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Review

Review and perspectives on Life Cycle Analysis of solar technologies with emphasis on building-integrated solar thermal systems

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ABSTRACT

Building-Integrated (BI) solar thermal are systems which are integrated into the building, are a new tendency in the building sector and they provide multiple advantages in comparison with the Building-Added (BA) solar thermal configurations. The present investigation is a critical review about Life Cycle Analysis (LCA) studies of solar systems. Emphasis is given on the BI solar thermal installations. Studies about BA configurations and systems which produce electrical (or electrical/thermal) energy are also presented in order to provide a more complete overview of the literature. The influence of the BI solar thermal systems on building environmental profile is also examined. Critical issues such as ongoing standardization and environmental indicators are discussed. The results reveal that there is a gap in the field of LCA about real BI solar thermal (and solar thermal/electrical) installations. Thus, there is a need for more LCA studies which examine the BI solar thermal system itself and/or in conjunction with the building. Active systems which could provide energy for the building would be interesting to be studied. Investigations about the influence of the BI solar thermal systems on building life-cycle performance could also provide useful information in the frame of a more sustainable built environment.

1. Introduction

Solar thermal systems play an important role towards the reduction of the energy consumption in the building sector. The integration of these installations into the building (Building-Integrated (BI) systems) is a new tendency and it should be promoted since it provides multiple advantages (e.g. higher aesthetic value) towards zero or nearly zero energy buildings, in comparison with the Building-Added (BA) solar thermal configurations [1].

In the literature there are some studies about BI solar systems; however, most of them are about BI Photovoltaics (PVs) [2]. There is a small number of studies about real BI solar thermal systems. These studies are experimental-based [3] and/or modelling-based [4–6] and they regard integration into building façade [3] or into building gutters [4,5]. Concerning the modelling studies, some they give emphasis on the system itself [4,5] and some examine the system in conjunction with the building [6].

On the other hand, there are few Life Cycle Analysis (LCA) works about BI solar thermal systems; nevertheless, they are mainly about passive solar walls (Trombe walls) [7]. Moreover, there is a small number of LCA studies about BA solar thermal configurations. In that category, representative references are those of: Kalogirou [8] for a solar water heating and a solar space/water heating system; Otanicar and Golden [9] about a nanofluid solar collector vs. a conventional collector; Ardente et al. [10,11] for a passive solar collector. Most of these studies regard Domestic Hot Water (DHW) applications while the most commonly adopted life-cycle impact assessment methodologies are based on embodied energy and embodied carbon.

In the frame of the present article, a critical review about LCA studies of solar systems is conducted. The review focuses on the BI solar thermal installations. Studies about BA configurations as well as about solar systems which produce electrical (or electrical/thermal) energy are also cited in order to have a more complete picture of the studies which are available in the current literature. The effect of the BI solar thermal systems on building environmental performance is also discussed along with critical issues such as ongoing standardization and environmental indicators.

In the literature there are no review studies about the role of LCA in the field of solar thermal systems (especially for BI solar thermal configurations) and this is the innovation of the present investigation. The present study fills this gap which exists in the literature while in parallel it highlights critical issues such as the influence of the BI solar thermal systems on building life-cycle performance.

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The cited references are critically discussed and BI configurations which would be interesting to be studied from LCA point of view as a future prospect are also proposed. In this way, the present investigation provides useful information for the development of future BI solar thermal systems/buildings with low environmental impact.

2. Solar thermal systems

2.1. Building-integrated solar thermal systems

2.1.1. Building-integrated solar thermal collectors

The recent investigation of Lamnatou et al. [12] is the only LCA study about a real BI active solar thermal system. The studied system is patented [13], regards integration into building gutters and it has been developed/tested at the University of Corsica, in France [4,5,14,15]. Three alternative configurations were evaluated: 1) collectors in series connection with tubes (for cold and hot water flow) at different levels (System 1), 2) collectors in parallel connection with the two tubes at different levels (System 2), 3) collectors in series connection with the two tubes at the same level (theoretical configuration) (System 3). The phases of material and collector manufacture, material manufacture of system additional components, system installation, use/maintenance, transportation and disposal were taken into account. The life-cycle impact assessment methodologies of embodied energy and embodied carbon, based on two databases (ICE [16] and Alcorn [17]), were used. Multiple scenarios: 'No Recycling' vs. 'Recycling', 'France's vs. Spain's electricity mix', etc were adopted. The results demonstrated that:

- The embodied energy of the systems (for both databases) was around 3 GJ_{prim}/m^2 of absorber surface. By using recycling this value was reduced to around 0.4–0.5 GJ_{prim}/m^2.
- The embodied carbon of the systems (according to both databases) was around 0.16 t $CO_{2.eq}/m^2$ and by using recycling this value was approximately 0.02–0.03 t $CO_{2.eq}/m^2$.
- By recycling, the Energy Payback Time (EPBT) of System 1 was approximately 1.5 years while by utilizing System 2, this value decreased to around 0.5 years.
- $CO_{2.eq}$ emissions were strongly related with the adopted source of electricity: France's electricity mix showed considerable lower $CO_{2.eq}$ emissions than Spain's electricity mix or than a natural gas power plant. This is related with the high penetration of nuclear energy in France's electricity [18]. For all the studied systems, the scenario 'France's electricity' showed the lowest impact regarding $CO_{2.eq}$ emissions. However, the high penetration of nuclear energy results in higher cumulative energy demand for the French electricity comparing with the other two sources of electricity [18].
- A considerable reduction (28–96%) of Systems 1-3 $CO_{2.eq}$ emissions was achieved by utilizing their corresponding theoretical systems with double collector surface and double thermal energy production.
- Regarding Indicator of Sustainability (IS), System 2 had a value of 0.78 which is close to the 'ideal' System 3 ($IS = 1$) and System 2 is a system which can exist in practice. It should be noted that System 3 was only theoretically studied [14] since it is not commercially available.

Conclusively, the results demonstrated that the proposed BI solar thermal system with small modifications such as collectors of parallel connection shows considerable improvement of its efficiency and thus, of its environmental profile. Certainly, the environmental performance of the system is better for regions with high solar radiation and electricity mixes of high impact. In general, the studied BI system is promising and it has the potential for further development (for example by improving heat transfer processes): currently research is being conducted in the University of Corsica towards this direction, by keeping the same concept (integration into the gutters). In a future prospect, the proposed BI solar thermal system could considerably improve its thermal output and thus, its environmental performance [12].

2.1.2. Trombe walls

Stazi et al. [19] conducted an LCA study for the optimization of solar wall systems. A Trombe wall in a solar residential building prototype was evaluated as case study (Ancona, Italy). The system was made up of a 40 cm concrete with plaster on the inner face and a window with single glazing and aluminium frame on the exterior. The system also included black vertical aluminium bands insulated by polyurethane. The software Simapro and the database Ecoinvent were used. The results for the solar wall in the built case showed that the system has high environmental impact both in the pre-use and use phases. During the stage of production, the high environmental burdens were associated with aluminium and concrete while during operational phase the high CO_2 emissions and energy requirements were due to the energy use for summer cooling. The optimization demonstrated that it is possible to reduce CO_2 emissions and energy demand of solar walls (for both production and use phase) up to −55% from a traditional setup (concrete layer 40 cm thick, aluminium frame, single glazing) to an optimized setup (aerated concrete blocks layer 20 cm thick, wood frame, double glazing).

Nowzari and Atikol [20] examined the temperature behaviour of a hypothetical two-story building with a total floor area of 120 m^2 by modelling and simulation with TRNSYS. A vented Trombe wall was adopted for the south façade of the ground floor while a direct gain window of 6.5 m^2 was placed on the south façade of the first floor. It was assumed that the model building was located in the region of Larnaca, Cyprus. The study also included a Life Cycle Cost Analysis (LCCA) which indicated that constructing a 15 m^2 thermal storage wall in Cyprus was economically feasible compared to installing a 3 kW gas heater, given the fact that the saving-to-investment ratio was calculated to be 2.3.

Moreover, Bojíc et al. [7] studied the energy/environmental performance of buildings with/without Trombe walls. The indicator for environmental performance was a sum of primary operating energy for heating during winter and the annualized embodied energy consumed by using the Trombe walls. Two Trombe walls were used at the south side of a "Mozart" house in Lyon, France (the house fulfilled the French thermal regulation). The performance of several constructions of Trombe walls was examined. EnergyPlus software was adopted to simulate the thermal behaviour of these houses. The authors noted that the annualized life-cycle energy use by the houses with Trombe walls could be lower when the core material has lower density and lower embodied energy. For heating by electricity there were much higher values of the optimum thickness of the core layer and that of the primary energy consumption than that for heating by using natural gas. When the building with Trombe walls was utilized, the annual final energy savings during heating were found to be around 20%. For the electrical heating and optimum core thickness, the energy ratio was approximately 6 and the EPBT was around 8 years. For the natural gas heating these values were about 3 and 18 years, respectively.

Finally, it should be noted that Chel [21] conducted a study about various renewable energy technologies (including Trombe walls) that can be integrated into buildings. The author mentioned that the three main aspects which are important for energy savings in a building include: building design, low energy building