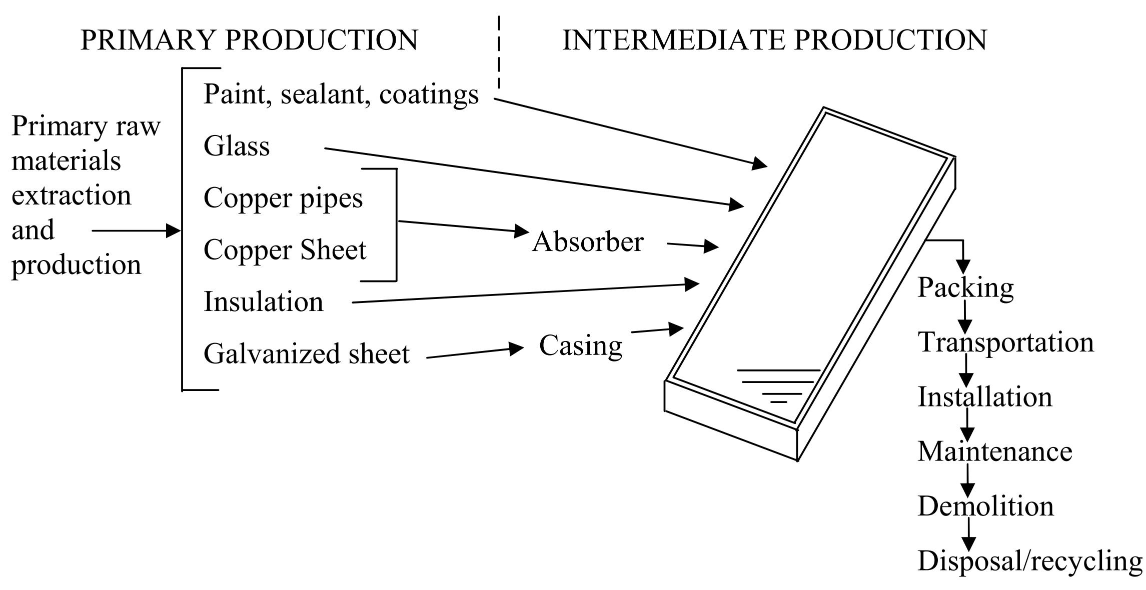

Fig. 1 Factors considered in the calculation of embodied energy of a flat-plate collector

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 3 summarizes the unit materials used and lists their corresponding mass and embodied energy content. As can be seen from Table 3, the total embodied energy content for the production of one flat-plate collector panel is calculated at 2,790 MJ. This comprise the primary embodied energy of materials and the intermediate embodied energy, i.e., the amount of energy used in the production and assembly of the component parts during the construction stage and was determined through a stage-by-stage appraisal of the power sources used. Inherent within this intermediate stage is the fabrication of purchased components like screws, glass and insulation.

An analysis of the embodied energy content of a complete solar hot water system is shown in Table 4. 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 the conventional system. As can be seen the total embodied energy for the complete system is 7,260 MJ.

Table 3 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
2m, 22mm copper pipe	2.4	70.6	169.5
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	55.0
Black paint	0.3	44	13.2
Casing paint	0.9	44	39.6
20 No. screws	0.00125	34.8	Ignored
1.6x0.85x0.003m copper absorber	3.6	70.6	254.2
Total			2,170
Add 10% for contingencies			217
Unit manufacture using a net to gross value of conversion rate of 27%			403
Grant Total			**2,790**

Table 4 Embodied energy content for the construction and installation of the complete solar hot water system

Description	Mass (kg)	Embodied energy index (MJ/kg)	Embodied energy content (MJ)
Solar panels	-	-	5,580
4m, 22mm copper pipe	3.8	70.6	268.3
4m, pipe insulation	1	120	120
Steel frame	30	34.8	1,044
Total			7,012.3
Installation			247.7
Grant Total			**7,260**

The objective of this analysis 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 systems. Therefore, for the life cycle assessment of the system considered the useful energy supplied by solar energy per year (6,394 MJ) is compared with the total embodied energy of the system shown in Table 4. As can be seen the total energy used in the manufacture and installation of the system is recouped in about 1.14 years, which is considered as very satisfactory.

6. CONCLUSIONS

In this paper a description of the general characteristics of thermosyphon units is presented followed by a study on the performance characteristics and environmental protection offered by the systems. A thermosyphon system consists of two flat-plate collector panels 1.35m^2 in aperture area each and a 150 lt hot water cylinder. The thermosyphon system is modeled with TRNSYS and simulated with the weather conditions of Nicosia. The results show that such a system can provide 6,394 MJ of energy per year and the solar contribution is 0.8, i.e., 80% of the needs for hot water are satisfied with solar energy. The financial characteristics of the system investigated give positive and very promising figures. By considering a rate for electricity equal to 0.05 C£/kWh, the pay back time is 5.6 years and the life cycle savings, representing the money saved because of the use of the system throughout its life (20 years) instead of using conventional energy (electricity), is C£687. By considering diesel as auxiliary at a rate equal to C£0.415/lt the pay back time is 7.5 years and the life cycle savings are C£485.

With respect to the life cycle assessment, the pollution created for the production of the system is estimated by calculating the embodied energy invested in the manufacture, assembly and installation of the collectors and other parts of the system. For the present thermosyphon system the embodied energy is found to be equal to 7260 MJ. This is estimated by considering both primary and intermediate production stages. By considering the useful energy collected by the system each year, the embodied energy is recouped in about 1.14 years. It can therefore be concluded that solar energy systems offer significant protection to the environment and cost savings and should be employed whenever possible in order to achieve a sustainable future.

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