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Research article

Cumulative energy demand and global warming potential of a building-integrated solar thermal system with/without phase change material

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ABSTRACT

Building-integrated solar thermal (BIST) systems are a specific type of solar thermal systems which are integrated into the building and they participate in building functionality. The present article is about the life-cycle assessment of different options of a BIST system (Mediterranean climatic conditions: Ajaccio, France). The environmental profile of the studied configurations is assessed by means of CED (cumulative energy demand), GWP (global warming potential) and EPBT (energy payback time). The proposed configurations (for the collector) include: i) a system without PCM (phase change material) using only rock wool as insulation and ii) a system with PCM (myristic acid) and rock wool. Concerning life-cycle results based on CED and GWP 100a (scenario without recycling), the configuration without PCM shows 0.67 MJ_{prim}/kWh and 0.06 kg $CO_{2.eq}$/kWh while the configuration with PCM presents 0.74 MJ_{prim}/kWh and 0.08 kg $CO_{2.eq}$/kWh. Regarding EPBT, if the inputs for pumping/auxiliary heating are not taken into account, both configurations (with/without PCM) have almost the same EPBT (about 1.3 years). On the other hand, if the inputs for pumping/auxiliary heating are considered, EPBT is lower for the system with PCM. In addition, scenarios with recycling have been examined and the results demonstrate that recycling considerably improves the environmental profile of the studied configurations.

1. Introduction

Building-integrated solar thermal (BIST) systems provide multiple advantages in comparison to solar thermal systems which are BA (building-added) and not integrated into the building. By taking into account that BIST configurations replace certain building elements and participate in building functionality, several interesting issues such as heat storage and insulation arise (Lamnatou et al., 2015a, 2015b, 2015c).

In the literature, there are experimental as well as theoretical/modelling studies about BIST systems. Experimental results and modelling of a solar thermal system integrated into building gutters have been presented by Notton et al. (2013). Based on the system mentioned above, characterization of the performances (Motte et al., 2013a) and design/modelling (Motte et al., 2013b) have been conducted. Lamnatou et al. (2015a, 2015b) presented reviews about modelling of BIST. Claros-Marfil et al. (2016) investigated a BIST water-flow window. Beccali et al. (2016) evaluated the yearly performance of a low-cost BIST configuration (solar wall). Li et al. (2017) studied the performance of a BIST shading system. Zhang et al. (2015) investigated a solar thermal façade for water-heating.

On the other hand, in the literature there are systems with latent-heat storage by means of PCM (phase change material). There are studies which propose PCMs for different types of solar thermal systems (including BIST).

Regarding investigations about several types of solar thermal collectors with PCMs, Desgrosseilliers et al. (2013) investigated dodecanoic acid and certain tests showed that this fatty acid is a promising PCM for latent-heat energy-storage systems for solar thermal applications. Hasan and Sayigh (1994) studied fatty acids for thermal energy storage in domestic solar water heating systems. Noël et al. (2015) conducted a study about LCA (life cycle assessment) of two biologically produced PCMs with emphasis on domestic solar thermal applications. Haillot et al. (2009) proposed a numerical model for domestic hot water systems with integrated-collector-storage including PCM (paraffin). Feliński and Sekret

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List of abbreviations and symbols

BA	Building-added
BI	Building-integrated
BIST	Building-integrated solar thermal
CED	Cumulative energy demand
$CO_{2.eq}$	$CO_{2.equivalent}$
E_{disp}	Primary energy for the disposal of the components/materials at the end of their life
E_{in}	Total input (primary energy) for: i) manufacturing of the materials, the collectors and the additional components, ii) system installation, iii) transportation, iv) disposal of the components/materials
E_{inst}	Primary energy for system installation
E_{mat}	Primary energy for material manufacturing (materials for the collectors and for the additional components) and module manufacturing
$E_{O\&M.a}$	Annual primary energy for use/operational phase
$E_{out.a}$	Annual output of the collectors (converted into primary energy)
EPBT	Energy payback time
E_{transp}	Primary energy for transportation of the materials/components from the factory gate to the building and from the building to the disposal site
GWP 100a	Global warming potential based on a time horizon of 100 years
GWP 20a	Global warming potential based on a time horizon of 20 years
GWP 500a	Global warming potential based on a time horizon of 500 years
GWP	Global warming potential
IPCC	Intergovernmental panel on climate change
LCA	Life cycle assessment
MJ_{prim}	$MJ_{primary}$
PCM	Phase change material

(2016) conducted an experimental study about an evacuated-tube collector/storage system with PCM (paraffin). Chen et al. (2010) presented a work about a flat-plate solar thermal collector with integrated metal foam porous structure filled with paraffin. The numerical results showed that the heat transfer performance can be considerably enhanced by adopting the solution of aluminium foams filled with paraffin.

With respect to the specific case of BIST systems with PCMs, Hengstberger et al. (2016) investigated high-temperature PCMs for the overheating protection of façade-integrated solar thermal collectors. The numerical simulations of Hengstberger et al. (2016) revealed that a thin layer of a high-temperature PCM (placed near the component of the absorber) offers thermal comfort in the room which is behind the collector. Bouhssine et al. (2014) conducted a numerical optimization of the thermal performance of a BIST with PCM.

Based on the studies mentioned above, it can be seen that PCMs offer multiple solutions for different types of solar thermal collectors, including BIST, and they are based on different materials (such as fatty acids and paraffins). Moreover, there are few investigations about the environmental profile of BIST systems with PCMs. Therefore, by taking into consideration that:

1) BIST show interesting characteristics from environmental perspective (replacement of building elements, etc.) (Lamnatou et al., 2015c) and they are important towards zero or nearly zero energy buildings (Beccali et al., 2016).
2) PCMs based on fatty acids offer multiple advantages (for example, they are suitable for applications which require tunable dimension (Yuan et al., 2014)).
3) There are few LCA studies about the environmental profile of active BIST systems which produce thermal energy for the building (Lenz et al., 2012; Lamnatou et al., 2014, 2015d, 2015e, 2016).
4) There are few LCA studies about the environmental profile of solar thermal collectors with PCMs (Allred, 2014; Noël et al., 2015), it can be seen that there is a need for more investigations which examine BIST environmental issues (Lamnatou et al., 2015c), including heat storage/insulation options with PCMs.

Consequently, the present article assesses the environmental profile of a BIST system according to different scenarios in terms of heat storage/insulation (with/without PCM (fatty acid)). The two scenarios with/without PCM have differences not only in terms of the materials but also in terms of energy outputs/inputs. In this way, the present article examines the influence of multiple parameters on the environmental profile of the studied configurations and it provides useful information for the selection of the most environmentally-friendly option.

2. Materials and methods

It is known that there are different types of LCA. For example, in process-based LCA the inputs (materials; energy sources) and the outputs (wastes/emissions to the environment) during the production of a product/system (or during the life-cycle of a product/system) are itemized. Other examples are the economic input-output approaches to life-cycle inventory and the hybrid models that combine economic input/output models with process models (SAIC, 2006). The present study is based on process LCA.

The implementation of the LCA has been conducted according to ISO 14040 (2006) and ISO 14044 (2006), by taking into account the following phases: 1) goal and scope definition, 2) life-cycle inventory, 3) life-cycle impact assessment and 4) interpretation.

2.1. Functional units and system boundaries

The functional unit is the whole system and it includes: 1) 35 flat-plate solar thermal collectors (total absorber surface: 5.1 m^2), 2) the additional components of the system (storage tank (200 *l*), tubes (with their insulation), anti-freezing fluid and pump). In subsection 2.3 (Table 2), details about the components/materials mentioned above are presented. In addition, it should be noted that certain results are presented per m^2 of absorber surface and per kWh of produced thermal energy. For the life-cycle calculations, the phases of material manufacturing (for the collectors and for the additional components of the system), manufacturing of the collectors, installation, use/maintenance, transportation and disposal are considered. In certain cases, emphasis is given on the phase of manufacturing and therefore, certain results are presented only for this phase.