ECONOMIC AND ENVIRONMENTAL IMPACTS OF SOLAR THERMAL TECHNOLOGIES THROUGH LIFE CYCLE ASSESSMENT

M. Milousi[1], M. Souliotis[2], S. Papaefthimiou[1]

[1]School of Production Engineering and Management, Technical University of Crete, Chania, Greece

[2]Department of Chemical Engineering, University of Western Macedonia, Kozani, Greece

*email: mmilousi@isc.tuc.gr

ABSTRACT

The objective of this study is the holistic evaluation of the energy, environmental and economic performance of the most commercially available types of solar thermal collectors: flat plate and vacuum tube systems. These collectors are both broadly used in the market and can considerably cover significant domestic thermal needs. Their economic and environmental implications were assessed through techno-economic analysis, conducted via RETScreen and detailed cradle to grave Life Cycle Assessment (LCA), executed from the production and acquisition of raw materials to the final disposal of the selected energy systems, carried out through SimaPro [1,2].

The results for both selected collectors reveal that the production stage is responsible for the majority of the total environmental impacts but over their operation they succeed to diminish significant amounts of emitted greenhouse gases due to the avoidance of fossil fuels. The obtained outcomes of the combined evaluation not only identify the products' hot-spots but also give useful insights for the selection of the most appropriate system when installing such solar energy harvesting technologies.

KEYWORDS

Life Cycle Assessment; Solar thermal collectors; Solar water heating; Techno-economic assessment

1. INTRODUCTION

Solar thermal technologies are becoming widespread and contribute significantly to the decrease of the residential energy requirement as they practically deal with domestic hot water production and can cover significant thermal needs. Domestic solar water heating is an effective method of utilizing available energy sources to perform useful work. The energy from th sun can provide hot water for many domestic and industrial applications, displacing the need to burn fossil fuels. Cheap and abundant energy with minimum area requirement and environmental impacts are the important factors for the development of solar energy systems. Although solar energy is considered a "clean" energy form, both manufacture and final disposal of Domestic Solar Hot Water Systems (DSHWS) are associated with environmental transactions. This is due to the energy required for the raw material extraction and the final product assembly as well as due to the final disposal and/or recycle of the system at the end of its life. Therefore, it is necessary to evaluate solar technology accounting for the indirect environmental impacts caused by these systems over their whole life cycle. In order to validate the environmental hot spots a cradle to grave LCA was implemented from raw material extraction through manufacture, use, and end of life of the two studied energy systems. In addition, a comparative techno-economic assessment for the quantification of the energy output and the economic income associated with each of the selected collector was carried out. The goal of the combined analysis of the two types of solar collectors is to evaluate over their lifecycle, the environmental and economic impacts of the thermal energy converted to hot water needs and consequently to the equivalent avoided electricity. The two step evaluation confirmed that DSHWS are proven technologies, with reduced maintenance costs and increased energy savings with less payback periods [3-5].

2. METHODOLOGY

2.1. LCA

LCA is an internationally recognized method for quantifying the environmental impacts of a product, process, or a system. According to the international standards ISO14040 series this study has been conducted by considering the following steps: (1) Goal and scope definition, (2) Life-cycle inventory (LCI), (3) Life-cycle impact assessment (LCIA), (4) Interpretation of the results [6].

2.1.1. Goal and scope definition

The overall goal of the study is to estimate the lifecycle impacts of the thermal energy converted to hot water needs and consequently to the equivalent avoided electricity, thus the functional unit was the saving of 1 kWh electricity for hot water production, for the two types of solar collectors for use in a typical single house family.

The system boundaries account for all the impacts from materials extraction and processing, manufacture, transportation, use and disposal for both solar systems (excluding auxiliary heating), including various technical components, heat exchange fluid, installation of copper pipes, transportation of parts, delivery with a van and montage on the roof. The main parts of the studied systems are the solar collectors – absorbers with aperture area 12.3 m^2 and 10.5 m^2 for the flat plate and the vacuum tube collectors respectively, the 200l heat storage tank, and the roof mounting structure.

Both systems are aimed for installation on existing buildings (slanted roof installation) and their operational lifetime has been assumed to be 20 years.

2.1.2 Life-cycle inventory

The complete set of LCI data was compiled according to the data format and quality guidelines of ecoinvent. This database provided detailed and transparent background data for a range of materials and services used in the production chain of the selected systems and is already included in the software SimaPro 8.5 that has been employed for the realization of the LCA study [7].

2.1.3 Life-cycle impact assessment

In this research, the environmental impacts were determined from a midpoint-level approach. The LCIA method used for the characterization of solar collectors was ReCiPe Midpoint, as it provides the most extensive set of midpoint impact categories, aiming to highlight the global warming potential and GHG emissions, fossil fuels and climate change impacts related to each technology [8].

2.2. Techno-economic analysis

The comparative techno-economic assessment of the installation of the two solar thermal collectors has been carried out through RETScreen. The installation location site was chosen to be the Acrotiri area of Chania in Crete, while all meteorological data (annual time series of average climate conditions) have been extracted from the same software referring to a weather station in Chania. After selecting the location area, the complete analysis for each solar collector has been conducted. This analysis comprised the following discrete steps: **i.** determination of the annual hot water needs for the studied single family house, **ii.** selection of the auxiliary hot water heating system, **iii.** selection of the solar collector technology (i.e. flat plate and vacuum tube) and specification of the technical parameters, **iv.** energy analysis (see aggregated results in Table 1), **v.** financial analysis (see Figure 1 and Figure 2).

Figure 1. Financial analysis results of the studied flat plate solar collector.

Figure 2. Financial analysis results of the studied vacuum tube solar collector.

3 RESULTS AND DISCUSSION

3.1 LCA

In order to validate the environmental impacts a cradle to grave LCA has been implemented for flat plate collectors with copper absorber and vacuum tube collectors.

3.1.1 Environmental impacts

The results from the environmental evaluation for the flat plate system indicated that 57% and 27.1% of all total inflows and outflows were due to the production of the collector and the tank respectively, while for the vacuum tube system the corresponding values were 45.3% and 34.8%. Thus, the production stage of the collector component contributed the most important part of the environmental impacts in the life cycle for both studied systems.

3.1.2 Comparison of the LCA results

The objective of conducting the LCA study is to make a comparative environmental analysis of different solar systems with a focus on comparing flat plate and vacuum tube collectors. The results are used to validate the environmental impacts of each solar system. In Table 1 and Figure 3 the aggregated LCA inventory results for the studied solar thermal systems are depicted. These are harmonized data representing the LCA results (for each impact category) per total energy produced per aperture area (in kWh/m^2) by each solar collector, thus providing a holistic evaluation indicator (i.e. environmental burden per total energy produced). It is important to stress the fact that the electricity mentioned above in kWh corresponds to the necessary energy for heating water, which is substituted by the operation of the solar collectors which convert solar radiation to heat transferred to stored hot water in their tank. As depicted in Table 1 the cumulative CO_2eq emissions over the whole life cycle of the solar systems were quite close, varying between 2.22×10^{-2} and 2.38×10^{-2} kg CO_2eq/kWh·m^2, and the lowest value corresponded to the vacuum tube collector.

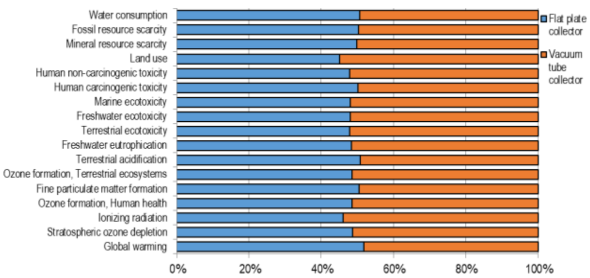

Figure 3. LCA results for the studied solar thermal

systems: relative contributions to the impact categories.

These outcomes are helpful in distinguishing the impacts of each solar system and can be used during the combined environmental and technical assessment of installing such solar energy harvesting technologies.

3.2 Techno-economic analysis

For the financial analysis we considered that the electricity price has been set to 0.15€/kWh and the installation was funded by own means. The hot water needs for a typical family house with 4 occupants have been estimated to 2817kWh per year. A typical auxiliary hot water heating system burning oil has been considered for backup.

Table 1. Aggregated LCA inventory results for the studied solar thermal systems.

Impact category	***Unit (per m^2)***	***Flat plate collector***	***Vacuum tube collector***
Global warming	kg CO_2 eq/kWh	2.38×10^{-2}	2.22×10^{-2}
Stratospheric ozone depletion	kg CFC-11 eq/kWh	1.29×10^{-8}	1.36×10^{-8}
Ionizing radiation	kBq Co-60 eq/kWh	1.61×10^{-3}	1.88×10^{-3}
Ozone formation, Human health	kg NO_x eq/kWh	6.50×10^{-5}	6.89×10^{-5}
Fine particulate matter formation	kg $PM_{2.5}$ eq/kWh	8.78×10^{-5}	8.61×10^{-5}
Ozone formation, Terrestrial ecosystems	kg NO_x eq/kWh	6.66×10^{-5}	7.07×10^{-5}
Terrestrial acidification	kg SO_2 eq/kWh	2.07×10^{-4}	2.01×10^{-4}
Freshwater eutrophication	kg P eq/kWh	3.89×10^{-5}	4.16×10^{-5}
Terrestrial ecotoxicity	kg 1 4-DB eq/kWh	8.55×10^{-1}	9.31×10^{-1}
Freshwater ecotoxicity	kg 1,4-DB eq/kWh	6.42×10^{-3}	6.94×10^{-3}
Marine ecotoxicity	kg 1,4-DB eq/kWh	9.27×10^{-3}	1.00×10^{-2}
Human carcinogenic toxicity	kg 1,4-DB eq/kWh	6.56×10^{-3}	6.53×10^{-3}
Human non-carcinogenic toxicity	kg 1,4-DB eq/kWh	2.24×10^{-1}	2.44×10^{-1}
Land use	m^2a crop eq/kWh	1.25×10^{-3}	1.52×10^{-3}
Mineral resource scarcity	kg Cu eq/kWh	1.02×10^{-3}	1.03×10^{-3}
Fossil resource scarcity	kg oil eq/kWh	5.45×10^{-3}	5.38×10^{-3}
Water consumption	m^3/kWh	2.39×10^{-4}	2.33×10^{-4}

Table 2. Results of the techno-economic assessment for the studied solar thermal collectors.

Solar collector type	***Flat plate***	***Vacuum tube***
Aperture area [m^2]	2.32	2.61
FrUL [(W/m^2)/°C]	4.6	1.7
Cost [€]	900	1300
Total energy saved [kWh]	27260	29980
Total energy saved per aperture area [kWh/m^2]	11750	11487
Solar fraction [%]	55.3	62.7
Annual savings [€/yr]	352	341
Payback time [yr]	2.6	3.8

In Table 2 the main results of the RETScreen analysis for the studied solar thermal collectors have been gathered. Both selected systems can be considered as top-class products, while the purchase cost of the vacuum tube collector is significantly higher, i.e. 1300€ versus 900€. The thermal losses coefficient, FrUL, was increased for the flat plate collector compared to the vacuum tube system, i.e. 4.6 vs 1.7 $(W/m^2)/°C$ respectively. This is due to the completely different thermal losses suppression design followed in each system, which practically makes vacuum tube collector unaffected by variations in ambient temperature. In addition, the solar fraction value for the vacuum tube system was higher than the flat plate collector (i.e. 62.7% vs. 55.3% respectively). On the other hand, it is evident that overall this parameter does not play an important role in the energy outcome of the systems, as finally the flat plate collector provided slightly more energy per aperture area throughout the year. This is mainly due to two reasons: i. the weather conditions in Crete (high intensity solar radiation for extended time periods and with increased ambient temperatures throughout the year) are favorable for solar systems and thus the advantageous thermal insulation and the ability to reach high temperatures of the vacuum system was not necessary, ii. the pump in the vacuum system requires more electricity due to increased friction in the collector (more complex circulation system).

4 CONCLUSIONS

The comparison of flat plate and vacuum tube solar thermal collectors aimed at stressing the advantages and disadvantages of both technologies. For the environmental profile of the studied systems the production stage of the collector component contributed the most important part of the environmental impacts in the life cycle for both studied systems followed by the production of the tank. The two technologies exhibited similar environmental impacts in most categories, but the vacuum tube collector had highest values in most cases.

Regarding the techno economic assessment both collectors could cover more than half of the annual hot water needs for a family house with 4 occupants, as the solar fraction values - practically denoting the percentage of hot water needs covered by the system annually - were satisfactory. Additionally, the vacuum tube collector was practically unaffected by the variations in ambient temperature due to its significantly lower thermal losses coefficient, but this technical advantage was not reflected in its final energy outcome mainly due to the favorable weather conditions in the selected installation location which made the flat plate collector equally efficient and to the increased electricity consumption of its pump. Moreover, the purchase cost of the vacuum collector is almost 45% higher, thus stressing the fact that for typical installations in Crete the flat plate system should be the principal option. Nevertheless, the economic viability of both systems was proved as the simple payback period estimated to be 2.6 and 3.8 years for the flat plate and the vacuum tube system respectively.

ACKNOWLEDGEMENTS

Research co-financed by the European Union and Greek national funds through the Operational Program Competitiveness, Entrepreneurship and Innovation, under the call RESEARCH – CREATE – INNOVATE

(project name ASVaCS, code: T1EDK-01740).

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