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Building-integrated solar thermal systems based on vacuum-tube technology: Critical factors focusing on life-cycle environmental profile

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ABSTRACT

The present study refers to Building-Integrated Solar Thermal (BIST) systems based on vacuum-tube collectors and it consists of two parts. In the first part, a literature review is presented, including studies about vacuum-tube technology (vacuum-tube/BIST systems, the environmental profile of vacuum-tube collectors, etc.). Critical issues, for example related to the integration of vacuum-tube collectors into the building, are highlighted. The review shows that most of the proposed vacuum-tube/BIST concepts are about façade-integration and there are few studies about the environmental profile of vacuum-tube collectors. As a continuity of the issues presented in the first part, the second part includes a case study about the environmental comparison of a vacuum-tube/BIST system with a flat-plate/BIST configuration, based on life cycle assessment. The systems are gutter-integrated, patented and they have been developed/tested at the University of Corsica, in France. Multiple life-cycle impact assessment methodologies, environmental indicators, scenarios and databases are adopted. The results reveal that the energy-payback time is 1.8 and 0.5 years, for the flat-plate/BIST and for the vacuum-tube/BIST, respectively, while by using recycling these values become 0.5 and 0.1 years, respectively. Energy-return-on-investment, greenhouse-gas payback time and avoided impact during use phase (by adopting USEtox, ecological footprint and France´s electricity as well as with reference domestic-gas-boiler $CO_{2.eq}$ emissions) are also presented. The findings of the present work: 1) are compared with the literature and good agreement is observed, 2) verify that considerably higher impact can be avoided by utilizing the vacuum-tube/BIST instead of the flat-plate/BIST system.

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1. Introduction

In the building sector there is a new tendency to integrate solar thermal systems into buildings. This specific type of systems is known as Building-Integrated Solar Thermal (BIST) and it offers several benefits (higher esthetic value, etc.) in comparison to Building-Added (BA) configurations. A critical review on the modeling of BIST with emphasis on the behavior of the coupled building/system configuration [1] as well as with emphasis on the behavior of the system [2] has been presented, highlighting critical issues related with the architectural integration of solar thermal systems. In the study of Lamnatou et al. [2] it was noted that there is a need for further development in the field of BIST modeling and towards this direction, except of the presented in [2] types of models (energetic simulation, thermal simulation, etc.), Life Cycle Assessment (LCA) models could also offer useful information about BIST environmental performance. Furthermore, a critical literature review about LCA of solar technologies with emphasis on BIST configurations has been presented [3], verifying that there is a need for more LCA studies which evaluate the BIST system itself and/or in conjunction with the building. In the following paragraphs LCA studies about solar thermal systems for domestic applications are presented, revealing the gap within the field of BIST LCA.

Regarding LCA studies about BA active flat-plate collectors, Kalogirou [4] investigated solar water heating and solar space/water heating systems for the case of Nicosia, Cyprus. The results revealed that the total energy for manufacture and installation was recouped in about 1.2 years for both systems. Rey-Martínez et al. [5] presented a work (based on EPS 2000 method) about a solar thermal installation (flat-plate collectors; domestic hot water production) for a rural house (Valladolid, Spain). Otanicar and Golden [6] presented a comparative environmental and economic analysis of conventional (flat-plate collector) and nanofluid solar hot-water technologies. Carlsson et al. [7] evaluated three solar collectors (flat-plate, evacuated-tube and polymeric), based on EI99 (Eco-indicator 99), IPCC 100a and CED (cumulative energy demand). The results revealed that the polymeric system has the best environmental performance. Furthermore, Streicher et al. [8] investigated two domestic hot water systems. The Energy Payback Time (EPBT) was calculated to be 1.4 and 2.1 years for the first and the second configuration, respectively.

In addition, LCA studies about BA passive flat-plate collectors for domestic hot water production have been presented by Ardente et al. [9,10], Kalogirou [11] and Marimuthu and Kirubakaran [12]. Moreover, Carnevale et al. [13] conducted a study about a flat-plate solar thermal collector (2.13 m^2 surface; 160 l water tank capacity; natural circulation) for domestic hot water applications. A PV system was also investigated. EI95 (Eco-indicator 95), energy- and $CO_{2.eq}$-payback times were utilized for the evaluation of the systems. The above mentioned payback times for the solar thermal system showed values ranging from around 0.6–1.2 years [13].

At this point it should be noted that Comodi et al. [14] performed an LCA for solar thermal collectors (for domestic hot water). Configurations with traditional glazed panels and unglazed were evaluated. EI99, energy-, CO_2- and economic payback times were adopted. For the traditional system, 93% of the impact was related to panel production. For the system with unglazed panel, the impacts of the accumulation tank and panel production were more balanced (54% and 44%, respectively). The performance of the systems was examined for three different locations (Rome, Madrid and Munich). In addition, the payback times of the systems were evaluated, having as basis natural gas and electrical boiler. The EPBT was found to range between 2 and 12 months, and the CO_2-payback time varied between 1 and 30 months. The unglazed solar thermal panels presented EPBT and CO_2-payback time values lower than the glazed ones.

Regarding LCA about other types of small-scale solar thermal systems for water heating, Smyth et al. [15] investigated an integrated collector/storage solar water heater. The results showed that the total energy for the manufacture of the unit was recouped in less than 2 years. Battisti and Corrado [16] studied an integrated collector/storage solar water heater (energy- and CO_2-payback times ranged from 5 to 19 months, depending on the configuration). Moreover, Hang et al. [17] presented a study about evacuated-tube and flat-plate collectors with auxiliary systems (natural gas; electricity). The energetic/environmental payback periods of the solar water heating systems were calculated to be less than half of a year. In addition, in references [18,19] the environmental profile of vacuum-tube solar thermal collectors was examined. In the study of Hoffmann et al. [19], flat-plate and evacuated-tube solar thermal collectors were compared. The results revealed that from environmental point of view, evacuated-tube solar collectors are the best choice. Furthermore, Crawford and Treloar [20] presented a net energy analysis of solar and conventional domestic hot water systems (Melbourne, Australia).

By focusing on LCA studies about small-scale solar thermal systems for buildings, the literature review shows that most of these works are about BA solar thermal while there are few investigations within the field of BI active solar thermal [21–23]. In addition, most of the studies examine embodied energy and CO_2 emissions. Given the fact that BIST systems offer multiple advantages compared to BA configurations [24], there is a need for more LCA investigations about BIST systems.

On the other hand, by focusing on reviews about BIST, it can be seen that there are studies which refer to: 1) transparent/translucent [25] and opaque [26] solar façades (in [25,26] modeling as well as experimental studies were presented); 2) active solar thermal façades (in terms of concept, classification, standard, performance measures, application and research questions, etc.) [27]; 3) BIST collectors (performance evaluations and applications were presented) [28]; 4) LCA of solar technologies with emphasis on BIST [3]; 5) modeling/simulation of BIST configurations [1,2].