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Life cycle environmental impact assessment of a solar water heater

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A B S T R A C T

The technical and environmental performance of a solar water heater (SWH) is examined using the method of life cycle assessment (LCA). The present LCA study quantifies the environmental benefits of the installation of a SWH with electricity as auxiliary for domestic use in the city of Thessaloniki. Solar thermal heating produces no emissions during operation but some small levels of emissions are produced during the manufacture and installation of components and systems. This work examines the manufacturing stages of the SWH and records resource consumption and waste streams to the environment. The system boundary includes the production of raw materials such as steel, glass, copper, aluminium, glass fibber and polyurethane insulators, the manufacturing of the various parts of the SWH such as the solar collector and the heat storage tank, and finally the assembly process. The functional unit chosen is 1 MW of produced hot water. The environmental impacts taken into consideration in the study, are the greenhouse effect, ozone depletion, acidification, eutrophication, heavy metals, carcinogens, winter smog and summer smog. The system can provide 1702 kWh year^{-1} and the solar contribution is 58.5%. The financial characteristics of the system investigated give life cycle savings equal to 4280.0 € and pay-back time equal to 5 years.

1. Introduction

Energy use in the European domestic and tertiary sectors represents about 40% of the annual EU-15 total energy use, and about a third of greenhouse gas emissions. Among these about two-thirds are concentrated in residential sector, and the remaining part in the commercial buildings. The household sector represents about 70% of total energy use in the building sector (EU Commission, 2004). The biggest part of this energy is used for water heating and space heating. One viable solution to reduce this amount of energy coming from conventional energy sources is to employ solar energy. Solar energy is a sustainable energy supply technology due to the renewable nature of solar radiation and the ability of solar energy conversion systems to generate greenhouse gas-free heat and electricity during their life time. The utilization of "zero emission" technologies plays a significant role in the reduction of hydrocarbons use and the reduction of CO_2 emissions.

The continuous increase of the cost of energy, associated with the subsidies attached to renewable energy sources use, in many countries, has made it possible for a significant solar thermal sector growth. In particular, with a 2.1 million square meters (m^2) of newly installed capacity, the German domestic market increased its share of the European market (EU27 + Switzerland) to 44% in 2008. Spain, Italy and France share over-passed Greece, which was in second position in 2007. The previously mentioned countries, currently account for 84% of Europe's solar thermal market (European Solar Thermal Industry Federation (ESTIF), May 2009). It should be noted that the installed solar collector area per capita in Greece was the highest in Europe for a number of years, reaching an average of 0.264 m^2 per capita, tenfold higher the EU's average (European Solar Thermal Industry Federation (ESTIF)). However, due to the economic recession, new installations continued to decline in some key European markets, including Austria, Germany, and France. The Greek and Italian markets increased slightly, while Spain's market held constant in 2010 after increasing about 21% the previous year. Total EU additions in 2010 came to 2.6 GWth, down 10% relative to 2009 and nearly 19% below the 2008 market, bringing existing capacity to 25.1 GWt (REN 21 and Renewables, 2011).

Despite the fact that solar energy is considered as the cleanest energy source available, important interactions with the environment are taking place over the whole lifecycle of a SWH system

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(materials, manufacturing, transportation, utilization and final disposal). These interactions may result to depletion of natural sources, greenhouse effect, acidification, eutrophication etc.

A technique that can be used in order to assess the environmental impacts of a SWH over its whole lifecycle, is Life Cycle Assessment. LCA is a recently developed and a continuously improving methodology which has a main goal to contribute towards a sound environmental management (Koroneos et al., 1999).

LCA is a method that provides a picture as complete as possible about the impacts related to the whole life cycle of a product: from the extraction of the raw materials to the final disposal (Fig. 1). With the use of LCA, the required energy and raw materials that are consumed, as well as solid, gaseous and liquid wastes that are produced at every stage of the life cycle of a product, can be quantitatively defined. At the same time, an initial estimation of the environmental impacts that result from the production, use and disposal of this product, as well as of impacts that are related to raw materials and energy provision needed for the product, can be quantified. Additionally, possible measurements that should be taken into consideration with the objective to reduce the environmental impact can be laid out. Thus, LCA is a tool that can play a significant role in decision – making with regards to the environmental protection.

In this study emphasis is given to the environmental impact associated with the production and utilization of solar energy systems and in particular to the atmospheric emissions of a solar water heating system during its life span. The biggest environmental impact occurs during the production stage of the SWH systems followed by the use phase. The end of life cycle of the system is not taken into consideration since there are no data available in the market on whether parts of the SWH are recycled. In literature there are numerous studies on the environmental life cycle analysis of thermal systems. Some of them deal with solar water heating systems (Mirasgedis et al., 1996; Tsillingrides et al., 2004; Ardente et al., 2005). In this work, the LCA methodology has been applied to the SWH system under study, as it constitutes an industrial product made up of many parts with the use of many different materials which account for different environmental impacts. A large database and a wide variety of data concerning the LCA of different materials is used. The results obtained give a very good picture of the releases of solid and liquid wastes and the emissions to the atmosphere during the life cycle of a solar water heater system. The results also relate these releases to the environment with their environmental impacts. These results can play a significant role since they can help industries to estimate the environmental performance of a product or a process and thus find alternatives that have less or no impacts to the environment.

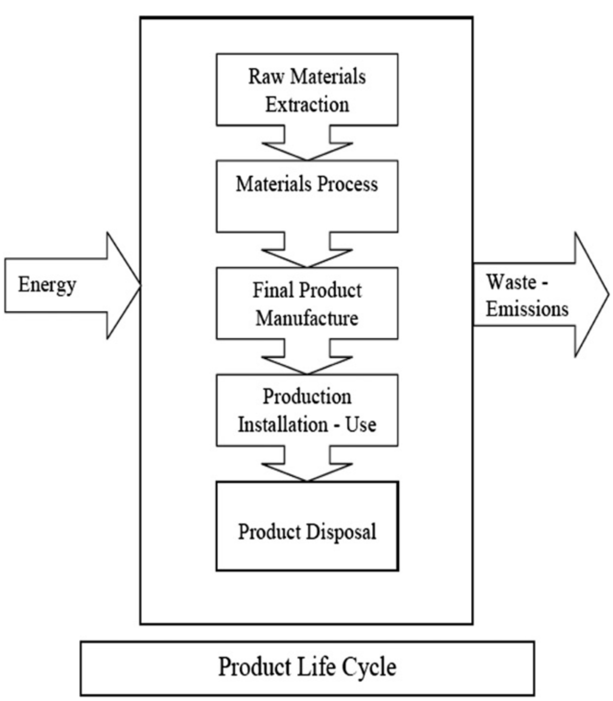

Fig. 1. Life cycle of a product (Koroneos et al., 1999).

2. Methodological approach

LCA originates from "net energy analysis" studies, first published in the 70s (Boustead, 1972; Hannon, 1972; Sundstrom, 1973). These studies took into consideration only energy use over the lifecycle of a product or a process. Later studies included wastes and emissions (Lundolm and Sundstrom, 1985; Boustead, 1989); nevertheless none of them went further than the quantification of materials and energy use. As a result the Society of Environmental Toxicology and Chemistry and the International Organization for Standardization (ISO 14040, 1997; ISO 14041, 1998; ISO 14042, 2000a; ISO 14043, 2000b) developed in the 1990s a complete LCA methodology. In 2006, standard ISO 14040 was revised (ISO 14040, 2006a, b) and a new standard ISO 14044 (ISO 14044, 2006a, b) was presented. Formal changes include the reduced number of standards, the reduced number of annexes and the reduced number of pages that contain requirements. All these changes are intended to increase the readability and accessibility of the standards. The two new standards, ISO 14040 and ISO 14044, reconfirm the validity of the main technical content of the previous standards. Errors and inconsistencies were removed and the readability was improved (Finkbeiner et al., 2006). Further details on the current state-of-the-art LCA methodology can be found for example on the publications pages of the European Platform of Life Cycle Assessment or the UNEP/SETAC Life Cycle Initiative (UNEP/SETAC, 2010; European Platform, 2010).

The methodological approach that this study is following falls under the international standards series ISO 14040. It is made up of four steps:

- Goal definition and scoping
- Inventory analysis
- Impact assessment
- Interpretation

Three stages follow the definition of the goal and scope:

- Life Cycle Inventory (LCI); Quantification of energy and raw materials input and product, liquid, solid and gaseous wastes output of the product's life cycle (wastes include releases to air, soil and waters).
- Life Cycle Impact Assessment (LCIA); Evaluation of the environmental impacts based on the data of LCI stage.
- Improvement Assessment; Assessment of possibilities and possible solutions that exist regarding the environmental impacts of a product's life cycle. This assessment could include quantitative and qualitative prevention measures such as changes in production design, materials and energy use, waste management, etc.

The analysis included in this study is based on the Gemis (GEMIS software, May 2007) software tool, which depends on the incorporated database of Eco-Indicator 99 (Goedkoop et al., 2000) covering a variety of manufacturing procedures and impacts. GEMIS (Global Emission Model for Integrated Systems) is a life-cycle analysis program and database, developed as a tool for the comparative assessment of environmental effects of energy by Öko-Institut and Gesamthochschule Kassel (GhK). As the database offers information on fuel data, processes, materials and transport, it was used for the performance of the LCA.

3. Solar water heating system specification

Solar water heating 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 so called thermosyphon principle. They supply hot water at a temperature of about 60 °C and consist of a collector, storage tank and connecting pipes (Fig. 2).

The majority of SWH systems in Greece are manufactured close to Athens in Central Greece and in Thessaloniki, Northern Greece. For the purposes of the study the SWH system is assumed to be manufactured in Thessaloniki. Data regarding the location of the SWH system under study, include the longitude (40, 64), latitude (22, 95), altitude (30 m), annual solar radiation, annual average air temperature (16 °C) as well as the annual average grid water temperature (15, 6 °C). The meteorological data were taken from literature (Pelekanos, 1982) and are analytically presented in Table 1.

The SWH system is the flat plate collector type, which is the typical solar system used in Greece for water heating purposes (Pafilias, 1993). The collector consists of copper tubes extended with copper foils and in order to boost absorbency, sprayed with black solar powder. A layer of expanded polyurethane is sprayed at the back of the collector for insulation. The sides of the collector are insulated with rock wool. The back cover of the collector is galvanized steel, while the sides consist of aluminium. The front area of the collector is covered with a single solar glass. The boiler consists of a stainless steel mantle heat exchanger, with stainless steel sheet casing. A high density expanded polyurethane layer between boiler and casing is used for thermal insulation. The storage tank is well insulated to reduce thermal losses 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; nevertheless in this study the auxiliary is electricity. The basic components of a SWH system (Kreith and Kreider, 1978) are presented in the schematic diagram of Fig. 3. The household considered is of four person's family; whereas the technical characteristics of the SWH system under study are summarized in Table 2. The calculation and the data used for the Life Cycle Environmental Assessment (LCEA) of the SWH system under study are listed in Table 3. The values used correspond well to the literature (Handbook App, 2003). Using the f-chart method, the annual percentage of solar coverage of load for domestic hot water production as well as the annual total and covered load are calculated (Duffie and Beckman, 1991). The purpose of the method is to calculate *f*, the fraction of the hot water load that is provided by the solar heating system (*solar fraction*). The method enables the calculation of the monthly amount of energy delivered by hot water systems with storage, given monthly values of incident solar radiation, ambient temperature and load. Based on the annual solar coverage, (*f*) is estimated to be 0.585, whereas the annual total load is calculated to be 2909.0 kWh year^{-1}, and the annual covered load is equal to 1702.0 kWh year^{-1}.

Table 1
Thessaloniki's meteorological data (monthly mean values) (Goedkoop et al., 2000).

Month	H_{45} [kWh/m^2]	T_a [°C]	T_w [°C]
January	82	5.5	8.2
February	92	7.0	7.9
March	113	9.9	9.2
April	135	14.6	12.8
May	152	19.7	16.8
June	153	24.1	20.2
July	172	26.7	21.5
August	169	26.3	22.8
September	149	22.2	22.1
October	120	16.7	19.4
November	90	11.9	15.7
December	78	7.4	11.0
Annual	125	16.0	15.6

H_{45}: annual solar radiation, T_a: annual average air temperature, T_w: annual average grid water temperature.

4. Environmental impact assessment

Based on the technical characteristics of the system described above, the procedures presented in Fig. 4 are quantified and the environmental impacts based on the EcoIndicator 95 database (Goedkoop et al., 2000) are estimated. The functional unit of the system is taken as 1 MW of produced hot water. The functional unit

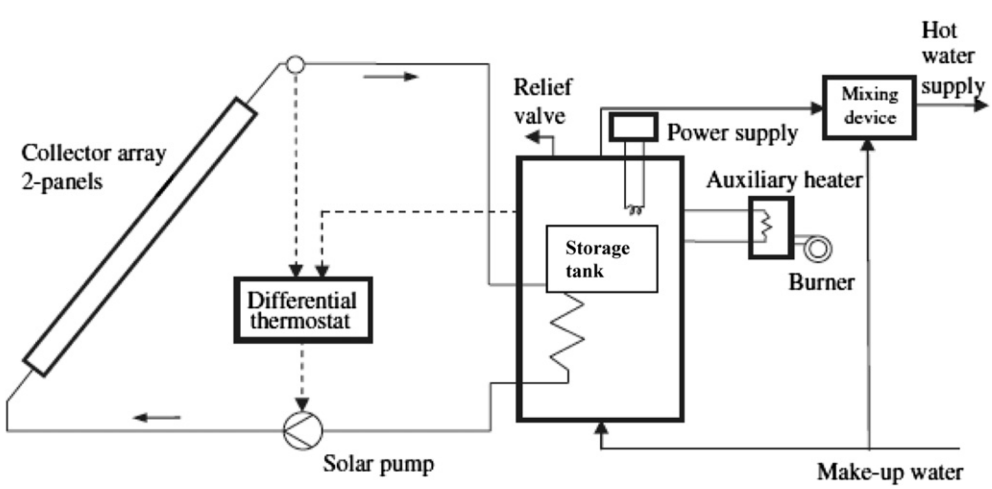

Fig. 2. Solar water heating (SWH) system.

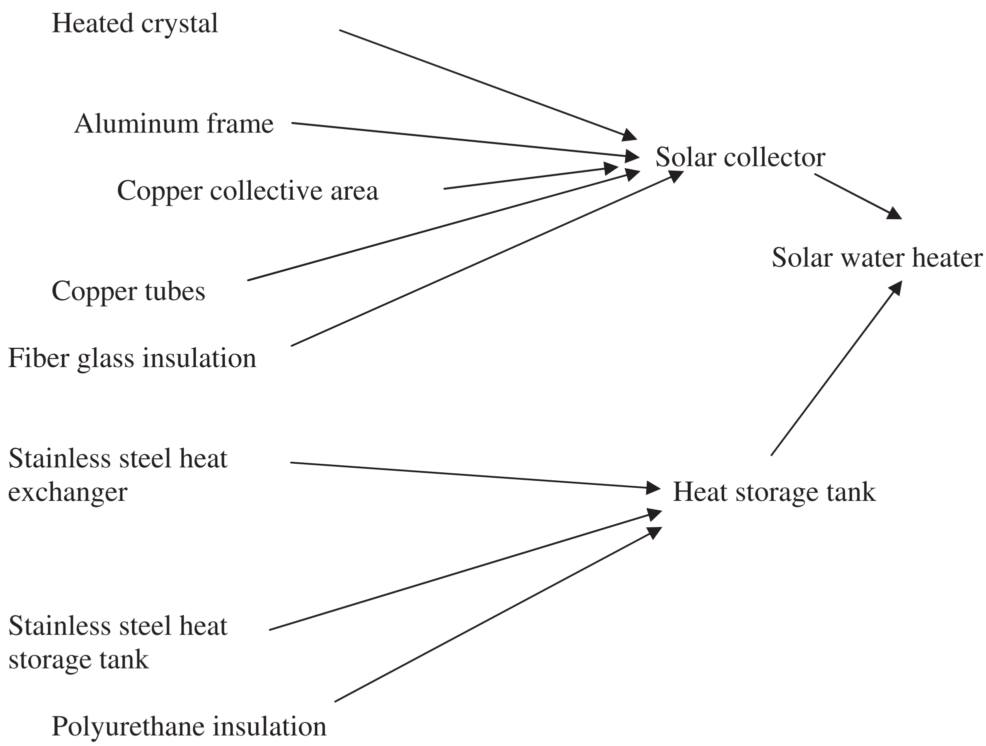

Fig. 3. Components of a solar water heater.

is a measure of the function of the studied system and it provides a reference to which the inputs and outputs can be related. In addition, the functional unit is related to the function that the SWH will deliver. In this context, the functional unit chosen is 1 MW of solar heat used for the production of hot water. The amount of hot water produced depends on the monthly solar radiation and the grid water temperature (See Table 1).

The performance of the Life Cycle Inventory (LCI) resulted in the calculation of the liquid and solid waste streams and the emissions to the environment. The LCI took into consideration all the stages of the life cycle of the system, from material extraction to the end of life of the SWH. The waste streams and emissions are listed in Table 4a–d. Examining these data conclusions can be extracted concerning their environmental impacts. Furthermore, the calculation of total environmental impact took into consideration the impact from the collector, the boiler, the aperture as well as from the transportation to the installation site. Since the SWH system is produced in Thessaloniki and is installed in a radius of 20–50 km from the manufacturing plant, its impact is considered negligible.

Table 2
Specifications of the understudy SWH system.

Collector type	Flat-plate, Copper tube with copper foils
Glazing	Single glass
Selective Paint	Black solar powder
$F_R\ U_L$	8.42 Wm^{-2} K
$F_R(\tau\alpha)_n$	0.77
Collector inclination	45°
Length/Width ratio	2.05 cm
Tank capacity	200 lt
Hot water temperature	60 °C
Hot water demand/ Day	200 lt (4 persons)
Collector Area	4 m^2

F_R: collector heat removal factor, U_L: heat loss coefficient, n: collector efficiency, τ: transmission coefficient of glazing, α: absorption coefficient of plate.

Based on the methodology of LCA, the stages of normalization and valuation follow. The emissions are being converted with the use of weighting factors (normalization and valuation factors) to scores that can easily be aggregated and compared based on their contribution to various environmental impacts. Each type of waste has a different impact contribution on the environment. The equation used is:

$$\text{Total Assesment} = \sum i(\text{Total Emission} \times \text{Normalization factor } i \times \text{Characterization factor } i) \quad (1)$$

Total emissions refer to the equivalent emissions. Table 5 presents the quantitative effect of these emissions on the environment. It should be noted that the global environmental impacts after weighting need to be interpreted with caution.

The environmental impacts analysed include the categories of global warming, acidification, eutrophication (air), eutrophication (water), heavy metals, cancerogenic effects, winter smog and summer smog. The impacts are normalized and evaluated based on weighting factors. From the impact assessment, it is obvious that the acidification effect has the largest contribution to the total environmental score impact (Fig. 5). The environmental impacts of

Table 3
Quantities of materials used in SWH production.

Material	Quantity kg	Quantity kg/$MW_{Hot\ water}$
Heated glass	12	41.3 × 10^3
Copper	5.3	18.2 × 10^3
Aluminium	11	37.8 × 10^3
Steel	40	137 × 10^3
Polyurethane	7	24.1 × 10^3
Fiber glass	5	17.2
Plastic insulator EPDM	2	6.9 × 10^3

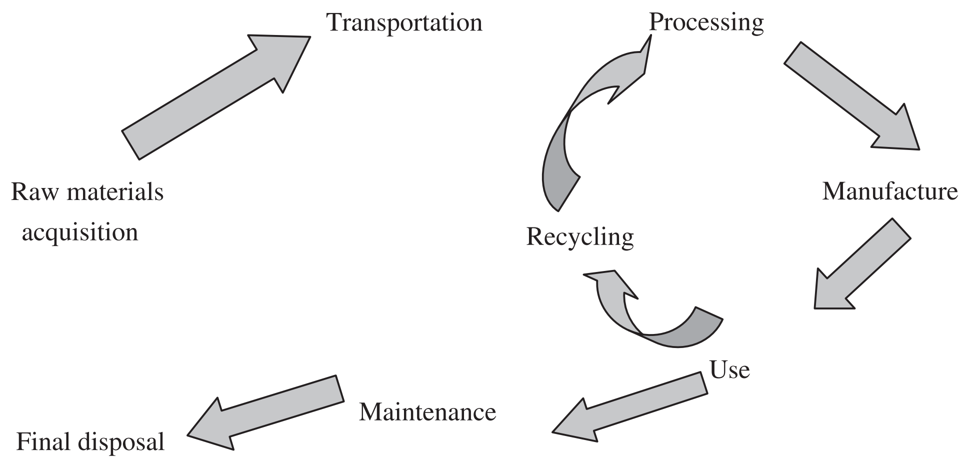

Fig. 4. Life cycle of a SWH system.

Table 4
a: Greenhouse gases emissions. b: Emissions of liquid wastes. c: Emissions of solid wastes. d: Emissions of gaseous wastes.

Greenhouse gases emissions [kg]			
CO_2	12638.22		
CH_4	37.08		
N_2O	0.36		
Perfluromethane	0.11		
Perfluroethane	0.01		
Emissions of liquid wastes [kg]			
N	2.52×10^{-6}		
AOX	8.46×10^{-6}		
COD	39.28		
BOD5	1.21		
Inorganic salts	65.84		
Emissions of solid wastes [kg]			
Ash	478.92		
Solid residues FGD	32.09		
Scrap/Sludge	0.70		
Production residues	8949.11		
Scrap materials	25888.96		
Emissions of gaseous wastes [kg]			
TOPP	123.64	CO	72.50
SO_2	96.51	NMVOC	2.57
NO_x	33.30	H_2S	9.26×10^{-6}
HCl	2.49	NH_3	0.18
HF	0.067	As	9.57×10^{-5}
Particles	20.14	Cd	5.35×10^{-5}
Cr	0.00039	Ni	0.00037
Hg	0.00012	Pb	0.0024

the four major parts of solar water heater, as they result from LCA, are shown in Fig. 6. It is evident that the major contribution comes from the storage tank, accounting for 58% of the total environmental impact. The solar collector accounts for 25% whereas the aperture and component box have the smallest impact 10% and 7% respectively.

5. Economic assessment

In the investigation of the economic benefits of utilizing solar energy instead of conventional source of energy, it is mandatory to take into consideration the all the economic parameters of such an investment. It is assumed that the cost of the solar water heater is paid at the beginning. The life span of the solar water heater is taken to be 20 years and the thermal performance degradation of the system is assumed to be 1% per year. Electricity at a price of 0.08 €/kWh is used for auxiliary tank system with a discount rate of 6% and interest rate of 8%. No subsidies were considered. It is considered that electricity prices are increased by 3.5% every year. The initial cost of the solar water heater with electricity backup is 1475.0 Euros (€), including the installation and transportation cost. The maintenance cost is considered to be 5% of the initial investment.

The techno-economic model used for the evaluation of the technical and financial viability of such an investment is based on the advanced mathematical model of RETscreen v.4.1 (Manual RETscreen). The RETScreen Software can be used worldwide to evaluate the energy production and energy savings, energy costs, and emission reductions. It can also be used to analyse the financial viability and risk for solar water heating projects, ranging in size from solar collectors for small-scale domestic hot water

Table 5
Calculation of total emissions released to the environment.

	Normalization factors	Characterization factors	Total emissions	Total assessment
Global Warming potential	0.0000742	2.5	13144.34	2.44
Ozone Layer Depletion	1.24	100	0	0
Acidification	0.00888	10	123.42	10.96
Eutrophication (air)	0.0262	5	4.39	0.57
Eutrophication (water)	0.0262	5	0.060	0.00788112
Heavy metals	17.8	5	0.00936	0.83
Cancerogenic	106	10	0.00017587	0.19
Winter Smog	0.0106	5	96.51	5.11
Summer Smog	0.0507	2.5	1.33	0.17
Total				20.28

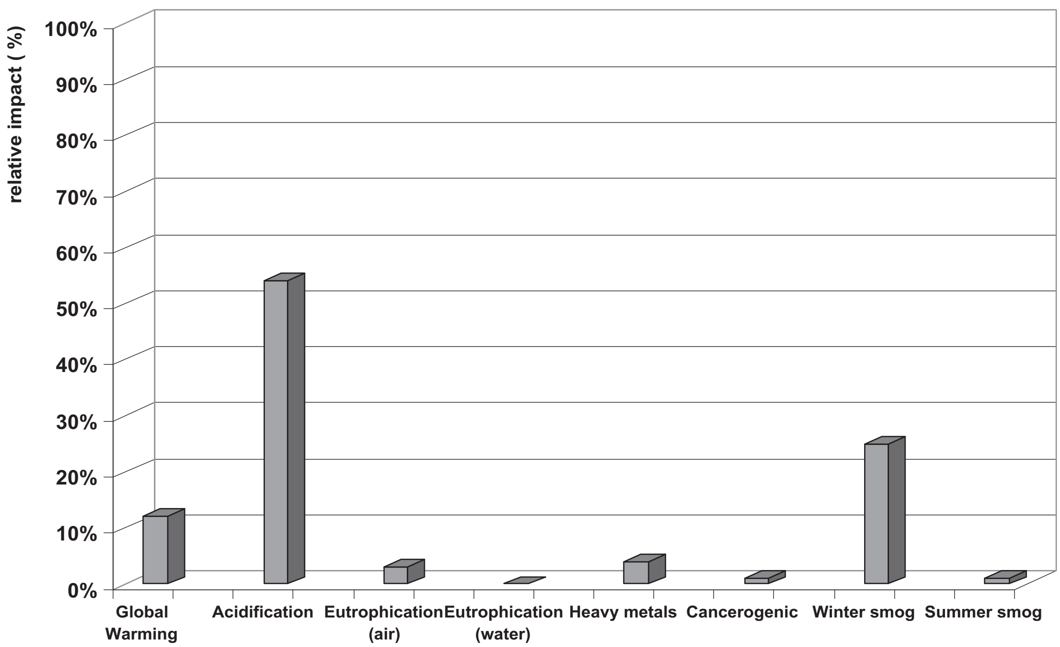

Fig. 5. Environmental impact assessment of each category during SWH life span.

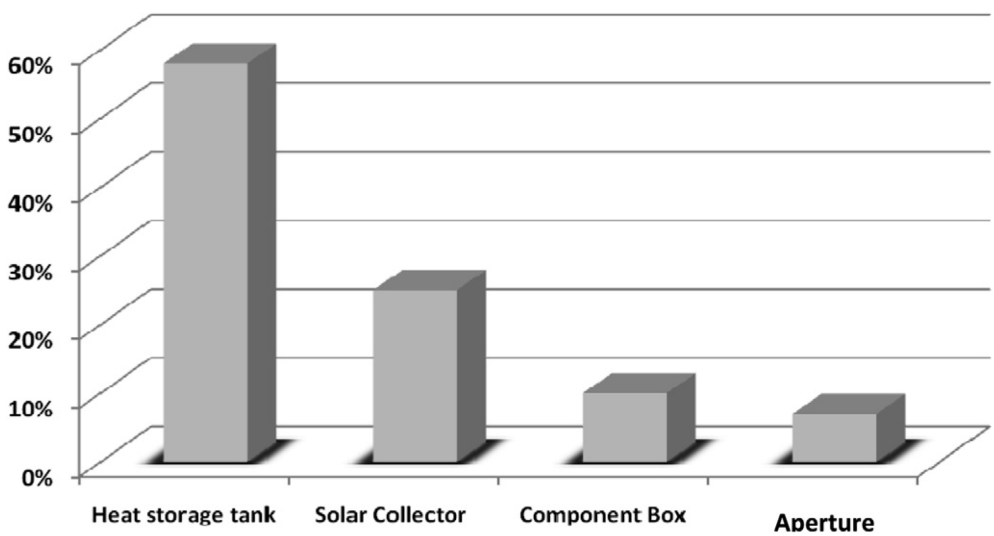

Fig. 6. Participation to the environmental impact of each part of the under study SWH system.

applications, for indoor and outdoor swimming pools for residential, commercial and institutional buildings, and for large-scale industrial processes and aquaculture applications, to improved water heating system designs including solar collectors installation, hot water temperature and use reduction, and improved pipe insulation. The software contains a database of typical daily hot water use for loads such as houses, apartments, hotels and motels, hospitals, offices, restaurants, schools, laundry rooms and car washes. The software (available in multiple languages) also includes product, project and climate databases, and a detailed user manual. The electricity price and the cost analysis is based on the data provided by RETscreen. It is noted that the RETscreen's energy model is in accordance with the energy model calculated by the *f*-chart method.

The cost analysis performed takes into account the initial costs and annual costs of the solar water heater. The financial terms which were used in the economic assessment include: *Internal Rate-of-Return* (IRR), *Net Present Value* (NPV) as well as the *Pay-Back Period* (PBP). The IRR represents the true interest yield provided by the project over its life. It is also referred to as the return-on-investment (ROI) or the time-adjusted rate-of-return. It is

Table 6
Economic assessment of the understudy solar water heater.

Economic parameter	
After TAX IRR- ROI (%)	21.8
Payback period time (yrs)	4.9
Positive cash flow (yrs)	4.6
Net present value (€)	2103
Annual life cycle savings (€)	214
Benefit − cost ratio	2.43

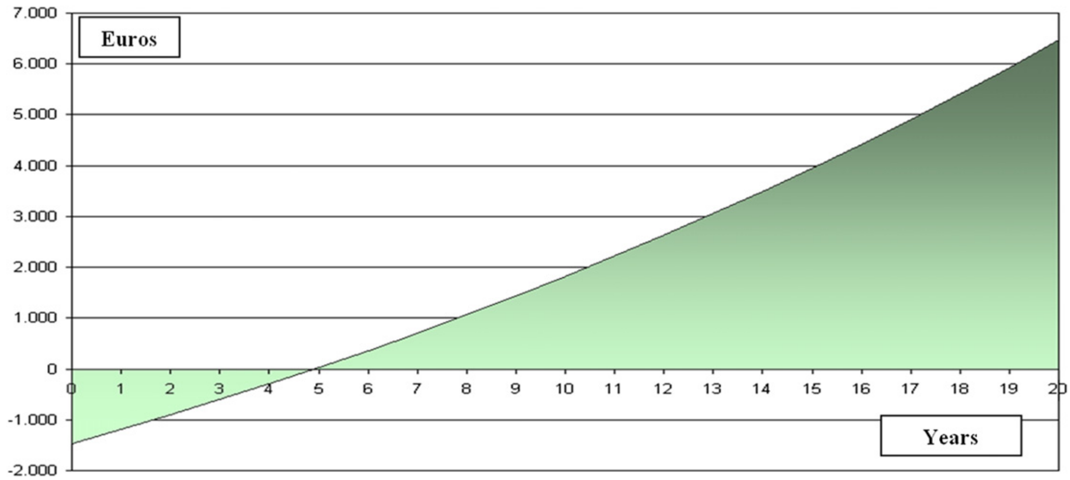

Fig. 7. Cumulative cash flows for the understudy solar water heater.

calculated by finding the discount rate that causes the net present value of the project to be equal to zero. Under the NPV method, the present value of all cash inflows is compared against the present value of all cash outflows associated with the investment project. The difference between the present values of these cash flows, called the NPV, determines whether or not the project is generally an acceptable investment. The PBP represents the length of time that it takes for an investment project to get back its own initial cost, out of the cash receipts it generates. In general the *NPV* of an investment is calculated by the following equation:

$$\mathrm{NPV} = \sum_{j=1}^{n}\left[F_j/(1+i)^j\right] - I_0 \tag{2}$$

where:

F_j is the annual cash flow of the investment, i is the interest, I_0 is the initial investment and n is the life time of the investment. The results of the economic assessment are presented in Table 6. The payback time for the SWH is equal to approximately 5 years (Fig. 7). Life cycle savings represent the amount of money that the owner will save by installing the solar water system to satisfy the hot water needs. This was calculated to be equal to 4280.0 €.

6. Conclusions

The abundance of solar radiation together with a good technological base, creates favourable conditions for the exploitation of solar energy in Greece. The dependency of economies on fossil fuels necessitates the use of renewable energy systems with the employment of a variety of technologies. Renewable energy sources could provide a solution to the problem, as they are inexhaustible and have less adverse impacts on the environment than fossil fuels. Especially solar energy systems offer significant environmental protection. Nevertheless as it has been shown from previous studies (Koroneos et al., 2003; Koroneos and Koroneos, 2007) renewable energy technology system has not reached a high standard at which it can be considered competitive to fossil fuels. In the present study the environmental impacts followed by a study on the economic performance of such a system has been investigated. The solar water heater system, sui for the city of Thessaloniki, located in Northern Greece consists of a flat plate collector panel 4 m^2 and a 200 lt. hot water cylinder.

The emissions released to the environment during the life cycle of the SWH system are investigated with the use of the Eco-Indicator 99 method. The main environmental impact of the system under study is acidification with a percentage reaching up to 54%. Pollutants of this type are composed mainly of sulphur (S); thus their formation and emissions can be attributed to combustion processes. The second highest environmental effect is the winter smog potential with a value reaching 25%. The formation of this environmental effect derives mainly from solid particles releases; it should be noted that they can also be attributed to combustion processes. For instance, the combustion of lignite for the production of electric energy can be associated with winter smog. The contribution to the global warming potential due to CO_2 is also present, although in lower percentage (12%). The contribution to other environmental effects is of lower values (9%).

The financial characteristics of the solar water heating system investigated results in savings equal to 4280.0 € over its life time with a payback period equal to 5 years. These characteristics can motivate people to buy a solar water heating system since they have a short payback period (4–6 years), they can be easily installed in either flat or slope roof, they have low acquisition cost, low maintenance cost (approximately 1–4% of the investment cost) as well as positive net present value. Furthermore, they can improve the quality of life (availability of hot water).

These results can be very useful in decision-making by providing a quantification basis for assessing potential improvements in environmental performance of an energy system throughout its life cycle. In addition a sound environmental policy from the industries perspective, should aim to reduce waste releases as much as possible throughout all the stages of the production chain. As far as low carbon buildings are concerned, emphasis should be given to the development of green hotels, especially in the Greek islands, which have favourable climatic conditions, so as to promote energy conservation and environmental protection. Hospitals and schools are some other sectors of the economy that can adopt solar energy for water heating. With the implementation of the directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on energy performance of buildings (known as directive EPBD) (Directive, 2002/91) in Europe, the need for a sustainable heating system in buildings is of great significance.

References

Ardente, F., Baccali, G., Cellura, M., Lo Brano, V., 2005. Life solar assessment of a solar thermal collector. Renewable Energy 30, 1031–1054.
Boustead, I., 1972. The Milk Bottle. Open University Press, Milton Keynes.
Boustead, I., 1989. Environmental Impact of the Major Beverage Packaging Systems-UK Data 1986 in Response to the EEC Directive 85/339. INCPEN, London.
Directive, 2002/91/CE of Energy Performance of Building (EPBD).

Duffie, J.A., Beckman, W.A., 1991. Solar Engineering of Thermal Processes. Wiley Publication.
EU Commission, 2004. Energy and Transport in Figures", Energy and Transport. Directorate- General for Energy and Transport.
European Solar Thermal Industry Federation (ESTIF), "Sun in action II", vol. 2.
European Platform of LCA Including the ILCD Handbook, 2010. European Commission, Brussels, Belgium. Available online: http://lct.jrc.ec.europa.eu/publications.
European Solar Thermal Industry Federation (ESTIF), May 2009. Solar Thermal Markets in Europe- Trends and Market Statistics 2008.
Finkbeiner, M., Inaba, A., Tan, R.B.H., Christiansen, K., Klüppel, H.J., 2006. The new international standards for life cycle assessment: ISO 14040 and ISO 14044. Int. J. Life Cycle Assess. 11, 80–85.
GEMIS software, May 2007. Global Emission Model of Integrated Systems. Őko-Institut (Institute for Applied Ecology), Darmstadt. www.gemis.de.
Goedkoop, M., Effting, S., Collingo, M., 2000. The Eco-Indicator'99 – A Damage Oriented Method for Life Cycle Impact Assessment – Manual for Designers. Pre Consultants.
ASHRAE Handbook, HVAC Applications, 2003. New York, USA.
Hannon, B., 1972. "A Study of the Beverage Industry", System Energy and Recycling. Center for Advanced Computation, University of Illinois, Urbana, IL.
ISO 14040, 1997. Environmental Management – Life Cycle Assessment- Principles and Framework. International Organization for Standardization, Geneva.
ISO 14041, 1998. Environmental Management – Life Cycle Assessment – Goal and Scope Definition and Inventory Analysis. International Organization for Standardization, Geneva.
ISO 14042, 2000a. Environmental Management – Life Cycle Assessment- Life Cycle Impact Assessment. International Organization for Standardization, Geneva.
ISO 14043, 2000b. Environmental Management – Life Cycle Assessment- Life Cycle Interpretation. International Organization for Standardization, Geneva.
ISO 14044, 2006a. Environmental Management – Life Cycle Assessment – Requirements and Guidelines. International Organization for Standardization, Geneva.
ISO 14040, 2006b. Environmental Management – Life Cycle Assessment – Principles and Framework. International Organization for Standardization, Geneva.
Koroneos, Christopher J., Koroneos, Yanni, 2007. Renewable energy systems: the environmental impact approach. Int. J. Glob. Energy Issues 27 (4), 425.
Koroneos, Christopher J., Spachos, Thomas, Moussiopoulos, Nikolaos, 2003. Exergy analysis of renewable energy sources. Renewable Energy 28, 295–310.
Koroneos, et al., 1999. Life cycle analysis: a complete approach. In: Proceedings of 3rd international Exhibition and Conference HELECO '99, 3–6 June 1999, Thessaloniki, vol. 2, pp. 378–387.
Kreith, F., Kreider, J.F., 1978. Principles of Solar Engineering. McGraw-Hill, New York.
Lundolm, M.P., Sundstrom, G., 1985. Resource and Environmental Impact of Tetra Brik Carton and Refillable and Non-Refillable Glass Bottles. AB Tetra Pak, Malmo.
Manual RETscreen: www.retscreen.net.
Mirasgedis, S., Diakoulaki, D., Assimakopoulos, D., 1996. Solar energy and the abatement of atmospheric emissions. Renewable Energy 7 (4), 329–338.
Pafilias, A., 1993. Materials Used for Manufacturing Solar Domestic Hot Water Systems and Comments on Their Reliability. Technical Report. Centre of Renewable Energy Sources. Programme Valoren.
Pelekanos, A., 1982. Meteorological data for implementation of solar applications in various cities in Greece. In: Proceeding of First National Conference for the Renewable Energy Sources, vol. A. Institute of Solar Technology, Thessaloniki, Greece (in Greek).
REN 21, Renewables, 2011. Global Status Report. Paris 2011.
Sundstrom, G., 1973. Investigation of the Energy Requirements from Raw Materials to Garbage Treatment for 4 Swedish Beer Packaging Alternatives. Report for Rigello Park AB, Sweden.
Tsillingrides, G., Martinopoulos, G., Kyriakis, N., 2004. Life cycle environmental impact of a thermosiphon domestic solar hot water system in comparison with electrical and gas heating. Renewable Energy 29 (8), 1277–1288.
UNEP/SETAC, 2010. Life Cycle Initiative. UNEP, Nairobi, Kenya. Available online: http://lcinitiative.unep.fr.