LIFE CYCLE ASSESSMENT OF SOLAR THERMAL SYSTEMS

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Abstract *The better understanding of cost-benefit, economic and environmental performances of solar thermal systems (STSs) is crucial for designers to be able to take a conscious and weighted decision about the installation of these systems. Therefore the goal of this research was to create a methodology for designers to support decision-making in the selection of the most adequate STS for a project and as result to contribute to a more sustainable built environment. This methodology allows the calculation of the potential environmental impacts, such as the global warming potential, acidification, eutrophication, ozone depletion, embodied energy, amongst others, together with the life-cycle costs resulting from the implementation of STSs in buildings. The system boundary includes the production of the various parts of the solar thermal system, such as the solar collector and the hot water tank, the assembly process, the maintenance stage, the auxiliary energy consumption and the end of life of this system. In the economic analysis, both initial and maintenance costs are considered together with the cost of the auxiliary energy. At the end, it is possible to quantify carbon, energy and cost payback periods. One practical application of the methodology will be carried out in the end of this work, aiming the comparison between four different STSs to be applied in a case study. The case study showed that both the energy and environmental payback times of a STS are less than 3 years and the life cycle cost payback period vary from 7 to 13 years.*

1. INTRODUCTION

The Renewable Energy Framework Directive sets a target of 20% for renewables by 2020. Buildings account for 40% of the total primary energy requirements in the European Union (EU) and are responsible for 30% of greenhouse gas emissions. According to the Portuguese General Directorate for Energy and Geology (DGEG), the residential sector is a major consumer of energy, consuming around 20% of the total primary energy consumption and about 25% of it is used for domestic hot waters [1], [2]. The Energy Performance of Buildings Directive (EPBD) requires that renewable energy systems (RES) are actively promoted in offsetting conventional fossil fuel use in buildings. A better knowledge of solar thermal system (STS) integration will directly support this objective, leading to an increased uptake in the application of renewables in buildings. This uptake of RES in buildings is expected to rise dramatically in the next few years. This is further augmented by the recast of the Energy Performance of Buildings Directive (EPBD-recast) that specifies that the buildings in the EU should be nearly zero energy consumption (residential and commercial buildings by the year 2020 and public buildings by 2018, respectively) [3]. Meeting building thermal loads will be primarily achieved through an extensive use of renewables, following standard building energy saving measures, such as good insulation or advanced glazing systems. Solar thermal systems are expected to take a leading role in providing the thermal energy needs, as they can contribute directly to the building heating, cooling and domestic hot water requirements Therefore, developing effective energy alternatives for buildings is imperative. Energy in buildings is used primarily for heating and cooling and for the provision of hot water. One way to reduce the dependence on fossil fuels is by the use of renewable energy sources and systems and at this context the solar thermal systems play an important goal. A high-quality solar system can provide a substantial part of the building’s energy needs if the building has been designed in the right way.

Using and integrating a solar thermal system (STS) can result in several advantages during the building life cycle, both at environmental and economic level. At the environmental level, the STS has the advantage of using renewable energy (instead of fossil fuels) to heat the water and at the economic level the advantage is that the STC use a free energy (sun) for most of the energy need to heat the water.

Although the abovementioned context, Portugal experienced a strong decrease over the past three years in the solar thermal market. In 2013, the market contracted to 40 MWth, which represented a variation of - 37% [4]. If the trend is not reversed it will be unlikely that Portugal will meet the goals set in the EPBD-recast. One of the aspects that is constraining the wider application of this systems in Portugal is that although most building designers are aware of the benefits of using STS there is not in the market a tool to support-decision making in choosing the most adequate STS for a building. This tool should at the same time allow the calculation of both the life-cycle environmental and economic benefits resulting from STS integration in a building.

The scope of this document is to present a methodology and a software tool that allows quantifying holistically both the environmental and life cycle costs benefits resulting from the integration of a solar thermal collector (STC) to heat the hot water in a residential building, based in up-to-date context and standards. Although there are several STS, this work is focused in solar systems used for domestic hot water production. The developed methodology is able to assess the environmental and economic benefits resulting from the implementation of solar thermal systems in buildings, based in the life cycle assessment (LCA) and life cycle cost (LCC) methods.

2. METHODOLOGY

The methodology used for the life cycle assessment (LCA) study was based on the ISO 14040 and 14044 standards and on the EN 15804 standard. The assessment of the economic performance of the solar thermal systems follows the rules presented by the Federal Energy Management Program (FEMP) [5], [6] for the use of energy systems in buildings. The methodology developed to assess the carbon, energy and cost payback period are based in previous studies developed by Marimuthu and Kirubakaran [7] and Duffie and Beckman [5].

2.1. Goal, scope and system boundaries

The goal of the study is to define a methodology that allows the comparison of the life-cycle performance of different solar systems used for domestic hot water production. This methodology is both based in the assessment of the environmental, energy and economic performances and in the assessment of the carbon, energy and economic payback times of different systems.

The LCA boundary is from cradle to grave, including production, use and end of life stages (Figure 1). Based on state of art review, the lifetime considered for the solar thermal systems is 20 years [8]. In order to assess the applicability of the developed methodology, it was applied to a real case study. The case study is a three bedroom detached house located in the climate condition of the city of Penafiel (Portugal). For this case study, the performance of four alternative STSs (two forced circulation two thermosyphon systems) was assessed. For the auxiliary heater either electricity or butane gas was considered as energy source. Table 1 presents the technical characteristics of the alternative STSs considered in this study. For the assessment it was considered that the STCs are mounted in a sloped roof with the inclination presented in the architectural plans. At the end an optimization of the inclination of the roof was carried out to optimize the STSs' efficiency for this latitude.

2.2. Environmental life cycle inventory

Since the developed methodology is aimed at supporting decision-making since the early design phases, generic life-cycle inventory (LCI) databases are used in the assessment of the environmental performance. Ecoinvent 2.2 database [9] was used for LCI.

2.2.1. Production phase

Based on other studies [10], the LCI for this phase includes, for the different types of solar collectors and systems, the production (i.e. materials, heat exchange fluid, copper pipes used in the installation of the system, water and energy used during production), delivery of the system parts with a van and mounting processes in the roof.

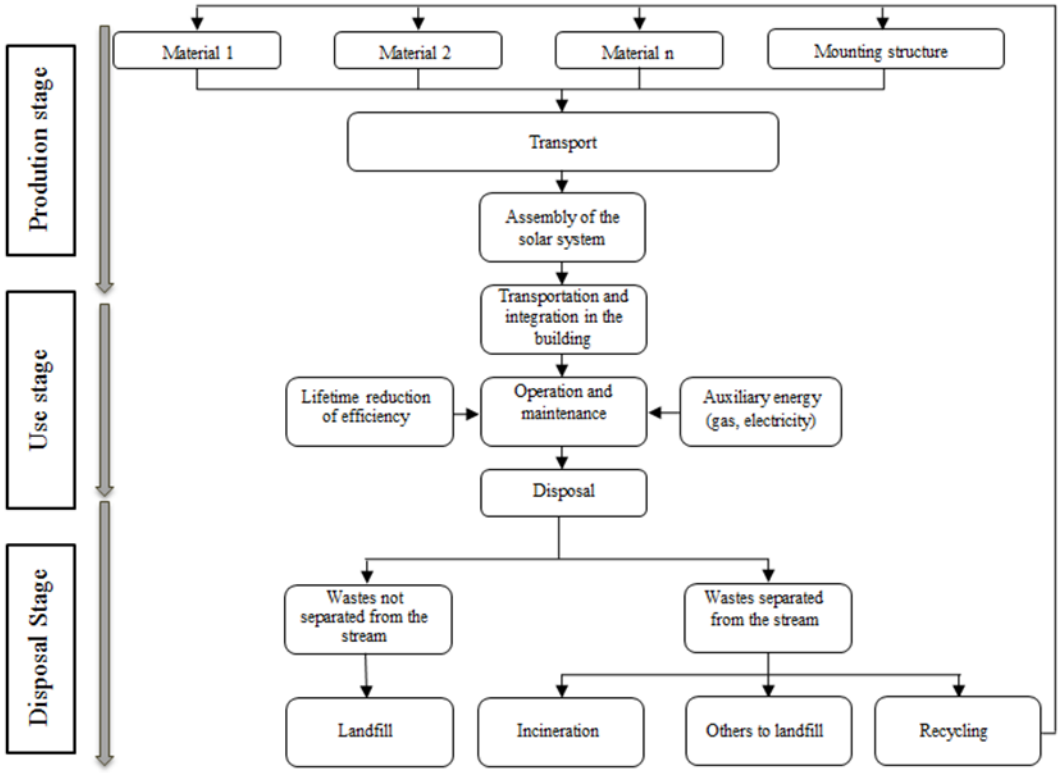


Figure 1. System boundaries of the study

Characteristics	Solution 1	Solution 2	Solution 3	Solution 4
System type	Forced circulation	Forced circulation	Thermosiphonic	Thermosiphonic
Accreditation	DIN CERTCO	DIN CERTCO	DIN CERTCO	DIN CERTCO
Aperture area (m^2)	2.426	2.26	1.936	1.936
Optimal opptical efficiency (n_0)	0.794	0.648	0.761	0.761
1st order heat loss coefficient (a_1) W/m^2K	0.386	4.76	4.008	4.008
2nd order heat loss coefficien (a_2) W/m^2K2	0.013	0.013	0.013	0.013
Auxiliary energy	Heat pump (COP=4.3)	Butane gas boiler (η=93.6%)	Electrical resistance (η=93%)	Butane gas boiler (η=93.6%)

Table 1. Technical specifications of the alternative STCs systems considered in the case study

2.2.2. Use phase

The use phase of solar thermal systems corresponds to the use phase of the building [11]. In this study it was considered that the lifetime of the building is 60 years. The quantification of the energy required for domestic hot water production is based on methodology of the Portuguese Regulation of Energy Performance of Residential Buildings (REH) [12].

In this stage, the inputs and outputs to and from the system boundary resulting from the maintenance of the STS together with the energy consumption in the auxiliary systems are considered. The LCI of both the maintenance operations and the Portuguese energy mix are also based in the Ecoinvent V2.2 database [9].

2.2.3. End-of-life phase

In this study it is considered the worst end-of-life scenario, i.e. after the lifetime of 20 years all components of the STC will be sent to the landfill [10].

2.3. Life cycle costs analysis

According to the rules of the FEMP [6], the life cycle costs of a solar thermal system should include the capital cost, replacement cost, auxiliary energy costs, maintenance and repair costs and the residual costs. In this methodology and study, only the residual costs where not addressed due to the lack of information found in the bibliography. Table 2 presents the capital and the repair plus the maintenance costs of the solar thermal collectors considered. Figures presented in Table 2 are based on maintenance study of solar thermal systems and on prices of solar thermal systems in the market [13], [14], [15], [16].

Solutions	Capital cost (€)	Repair and maintenance costs over the life cycle of solar thermal system (€)
Solution 1	4987.00 €	1990€
Solution 2	4336.00 €	1990€
Solution 3	2743.00 €	1990€
Solution 4	2743.00 €	1990€

Table 2. Figures considered in the life cycle cost analysis

2.4. Environmental life cycle impact assessment

According to EN ISO 14044:2006, Life Cycle Environmental Impact Assessment (LCIA) is a stage of LCA aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product. Therefore, this stage is aimed to convert the LCI data collected into potential environmental impacts using one or more normalized LCIA method [9]. Table 3 presents the LCIA method and the declared unit used in the study to quantify the considered environmental indicators (potential environmental impacts and aspects).

Environmental Indicators	Units	Methods
Abiotic Depletion Potential (ADP)	[Kg Sb equiv.]	CML 2 baseline 2000 V2.04
Global warming potential (GWP)	[Kg CO_2 equiv.]	CML 2 baseline 2000 V2.04
Depletion of the stratospheric ozone layer (ODP)	[KgCFC-11 equiv.]	CML 2 baseline 2000 V2.04
Acidification potential (AP)	[Kg SO_2 equiv.]	CML 2 baseline 2000 V2.04
Formation potential of tropospheric ozone (POCP)	[Kg C_2H_4 equiv.]	CML 2 baseline 2000 V2.04
Eutrophication potential (EP)	[Kg PO_4 equiv.]	CML 2 baseline 2000 V2.04
Abiotic depletion potential of fossil resources (ADP_FF)	[MJ equiv.]	Cumulative Energy Demand V1.0
Embodied renewable energy (ERE)	[MJ equiv.]	Cumulative Energy Demand V1.0

Table 3. Environmental indicators, declared units and respective LCIA methods used for their quantification

3. SOFTWARE LCABISTS

Based in the presented methodology a software tool (LCABISTS) was developed. This tool is aimed to foster the integration of solar thermal system in buildings and therefore to improve their sustainability by providing a simplified approach to assess the environmental performance and economic viability of using different types of STSs.

This software allows the calculation of the potential environmental impacts presented in Table 3 that result from the life cycle of a solar thermal system, considering the embodied impacts, the impacts resulting from its installation in the building and the impacts arising from its maintenance and repair. This assessment is done together with the life cycle cost analysis of the STS. For this purpose the software has a database with the LCI data, initial cost and maintenance and repair costs of most common STSs used in Europe. At the end the software produces for the STC under analysis a report with the carbon payback period, energy payback period and the cost payback period. The results presented in the next section for the abovementioned case study are calculated using this tool.

4. RESULTS AND DISCUSSION

Using the presented methodology and software tool, tables 4 and 5 present the environmental impacts and sustainability indexes for each alternative STS solution over the life cycle of the building (60 years). In these tables the original roof slope (24º) and the replacement of the STS each 20 years was considered.

Table 5 shows that in single-family buildings the thermosyphon system (solutions 3 and 4) is more economically viable than the forced circulation system for preparation of domestic hot water, due to lower initial cost. Another aspect that affects the economic viability of a solution is the type of energy used in the auxiliary system, depending on its cost per kWh, i.e., the higher is the cost of the energy used in the conventional system used for hot water production, the lower the cost payback is. Comparing the two thermosyphon systems, the results highlighted that although the electric auxiliary systems have higher environmental impacts than a butane gas boiler, their carbon payback period is lower. Analysing the results it is possible to conclude that solution 4 is the best alternative for the project since it has the lower life cycle impact and the lower economic payback time period.

Environmental Indicators	Solution 1		Solution 2		Solution 3		Solution 4	
	Before	After	Before	After	Before	After	Before	After
ADP	5.31E+01	5.18E+01	1.93E+02	1.89E+02	3.79E+02	3.56E+02	1.79E+02	1.69E+02
GWP	6.91E+03	6.75E+03	2.38E+04	2.33E+04	5.02E+04	4.72E+04	2.21E+04	2.09E+04
ODP	7.80E-04	7.50E-04	3.00E-03	2.90E-03	3.20E-03	3.00E-03	2.79E-03	2.64E-03
AP	3.26E+01	3.24E+01	4.57E+01	4.53E+01	4.48E+02	4.20E+02	4.18E+01	4.08E+01
POCP	2.38E+00	2.37E+00	4.22E+00	4.17E+00	1.76E+01	1.66E+01	3.92E+00	3.79E+00
EP	2.10E+01	2.10E+01	2.29E+01	2.28E+01	9.67E+01	9.17E+01	2.08E+01	2.06E+01
ADP_FF	1.15E+05	1.13E+05	4.02E+05	3.94E+05	7.23E+05	6.81E+05	3.71E+05	3.51E+05
ERE	9.46E+03	9.47E+03	9.91E+03	9.90E+03	1.25E+05	1.18E+05	8.67E+03	8.62E+03

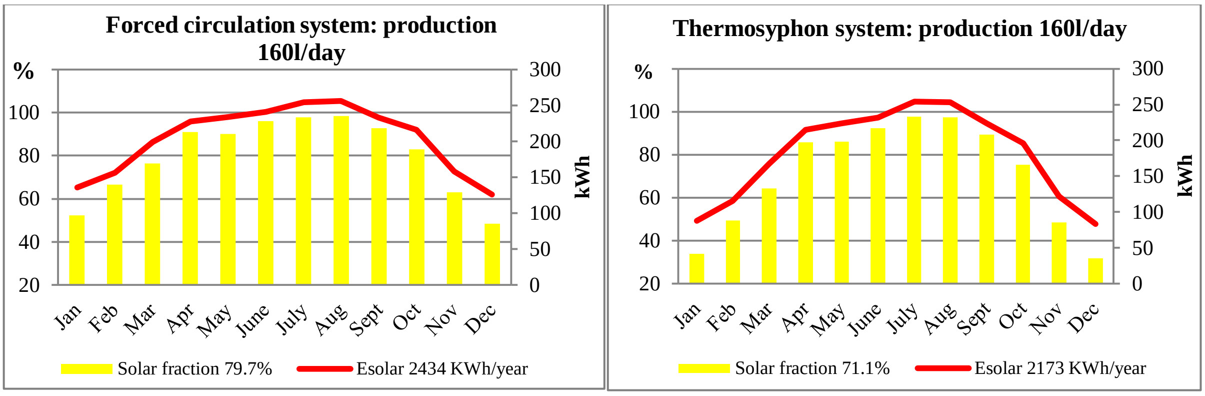
Table 4. Results from the software developed: Environmental impacts of each STC alternative, before and after optimization

Sustainability Indexes	Solution 1		Solution 2		Solution 3		Solution 4	
	Before	After	Before	After	Before	After	Before	After
Carbon Payback Period	0.73	0.73	2.53	2.49	0.89	0.87	2.24	2.17
Energy Payback Period	0.8	0.8	2.75	2.71	0.94	0.91	2.35	2.28
Economic Payback Period	12.59	12.55	11.39	11.25	9.57	9.29	7.23	7.01

Table 5. Results from the software developed: Sustainability indexes of each STC alternative, before and after optimization

The second part of the study aimed to analyse the influence of an optimized slope in the results. For this purpose and using the Solterm V5.0 software [17] tool the optimal slope was calculated and the results showed that for this latitude the optimized roof slope is 39º for forced circulation system and 46º for thermosyphon system. Afterwards the above-mentioned methodology was applied again to the four STC alternatives, considering the optimized slope.

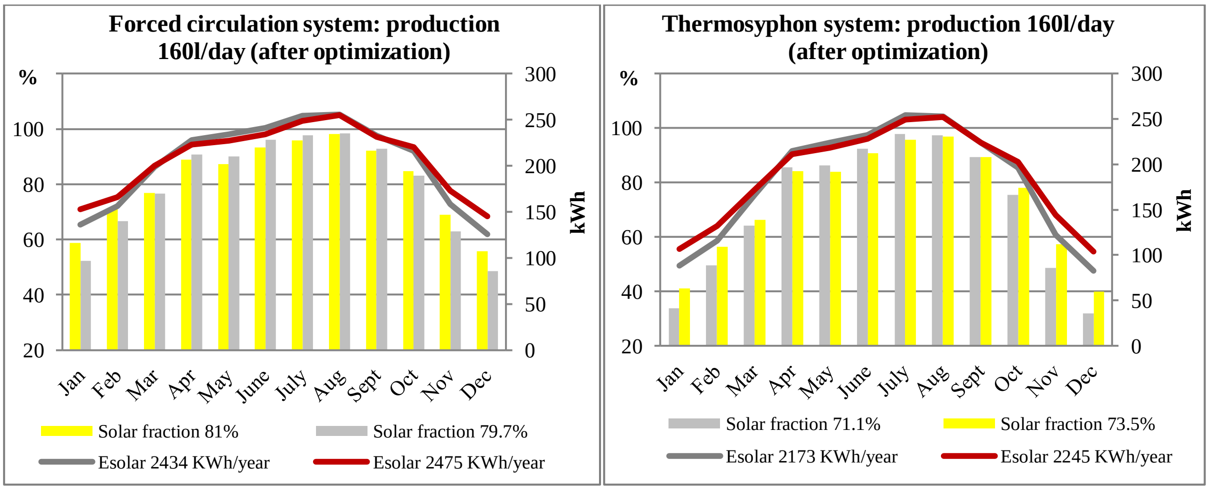
In the optimization study it was found an increased uptake of solar energy in January and December. This is an important improvement since these are the months of lower solar radiation. Figures 2 and 3 show an increase of 3.3% in the annual energy netted by the thermosyphon systems and an increase of 1.6% of annual energy netted by forced circulation systems. This variation is reflected in the environmental impacts and sustainability indexes of the presented systems (Tables 4 and 5).



Forced circulation system: production 160l/day

Thermosyphon system: production 160l/day

Figure 2. Energy captured by month, before optimization



Forced circulation system: production 160l/day (after optimization)

Thermosyphon system: production 160l/day (after optimization)

Figure 3. Energy captured by month, after optimization

From these results it is also possible to conclude that the thermosyphon systems are more susceptible to the inclination of solar collectors than forced circulation systems.

As final conclusion of this study, it was possible to conclude that the passive solar system for domestic hot water production is economically more viable than a forced circulation domestic hot water production system when applied to a single-family house.

5. CONCLUSIONS

In summary, the payback period of the additional environmental, energy and economic impacts of installing a STS in a building must always be less than the life span of the system. In Portugal due to the fact that STS are mandatory, for a building owner it is always more attractive to implement a system with a short economic payback period. From this study, it was possible to conclude that the thermosyphon system has the best economic performance and approximately the same energy and environmental performance as the forced circulation system. The energy and environmental payback periods for thermosyphon systems are less than 3 years, and the economic payback period of thermosyphon systems vary from 7 to 9 years, according to the used vector as auxiliary energy.

The software developed presents a detailed LCA and LCC analysis of solar systems, as well as their contribution to the life cycle performance of buildings. This software provides a tool for the economic and environmental cost-benefit analysis of solar thermal systems.

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