LIFE CYCLE ANALYSIS OF A POLYMER BLACK LIQUID FLAT PLATE COLLECTOR

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1. Introduction

Solar hot water/heating technologies are becoming widespread reaching 196 GW_{th} for 2010, more than doubling the installed capacity of 2004, therefore significantly contributing to the hot water/heating markets worldwide. China currently accounts for more than 58% of the total installed capacity, European countries account for 19%, followed by the United States of America, Australia and Japan (IEA-SHC, 2011). Space heating from solar energy is gaining ground in several countries, although the primary application remains hot water production usually in the form of Domestic Solar Hot Water Systems (DSHWS).

The increase in the use of solar thermal energy systems is subjected to their economic viability, in comparison with conventional systems, and their simplicity in manufacturing and use. In order to minimize the production cost of current solar collectors, new materials of lower cost and preferably more environmental friendly must substitute the ones that are employed today, without any deterioration of collector efficiency.

Although solar energy is considered a “clean” energy form, both manufacture and final disposal of DSHWS are associated with significant environmental transactions, due to the energy required for the raw material production and the final product formation and assembly as well as due to the final disposal of the system at the end of its life. It is necessary therefore to evaluate solar technology accounting for the indirect environmental impacts caused by the DSHWS over their whole life cycle.

In this work a 1,5 m^2 polymer collector, that was developed aiming at producing a solar collector which combines similar or better technical characteristics with typical flat plate collectors at the same operational uses and for a wide variety of operating temperatures but with reduced cost (manufacturing and operational), is analyzed employing Life Cycle Analysis (LCA) (through the widely used SimaPro software) in order to evaluate its overall performance and is then compared with a typical flat plate DSHWS.

2. Solar Collector Description

The most commonly used solar system is the one producing hot water for domestic use. The basic unit of such a system is the solar collector. Among the solar collector configurations used, the most common is the flat plate one (ESTIF, 2011) which has been studied by many researchers (Hottel and Woertz, 1942; Bliss 1959; Nahar and Garg 1980; Francken, 1984).

Typical flat plate collectors are either corrugated, bond duct or tube-in-plate type and their performance depends on various design parameters, including the number of covers, the type and thickness of glazing, the anti-reflecting coating on cover glass, the type of coating on the collector plate, the spacing between the collector and the inner glass, the type and thickness of insulation used, etc.

Operational parameters affecting the performance of a solar collector are the mass flow rate of fluid, the amount of incident solar radiation, the inlet and ambient temperatures and sky conditions, to name a few.

In recent years, a number of researchers have adopted the use of polymers in solar collector design as their cost and physical properties make volume production of lightweight low-cost and corrosion resistance collectors possible. The use of polymer glazing has been moderately successful, as they offer significant potential for cost savings both as direct substitutes for glass cover plates in traditional collector systems and as an integral part of all-polymeric systems. Polymer heat exchangers offer the potential advantages of reduced cost of materials and manufacture, corrosion resistance, as well as better integration with other components (Alghoul et al, 2005).

All-polymeric solar collectors are wide spread, mainly in the form of low cost unglazed swimming pool collectors (Meir and Rekstad, 2003), with an installed capacity of 19,7 GWth worldwide (IEA-SHC, 2011). Unglazed liquid flat-plate collectors of this type are usually made of a black polymer. They don't normally have a selective coating, a frame or insulation at the back resulting in high thermal losses to the environment, that increase rapidly as water temperature increases, particularly in windy locations. These disadvantages limit their use in applications requiring energy in low temperatures.

In this work a polymer collector combining similar or better technical characteristics with typical flat plate collectors at the same operational uses is employed in a typical DSHWS and is analyzed employing LCA in order to evaluate its overall performance compared not only with the conventional energy substituted but also to that of a typical flat plate DSHWS.

The polymer collector comprises of all the usual components of a typical solar collector. The main difference is that instead of a metal absorber, a black fluid acts as both absorber and heat carrier. The fluid flows in a transparent polymer honeycomb construction. The cross-section of the collector is shown in Figures 1 and 2.

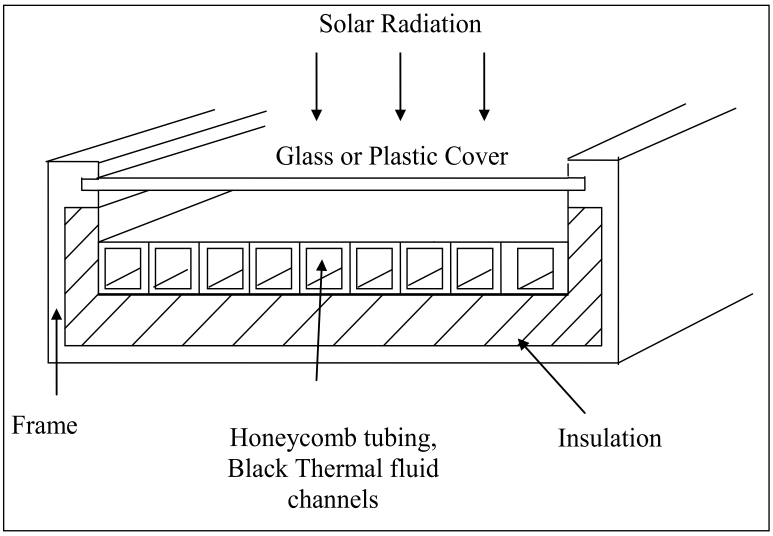

Fig. 1: Collector cross-section

As the collector should be able to withstand liquid pressure and large temperature variations (267 to 383 K) over time while at the same time presenting a refractive index similar or better than that of glass, low emissivity and good durability to weathering from ultraviolet radiation, the hydraulic channels were made of a single transparent, UV stabilized, honeycombed, polycarbonate sheet with a 10mm thickness. The upper and lower collector channels were made of semi-transparent acrylic. A 1.000/1 solution of black Indian ink in water was used as heat transfer fluid.

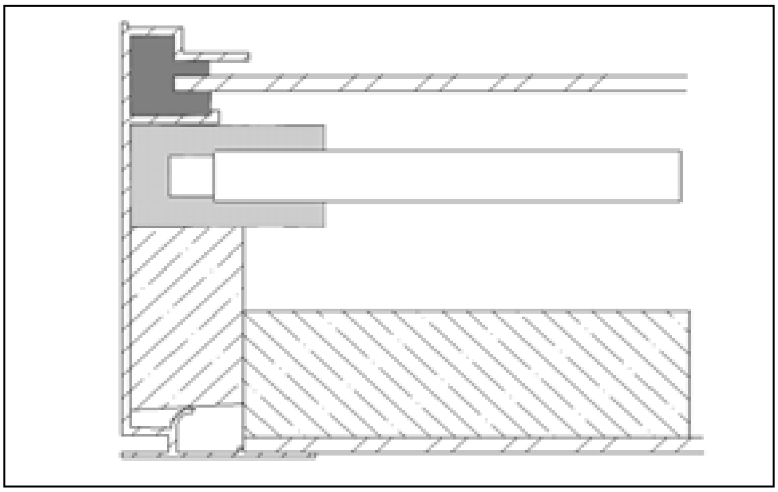

Fig. 2: Collector cross-section

In Figure 3, the dimensions of the collector and the inlet and outlet position are presented.

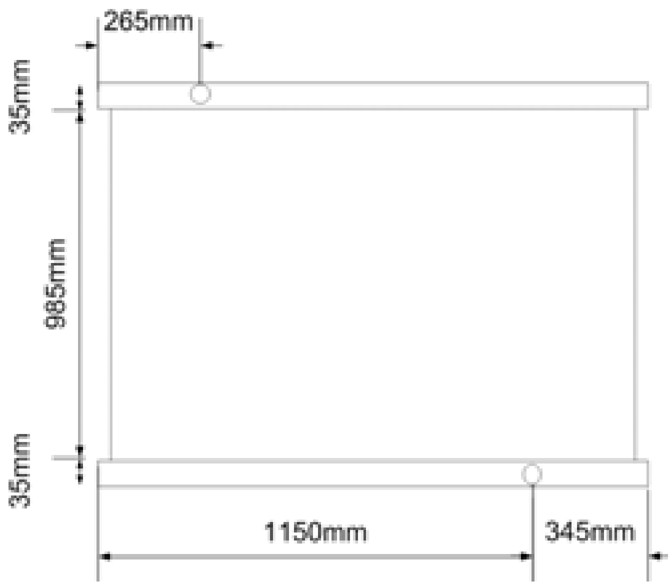

Figure 3: Collector inlet and outlet position

The glazing consists of a 3mm thick solid, transparent, UV stabilized polycarbonate sheet while at the back a nanogel filled honeycombed polycarbonate sheet of a 10mm thickness is used for insulation. The sides of the collector are insulated using 30mm thick extruded polyurethane. All of the above are packed in an aluminium casing. The main technical characteristics of the collector are summarized in Table 1.

Table 1. Collector Technical Characteristics

Total Area	1,448 m²
Glazing Area	1,252 m²
Absorber Area	1,252 m²
Number of Glazings	1
Glazing Material	3mm solid transparent UV stabilized polycarbonate
Heat Carrier Fluid	Water and Indian Ink solution (1.000:1)
Absorber	Transparent UV stabilized honeycombed polycarbonate sheet (10mm)
Headers	Acrylic 8mm rectangular
Fluid weight	~14kg
Back Insulation	Honeycombed polycarbonate sheet with a 10mm thickness filled with nanogel
Side Insulation	Extruded PU 30mm

3. Collector Performance Evaluation

The performance of the polymer collector was measured at an ISO 9806-1 complying test bed (ISO, 1994).

A heating immersion circulator was used for the temperature regulation of the heat transfer solution, in order to maintain the temperature at the collector inlet within a range of ± 0,1 K of the desired value. The flow was measured with a rototron flow meter while solar radiation was measured with a precision pyranometer. The signals from all the sensors were collected by a 24–bit data logger and were stored in a computer for further processing.

The temperature of the heat carrier solution at the inlet was appropriately set before every measurement, starting from 293 K (ambient temperature) and, before measuring, the system was left to reach steady state conditions. The collector flow rate during measurements was set at 1,27 dm^3.

The polymer collector produced a maximum instantaneous efficiency of 65% and F_rU_L of 6,08 W m² K^{-1}. The collectors' efficiency curve is depicted in Figure 4.

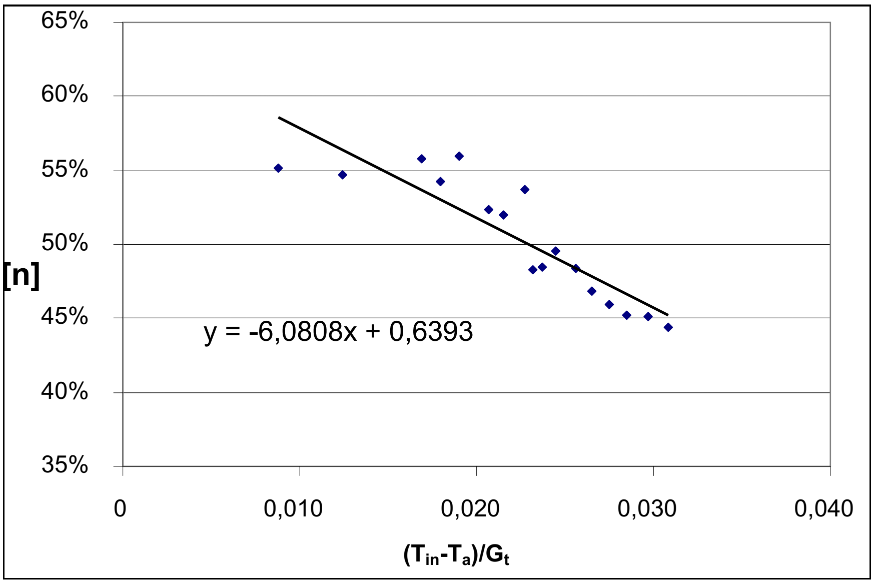

Figure 4: Polymer collector's Instantaneous Efficiency Curve

4. Life Cycle Assessment

LCA methodology was initially developed by the Society of Environmental Toxicology and Chemistry (SETAC) and was later optimized by ISO, but its real breakthrough into the business world occurred only during the '90s. Using LCA, the environmental impacts associated with the production and utilization of DSHWS can be assessed in a compatible and comparable way. This can be accompliced by recording the energy and raw materials used in the manufacturing stage and also the air, liquid and solid pollutants emitted over the products life cycle. Apart from obtaining a reliable assessment of the total impact, LCA can enable an existing situation to be improved by evaluating, in environmental impact terms, suggestions for manufacturing procedure modifications or substitution of materials.

4.1. Goal and scope definition

Main objective of the study is the investigation of the environmental performance of a DSHWS employing the polymer collector compared not only with the conventional energy substituted but also to a reference flat plate DSHWS.

The functional unit of the study is a DSHWS that covers the hot water needs of a three person family in Thessaloniki - Greece (40°38΄, 22°57΄). The DSWHS consists of a nominal 4 m² collector, a 150 dm^3 storage tank and a mounting base.

The reference systems collector is made from copper tubes extended with copper foils and, in order to boost the collector's absorbency, sprayed with black solar powder. A layer of expanded polyurethane with 30 mm average thickness is sprayed at the back of the collector, for insulation. On the sides of the collector area, rock wool is used for insulation, with a 20 mm thickness. The back cover of the collector is galvanised steel, while the sides consist of aluminium. At the front of the collector a single solar glass is used.

For the estimation of the environmental savings during the DSHWS use, due to replacement of conventional energy sources (namely electricity), the assumption that the necessary heat would be produced by an electrical water heater with an average efficiency of 95% is made.

The system boundaries of the LCA study include the following stages:

- Extraction of raw materials
- Production of system components
- System assembly

- System use
- System disposal
- All transportations

The life span of the DSHWS was assumed 15 years.

For the quantification of the benefits due to material recycling from the system disposal, the assumption that no recycling takes effect and the systems are put in a landfill is made. In this manner the worst case scenario is considered (no environmental gains from the reuse - recycling of materials).

4.2. Life Cycle Inventory

The data for the life cycle inventory analysis were primary data.

4.3. Life Cycle Assessment

LCA is performed with the help of the widely used "SimaPro" software (Raluy et al, 2005; Weinzettel et al, 2009; Desideri et al, 2011) and the incorporated methodology of "Eco-Indicator '99".

Eco-Indicator '99 includes standard values for (Goedkoop et al, 2000):

- Materials. In determining the indicator for the production of materials, all the processes involved are included, from the extraction of the raw materials up to and including the last production stage, resulting in bulk material. Transport processes along this route are also included up to the final process in the production chain.

- Production processes. Treatment and processing of various materials, expressed for each treatment in the unit appropriate to the particular process (e.g. square metres of rolled sheet or kilo of extruded plastic). The indicators of the production process account for the emissions not only during the manufacturing stage, but also for those resulting from the production of the energy needed.

- Transportation processes. These are mostly expressed in the unit tonne-kilometre. Transportation processes include the impact of emissions caused by the extraction and production of fuels and the fuel consumption during transportation. A loading efficiency for average European conditions is assumed and a possible empty return journey is accounted for.

- Energy generation processes. The energy indicators refer to the extraction and production of fuels and to the energy conversion, using average efficiencies. For the electricity score the various fuels used in Europe to generate electricity are accounted for. Different Eco-indicators have been determined for high- and low-voltage electricity, intended for industrial processes the first and mainly for household and small-scale industries the second.

- Disposal scenarios. These are per material unit (kg), subdivided into types of material and waste processing methods (recycling of different materials, incineration, landfill, etc). Not all products are disposed of in the same manner, therefore the most appropriate waste-processing method must be carefully considered in using indicators. In addition, scenarios have been provided for the incineration, landfill disposal and recycling of products.

Standard "Eco-indicator '99" values can be regarded as dimensionless figures, called Eco-indicator points (Pt). One Pt is defined to represent one thousandth yearly environmental load of an average European inhabitant.

Furthermore, "Eco-Indicator '99" methodology analyzes the following five environmental impact categories: climate change, acidification/eutrophication, ecotoxicity, fossil fuels (resources) and respiratory inorganics. The impact assessment involves three main steps: characterization or classification, normalization and final weighted scores. There are three damage categories for the final weighted scores (Goedkoop et al, 2000):

- Human health. This is measured in DALY (Disability Adjusted Life Years); that is, the different disabilities caused by diseases are weighted. DALY has been developed for the World Health Organization and the World Bank. Climate change is categorized under this damage category.

- Ecosystem quality or ecotoxicity. This is measured in PDF m^2 yr, which is the Potentially Disappeared Fraction of plant species. The impact category of acidification/eutrophication is listed here. In terms of ecotoxicity, this is measured as the percentage of all species present in the environment living under toxic stress (Potentially Affected Fraction or PAF m^2 yr).
- Resources. This final damage category is measured in MJ surplus energy, including fossil fuels.

More information regarding LCA for DSWHS can be found in the literature (Tsilingiridis et al, 2004; Ardente et al, 2005; Martinopoulos et al, 2007).

5. DSHWS Thermal Load Calculation

For the calculation of the solar heat gains from the use of DSWHS the TRANSOL software, which is based on the TRNSYS (SEL, 2009) calculation engine, was employed. In order to estimate the total energy gain from the DSHWS, the daily and monthly consumption of hot water was assumed to comply with the profile depicted in figures 5 and 6. A daily consumption of 50 dm^3 of hot water per person at a 45°C (ASHRAE, 2003), temperature was assumed. The meteorological data needed for the calculations (air and water temperature, solar irradiance) are based on a typical meteorological year (TMY2) for Thessaloniki, while the inclination of the collector was set at 45°, well within the recommendation (latitude ± 15°).

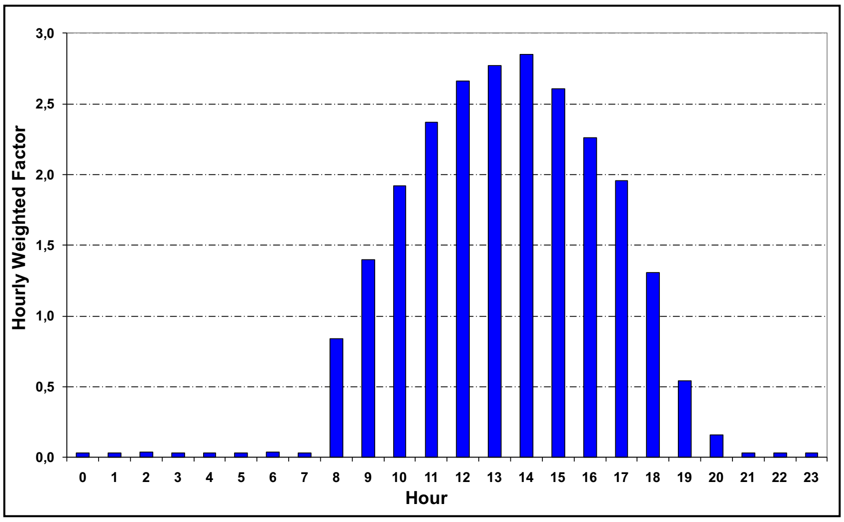

Figure 5: Daily Hot Water Consumption Profile

The covered thermal load and auxiliary energy needed are presented in Table 2 for the reference system and the one employing the polymer collector.

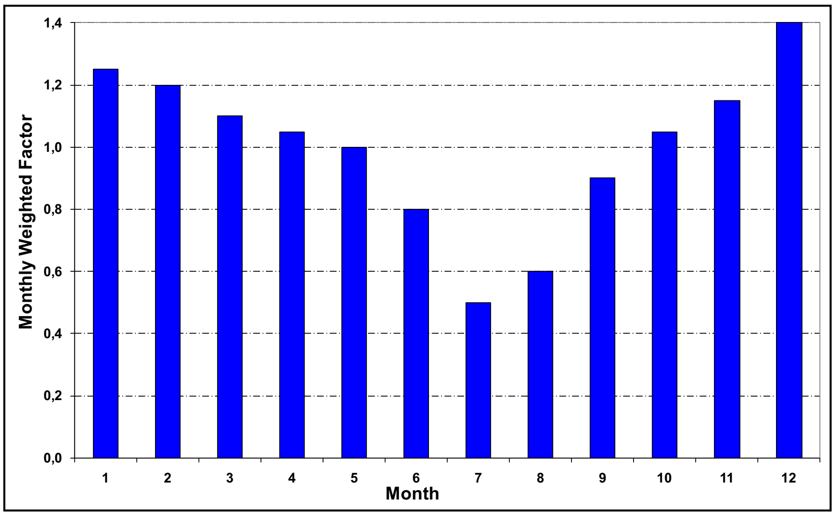

Figure 6: Monthly Hot Water Consumption Profile

Tab. 2: **Technical Characteristics and covered thermal load for both DSHWS**

DSHWS	$F_r(\tau\alpha)$	F_rU_L (W/m²K)	Annual Coverage	Covered load (kWh)	Aux. Energy (kWh)
Reference collector	0,657	5,538	0,579	1.114,7	817,4
Polymer collector	0,639	6,091	0,572	1.103,96	826,0

The impact for the energy used in order to fully cover the total thermal load (in the form of electricity) for the whole life span of the DSHWS is added on the impact from the production and transportation of the systems in order to calculate their total environmental performance.

In case that the thermal load for the hot water was covered from an electrical water heater (without taking into account the environmental impact from the electrical water heater) the impact to the environment would be (~1.983 kWh) 8,25 kg CO, 43.513 kg CO_2, 15,33 kg CH_4, 0,92 kg N_2O, 17,59 kg NMVOC, 87,37 kg NO_x και 561,39 kg SO_x for the 15 years of the DSHWS life span (based on emission factors of the Greek interconnected electricity system).

6. Environmental Performance

The environmental performance of the DSHWS is related to the environmental impact that it causes in all stages of its life cycle, except during use, and to the thermal load that it covers. The thermal load covered is related, in turn, with the collector's technical characteristics and the meteorological conditions of the installation site.

The DSHWS covers part of the thermal load, substituting electricity, thus reducing the impact that the electricity would cause.

The environmental performance of the DSHWS analyzed is presented in two stages; first by comparing the environmental impacts of the systems during all the life cycle stages, excluding utilization, and second including utilization.

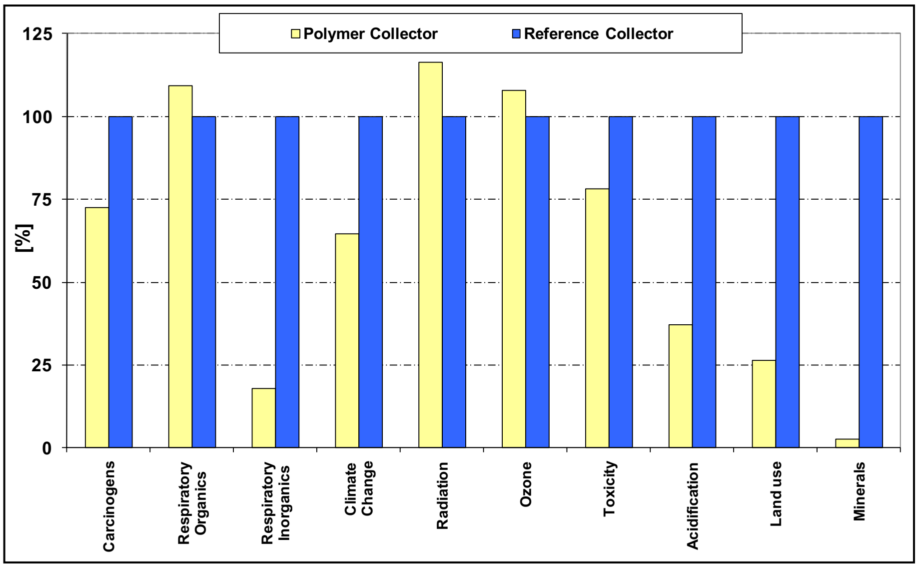

Figure 7: Comparison of the Environmental Impact during the first stage, between the polymer and reference collector

For the first stage, the aggregated impact to each category calculated is presented in figure 7, while in figure 8 the impact to human health, ecosystem quality and resources is presented. It is evident that for the polymer collector the impact is related with respiratory organics due to the mostly carbon based materials used. The higher impact to the radiation and ozone categories are of no real consequence, as their absolute value is very small. In all other categories the impact of the polymer collector is 20 to 75% less than that of the reference collector. Finally in figure 9 the total impact of the polymer collector in Pt is presented in comparison with the impact of the reference collector. During the first stage, the total impact of the polymer collector is only a small fraction of that of the reference collector, due to the fact that it minimizes metallic and glass parts. The environmental impact for the reference system is presented in Table 3.

Tab. 3: Environmental Impact of the Reference System

Impact Category	Unit	Reference Collector
Carcinogens	DALY	1,04E-04
Resp. organics	DALY	1,06E-06
Resp. inorganics	DALY	1,25E-03
Climate change	DALY	1,13E-04
Radiation	DALY	1,76E-07
Ozone layer	DALY	1,26E-07
Ecotoxicity	PDF*m^{2}yr	8,1
Acidification	PDF*m^{2}yr	29,6
Land use	PDF*m^{2}yr	34,2
Minerals	MJ surplus	975,0
Fossil fuels	MJ surplus	727,0

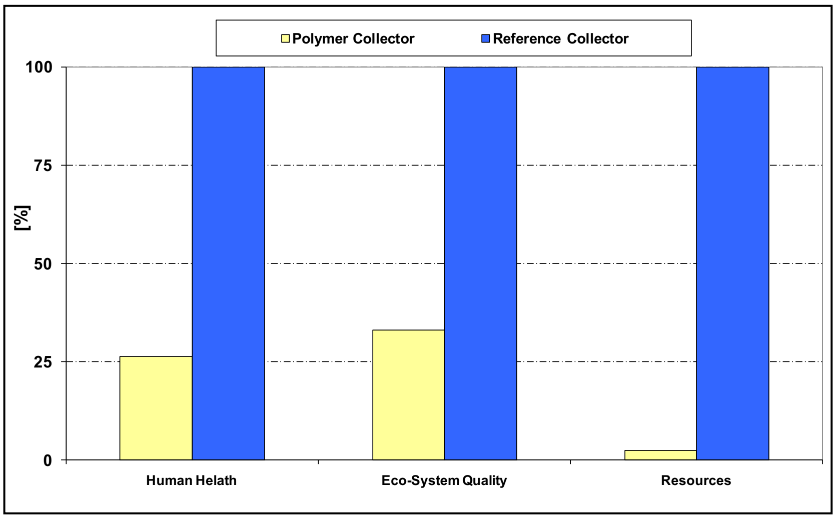

Figure 8: Comparison of the Environmental Impact during the first stage, between the polymer and reference collector

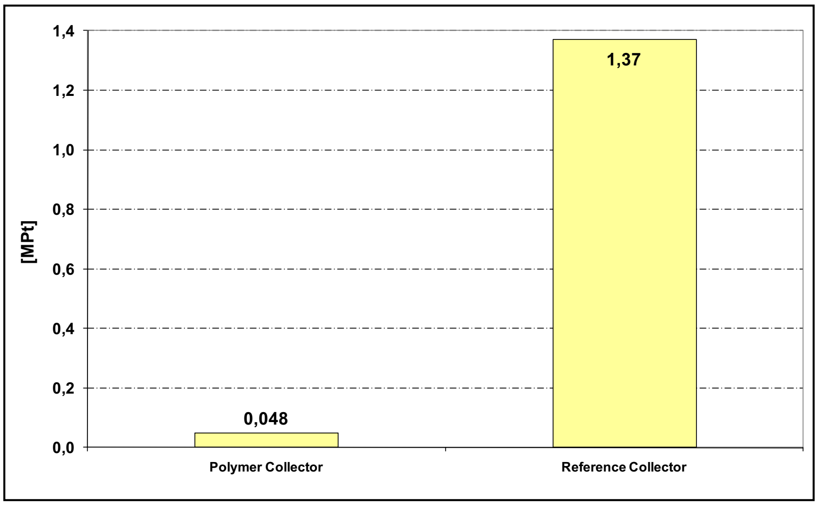

Figure 9: Comparison of the Environmental Impact during the first stage, between the polymer and reference collector

In the second stage, utilization of the system is included. That means that, at the environmental impact caused during production, the impact from the necessary auxiliary energy, for the 15 years of the systems life cycle, is added. As stated above, auxiliary energy is electricity in the form of an electrical water heater with an average efficiency of 95%. In the case of the electric water heater, in order to calculate thermal losses, it was assumed that the heater was installed in a room with a constant air temperature of 20°C.

The environmental performance of both systems is presented in Table 4 in the form of the emissions produced during their whole life cycle (including auxiliary electricity).

Tab. 4: Environmental Impact of both DSHWS and electricity for the 15 year period in the form of air emissions (kg)

Emission	Polymer System	Reference System	Electricity
CO	6,42	6,76	8,44
CO_2	16033,00	16035,19	44525,00
CH_4	6,16	5,92	15,69
N_2O	0,35	0,34	0,94
NVOC	6,47	6,40	17,99
NO_x	31,71	31,40	89,40
SO_x	206,46	218,71	574,44

As in this stage the thermal load covered is related, with the collector's technical characteristics, the slightly better technical characteristics of the reference collector bridge the environmental gap of the previous stage. It is of important to notice that the two systems have the same environmental performance, despite the experimental nature of the polymer collector.

7. Conclusions

It is clear from the life cycle analysis of the DSHWS that the environmental impact from the use of these systems is at all times considerably less than that of the substituted electricity.

It is interesting that the proposed polymer collector, although experimental in nature, provides the same environmental performance with that of typical flat plate collectors. The polymer collectors low cost, ease of production, coupled with the ability to enhance its performance would provide an interesting alternative for the emerging markets.

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