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Research Article

Assessment of the environmental impacts deriving from the life cycle of a typical solar water heater

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Abstract

According to life cycle thinking, the environmental burden deriving from different life cycle stages of a product or a system, such as manufacturing, transportation, maintenance and landfilling should be taken into consideration while assessing its environmental performance. In that aspect, the environmental impacts deriving from the life cycle of a typical solar water heater (SWH) in Greece are analyzed and assessed with the application of relative life cycle assessment (LCA) software in this study. In order to examine various impact categories such as global warming, ozone layer depletion, ecotoxicity and so forth, the IMPACT2002+ method is applied. The aim of this study is to examine the life cycle stages, processes and materials that significantly affect the system under examination and to provide a discussion regarding the environmental friendliness of solar water heaters.

Keywords: solar water heaters, life cycle assessment, sustainability, renewable energy

1. Introduction

Solar water heaters (SWH) are considered a much more environmentally viable choice in comparison with the electrical heaters since they utilize the "clear" energy derive form the sun. In Europe an estimated 4.2 million m^2 of surface area were installed in 2009, whereas Greece, basically due to its climate characteristics, was the third European country in terms of solar thermal capacity in operation per 1000 capita (360 m^2/1000 inhab.) in 2009 [1].

Summarizing the function of SWH, in order to heat water using solar energy, a collector heats a fluid that is either pumped (active system) or driven by natural convection (passive system) through it. The collector is made of a glass topped insulated box with a flat solar absorber made of sheet metal attached to copper pipes and painted black. The heat transfer fluid is either water or a heat transfer fluid, such as water-glycol antifreeze mixture. The bulk of the Greek market comprises thermosiphon systems which are suitable for the Mediterranean climate and work out less expensive than forced circulation solar systems [1].

However, there is a significant material and energy flow during SWH manufacturing and setup that should be appreciated while assessing its environmental performance. In that aspect an increasing number of studies apply the life cycle assessment (LCA) approach in order to holistically analyze various systems in terms of their environmental performance. LCA is a specific elaboration of a generic environmental evaluation framework [2] that evaluates the environmental impacts during the life cycle of a product, process or activity [3]. In this work the LCA of a typical SWH is performed in order to examine the life cycle stages, processes and materials that significantly affect the system under examination and to provide a discussion regarding the environmental friendliness of solar water heaters.

2. Life Cycle Assessment Implementation

In order to holistically examine different aspects of SWH life cycle, the environmental impacts deriving from the life cycle of a typical SWH were analyzed and assessed with the application of relative life cycle assessment (LCA) software (SimaPro). Moreover, the standard four steps approach that has been developed according to the principles of ISO 14040 standard series was followed for the implementation of the current LCA. A more detailed presentation of this approach can be found elsewhere [4].

2.1 Goal and Scope (1st Step)

The goal set for the specific study is the screening of the environmental impacts deriving 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. According to the aim set, the scope of this work had to

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include all life cycle stages from raw material acquisition and production to disposal.

The functional unit set was one typical SWH manufactured in North Greece, weighting 175kg, including a water tank with a capacity of 150lt and a $3m^2$ solar collector. This solar collector was chosen due to the availability of raw data (materials and processes) regarding its manufacturing [5]. Basic materials comprising the SWH include galvanized steel, copper, glass and polyurethane (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.

2.2 Life cycle inventory (2nd Step)

In order to perform the inventory analysis, 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 1). Life Cycle Inventory (LCI) is a list of all raw materials, extractions and emissions that take place in the production of the assembly and the materials and processes that are linked to it [6].

2.3 Impact assessment (3rd Step)

Without an LCI, no basis exists to evaluate comparative environmental impacts or potential improvements [4]. Thus impact assessment is needed to better understand the inventory results. During this step, the effects of the resources used and the emissions generated are grouped and quantified into a number of impact categories which may be weighted for importance. In order to perform an impact assessment, some impact categories must be chosen according to the needs of the study. Impact assessment in LCA traditionally focused on environmental impacts derive from emissions, wastes, resource use and energy consumption and are categorized by practitioners in global warming potential (GWP), acidification, eutrophication, stratospheric ozone depletion, photo oxidant formation, resource use, land use, and others [7]. Then these impacts can be weighted in order to quantify and compare different categories.

In this study the IMPACT 2002+ method was applied. IMPACT 2002+ is a combination of four methods: IMPACT 2002, Eco-indicator 99, CML and IPCC. The Eco-Indicator 99 method offers a way to measure various environmental impacts, and shows a final result in a single score. The normalization and weighting are performed at damage category level (human health, ecosystem quality and resources) while the damage categories are normalized on a European level (damage caused by 1 European per year). Moreover, CML is a LCA methodology developed by the Institute of Environmental Sciences (CML) of Leiden University in the Netherlands, containing further characterisation factors for baseline characterisation methods, whereas the Intergovernmental Panel on Climate Change (IPCC) method includes characterization factors for the direct (except CH_4) global warming potential of air emissions expressed in kg CO_2 equivalent (kg CO_2 eq.), the basic unit for measuring global warming.

Table 1. 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		

The IMPACT 2002+ methodology proposes a feasible implementation of a combined midpoint/damage approach, linking all types of life cycle inventory results (elementary flows and other interventions) via 14 midpoint categories to four damage categories [8]. The four damage oriented impact categories include human health, ecosystem quality, climate change, and resources. In SimaPro, 15 different impact categories are presented, as human toxicity is split up in Carcinogens and Non-carcinogens.

2.4 Interpretation (4th Step)

Finally, the results were interpreted and are presented in the results and discussion section. In order to interpret the results a weighting procedure was applied. According to IMPACT2002+, if aggregation is needed, self-determined weighting factors or a default weighting factor of one should be applied thus the default weighting of 1:1:1:1 was applied in this study. More details and information about IMPACT2002+ can be found elsewhere [9].

3. Results and Discussion

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 1.

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.

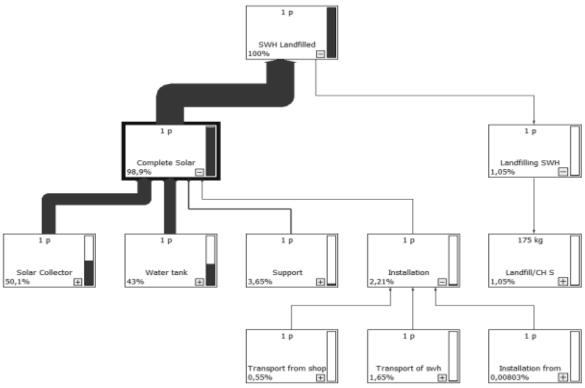

Fig. 1. Tree developed in software using the Impact 2002+ method.

Further analysis of the results indicated that the assembly of the solar collector was the main factor affecting 12 out of 15 impact categories included in the Impact 2002+ method with the rest of it regard the water tank. These results are summarized in Table 2.

Table 2. LCA results with the application of the Impact 2002+ method (characterization).

Impact Category	Unit	Total		Solar collector		Water tank		Support		Installation	
		Value	(%)	Value	(%)	Value	(%)	Value	(%)	Value	(%)
Carcinogens	kg C2H3CL eq	14.4	100	7.98	55.4	5.46	37.9	0.55	3.86	0.41	2.91
Non-carcinogens	kg C2H3CL eq	36.8	100	14.1	38.4	19.1	51.9	3.41	9.27	0.179	0.48
Respiratory inorganics	kg PM2.5 eq	1.3	100	0.672	51.8	0.586	45.2	0.023	1.78	0.016	1.24
Ionizing radiation	Bq C-14 eq	6.93E3	100	3.63E3	52.5	2.42E3	35	454	6.55	416	6.01
Ozone layer depletion	kg CFC-11 eq	8.4E-5	100	3.7E-5	44	3.8E-5	45.7	5.6E-6	6.72	3.0E-6	3.6
Respiratory organics	kg C2H4 eq	0.55	100	0.257	46.8	0.264	48	0.009	1.77	0.019	3.47
Aquatic ecotoxicity	kg TEG water	1.55E5	100	1.08E5	69.2	3.9E4	25.1	7.81E3	5.02	1.15E3	0.73
Terrestrial ecotoxicity	kg TEG soil	3.23E4	100	1.33E4	41.2	1.29E4	40	5.67E3	17.6	387	1.2
Terrestrial acid/nutri	kg SO2 eq	22.2	100	11.1	50	10.1	45.4	0.553	2.49	0.484	2.19
Land occupation	m2org.arable	9.9	100	6.29	63.5	2.99	30.2	0.222	2.24	0.402	4.06
Aquatic acidification	kg SO2 eq	13.5	100	6.72	49.8	6.52	48.3	0.166	1.23	0.088	0.65
Aquatic eutrophication	kg PO4 P-lim	0.132	100	0.066	49.9	0.050	38.4	0.012	9.09	0.003	2.61
Global warming	kg CO2 eq	620	100	326	52.6	254	41	18.5	2.98	21	3.39
Non-renewable energy	MJ primary	9.14E3	100	4.63E3	50.7	3.87E3	42.4	274	3	358	3.92
Mineral extraction	MJ surplus	474	100	289	61	183	38.6	1.74	0.36	0.369	0.07

In order for the results to be comparable, a weighting procedure was followed (Table 3 – see Sec.2.2 for weighting characteristics). Results indicated the emissions of respiratory inorganics (43.2%) and global warming (21.1%) as the two main impact categories that were highly affected by the SWH life cycle, followed by non-renewable energy use (20.3%). Respiratory inorganics impact category is expressed through kg PM2.5 equivalent unit. PM2.5 expresses particulate matter with an aerodynamic diameter less than 2.5μm and is a common used indicator of air quality. Global warming potential (GWP) on the other hand, is the primary method in the policy for quantifying climate impacts of greenhouse gases thus expressing climate change [10]. GWP is expressed in kg CO_2 equivalent (kg CO_2 eq.), a method that exalts the environmental impacts deriving from all the emissions of a predefined system (mainly greenhouse gases) to CO_2 equivalent.

Table 3. LCA results with the application of the Impact 2002+ method (weighted results, contribution %).

Impact category	Unit	Total	Solar collector	Water tank	Support	Installation
Carcinogens	%	1.92	1.06	<1	<1	<1
Non-carcinogens	%	4.9	1.88	2.54	<1	<1
Respiratory inorganics	%	43.2	22.4	19.5	<1	<1
Ionizing radiation	%	<1	<1	<1	<1	<1
Ozone layer depletion	%	<1	<1	<1	<1	<1
Respiratory organics	%	<1	<1	<1	<1	<1
Aquatic ecotoxicity	%	<1	<1	<1	<1	<1
Terrestrial ecotoxicity	%	6.3	2.6	2.52	1.11	<1
Terrestrial acid/nutri	%	<1	<1	<1	<1	<1
Land occupation	%	<1	<1	<1	<1	<1
Aquatic acidification	%	-	-	-	-	-
Aquatic eutrophication	%	-	-	-	-	-
Global warming	%	21.1	11.1	8.67	<1	<1
Non-renewable energy	%	20.3	10.3	8.6	<1	<1
Mineral extraction	%	1.05	<1	<1	<1	<1
Total	%	100	50.6	43.4	3.69	2.23

Regarding specific processes and materials, the top-5 processes that contributed in the LCA of the system examined are presented in Table 4. Results are aggregated by the software into a weighted non-metric unit named Point, in order for a common reference base to be applied whereas in Table 4 the contribution in percentages is provided. According to the results the use of copper and nickel in SWH should be further analyzed whereas substituting these materials could be of high environmental importance. Additionally milling steel and zinc coating found to be especially adverse for the environment.

Table 4 Impact 2002+ V2.06 method Single score process contribution.

No	Process	Project/Database	Unit	Total
1	Copper	IDEMAT 2001	%	19.8
2	Milling, steel, average	Ecoinvent system process	%	17.5
3	Zinc coating	Ecoinvent system process	%	11.0
4	Nickel	IDEMAT 2001	%	9.5
5	Heat oil	BUWAL 250	%	6
	Total of all processes		%	100

Finally in order to examine the benefits from the use of the specific SWH, the environmental burden deriving from its life cycle (including land filling) was compared with the environmental burden deriving 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 [5]. 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 5 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 examined. 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 5 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 this study the LCA of a typical SWH in Greece was performed with the application of relative software. 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. Additionally, the emissions of respiratory inorganics (43.2%) and global warming (21.1%) were identified as the two main impact categories that were highly affected by the SWH life cycle, followed by non-renewable energy use (20.3%). Regarding specific processes and materials the use of copper and nickel in SWH should be further analyzed whereas substituting these materials could be of high environmental importance. Moreover, further analysis indicated that the application of SWH instead of electrical ones could lead to a reduction over 80% to most impact categories examined.

In order to further support the comprehensiveness of the study, a number of ameliorative actions were identified by the authors. LCA includes a significant amount of uncertainty due to data unavailability and/or data inefficiency, thus the integration of more analytical raw data in order for the life cycle inventory to be developed, would be of high importance regarding the amelioration of the study. Furthermore in order to holistically examine the sustainability of SWH, the life cycle costs should be also taken into account whereas more SWH types should be examined.

Despite the shortcomings identified, this study still provides rare to be found LCA based results, thus it could be concluded that the application of SWH seems an environmentally friendly action and should be further promoted. This study is expected to be used by decision makers who want to take environmentally responsible actions and SWH manufacturers who are interested in "greening" their products.

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