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. The results, for material manufacturing phase (collectors; additional components; replacements over lifespan), based on CED and GWP, show that the three materials with the highest impact are aluminium, steel and PCM. By focusing on the differences (in terms of CED and GWP 100a per m^2 of absorber surface) between the two configurations (with/without PCM), it can be noted that these are mainly attributed to the component of PCM. 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). In addition, scenarios with recycling are examined.

Keywords: Life Cycle Assessment (LCA); Building-Integrated Solar Thermal (BIST) system; Phase Change Material (PCM); Cumulative Energy Demand (CED); Global Warming Potential (GWP); Energy Payback Time (EPBT)

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

1. INTRODUCTION

Within the field of solar thermal technology, BIST (building-integrated solar thermal) systems provide multiple advantages (aesthetically pleasing design, replacement of the materials e.g. of a wall, etc.) 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 arise such as heat storage, insulation and performance from environmental point of view (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 above mentioned system, characterization of the performances (Motte et al., 2013a) and design/modelling (Motte et al., 2013b) have been also conducted. Lamnatou et al. (2015a, 2015b) presented reviews about modelling and simulation 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 (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.

BIST systems replace different building elements (walls, windows, façades, etc.) and therefore, heat storage and insulation are important. For example, systems based on latent-heat storage with PCM (phase change material) are interesting. Especially for BIST, PCMs offer multiple solutions (active solar systems, passive solar systems, etc.), affecting the ability of BIST elements and, in general, the ability of the building to store heat (Hengstberger et al., 2016; Bouhssine et al., 2014).

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 (2016) conducted an experimental study about an evacuated-tube collector/storage system with paraffin as PCM. Chen et al. (2010) presented a work about a flat-plate solar 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 that are 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 the work 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. Bouhssine et al. (2014) performed simulations in order to optimize PCM conductivity during the cold period (January) for Casablanca (Morocco).

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 present multiple advantages (their shape is stable, they are cost-effective, they present readiness for applications which require for example tunable dimension, etc.: 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 (Noël et al., 2015; Allred, 2014), 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 the energy output and the energy consumed by the pumps. In this way, the present article examines the influence of these parameters on the environmental profile of the studied configurations and it provides useful information for the selection of the most environmentally-friendly configuration.

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 black-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 above mentioned components/materials 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 thereby, certain results are presented only for this phase.

2.2. Definition of the system

2.2.1. Technical characteristics

In Fig. 1(a) the studied BIST system that has been developed and tested at the University of Corsica, in France, is illustrated. The system consists of gutter-integrated flat-plate solar thermal collectors for water heating and it has been patented by Cristofari (2006). One unit includes a highly-selective absorber, a glass cover, one cold-water-flow tube, one hot-water-flow tube, thermal insulation, external casing, gutter and PCM (the component of PCM is included for a certain theoretical scenario): Fig. 1(a, b, c). More details about the studied BIST system can be found in the following references: Cristofari (2006), Notton et al. (2013, 2014), Motte et al. (2013a, 2013b).

In Table 1, the performance of the studied system (Scenario A: configuration without PCM and flow rate 50 *l*/h; Scenario B: configuration with PCM (myristic acid 51) and flow rate 45 *l*/h), based on the Mediterranean climatic conditions of Ajaccio, in France (Motte et al., 2017), is presented. The configurations studied in the frame of the present LCA, include connection in series and the tubes (for the cold water and for the hot water) are at the same level (into the absorber) (Fig. 1c).

The proposed BIST has been tested at the University of Corsica, in France (Motte et al., 2013a), modelled (Motte et al., 2013b) and numerically optimized (Notton et al., 2014) based on certain design modification. In the frame of this optimization, an improvement of the thermal performances and increase of the annual solar fraction from 41% to 76% were achieved. Nevertheless, it was found that the structure of the collector shows high thermal losses and thereby, the performances of the collector are limited. This is mainly related with the specific shape of the collector. In this way, an investigation has been conducted in order to replace a part of the thermal insulation (rock wool) by a PCM, for using the PCM component as thermal energy storage but mainly for limiting the water temperature and thereby, reducing the thermal losses.

Concerning the position of the tubes, based on the optimization study (Notton et al., 2014), the optimized configuration of the solar collector (tubes (for cold water and hot water) at the same level with the absorber) was chosen (Fig. 1c).

In terms of the selected PCM, different types of PCMs were evaluated (paraffins, myristic acids, etc.) with melting temperatures around 50°C and the results demonstrated that for the proposed system/application, myristic acid 51 is the most appropriate (Motte et al., 2017). At this point it should be mentioned that Hasan and Sayigh (1994) noted that fatty acids (myristic acid, palmitic acid and stearic acid) are appropriate for thermal energy storage in domestic solar water heating systems.

With respect to the selected flow rates, the configurations with/without PCM have been evaluated for different flow rates (ranging from 30 to 60 *l*/h) in order to determine the best flow rate for each case. For the configuration with rock wool (without PCM) the optimum flow rate of 50 *l*/h has been confirmed (Notton et al., 2014). For the configuration with PCM, the best results were for 45 *l*/h flow rate (and the performances for this case were found to be better than for the case of rock-wool configuration). The utilization of the PCM modifies the dynamic behaviour of the collector (the main factor related to this, is the reduction of the temperature and the increase of the inertia of the collector). This leads to lower optimum flow rate and thereby, a smaller circulation pump can be used (Motte et al., 2017). The thickness of the PCM layer has been also optimized and a value of 1 cm (just underneath the absorber) had been selected (Motte et al, 2017).

a)

b)

c)

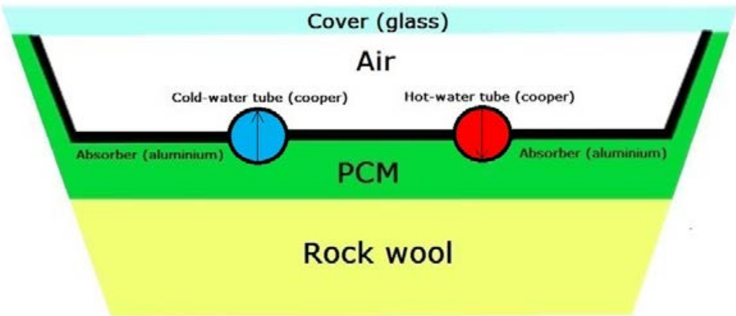


Figure 1. a) The studied BIST system (Source: Lamnatou et al., 2015d), b) Solar collector with the gutter, c) Structure of the configuration with PCM (the tube of the cold water (left) and the tube of the hot water (right) are indicated with blue and red color, respectively; the absorber is indicated with a black-colour line).

Table 1. Annual thermal energy production and annual electricity consumption (for pumping and auxiliary heating) of the studied BIST system: A) scenario A: configuration without PCM and B) scenario B: configuration with PCM (myristic acid).

Configuration	**Thermal energy production (kWh/year)**	**Electricity consumption for pumping (kWh/year)**	**Electricity consumption for auxiliary heating (kWh/year)**
Without PCM Flow rate: 50 *l*/h (scenario A)	1467	124	703
With PCM Flow rate: 45 *l*/h (scenario B)	1516	108	679

2.2.2. Assumptions

The impact of the processes for the manufacturing of the collectors is assumed to be 27% of the impact that is related with the manufacturing of the materials of the collectors. The impact of system installation is assumed to be 3% of the total impact for the manufacturing of the collectors and the additional components (Lamnatou et al., 2014; 2016).

Regarding system lifespan, it is considered that it is 25 years. For the calculation of the lifespan output of the system, it is assumed that there is no reduction of the output (i.e. the output of the last year is assumed to be the same with the output of the first year). During use phase, there is replacement of some components: One replacement of the cover (glass); one replacement of the storage tank; five replacements of the glycol; five replacements of the PCM (Hasan and Sayigh, 1994) for the configuration which includes PCM). General maintenance (cleaning, etc.) has been also included. In addition, for certain scenarios, for the use phase, are taken into account the inputs for pumping and auxiliary heating (Table 1). In terms of the impact of the general maintenance, it is assumed to be 10% of the material manufacturing impact of the collectors (Lamnatou et al., 2014; 2016).

Furthermore, there is transportation of the materials/components from the factory gate to the building and from the building to the disposal site (50 km; transportation by lorry).

For the phase of disposal, landfill is assumed and the disposal includes the components of all the collectors, the additional components of the system and the elements which are replaced over system lifespan. In certain cases scenarios which include recycling of some materials/components are included.

2.3. Life cycle inventory

SimaPro 8 software and ecoinvent 3 database have been used. In Table 2, the components/materials of the studied configurations are presented: (A) indicates scenario A (configuration without PCM) while (B) indicates scenario B (configuration with PCM). From Table 2 it can be seen that certain components are common (in terms of the type of the material and in terms of the quantity) for both configurations (without/with PCM) and these are indicated with (A, B). Table 2 includes the materials needed for the collectors as well as the additional components of the system.

Table 2. Components/materials for the life-cycle inventory of the BIST system: (A) indicates scenario A (configuration without PCM) and (B) indicates scenario B (configuration with PCM).

COMPONENTS/MATERIALS	**MASS (kg)**
COMPONENTS/MATERIALS FOR THE 35 COLLECTORS:	
Black absorber (aluminium)	6.85 (A, B)
Cover (glass)	49.59 (A, B)
Tube for cold water (copper)	8.86 (A, B)
Tube for hot water (copper)	8.86 (A, B)
Thermal insulation (rock wool)	8.09 A (5.70 B)
External casing (aluminium)	21.53 (A, B)
Two blades (polycarbonate)	1.68 (A, B)
Polyester (at the casing)	0.23 (A, B)
Gutter (aluminium)	25.47 (A, B)
Polyester (at the gutter)	0.35 (A, B)
PCM (fatty acid)	28.73 (B)
ADDITIONAL COMPONENTS/MATERIALS FOR THE SYSTEM:	
Storage tank (stainless steel)	31.20 (A, B)
Storage tank (rock wool insulation)	10.20 (A, B)
Tubes (copper)	14.09 (A, B)
Tubes (polyurethane insulation)	4.51 (A, B)

Anti-freezing fluid (propylene glycol)	3.50 (A, B)
Pump (stainless steel)	3.00 (A, B)

2.4. Life cycle impact assessment methods and equations

By taking into account the importance of the reduction of embodied energy and embodied carbon in the building sector (Pomponi and Moncaster, 2016), the environmental profile of the studied BIST system has been assessed according to:

1) Cumulative Energy Demand V1.08 / Cumulative energy demand

2) IPCC 2013 GWP 20a V1.00; IPCC 2013 GWP 100a V1.00; IPCC 2013 GWP 500a V1.00

(Sources: SimaPro 8; ecoinvent 3 database).

Cumulative energy demand (CED) includes characterization factors for the energy resources divided in 5 impact categories: The categories of «Non-renewable» include fossil (1) and nuclear (2) while the categories of «Renewable» include biomass (3), wind/solar/geothermal (4) and water (5). On the other hand, IPCC 2013 is an update of the method IPCC 2007 which has been developed by the IPCC (intergovernmental panel on climate change). It should be noted that the above mentioned method lists the climate change factors of IPCC based on a timeframe of 20, 100 and 500 years (PRé, 2014).

In terms of the EPBT, it has been calculated according to the following equation (Lamnatou et al., 2014, 2016):

$$EPBT = \frac{E_{in}}{E_{out.a} - E_{O\&M.a}} = \frac{E_{mat} + E_{inst} + E_{transp} + E_{disp}}{E_{out.a} - E_{O\&M.a}} \quad (years) \qquad (1)$$

where,

E_{in} is the 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.

$E_{out.a}$ stands for the annual output of the collectors (converted into primary energy).
$E_{O\&M.a}$ represents the annual primary energy for use/operational phase.
E_{mat} is the primary energy for material manufacturing (materials for the collectors and for the additional components) and module manufacturing.
E_{inst} stands for the primary energy for system installation.
E_{transp} represents the primary energy for transportation of the materials/components from the factory gate to the building and from the building to the disposal site.
E_{disp} is the primary energy for the disposal of the components/materials at the end of their life.

2.5. Scenarios

Regarding the proposed BIST system, two configurations have been examined: i) scenario A (without PCM) and ii) scenario B (with PCM) (Table 1, Table 2). The major part of the results is based on scenarios without recycling (landfill has been assumed for the end-of-life) while only in certain cases recycling (for the materials: glass, aluminium, rock wool, plastics and steel) is included.

With respect to GWP (global warming potential) time horizon, three cases have been examined: GWP 20a (time horizon 20 years), GWP 100a (time horizon 100 years) and GWP 500a (time horizon 500 years). This is because certain substances, which are related with GWP, gradually decompose and they become inactive in a long run (PRé, 2014). In this way, by adopting different time horizons a broader picture of the climate change impact is provided. Certainly, it should be noted that the GWP over a time period of 100-years is the most common choice (PRé, 2014).

3. RESULTS AND DISCUSSION

In Fig. 2 (a, b, c) and Fig. 3 (a, b, c) the results are based on materials without recycling. Moreover, in Fig. 2 and in Fig. 3, the components which are indicated with B are only for scenario B (with PCM) while the other components are for both scenarios (B and A) with/without PCM.

3.1. Cumulative energy demand (CED)

In Fig. 2, CED results are presented, in terms of: a) the component/materials of the 35 collectors (material manufacturing) (Fig. 2a), b) the additional components of the system (material manufacturing) (Fig. 2b), c) the replacement of certain components/materials over system lifespan (use phase) (Fig. 2c), d) transportation and disposal (Fig. 2d). From the graphs of Fig. 2 it can be seen that:

1) For the manufacturing phase of the collectors (Fig. 2a), aluminium components (especially casing and gutter) are responsible for the highest CED showing a total value of 9333 MJ_{prim} (for absorber, casing and gutter). Tubes (copper), cover (glass) and PCM present CED values ranging from 517 to 699 MJ_{prim} (each component) while the other materials (rock wool, polycarbonate, polyester) show less than 183 MJ_{prim} (CED for each material/component). It should be noted that the high CED of primary aluminium is mainly related with the production of primary liquid aluminium and with the high inputs in terms of electricity in aluminium industry.

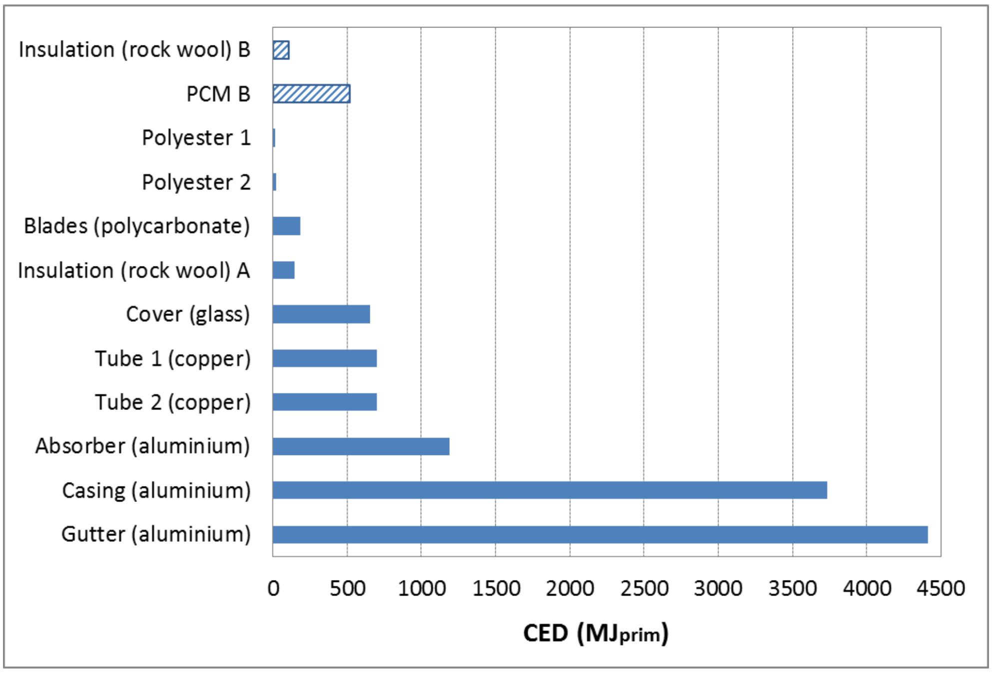
2) The manufacturing phase of the additional components of the system (Fig. 2b) reveals that tubes (copper) and storage tank (steel) present the highest CED (1111 and 1669 MJ_{prim}, respectively) while the other materials/components (pump (steel), anti-freezing (glycol), storage tank (rock wool), tubes (polyurethane)) show values less than 459 MJ_{prim} (CED value for case). The high CED of primary copper is mainly associated with copper concentrate necessary during material manufacturing phase of copper. Moreover, the greatest part of steel CED is related with the production of ferronickel.

3) By evaluating the system during its use phase (Fig. 2c), it can be seen that anti-freezing (glycol), storage tank (steel) and PCM present the highest CED for their replacements (1611, 1669, 2587 MJ_{prim}, respectively) while storage tank (rock wool) and cover (glass) present 187 and 657 MJ_{prim}, respectively. During the production of propylene glycol (liquid), the main part of CED is due to the inputs in terms of the propylene oxide liquid. Regarding the material manufacturing phase of the selected fatty acid (for the PCM component), the greatest part of CED is related with the inputs necessary for the production of the vegetable oil.

4) Transportation and disposal (landfill) have considerably lower CED (ranging from 41 to 162 MJ_{prim}: Fig. 2d) than the other stages of system life-cycle (Fig. 2a, 2b, 2c). By focusing on disposal, it can be noted that scenario B shows 60 MJ_{prim} higher CED than scenario A and this is mainly associated with PCM. By giving emphasis on transportation, it can be also seen that scenario B (mainly due to PCM) presents 23 MJ_{prim} higher CED than scenario A.

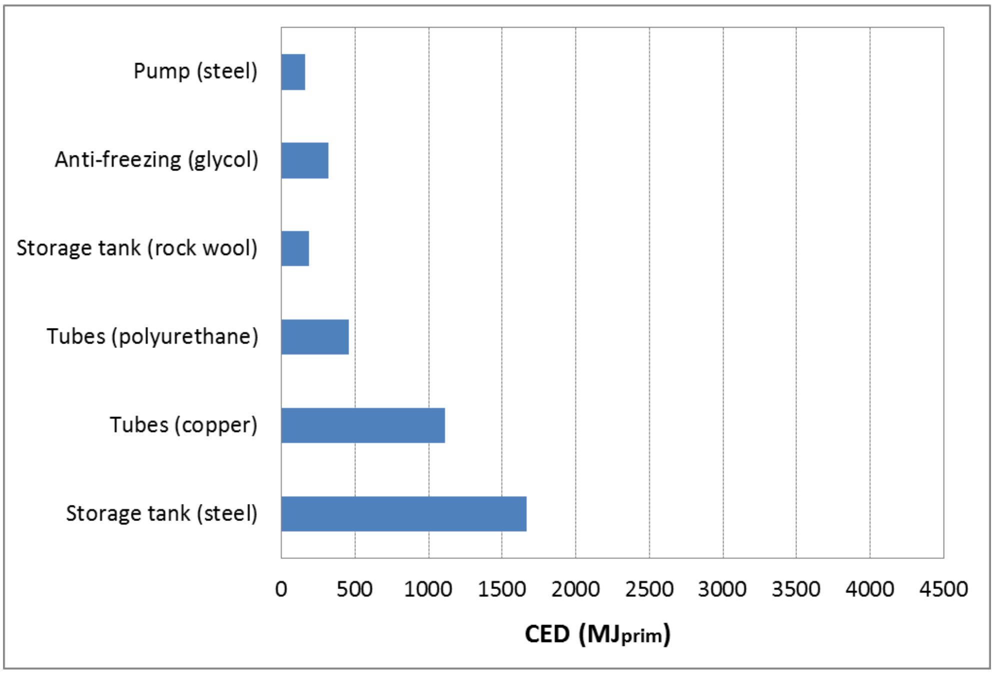
5) By focusing on material manufacturing (collectors; additional components; replacements over lifespan) among all the materials: i) aluminium components show the highest CED (total value: 9333 MJ_{prim} for the collectors), ii) steel is responsible for the second highest CED (total value: 3498 MJ_{prim} for the additional components and for the replacements), iii) PCM presents the third highest CED (total value: 3104 MJ_{prim} for the collectors and for the replacements). Related with the above mentioned findings, it should be taken into account that by adopting recycling a considerable part of the impact of the metals can be avoided (Lamnatou et al., 2014, 2015d, 2015e, 2016). The environmental and economic benefits of metal recycling have been highlighted for example in the study of Jaligot et al. (2016).

a)



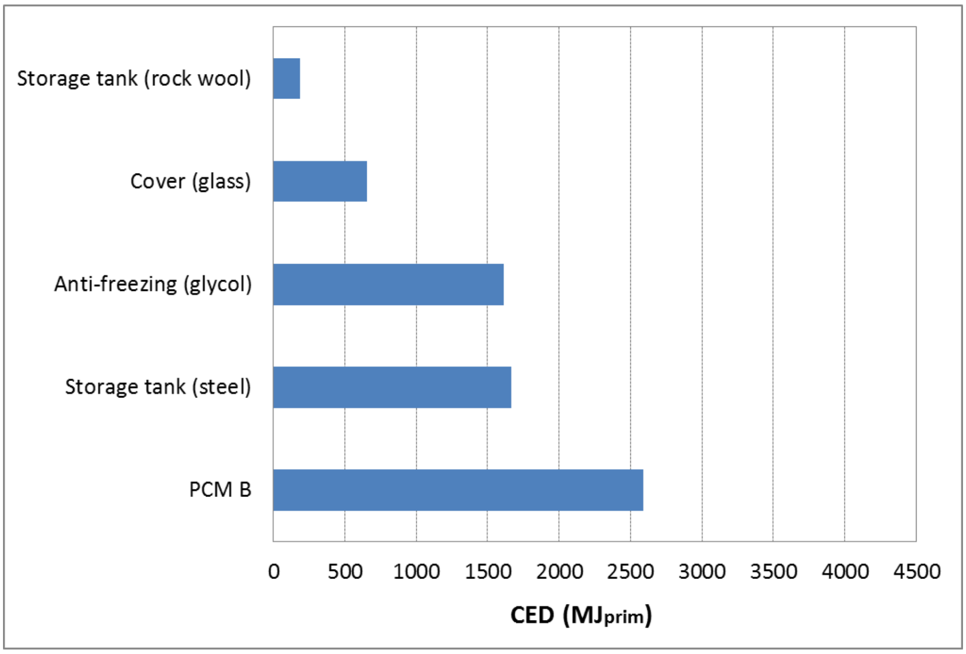
Insulation (rock wool) B
PCM B
Polyester 1
Polyester 2
Blades (polycarbonate)
Insulation (rock wool) A
Cover (glass)
Tube 1 (copper)
Tube 2 (copper)
Absorber (aluminium)
Casing (aluminium)
Gutter (aluminium)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
CED (MJprim)

b)



Pump (steel)
Anti-freezing (glycol)
Storage tank (rock wool)
Tubes (polyurethane)
Tubes (copper)
Storage tank (steel)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
CED (MJprim)

c)



d)

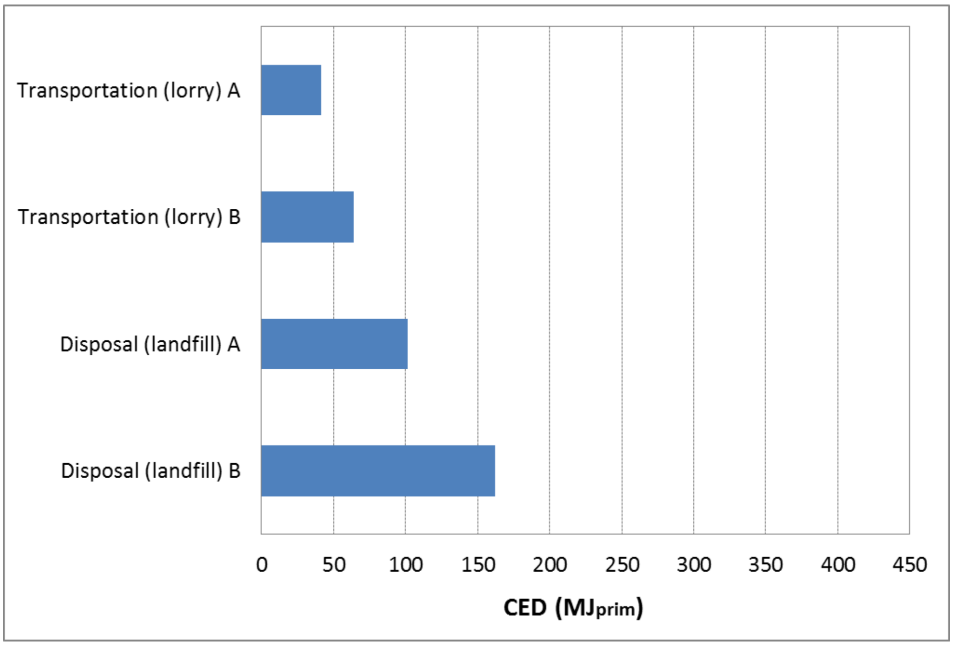


Figure 2. Results based on CED (scenario A and scenario B) for: a) the component/materials of the 35 collectors (material manufacturing), b) the additional components of the system (material manufacturing), c) the replacement of certain components/materials over system lifespan (use phase), d) transportation and disposal.

3.2. Global warming potential (GWP)

In Fig. 3, GWP results are illustrated, for: a) the component/materials of the 35 collectors (material manufacturing) (Fig. 3a), b) the additional components of the system (material manufacturing) (Fig. 3b), c) the replacement of certain components/materials over system lifespan (use phase) (Fig. 3c), d) transportation and disposal (Fig. 3d) and it can be noted that:

1) In terms of the manufacturing phase of the collectors (Fig. 3a), aluminium components present the highest GWP (ranging from 111 to 449 kg $CO_{2.eq}$, depending on the case). The material with the second highest GWP (after aluminium) is PCM with GWP values 96-106 kg $CO_{2.eq}$. On the other hand, cover (glass) and tubes (copper) present almost half GWP (49-60 kg $CO_{2.eq}$ each component, depending on the case) in comparison to PCM. For aluminium (primary) the main part of the GWP is due to the primary liquid aluminium/electricity inputs while for the selected fatty acid (for the PCM component) the greatest part of the GWP is due to vegetable-oil production.

2) Concerning manufacturing phase of the additional components of the system (Fig. 3b), tubes (copper) and storage tank (steel) show the highest GWP (ranging from 79 to 148 kg $CO_{2.eq}$) while the other materials/components (pump (steel), anti-freezing (glycol), storage tank (rock wool), tubes (polyurethane)) show values less than 30 kg $CO_{2.eq}$ (each material/component). For copper (primary) the main part of the GWP is due to the copper concentrate while for steel, the production of ferronickel presents a remarkable contribution to the total GWP during steel manufacturing phase.

3) The replacement of certain parts of the system during use phase (Fig. 3c) demonstrates that PCM is responsible for the highest GWP. More specifically, PCM presents GWP values 480-531 kg $CO_{2.eq}$, remarkably higher than the other

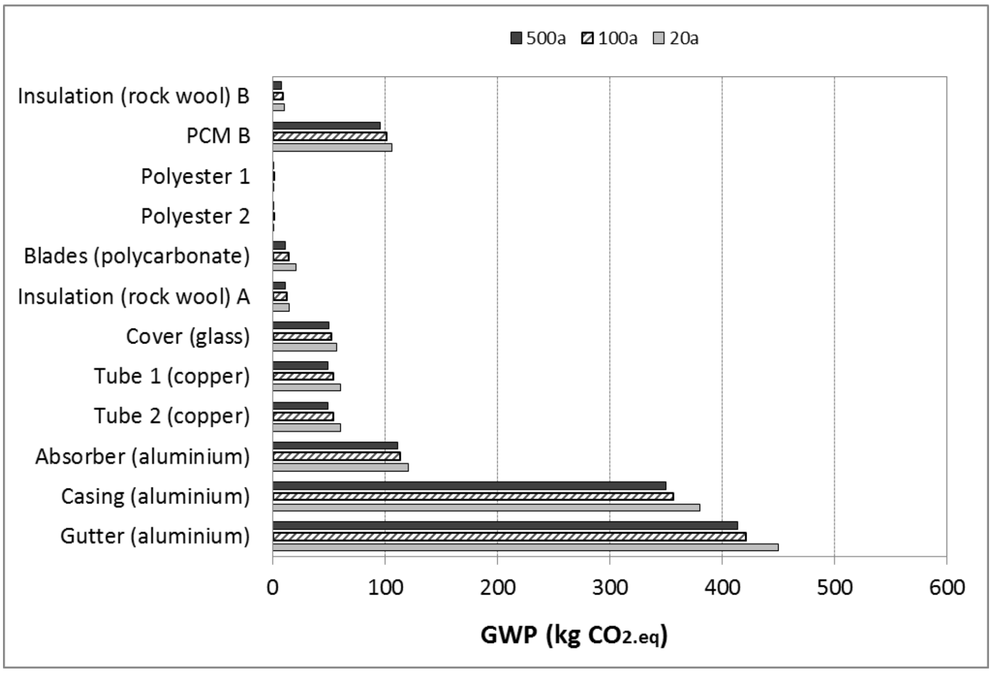
materials/components (storage tank (rock wool), cover (glass), anti-freezing (glycol), storage tank (steel)) which show GWP ranging from 14 to 148 kg $CO_{2.eq}$.

4) With respect to disposal and transportation (Fig. 3d), disposal presents considerably higher GWP in comparison to transportation, especially for scenario B (mainly due to PCM disposal). More analytically, by taking into account all the studied cases, transportation shows 2.5-4.3 kg $CO_{2.eq}$ while disposal presents 22-573 kg $CO_{2.eq}$.

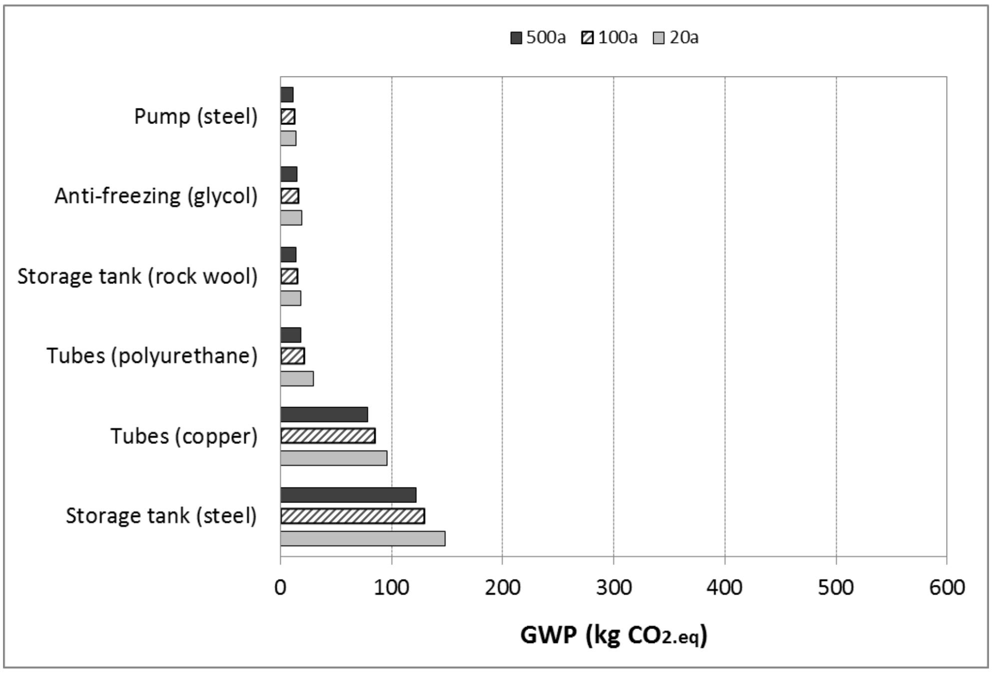
5) By considering only material manufacturing (collectors; additional components; replacements over lifespan) among all the materials: i) aluminium components present the highest GWP (total value: 889 kg $CO_{2.eq}$ (GWP 100a) for the collectors), ii) PCM shows the second highest GWP (total value: 607 kg $CO_{2.eq}$ (GWP 100a) for the collectors and for the replacements), iii) steel is responsible for the third highest GWP (total value: 271 kg $CO_{2.eq}$ (GWP 100a) for the additional components and for the replacements). For the case of the metals, as it was previously mentioned (subsection 3.1: results based on CED) it should be taken into account that recycling can result in a remarkable reduction of their impact (Lamnatou et al., 2014, 2015d, 2015e, 2016; Jaligot et al., 2016).

6) Regarding the effect of the time horizon (Fig. 3a-d), the adoption of a higher time horizon reduces GWP, as it was expected. For most of the greenhouse gases, GWP declines as the time horizon increases. This phenomenon can be interpreted based on the following explanation: the greenhouse gases are gradually removed from the atmosphere (by means of natural removal mechanisms), and in this way, their influence on the greenhouse effect declines (Singh, 2009).

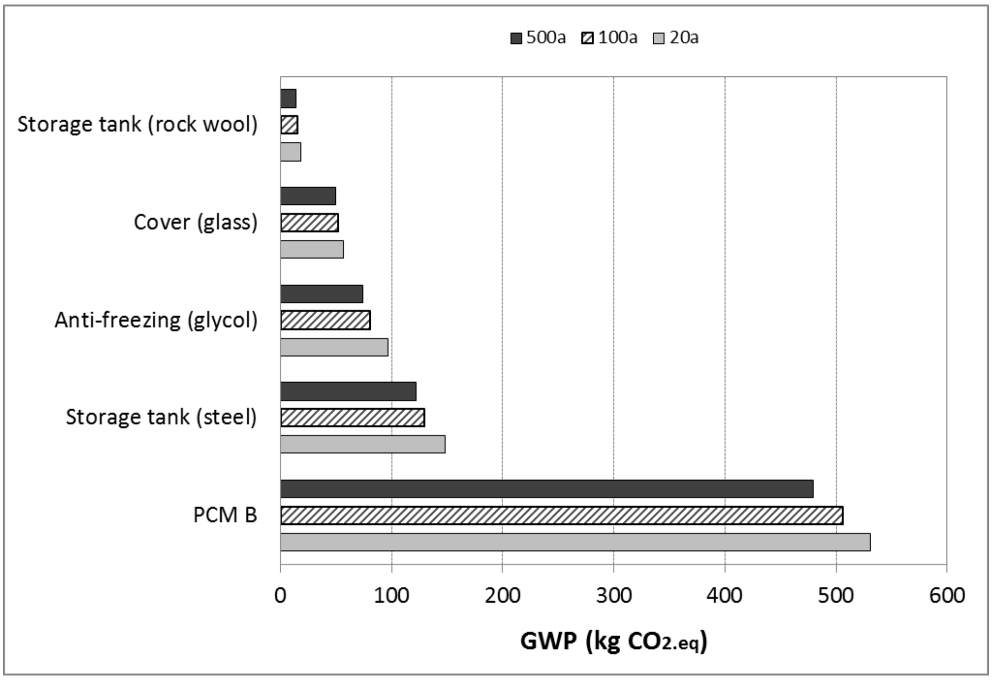
a)


500a
100a
20a
Insulation (rock wool) B
PCM B
Polyester 1
Polyester 2
Blades (polycarbonate)
Insulation (rock wool) A
Cover (glass)
Tube 1 (copper)
Tube 2 (copper)
Absorber (aluminium)
Casing (aluminium)
Gutter (aluminium)
0
100
200
300
400
500
600
GWP (kg CO2.eq)

b)


500a
100a
20a
Pump (steel)
Anti-freezing (glycol)
Storage tank (rock wool)
Tubes (polyurethane)
Tubes (copper)
Storage tank (steel)
0
100
200
300
400
500
600
GWP (kg CO2.eq)

c)



d)

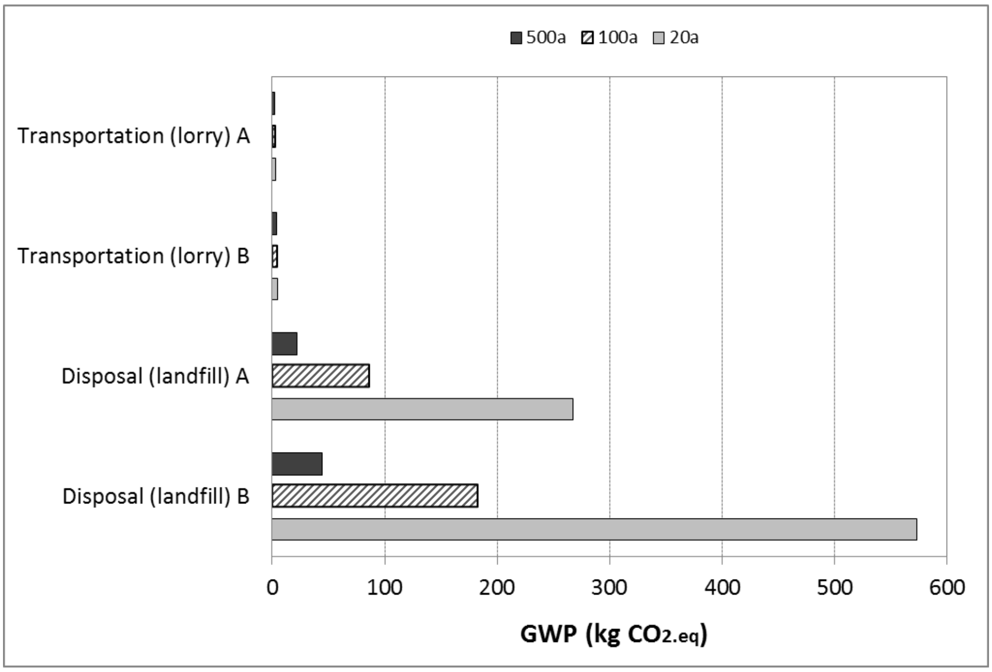


Figure 3. Results based on GWP (scenario A and scenario B; time horizons: 20a, 100a, 500a) for: a) the component/materials of the 35 collectors (material manufacturing), b) the additional components of the system (material manufacturing), c) the replacement of certain components/materials over system lifespan (use phase), d) transportation and disposal.

3.3. CED, GWP per m^2 of absorber, per kWh and comparisons with the literature

In Table 3 and in Table 4, the results of CED and GWP 100a per m^2 of absorber surface and per kWh of produced thermal energy are presented and it can be seen that:

1) With respect to CED/m^2, for both configurations (with/without PCM) gutter (aluminium) manufacturing is responsible for a considerable part (around 28-29%) of the total CED for manufacturing (materials, collectors) and disposal. In addition, for both configurations, recycling results in a remarkable CED reduction (2162 MJ_{prim}/m^2). By focusing on the differences (in terms of the CED/m^2) between the two configurations, it can be noted that these are mainly attributed to the component of PCM which is responsible for 102 MJ_{prim}/m^2 (PCM manufacturing for the collectors).

2) Concerning CED/kWh (based on the phases of manufacturing (materials, collectors, additional components); installation; use/maintenance; transportation; disposal), the results reveal that for both configurations (with/without PCM) recycling leads to a CED reduction of 0.3 MJ_{prim}/kWh.

3) With respect to GWP 100a/m^2, in both cases (with/without PCM) gutter (aluminium) manufacturing shows a high percentage (about 25-29%) of the total GWP 100a for manufacturing (materials, collectors) and disposal. Moreover, in both cases, recycling results in a remarkable GWP 100a reduction (216 kg $CO_{2.eq}/m^2$). By giving emphasis on the differences (with respect to GWP 100a/m^2) between the two configurations, it can be seen that these are mainly related with PCM material which accounts for 20 $CO_{2.eq}/m^2$ (PCM manufacturing for the collectors).

4) In terms of GWP 100a/kWh (phases of manufacturing (materials, collectors, additional components); installation; use/maintenance; transportation; disposal), the

findings show that for both configurations (with/without PCM) recycling reads to a GWP 100a reduction of 0.03 kg $CO_{2.eq}$/kWh.

5) By taking into account all the examined cases (Table 3 and Table 4), it can be noticed that recycling considerably improves the environmental profile of the studied configurations (with/without PCM). Recycling has been considered for the materials of glass, aluminium, rock wool, plastics and steel. However, the highest benefit is due to aluminium recycling. More specifically, aluminium recycling shows 84-96% (depending on the scenario) contribution to the reduction of the total CED and GWP 100a. At this point it should be mentioned that the effect of aluminium recycling on the environmental profile of a solar thermal collector has been examined for example by Ardente et al. (2005). It was noted that aluminium shows a remarkable influence on the global energy balance and this is mainly related to the high specific energy consumption during aluminium production. Ardente et al. (2005) also highlighted that a high variability was observed, depending on the percentage of the recycled material.

Table 3. CED per m^2 of absorber surface and per kWh of produced thermal energy. Scenarios with/without recycling.

Configuration	Method	Life-cycle stages considered	Results
Without PCM Flow rate: 50 *l*/h (scenario A)	CED	Manufacturing (materials, collectors); disposal	2961 MJ_{prim}/m^2 NO RECYCLING (870 MJ_{prim}/m^2 for gutter (aluminium) manufacturing) 799 MJ_{prim}/m^2 WITH RECYCLING
With PCM Flow rate: 45 *l*/h (scenario B)	CED	Manufacturing (materials, collectors); disposal	3092 MJ_{prim}/m^2 NO RECYCLING (870 MJ_{prim}/m^2 for gutter (aluminium) manufacturing) 930 MJ_{prim}/m^2 WITH RECYCLING
Without PCM Flow rate: 50 *l*/h (scenario A)	CED	Manufacturing (materials, collectors, additional components); installation; use/maintenance; transportation; disposal	0.67 MJ_{prim}/kWh NO RECYCLING 0.38 MJ_{prim}/kWh WITH RECYCLING
Without PCM Flow rate: 45 *l*/h (scenario B)	CED	Manufacturing (materials, collectors, additional components); installation; use/maintenance; transportation; disposal	0.74 MJ_{prim}/kWh NO RECYCLING 0.45 MJ_{prim}/kWh WITH RECYCLING

Table 4. GWP 100a per m^2 of absorber surface and per kWh of produced thermal energy. Scenarios with/without recycling.

Configuration	Method	Life-cycle stages considered	Results
Without PCM Flow rate: 50 *l*/h (scenario A)	IPCC 2013 GWP 100a	Manufacturing (materials, collectors); disposal	286 kg $CO_{2.eq}$/m^2 NO RECYCLING (83 kg $CO_{2.eq}$/m^2 for gutter (aluminium) manufacturing) 70 kg $CO_{2.eq}$/m^2 WITH RECYCLING
With PCM Flow rate: 45 *l*/h (scenario B)	IPCC 2013 GWP 100a	Manufacturing (materials, collectors); disposal	329 kg $CO_{2.eq}$/m^2 NO RECYCLING (83 kg $CO_{2.eq}$/m^2 for gutter (aluminium) manufacturing) 114 kg $CO_{2.eq}$/m^2 WITH RECYCLING
Without PCM Flow rate: 50 *l*/h (scenario A)	IPCC 2013 GWP 100a	Manufacturing (materials, collectors, additional components); installation; use/maintenance; transportation; disposal	0.06 kg $CO_{2.eq}$/kWh NO RECYCLING 0.03 kg $CO_{2.eq}$/kWh WITH RECYCLING
Without PCM Flow rate: 45 *l*/h (scenario B)	IPCC 2013 GWP 100a	Manufacturing (materials, collectors, additional components); installation; use/maintenance; transportation; disposal	0.08 kg $CO_{2.eq}$/kWh NO RECYCLING 0.05 kg $CO_{2.eq}$/kWh WITH RECYCLING

In terms of results from the literature about embodied energy, the findings of Kalogirou (2009) for a flat-plate collector for domestic hot water production show an embodied energy of 2663 MJ for a collector area of 1.35 m^2; thereby, the embodied energy per m^2 is expected to be 1973 MJ/m^2. For the proposed BIST system (configuration without PCM), if the CED of the gutter (aluminium) for manufacturing and for disposal is deducted from the total CED (2091 MJ_{prim}/m^2), the result is 1853 MJ_{prim}/m^2.

With respect to CO_2 emissions, Kalogirou (2009) presented 1.9 tons CO_2 as pollution from the construction and installation of the studied thermosiphon solar water heating system (based on flat-plate solar thermal collectors). By taking into account that the considered collectors give a useful energy of 1800 kWh/year (Kalogirou, 2009) and by assuming a lifespan of 25 years (equal to the lifespan of the present BIST system), the CO_2 emissions of the solar thermal system of Kalogirou (2009) are expected to be 0.04 kg CO_2/kWh. The present system (Table 4) shows 0.06 and 0.03 kg $CO_{2.eq}$/kWh, for the case without recycling and for the case with recycling, respectively.

From the above mentioned it can be seen that, in general, there is quite good agreement between the present results and those of Kalogirou (2009). However, a direct comparison is not possible due to differences between the present study and the study of Kalogirou (2009) (differences in terms of: the technical characteristics of the studied systems, the boundaries, the assumptions, the adopted databases, etc.). For example, the present investigation is based on $CO_{2.eq}$ emissions while the study of Kalogirou (2009) evaluates CO_2 emissions. In addition, it should be taken into account that in the present study the calculations include gutter (aluminium) which accounts for a considerable part of the total CED and GWP of the system. This is because aluminium is an energy-intensive material (SimaPro 8; ecoinvent 3 database) and the total mass of aluminium needed for the gutter of the 35 collectors is 25.47 kg (Table 2). It should be highlighted that the gutter could not be considered as part of the collectors because if classic flat-plate collectors were adopted, the building could also include gutters.

More comparisons of the proposed BIST (without PCM) with results from the literature can be found in authors´ previous study Lamnatou et al. (2015d).

3.4. Energy payback time (EPBT)

The EPBT has been calculated according to equation (1) and by having as reference (for the conversion of BIST output into primary energy) a conventional boiler (gas or oil) with 1.085 kWh primary energy per kWh of delivered energy (Streicher et al., 2004; Ardente et al., 2005). For pump/auxiliary heating, it has been considered the electricity mix of France (SimaPro 8; ecoinvent 3 database). By taking into account the inputs for pumping/auxiliary heating (as additional inputs during operational/maintenance phase for $E_{O\&M.a}$), the EPBT results show 4.2 years for the configuration without PCM and 3.7 years for the configuration with PCM. Thereby, PCM offers an EPBT reduction of around half year which is mainly related with the fact that it allows the utilization of lower flow rate. However, if the inputs for pumping/auxiliary heating are not taken into account, both configurations (with/without PCM) show almost the same EPBT value (around 1.3 years).

More EPBT results about the proposed BIST without PCM can be found in authors´ previous studies: Lamnatou et al. (2014, 2015d, 2016).

3.5. Limitations, discussion about the PCM material and future prospects

Based on the literature (Lamnatou et al. 2014, 2015a, 2015b, 2015c, 2015d, 2015e, 2016; Lamnatou and Chemisana, 2017) it can be seen that, in certain cases, BI solar systems result in reduced efficiency. Certainly, this efficiency reduction influences their environmental profile. There are multiple factors that affect the performance of BI solar systems: type of building-integration, colour of certain components, latitude of the region where the system is installed, combination (or not) of the production of thermal energy with the production of electrical energy, heat transfer fluid, materials of the components, adoption (or not) of recycling, etc. (Lamnatou et al. 2016; Lamnatou and Chemisana, 2017).

In authors´ previous studies (Lamnatou et al. 2014, 2015d, 2015e, 2016) it was highlighted that for gutter-integrated applications the limited area of the gutter (Fig. 1) limits the surface of the collector and this it results in collector output decrease. On the other hand, there is a relatively high consumption of electricity during use phase (Table 1) and this is another limitation for gutter-integrated solar systems. Except of the present investigation which gives emphasis on heat storage/insulation, additional options for the increase of the output of the proposed BIST have been examined: Adoption of vacuum-tube (instead of flat-plate) collectors (Lamnatou et al., 2016). According to different methods and environmental indicators, the BIST configuration based on vacuum-tubes showed better environmental profile than the BIST configuration based on flat-plate collectors (Lamnatou et al., 2016).

Moreover, it should be taken into account the issue that it was previously discussed (subsection 3.3) about the component of gutter (that it could not be considered as part of the solar system).

Concerning the material that has been adopted for the calculations of the impact of the PCM, it is fatty acid (SimaPro 8; ecoinvent 3 database). During the production of the selected fatty acid, vegetable oils (such as palm oil and coconut oil) are utilized, showing a considerable contribution to the total impact of fatty-acid production. Certainly, the inputs needed for the production of the above mentioned oils (for example, energy and fertilizers necessary for the cultivation of the related crops) remarkably contribute to the total impact of the fatty acid.

About palm-oil production, details can be found in the study of Noël et al. (2015). In addition, Noël et al. (2015) highlighted the influence of PCM on the environmental profile of solar thermal systems. It was noted that dodecanoic acid (which production phase is based on palm kernel oil) for utilization in solar-thermal-hot-water applications is a feasible PCM with payback-time values less than 3 years. Nevertheless, Noël et al. (2015) noted that the there is a high embodied energy associated with ethyl hexadecanoate which production phase is based on algae. Furthermore, Noël et al. (2015) highlighted that this high embodied energy results in a payback time that is too long for adoption in the frame of domestic thermal buffering configurations.

An additional limitation is related to process LCA. In this case, parameters such as data accuracy, inventory, assumptions and system boundaries can influence the results (SAIC, 2006). Moreover, there is an uncertainty related to the upstream impacts and the boundaries of the systems (system boundary cut-off). Ward et al. (2017) presented a study about truncation error in process LCA (using input-output analysis). It was noted that in terms of cut-off criteria, different modelling approaches exist in parallel, revealing that there is no distinct truncation procedure in case of flows in process LCA that affects the results (Ward et al., 2017). Another issue concerns the methodological limitations. The present article is based on CED and GWP. Huijbregts et al. (2010) compared the CED of 498 commodities with the results of six commonly-used environmental life-cycle impact assessment methodologies and it was concluded that a big range of environmental life-cycle assessment methodologies point into the same direction (from environmental point of view) for the production of many commodities.

As a future prospect, the present study could be extended in order to evaluate the environmental profile of the proposed configurations with additional methods, for example with midpoint/endpoint approaches. Economic parameters could also be studied.

4. CONCLUSIONS

The environmental profile of a BIST system is presented. Two configurations in terms of the collectors (without PCM component (scenario A) and with PCM component (scenario B)) have been examined.

The material manufacturing phase (collectors; additional components; replacements over lifespan), based on CED as well as based on GWP, shows that the three materials with the highest impact are aluminium, steel and PCM.

With respect to the results according to CED/m^2 and GWP 100a/m^2, for both configurations (with/without PCM), gutter (aluminium) manufacturing is responsible for a considerable part (around 25-29%) of the total CED and GWP 100a for manufacturing (materials, collectors) and disposal. By focusing on the differences (in terms of CED/m^2 and GWP 100a/m^2) between the two configurations, it can be noted that these are mainly attributed to the component of PCM, as it was expected.

Scenarios with recycling have been also examined. The results demonstrate that recycling considerably improves the environmental profile of the proposed BIST system.

On the other hand, EPBT findings reveal that PCM offers an EPBT reduction (around half year) which is mainly related with the fact that it allows the utilization of lower flow rate. However, 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).

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