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Life cycle analysis of a building-integrated solar thermal collector, based on embodied energy and embodied carbon methodologies

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ABSTRACT

The present study is a life cycle analysis of a patented building-integrated solar thermal collector which was developed/experimentally tested at the University of Corsica, in France, with the concept "integration into gutters/no visual impact". Three configurations (reference and two alternatives) are evaluated. The life-cycle impact assessment methodologies of embodied energy (EE)/embodied carbon (EC), two databases and multiple scenarios are adopted. The results reveal that the reference system can considerably improve its environmental performance by utilizing collectors connected in parallel. The Energy Payback Time of the reference system decreases to less than 2 years by parallel connection while it is around 0.5 years if recycling is also adopted. The EE of the systems is around 3 GJ_{prim}/m^2 and it is reduced to around 0.4–0.5 GJ_{prim}/m^2 by recycling. The EC of the configurations is approximately 0.16 t $CO_{2.eq}/m^2$ without recycling and around 0.02–0.03 t $CO_{2.eq}/m^2$ with recycling. $CO_{2.eq}$ emissions are strongly related with electricity mix. A reduction 28–96% in $CO_{2.eq}$ emissions of the systems is achieved by adopting configurations with "double collector surface/output". Concerning indicator of sustainability, the system with parallel connection shows a value of 0.78. The findings of the present investigation could be utilized for the design of building-integrated solar thermal systems as well as for research purposes.

1. Introduction

Towards the reduction of the energy consumption in the building sector, solar thermal systems play an important role especially for places with high solar radiation such as Corsica and Spain. A recent tendency is the integration of these systems into the building (building-integrated (BI) systems) since it provides advantages (high aesthetic value, etc) in comparison with the building-added (BA) installations.

In the literature there are some studies about BI solar systems but most of them regard BI Photovoltaics (PVs) [1]. There are few studies about real BI solar thermal systems and these works are experimental or numerical [2,3]. A survey on architectural integration of solar technologies [4] demonstrated that the architectural integration is important in the spreading of solar thermal technologies while D'Antoni and Saro [5] presented solar collectors based on their degree of building integration.

Moreover, there are few studies which examine the environmental performance of domestic solar thermal systems by means of life cycle analysis (LCA). However, these LCA investigations are mainly for BA configurations [6]. There are only few LCA works about real BI solar thermal systems; nevertheless, they concern passive solar walls [7]. In the following paragraphs a review of LCA investigations about solar thermal systems for buildings is presented. Emphasis is given on the studies which are based on embodied energy (EE) and embodied carbon (EC) life cycle impact assessment (LCIA) methodologies.

Among the LCA investigations of BA active flat-plate collectors is that of Kalogirou [8]. A solar water heating and a solar space/water heating system were investigated (Nicosia, Cyprus). The energy for manufacture/installation was recouped in about 1.2 years while the payback time in respect to the emissions ranged from few months to 9.5 years. Streicher et al. [9] studied two domestic hot water systems (same design; different materials). The energy payback time (EPBT) was 1.4 and 2.1 years for the first and the second system, respectively. Otanicar and Golden [10] compared a nanofluid solar collector with a conventional one (domestic hot water; Phoenix, Arizona, US). The nanofluid collector had lower embodied energy (≈9%) and about 3% higher pollution offsets than a conventional collector.

Regarding BA passive flat-plate collectors, Kalogirou [6] studied a domestic, thermosiphon solar water heater (Nicosia, Cyprus).

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The energy spent for manufacture/installation was recouped in approximately 13 months while the payback time varied from few months to 3.2 years. Ardente et al. [11] studied a passive solar device for domestic use (Palermo, Italy) and an overall primary energy of 11.5 GJ was estimated. Based on [11], Ardente et al. [12] also conducted a study with several scenarios: the results showed remarkable uncertainty regarding aluminium, copper, thermal fluid and galvanized steel.

In terms of technologies other than flat-plate configurations, Hang et al. [13] conducted an economic and environmental LCA of solar hot water systems, including evacuated-tube and flat-plate collectors (residential buildings). Two types of auxiliary systems (natural gas; electricity) and three locations (Los Angeles; Atlanta; Chicago) were examined. The flat-plate/natural gas auxiliary heater systems had the best performance among all the types and at all the locations. The energetic and environmental payback periods for solar water heating systems were less than half of a year. The life cycle cost payback for solar water heating systems ranged from 4 to 13 years (for different cities/configurations when using conventional electrical water heating system in each city as benchmark).

On the other hand, there are LCA investigations about integrated collector/storage systems. Smyth et al. [14] studied a heat retaining, integrated collector/storage solar water heater with reflector, for Northern Europe (Ireland). The primary embodied energy of the materials was 2.94 GJ while the total embodied energy for the unit was 3.81 GJ. The total energy used in the manufacture of the unit was recouped in less than 2 years. Battisti and Corrado [15] also studied an integrated collector/storage system (for Mediterranean countries) and its EPBT and CO_2 PBT ranged from 5 to 19 months.

Based on the above mentioned studies, it can be seen that there is a gap in the literature regarding LCA works about real BI solar thermal systems. Thus, in the frame of the present study a patented BI solar thermal collector is investigated based on a life-cycle assessment approach. The studied solar system consists of collectors which are integrated into building gutters. Three configurations are examined based on different LCIA methodologies (EE and EC). Multiple scenarios and two databases are adopted. The innovation of the present study lies in the evaluation of the environmental profile of the previously specified, innovative BI solar thermal configurations, by investigating the effect of different scenarios (related to material recycling, electricity mix, etc). The influence of system performance on its environmental impact is also examined. Moreover, the indicator of sustainability (IS) of the systems is calculated and critically commented. Thus, the present study fills the gap which exists in the literature while the results could offer useful information for the design of 'future' BI solar thermal systems since these systems are a new tendency in the building sector.

2. Materials and methods

For the LCA study, in compliance with ISO 14040-43 [16–19], the following steps are adopted: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, (4) interpretation of the results.

2.1. Functional unit and system boundaries

The functional unit is the whole system (14 solar collectors; additional components of the system: storage tank, pump, external tubes with their insulation, glycol). The system boundaries include the whole system in terms of: material manufacture (for collectors/system additional components); manufacture of the collectors; system installation; use/maintenance; transportation; disposal. Only for the comparison of the alternative configurations (from EE and EC point of view), with emphasis on material manufacture phase (materials of the collectors), the functional unit "1 m^2 of absorber surface" is adopted.

2.2. System definition

2.2.1. Technical characteristics of the studied solar systems

The studied BI solar thermal system is illustrated in Fig. 1. This system was developed and tested at the University of Corsica, in France and it is based on a patented concept of solar collector for water heating [20]. The name of the system is H2OSS®, it is integrated into building gutters and it shows high building integration with no visual impact. The system is arranged so that it could be also used on north-facing walls (facing south into the drainpipe). The solar collector is tilted 25° from the horizontal (Fig. 1a) in the gutter in order to avoid the shading effect of the gutter. The solar system is totally invisible from the ground level due to the drainpipe integration (Fig. 1a). The ducting connecting the house to the solar collector is hidden in the vertical drainpipe. One installation consists of several connected modules. One module is of approximately 1 m length and 0.1 m width for individual houses. Larger modules can be developed for applications at a larger scale. The components of one unit (Fig. 1b) include: a high-selective absorber; a glass cover; one tube for cold water flow (lower insulated tube); one tube for hot water flow (in thermal contact with the absorber); thermal insulation; external casing; gutter. More details about the materials/components are given in Section 2.3.

In Table 1, the basic technical characteristics and the performance of the studied configurations are presented (more details can be found in [2,3,20–22]). The reference system is connected in series and the tubes (cold water tube and hot water tube) are at different levels (Fig. 1b). System 2 is the same with System 1 but the collectors are connected in parallel. System 3 is connected in series and the tubes are at the same level (into the absorber). This third system was numerically optimized for achieving better performance than the two previous ones. Systems 1 and 2 were studied experimentally and numerically [2,22]. System 3 was studied only numerically [21] since absorbers of this size with the tubes at the same level are not commercially available.

2.2.2. Assumptions

In the frame of the present LCA study, the following assumptions are adopted:

- The calculations in terms of the outputs/inputs of Systems 1–3 were conducted for a system with 14 solar collectors (around 2 m^2 total solar absorber surface) and a 100 l-tank, suitable for two persons.
- One unit of solar collector (Fig. 1b) and the additional parts of the system include the materials/components that they were previously mentioned (Sections 2.1 and 2.2.1).
- The impact regarding the processes for collector manufacture is incorporated in the LCA model as 27% of the impact which is related to the manufacture of collector materials [6,10].
- The impact of system installation is included in the LCA model as 3% of the total impact for the manufacture of collector/additional components [6,10].
- Glycol is adopted as anti-freeze protection fluid. Given the fact that in Corsica the temperatures during winter are not very low [23], a proportion of 20% glycol in the glycol–water mixture is assumed. The impact of this mixture is calculated based on [12].
- The use/operational phase of the system includes: electricity for pumping/auxiliary heating, replacement of some parts of the system over its lifetime (one replacement of the glasses; one replacement of the storage tank; five replacements of the glycol), general maintenance of the system (cleaning, etc). The impact of the