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Life cycle costs and environmental life cycle analysis of solar water heaters in Greece

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ABSTRACT

Usually, the solar water heater (SWH) systems use the sun to heat a fluid, either water or a heat transfer fluid, such as water-glycol antifreeze mixture, in flat collectors generally mounted on the roof of residential or industrial buildings. The heated fluid is then stored in a tank similar to a convectional gas or electric water tank. Some systems use an electronic pump to circulate the fluid through collectors. In this paper, the basics of solar water heaters (SWH) life cycle costs analysis are discussed and the most popular types for Greece are examined. Life cycle costs are formed and the possibilities for reducing them are discussed. Specifically, for the cost analysis, a life cycle approach, in which the various costs are estimated annually, is considered. The analysis is performed in order to obtain the total cost (or life cycle cost) and the life cycle savings of the system.

Moreover, the environmental impacts derive from the life cycle of the systems examined are analyzed and assessed with the application of relative software. In order to examine various impact categories such as global warming, ozone layer depletion, ecotoxicity and so forth, the IMPACT2002+ method is applied. In that aspect the life cycle stages, processes and materials that significantly affect the system examined are identified whereas amelioration actions and redesign "hot spots" are further discussed. The fact that both the economical and environmental pillars of sustainability are examined in this study provides a holistic approach regarding different aspects of solar water heaters life cycle. The main aspect that can be concluded is that solar water heater systems are efficient, cost effective and environmental friendly. The reduction of greenhouse gasses is the main advantage of solar energy. Therefore, solar water heater systems should be employed whenever possible in order to achieve a sustainable future.

Keywords : solar water heater, life cycle cost analysis (LCCA), IMPACT 2002+ method, renewable energy, sustainability

1. INTRODUCTION

It is well known today that solar energy is a viable, clean and sustainable source. Also, it is a fact that most of the houses build today choose solar water heaters, especially in countries like Greece. The main reason is that they are easy to install and inexpensive. Also, the research has shown that in an average household with electric water heater spends about 25% of its home energy costs on heating water. It was found that homes using solar water heaters (SWH) can save as much as 50-85% annually on the electricity bills over the cost of an electric water heater. Depending of the fuel sources the solar water heater can be more economically over the lifetime of the system than heating water with electricity, fuel oil, propane or natural gas (American Solar Energy Society, 2010; Federal Energy Management Program, 2010; Duffie et al., 1980). Solar water heaters do not pollute because they avoid carbon dioxide (CO_2), nitrogen oxides (NO_x), sulphur dioxide (SO_2) and other air pollution and wastes. When a solar water heater replaces an electric water heater, the electricity displaced over 20 years represents more than 50 tons of avoided carbon dioxide emissions (Federal Energy Management Program, 2010).

One of the commonest collectors type for water heating (liquid type) is the flat plate collectors type (Figure 1). Flat plate collectors are divided into two main categories, a) liquid collectors and b) air collectors. A flat plate collector is mainly an insulated metal storage tank with either glass or plastic cover, which is called "glazing". The storage tank is well insulated to reduce thermal loses to the environment and is equipped with heat exchangers for heating the water with auxiliary energy. The auxiliary energy 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. The dark colored plate is called the "absorber plate" because it absorbs the sun radiation. The sunlight passes through the glazing and hits the absorber plate. The absorber plate then starts to heat up converting solar radiation into heat energy. The heat then is transferred to liquid passing through flow tubes.

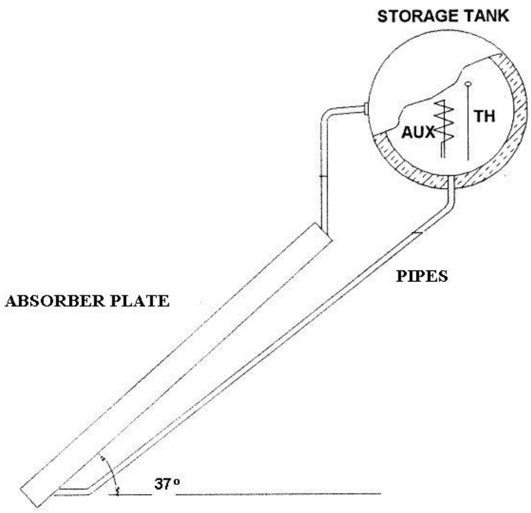

FIGURE 1. Flat plate solar collector type

The unit considered in this paper employs flat-plate collectors. The specifications of the various components of the solar system are shown in Table 1. The size of a solar water heater system depends on the prevailing weather conditions and the hot water requirements. The collector area is determined primarily by the daily hot water demand, which varies from place to place depending on local customs and lifestyles and is normally about 30 to 45 l/person/day. A typical unit operating in an environment like Greece usually consists of two flat-plate solar collectors having an absorber area between 2.5 and 4m^2, and a storage tank with capacity between 150 and 180 l. 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 radiation. Such a system covers about 80% of the hot water requirements of a four-person family. The flat-plate collector is generally fixed permanently in position, and therefore the tilt of the collector is determined primarily by consideration of the predominant season of hot water use. For year-round use, the collector tilt is kept equal to the latitude of the location plus 5^o. In the northern hemisphere, the collector faces direct south (azimuth angle = 0^o). For the considered unit the tilt angle is equal to 37^o (32^o latitude of the location plus 5^o). The storage tank is placed horizontally. An auxiliary pump of 0,75KW is used for helping liquid circulation.

TABLE 1. Specifications of the solar water heater considered

Parameters	Solar water heater
Collector area (m^2)	3 (2 panels)
Collector slope (^{o})	37
Storage capacity (l)	150
Auxiliary heating energy (KW)	3
Auxiliary pump (KW)	0,75
Heat exchanger	Internal
Hot water demand (l)	160 (4 persons)

2. LIFE CYCLE ANALYSIS

2.1 Life cycle cost analysis (LCCA)

Economic analysis plays a vital role in any decision making to purchase a solar water heater system. The homeowner is unlikely to decide buying a solar energy system if he knows that its only benefits are to the environment. During an economic analysis performance variables like solar energy availability, environment conditions, collector tilt angle, hot water usage e.t.a. as well as economic parameters like fuel costs, inflation rate, discount rate e.t.a. must be take into account. For the life cycle cost analysis (LCCA) the various costs are estimated annually. The LCCA is performed in order to obtain the life cycle cost and the life cycle savings (LCS) of the system. A LCCA can be performed either within an executive program (i.e. TRNSYS) or in a spreadsheet program. The current LCCA is based on a spreadsheet program and previous researcher's work (Kalogirou, 1996; Kalogirou, 2009). 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:

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

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:

$$PW_{LCS} = \sum_{N=1}^{N} \frac{SS}{(1+d)^N} \quad (2)$$

where SS=solar savings

The maintenance cost (C_m) is estimated to be 10% of the initial investment and is assumed to increase at a rate of 2% per year of the system operation. The total annual cost is given by:

$$C = C_S + C_m \qquad (€) \quad (3)$$

2.2 Environmental life cycle analysis

In order to holistically examine different aspects of SWH life cycle, the environmental impacts derive from the life cycle of a typical SWH were further analyzed and assessed with the application of relative life cycle assessment (LCA) software (SimaPro 7.1). Moreover, the standard four steps approach that has been developed according to the principles of ISO 14040 standard series was applied for the implementation of the current LCA. A more detailed presentation of this approach can be found elsewhere (EPA, 2006).

The goal of this part of the study is the screening of the environmental impacts that derive from the life cycle of a typical SWH and the identification of the life cycle stages, processes and materials that significantly affect the system under examination in terms of environmental burden (1st Step). According to the aim set, the scope of this work had to include all life cycle stages from raw material acquisition and production to disposal.

The functional unit set was the typical SWH of Table 1 manufactured in North Greece, weighting 175 kg. This solar collector was chosen due to the availability of raw data (materials and processes) regarding its manufacturing. Basic materials comprising the SWH include galvanized steel, copper, glass and PUR foam. Furthermore, it was assumed that the SWH was transported from storage area to the retailer and then to the house covering a total distance of 50 km whereas a small amount of energy was necessary for the installation. According to the manufacturer, the life of the specific SWH is estimated to be 20 years whereas at the end of its life an assumption was made that the SWH is landfilled. Due to software restrictions and unavailability of data, landfilling applying specific technology encountered in Switzerland in 2000 was applied.

In order to perform the inventory analysis (2nd Step), an analytical list of all the components (including their materials/processes and emissions) that were used for creating the model of the SWH to be assessed, was developed (Table 2). LCI is a list of all raw materials, extractions and emissions that occur in the production of the assembly and the materials and processes that are linked to it (Elcock, 2007).

TABLE 2. Life cycle inventory.

Category	Components	Sub-components
Solar Collector	Framework of Solar Collector	Galvanized steel, milling steel
	Coating of absorber plate and pipes	Welding of copper pipes with brass connections (inc: Brass, Rolling brass, welding gas), CuZn30, welding, gas, steel,
	Copper pipes of collector	CuZn30, Sheet rolling, copper
	Solar Glass, low iron	
	Others	X5CrNiMo18(316)I, AlMgSiO.5(6060)I, PVC, PUR rigid foam, PUR flex block foam, Foam Blowing, Welding, gas, steel,
Water Tank	Coating of welded framework	Powder coating, Welding gas, External framework (inc: sheet rolling, galvanized steel), Internal framework (inc: sheet rolling, galvanized steel), Interstice between the frameworks (inc: section bar rolling, galvanized steel), Copper pipes (inc: CuZn30I, sheet rolling)
	External bottom covering	X5CrNiMo18, Sheet rolling
	External upper covering	X5CrNiMo18, Sheet rolling
	Coating of closing profile	X5CrNiMo18, Milling steel, Powder coating
	Side Flange	X5CrNiMo18, Milling steel
	Others	CuZn30, MgMn, Brass, X5CrNiMo18, PUR rigid foam, Foam blowing
Support	Bars of support	Section bar rolling, galvanized steel
Installation	Transport of SWH to storage-shop-house	50km, Transport van <3,5t
	Installation from worker	Electricity use 0.05 kWh
Landfill		

3. RESULTS AND DISCUSSION

3.1 Environmental life cycle analysis

In the LCCA used in this work assumed that all the cost of the solar water heater system is paid from the beginning. The thermal performance degradation of the system is assumed to be 1% per year and the period of economic analysis is taken as 20 years. Electricity at a price of 0,140 €/kWh is assumed to be used for auxiliary. Table 3 gives a summary of the calculated economic parameters.

TABLE 3. Results of the LCC analysis

Parameter	Auxiliary energy (Electricity)
Initial cost of the system (€)	500
Resale or salvage value (€)	80
Rate of return of solar investment (%)	71,2
Payback period (y)	Almost 1
Present worth of total costs with solar (€)	1176
Present worth of total costs without solar (€)	4636
Present worth of cumulative cash flow (€)	18764
Fuel price considered in the analysis (€/kWh)	0.140

The results of the LCC analysis of Table 3 were obtained by using the current electricity rates, a 20-year period, a market discount rate of 6% and interest rate of 8%. The operation of the auxiliary pump of 0,75 KW power multiplying by the operation hours (4300) and by the price of electricity (0,140€/KWh) was the only parasitic cost (subsidies) was considered. As can be seen the solar system gives much lower specific energy cost than the conventional electric water heater. The payback period is very low and is equal almost to one year for electricity backup. The life cycle savings represent the money that the owner will save by installing the solar system instead of buying electricity to satisfy his hot water needs and is equal to 18764 € for electricity backup.

3.2 Environmental Analysis

Results indicated that the manufacturing of the solar collector and the water tank were the two key factors significantly affecting the environmental burden derive from the SWH life cycle. A fully detailed tree of the model that was developed in software to assess the system under examination is presented in Figure 2.

In a nutshell, every node in this tree consists of a number of materials and processes comprising the system examined. The lines between the nodes express their interconnection. The width of the lines represents their environmental burden (either expressed as a percentage or as a "thermometer" bar on the right) according to the impact assessment method applied. Wider lines indicate significant environmental impact. Moreover, not all the nodes are visible. The evaluation is based on the choice of the impact assessment method and can indicate either aggregated results (all impact categories normalized and weighted into a single score) or single impact category results. For the specific Figures the IMPACT 2002+ method single score was applied in order to provide a quick overview of the tree function. As it can be observed, environmental burden derive from landfilling the SWH (1.05%) is overwhelmed by its production and assembly (98.9%) thus this life cycle stage was decided to be further examined.

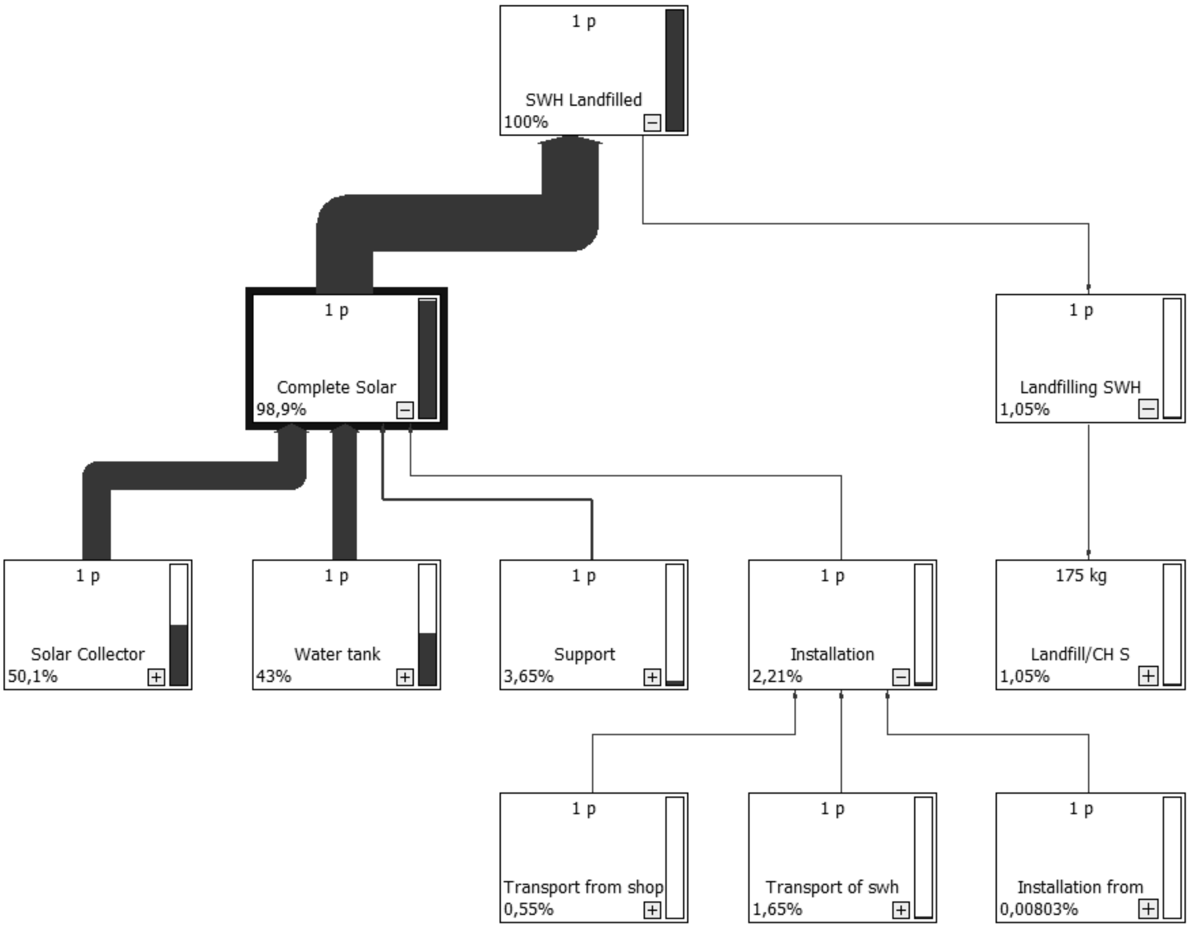

FIGURE 2. Tree developed in software using the Impact 2002+ method.

In order to examine the benefits derive from the use of the specific SWH, the environmental burden derive from its life cycle (including land filling) was compared with the environmental burden derive from the energy that would be required if an electrical water heater was used instead. For that reason it was estimated that a family consuming 160lt of hot water every day for twenty year needs 67,000 kWh (Eleftheriadis, 2009). The specific amount was assumed to be taken from the energy mix of Greece (at grid) with the application of the relative module found in the software. The final comparison is presented in Table 4 indicating the environmental friendliness of SWH. According to this table the application of SWH instead of electrical ones could lead to a reduction over 80% to most impact categories. The only exception was the impact category mineral extraction, further confirming the notion that the application of eco-friendly and renewable materials should be promoted. It should be noted however that these were based on rough estimations thus the assumptions applied during this work should be highly identified and taken into consideration.

TABLE 4. Impact 2002+ V2.06 Comparison.

Impact category	Unit	Electricity for 20 years	SWH including landfill	Reduction (%)
Carcinogens	kg C2H3CL eq	103	14.5	86
Non-carcinogens	kg C2H3CL eq	179	36.9	79
Respiratory inorganics	kg PM2.5 eq	72.3	1.3	98
Ionizing radiation	Bq C-14 eq	3.15E5	7.08E3	98
Ozone layer depletion	kg CFC-11 eq	0.002	8.25E-5	95
Respiratory organics	kg C2H4 eq	3.86	0.552	85
Aquatic ecotoxicity	kg TEG water	7.55E5	1.81E5	76
Terrestrial ecotoxicity	kg TEG soil	2.91E5	3.24E4	88
Terrestrial acid/nutri	kg SO2 eq	754	22.3	97
Land occupation	m2org.arable	23.7	10.2	57
Aquatic acidification	kg SO2 eq	394	13.6	96
Aquatic eutrophication	kg PO4 P-lim	58.3	0.139	99
Global warming	kg CO2 eq	6.62E4	639	99
Non-renewable energy	MJ primary	1.05E6	9.21E3	99
Mineral extraction	MJ surplus	64.7	474	-86

4. CONCLUSIONS

In the present paper, the benefits that a solar system offers are discussed in detail. From the analysis presented in this work it can be concluded that the environmental footprint of any energy system is an important factor and solar systems have the potential to reduce environmental pollution. Additionally, in this study the environmental protection offered by the most widely used renewable energy system, i.e., the solar water heating system is presented. The results show that by using solar energy considerable amounts of greenhouse polluting gasses are saved. For the domestic solar heating system considered here, with electricity backup the saving, compared to a conventional system, is about 70%. Additionally, the system investigated give positive and very promising performance and financial characteristics. The annual solar contribution is 80% whereas the payback time of the system is one year and the life cycle savings are 18764 € for electricity backup. The reduction of greenhouse gasses pollution is the main advantage of utilizing solar energy. Therefore, solar energy systems should be employed whenever possible in order to achieve a sustainable future.

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