Building-integrated solar thermal system with/without phase change material: Life cycle assessment based on ReCiPe, USEtox and Ecological footprint

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A R T I C L E   I N F O

A B S T R A C T

The present study assesses the environmental profile of a building-integrated solar thermal system that has been developed and tested in France. The investigation is based on life-cycle assessment according to ReCiPe, USEtox and Ecological footprint. Two configurations (for the solar collector) have been examined: 1) Without phase change material (using only rock wool as insulation) and 2) With phase change material (myristic acid) and rock wool. The main goal is the evaluation of the effect of the phase change material on the environmental profile of the solar thermal system. Both cases (with/without phase change material) have been studied based on the Mediterranean climatic conditions of Ajaccio (France). The results, according to ReCiPe midpoint (with characterization) demonstrate that the tubes (copper), the aluminium components (absorber, casing, gutter) and the phase change material are responsible for the highest impacts in terms of the material manufacturing phase of the collectors. With respect to ReCiPe/endpoint/single-score life-cycle results (scenarios: with/without PCM; with/without recycling; including the gutter), the values vary from 0.014 to 0.020 Pts/kWh. The configuration with phase change material presents 0.003 Pts/kWh higher impact (in comparison to the option without phase change material). Recycling offers an impact reduction of 0.003 Pts/kWh (for both configurations with/without phase change material). In addition, results according to USEtox (in terms of human toxicity and eco-toxicity) and Ecological footprint (with respect to the impact categories of carbon dioxide, nuclear and land occupation) are presented and discussed.

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1. Introduction

Building-integrated solar thermal (BIST) systems are a specific category of solar thermal systems which are integrated into the building (and not added, as the traditional building-added (BA) configurations). During the last years, there is an increasing interest for BIST systems, and in general for building-integrated (BI) solar systems (BI photovoltaic, BI photovoltaic/thermal, etc.), since they

offer several benefits (high aesthetic value, often cost reduction, etc.) in comparison to the solar systems which are BA. Given the fact that one of the basic characteristics of the BI solar systems is the replacement of the materials of certain building elements, it can be seen that issues such as insulation (Kalogirou, 2015; Lamnatou et al., 2015a, 2015b), heat storage (Kalogirou, 2015; Lamnatou et al., 2015a, 2015b) and environmental profile (Lamnatou et al., 2015c) show interest to be investigated.

With respect to experimental and modelling studies about BIST systems, in the literature multiple configurations can be found: solar thermal collectors integrated into building gutters (different scenarios have been examined: Notton et al., 2013; Motte et al., 2013a, 2013b), BIST water-flow windows (Claros-Marfil et al., 2016), low-cost solar wall (Beccali et al., 2016), BIST shading (Li et al., 2016). Details about BIST modelling have been presented in the review articles of Lamnatou et al. (2015a; 2015b): With

emphasis on the behaviour of the system (Lamnatou et al., 2015a) and with emphasis on the behaviour of the coupled building/system configuration (Lamnatou et al., 2015b).

As it was previously mentioned, the solar systems which are BI (and not BA) substitute the materials of certain building elements. For example, a BIST system can replace the materials of a façade or a wall. Therefore, it can be seen that insulation and heat storage are important parameters for BIST systems and building performance. In the case of BIST, in the same way with other types of solar systems, the role of heat storage is critical since solar radiation is periodically available. There are different options/materials for heat storage. For example there are systems based on latent-heat storage by means of a phase change material (PCM). In the specific case of BIST, PCM heat-storage options (for active and passive systems) influence the capacity of the BIST components (and, in general, the capacity of the building) to store heat. Related to the issues mentioned above, some examples are the works of Hengstberger et al. (2016) (about high-temperature PCMs for overheating protection of façade-integrated solar thermal collectors) and Bouhssine et al. (2014) (about the optimization of the thermal performance of a BIST collector with PCM).

In addition, there are studies which propose the utilization of PCMs for different types of solar thermal systems (including BIST). In the following paragraphs, selected literature references are presented.

With respect to several types of solar thermal collectors which include PCMs, Hasan and Sayigh (1994) investigated the fatty acids myristic acid, palmitic acid and stearic acid as thermal-energy-storage materials in domestic solar water heating systems. Haillot et al. (2009) presented a work about an integrated-collector-storage with paraffin PCM. Additional studies are those of Canbazoğlu et al. (2005) and Charvat et al. (2013) which verify the fact that PCMs offer advantages in the frame of solar thermal applications. Canbazoğlu et al. (2005) investigated (by means of experiments) a passive solar water heating system with sodium thiosulfate pentahydrate PCM. Additional theoretical scenarios with various types of PCMs were examined. It was noted that the storage time of hot water, the produced hot water mass as well as the total heat accumulated in the solar water heating system in the case of the heat storage tank combined with PCM were around 2.59–3.45 times higher than in the case of the conventional solar water heating system (Canbazoğlu et al., 2005). Charvat et al. (2013) studied solar air collectors with PCM integrated with the solar absorber plate and it was verified that PCM reduces the heat losses of the collector. On the other hand, Noël et al. (2015) examined environmental issues, based on life cycle assessment (LCA), about two biologically produced PCMs and their related products (focusing on domestic solar thermal applications).

Concerning BIST systems with PCMs, Bouhssine et al. (2014) presented a numerical optimization of the thermal performance of a BIST with PCM. The system was examined for the climatic conditions of Casablanca (Morocco) and it was concluded that it provides thermal comfort for the building. In addition, Hengstberger et al. (2016) presented a work about PCMs for overheating protection of solar thermal collectors (with emphasis on Austria). Numerical simulations for a façade-integrated solar thermal collector were performed. Hengstberger et al. (2016) noted that a thin layer of a high-temperature PCM placed close to the absorber offers thermal comfort in the room behind the collector.

According to the literature, it can be seen that PCMs offer solutions for multiple types of solar thermal systems, including BIST, and they are based on different materials (for example, fatty acids). In the light of the issues mentioned above and by considering that:

1) Solar thermal systems offer useful applications and environmental benefits for example in buildings (Arnaoutakis et al., 2017) and industry (Kylili et al., 2018).
2) BIST systems present interesting characteristics from environmental point of view (Lamnatou et al., 2015c).
3) BIST configurations are important towards zero or nearly zero energy buildings (Beccali et al., 2016).
4) There are few LCA studies about the environmental profile of active BIST systems which provide thermal energy for the building (Lenz et al., 2012; Lamnatou et al., 2014, 2015d, 2016, 2018).
5) In the literature, there are few LCA studies about the environmental profile of solar thermal collectors with PCM components (Noël et al., 2015; Allred, 2014),
6) There are few investigations about LCA of BIST systems with PCM (Lamnatou et al., 2018).
7) PCMs are useful materials offering numerous applications, for example in the building sector (Santos et al., 2017), the present article evaluates the environmental profile of a BIST system based on multiple life-cycle impact assessment methods and different scenarios. The two basic scenarios (in terms of heat storage/insulation) include one configuration without PCM (which is mainly based on rock wool as insulating material) and one configuration with fatty-acid PCM (which contains a small amount of rock-wool material). The two cases (with/without PCM) have differences in terms of the materials and the energy outputs/inputs.

The present article is an extension of the authors' previous study about the environmental profile of the same BIST system with/without PCM, based on cumulative energy demand and global warming potential (Lamnatou et al., 2018). The main goal of the present investigation is to examine the effect of the PCM component on the environmental performance of the system mentioned above, based on ReCiPe, USEtox and Ecological footprint. Additional cases (with/without recycling, etc.) have been studied as complementary scenarios.

The structure of the present article is the following:

- Presentation of materials and methods.
- Presentation of the results − Discussion:

- Subsection 3.1: *Results based on ReCiPe endpoint single-score:*
  - Results for: Collectors; Additional components of the system; Replacements of certain components over system lifespan; Transportation; Disposal
- Subsection 3.2: *Results based on ReCiPe midpoint/endpoint with characterization; USEtox with characterization; Ecological footprint single-score:*
  - Results only for the collectors
- Subsection 3.3: *Impact per m^2; Impact per kWh; Impact related to pumping/auxiliary heating*
- Subsection 3.4: *Limitations of the present study and discussion about the PCM*

- Conclusions

2. Materials - methods

The LCA study has been performed based on ISO 14040 (2006) and ISO 14044 (2006), by considering: 1) goal and scope definition, 2) life-cycle inventory, 3) life-cycle impact assessment and 4) interpretation.

2.1. Definitions about the goal of the LCA study, the functional units and the boundaries of the system

In certain cases (where emphasis is given on the material manufacturing phase of the whole system) the calculations are based on one solar thermal unit which is defined as: 35 flat-plate solar thermal collectors (total black-absorber surface: 5.1 m^2) and additional components of the system (storage tank (0.2 m^3), tubes with their insulation, anti-freezing fluid, pump). In subsection 2.3, more details about the components mentioned above are presented. In addition, it should be highlighted that certain results are presented: i) per m^2 of absorber surface, ii) per kWh of produced thermal energy. The presentation of the impact per m^2 of absorber surface has been adopted because absorber plays an important role in operation temperature and efficiency of a solar thermal collector. The evaluation of the impact per kWh of produced thermal energy has been used given the fact that solar thermal collectors are devices with the function of collecting solar energy and converting it into heat.

In terms of the life-cycle calculations, the phases of material manufacturing (for the collectors and the additional components of the system), manufacturing of the collectors, installation, use/maintenance, transportation and disposal have been taken into account. However, certain results focus on the phase of material manufacturing and this is clearly indicated in the text.

Additional explanations about the boundaries: Processes as well as transportation directly related to the production phase, the use phase and the disposal of the BIST system (and its additional components) have been taken into consideration. The flows include acquisition of the raw materials (or other resources). Allocation has been taken into account.

2.2. Definitions about the system

2.2.1. Technical characteristics of the solar system

In Fig. 1a, the BIST system is presented. It consists of flat-plate solar thermal collectors for water heating. The collectors are integrated into the building gutters and the system has been patented by Cristofari (2006). One unit (Fig. 1a, 1b, 1c) includes the following parts: a highly-selective absorber, glass cover, one cold-water-flow tube, one hot-water-flow tube, thermal insulation, external casing, gutter and PCM. The component of PCM has been considered for a certain theoretical scenario (in replacement of a part of the rockwool insulation). Additional information about the BIST system can be found in the following references: Cristofari (2006), Notton et al. (2013, 2014), Motte et al. (2013a, 2013b).

The thermal study has been conducted for a solar thermal system (composed by 35 serial connected collectors and a storage tank of 0.2 m^3) used by a 4-person household in Corsica (France). A numerical thermal model has been developed and validated based on experimental data (Motte et al., 2013b). It was found that due to the specific shape of the BIST collectors there are high thermal losses. The numerical model provided options for optimization of various parameters such as flow rate, insulation thickness and tube position (Notton et al., 2014). By means of the process of optimization, a reduction in the thermal losses mentioned above and an increase in the performances was achieved (the annual solar fraction increased from 41% to 76%). The utilization of PCM in order to replace the conventional thermal insulation was analysed in view to further improve the thermal performances (Motte et al., 2017). It has been found that the optimized flow rates for the highest thermal production were different for the two configurations (with/without PCM): 13.89×10^{-6} m^3/s (50 l/h) without PCM and 12.50×10^{-6} m^3/s (45 l/h) with PCM.

In Table 1, information about system performance (Scenario A: Configuration without PCM; Scenario B: Configuration with PCM (myristic acid 51)), according to the Mediterranean climatic conditions of Ajaccio, in France, is presented. The two flow rates have been optimized (in terms of their energetic productions) in the frame of a previous study (Motte et al., 2017). The configurations, which have been examined in the frame of the present LCA, include connection in series and the tubes (for the flow of the cold and hot water) are at the same level (into the absorber) (Fig. 1c). In the work of Motte et al. (2017), more details about the data presented in Table 1 can be found.

Regarding auxiliary heating (Table 1), there is consumption of electricity from the national grid and auxiliary-heating mode is activated when the solar energy from the sun is not enough to cover the needs of the building in terms of hot water of a certain temperature and quantity. On the other hand, an additional consumption of electricity (from the national grid) is for the water-circulation pump (Table 1) (Motte et al., 2017). In both cases (auxiliary heating, pumping) the electricity mix of France has been adopted. In subsection 3.3.2 the inputs for pumping/auxiliary heating are evaluated.

In terms of the position of the tubes, according to the optimization study that has been conducted (Notton et al., 2014) the optimized configuration of the solar collector (tubes (for cold and hot water) at the same level with the absorber) was chosen (Fig. 1c). The output water temperature ranges between 283 K and 353 K.

Concerning the PCM that has been selected, it should be highlighted that different types of PCMs (with melting temperatures around 323–328 K) have been evaluated (myristic acids, paraffins, etc.) and it was found that for the proposed system (and, in general, for domestic-hot-water applications), myristic acid 51 is the most appropriate material. The main characteristics of myristic acid 51 are following presented: Melting point temperature: 324 K; Enthalpy of fusion: 189 kJ/kg; Thermal conductivity: 0.17 W/mK; Density: 844 kg/m^3; Specific heat: 3 kJ/kg°C.

According to the literature, Hasan and Sayigh (1994) noted that the fatty acids myristic acid, palmitic acid and stearic acid are suitable for thermal energy storage for domestic solar water heating systems.

The use of the PCM component changes the dynamic behaviour of the collector due to the reduction in the temperature and the increase in the inertia of the collector. This means that the PCM configuration works with lower optimum flow rate and, therefore, a smaller circulation pump can be utilized (with lower consumption of electricity). Moreover, the thickness of the PCM layer has been optimized (it was taken equal to 1 cm, just underneath the solar absorber) (Motte et al., 2017).

The proposed BIST system has two functions: 1) Production of hot water for building energy needs, 2) Rainwater evacuation. More information about the functions of the system can be found in the following references: Cristofari (2006), Notton et al. (2013, 2014), Motte et al. (2013a, 2013b, 2017).

2.2.2. Assumptions which have been adopted

In terms of the impact related to the processes for the manufacturing of the collectors, it has been assumed to be 27% of the impact that is associated with the manufacturing of the materials of the collectors. In addition, the impact of system installation has been assumed to be 3% of the total impact for the manufacturing of the collectors and the additional components. According to the literature, these assumptions (for these types of solar thermal applications) are logical (Kalogirou, 2009; Lamnatou et al., 2014, 2015d, 2016, 2018).

Concerning the lifespan of the system, it has been assumed to be 25 years which (in the case of solar thermal collectors) can be considered as a realistic scenario (Kalogirou, 2009; Lamnatou et al.,
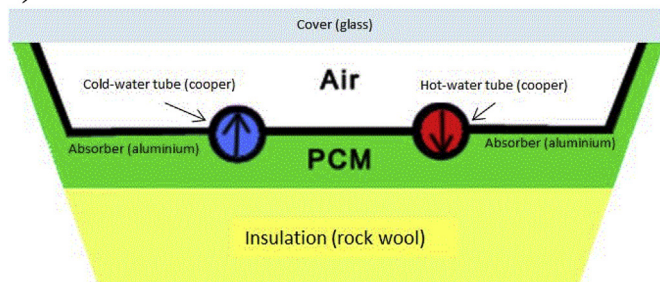
a)

b)

c)

Fig. 1. a) The BIST system, b) The solar collector with the gutter, c) The structure of the configuration with PCM (the tube for the cold water (left) and the tube for the hot water (right) are indicated with blue and red colour, respectively; the solar absorber is indicated with a black-colour line) (Source: Lamnatou et al., 2018). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2014, 2015d, 2016, 2018). Furthermore, for the evaluations based on the lifespan-output of the system, it has been assumed that the output does not show reduction (the output of the last year is considered to be the same with the output of the first year). During use phase, there are replacements of certain components. More specifically, there is one replacement of the cover (glass), one replacement of the storage tank, five replacements of the glycol, five replacements of the PCM for scenario B (Hasan and Sayigh, 1994; Motte et al., 2017), general maintenance (the general maintenance includes cleaning, etc., and it has been assumed to be 10% of the material manufacturing impact of the collectors: Lamnatou et al. (2014, 2015d, 2016, 2018)).

With respect to transportation, there is transportation of the components/materials from the factory gate to the building and from the building to the disposal site (the distance has been assumed to be 50 km; transportation by lorry).

Regarding disposal, landfill has been considered as disposal scenario and includes the components of all the collectors, the additional components of the system and the elements which are replaced during the system lifespan. The greatest part of the results is based on the scenario «without recycling» and in this case the end-of-life refers to landfill. Only certain scenarios include recycling (for glass, metals and plastics). The case «with recycling» has been adopted in order to verify the benefits that recycling offers for these types of solar systems which include large amounts of materials that can be recycled.

2.3. Data about life-cycle inventory

SimaPro 8 (a transparent, robust and reliable LCA software package) (Source: SimaPro) and the database ecoinvent 3 (a comprehensive and consistent life-cycle inventory database, with relevant data and high-quality datasets) (Source: ecoinvent) have been adopted. In Table 2, the components/materials of the two configurations are presented: (A) indicates scenario A (configuration without PCM) and (B) indicates scenario B (configuration with PCM). Some components are common (regarding the type of the material and the quantity) for both configurations (with/without PCM): These components are indicated with (A, B). Table 2 presents the materials needed for the collectors and the additional components of the system.

2.4. Life-cycle impact assessment methods

Multiple methods (Sources: SimaPro; ecoinvent) have been utilized in order to assess the environmental profile of the BIST system:

1) ReCiPe Endpoint (H) V1.10/Europe ReCiPe H/A: i) Single-score, ii) With characterization results.
2) ReCiPe Midpoint (H) V1.10/Europe Recipe H: With characterization results.
3) USEtox (default) V1.03/Europe 2004: With characterization results.
4) Ecological footprint V1.01/Ecological footprint: Single-score results.

Some issues about the adopted methods are following presented: ReCiPe includes impact categories based on midpoint (problem oriented) and endpoint (damage oriented) approach. In the case of midpoint level, 18 impact categories are taken into account (ozone depletion, human toxicity, etc.). At endpoint level, most of the midpoint impact categories are multiplied by certain damage factors and, then, they are aggregated into 3 endpoint categories (these impact categories include: Human health,

Table 1
The annual thermal energy production and the annual electricity consumption (for pumping and auxiliary heating) of the BIST system: 1) Scenario A: Configuration without PCM and 2) 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 (scenario A) Flow rate: 13.89×10^{-6} m^3/s (50 l/h)	1467	124	703
With PCM (scenario B) Flow rate: 12.50×10^{-6} m^3/s (45 l/h)	1516	108	679

Ecosystems, Resources). Points (Pts) express the total environmental load as a single score (endpoint approach). Moreover, the endpoint characterization factors (ReCiPe) can be described: 1) for human health by means of disability-adjusted life years (DALY), 2) for ecosystems by means of (species.yr) (loss of species over a certain area, during a certain time). It should be clarified that in the frame of the present LCA study (for ReCiPe), the perspective H (hierarchist) (that is based on the most common policy principles in terms of time-frame and other issues) has been adopted (PRé, 2014).

With respect to ReCiPe/midpoint, additional information for each midpoint category (about the characterization factors) is following provided: 1) Ozone depletion: destruction of the stratospheric ozone layer due to anthropogenic emissions of ozone depleting substances, 2) Human toxicity and ecotoxicity: environmental persistence and accumulation in the human food chain and toxicity of a chemical, 3) Radiation: ionising radiation refers to the level of exposure, 4) Photochemical oxidant formation: the marginal change in terms of the 24 h-average European concentration of ozone because of a marginal change in emission of substance x, 5) Particulate matter formation: the intake fraction concerning PM10, 6) Climate change: global warming potential, 7) Agricultural and urban land occupation: the amount of land (agricultural or urban) that is occupied for a certain time, 8) Natural land transformation: the amount of natural land that is transformed and occupied for a certain time, 9) Marine eutrophication: the environmental persistence in terms of the emission of N-containing nutrients, 10) Freshwater eutrophication: the environmental persistence regarding the emission of P-containing nutrients, 11) Fossil fuel and minerals depletion: the amount of fossil fuel that has been extracted, 12) Minerals depletion: the decrease in terms of grade, 13) Freshwater depletion: the amount of fresh water consumption (PRé, 2014).

USEtox is about the characterization of human and eco-toxicological impacts. Ecological footprint represents the biologically productive land and water a population needs in order to produce the resources that it consumes and absorb part of the waste related to fossil and nuclear fuel consumption. With respect to characterization, in the frame of LCA, the Ecological footprint of a certain product is the sum of time integrated direct as well as indirect land occupation, associated with nuclear energy use and CO_2 emissions from fossil energy use (PRé, 2014).

3. Results and discussion

It should be clarified that the results that are presented in Figs. 2–5 and Tables 3–5 are based on the scenario «without recycling». Moreover, it should be noted that in the graphs of Figs. 2a, 2c, 2d, 3a, 3b, 4a, 4b, 5 and Tables 3 and 4 the components that are indicated with the letter A refer to scenario A (configuration without PCM), the components that are indicated with the letter B refer to scenario B (configuration with PCM) and the other components (without any indication) are for both scenarios (with/without PCM).

Subsection 3.1 presents the impact related to: i) material manufacturing phase of the collectors and the additional components of the system, ii) the replacements of certain components over system lifespan, iii) transportation and disposal.

3.1. ReCiPe endpoint single-score

In Fig. 2, the results based on ReCiPe endpoint/single-score in terms of: a) the components/materials of the 35 collectors (material manufacturing) (Fig. 2a), b) the additional components of the system (material manufacturing) (Fig. 2b), c) the replacements of certain components/materials over system lifespan (use phase) (Fig. 2c), d) transportation and disposal (Fig. 2d) are illustrated. It can be seen that:

1) For the manufacturing phase of the collectors (Fig. 2a), the tubes (copper) show remarkably higher scores in comparison to the other components. By focusing on the impact categories it can be noted that, in general, in most of the cases, Resources and Human health present considerably higher values than Ecosystems.

2) The manufacturing phase of the additional components of the system (Fig. 2b) reveals that the tubes (copper) and the storage tank (steel) present higher scores than the other components.

3) In terms of the use phase and the replacements of certain parts of the system (Fig. 2c), the PCM component has remarkably higher score in comparison to the other components.

4) The disposal (Fig. 2d) shows higher scores than the transportation, especially for scenario B (a fact that is mainly associated with the PCM disposal).

5) By evaluating only material manufacturing (collectors; additional components; replacements over lifespan) (Fig. 2a, 2b, 2c) among all the materials: i) the copper-based parts of the system present the highest ReCiPe score (total value: 322 Pts for the collectors and the additional components), ii) the PCM

Table 2
The components/materials for the life-cycle inventory of the BIST system: (A) is for scenario A (configuration without PCM) and (B) is for scenario B (configuration with PCM). (A, B) is for both scenarios A and B.

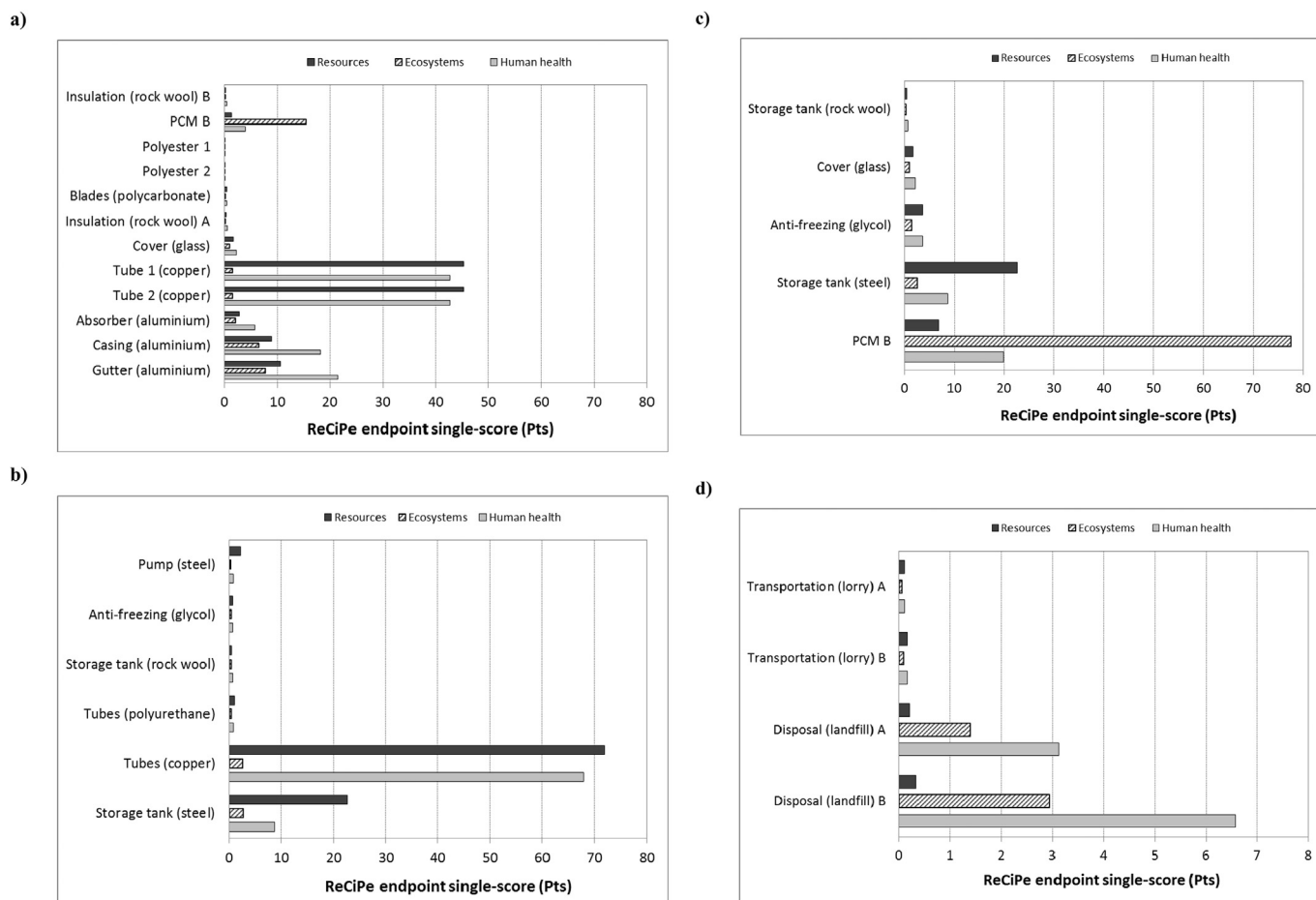| COMPONENTS/MATERIALS	MASS (kg)
COMPONENTS/MATERIALS FOR THE 35 COLLECTORS:	
Black absorber (aluminium)	6.85 (A, B)
Cover (glass)	49.59 (A, B)
Tube for hot water (copper): Tube 1	8.86 (A, B)
Tube for cold water (copper): Tube 2	8.86 (A, B)
Thermal insulation (rock wool)	8.09 (A) (5.70 (B))
External casing (aluminium)	21.53 (A, B)
Two blades (polycarbonate)	1.68 (A, B)
Polyester (at the casing): Polyester 1	0.23 (A, B)
Gutter (aluminium)	25.47 (A, B)
Polyester (at the gutter): Polyester 2	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)

a)

b)

c)

d)

Fig. 2. Results based on ReCiPe (endpoint approach, single-score) for: a) the components/materials of the 35 collectors (material manufacturing), b) the additional components of the system (material manufacturing), c) the replacements of certain components/materials over system lifespan (use phase; material manufacturing), d) transportation and disposal.

component shows the second highest score (total value: 125 Pts for the collectors and the replacements).

Related to the findings presented above, it should be noted that recycling can result in a remarkable reduction in the impact related to the metals (Lamnatou et al., 2014, 2015d, 2016, 2018).

With respect to aluminium, the sustainable management of aluminium components is a critical issue due to the fact that over the last years there is an exponential growth regarding the global demand of aluminium. Aluminium recycling prevents the valuable material stream from going to landfill. It is known that primary aluminium includes high environmental impact because there is high energy consumption and waste generation (Soo et al., 2018).

3.2. ReCiPe midpoint/endpoint with characterization, USEtox with characterization, Ecological footprint single-score

Subsection 3.2 presents results (based on different methods) about the impact related to the material manufacturing phase of the 35 collectors.

3.2.1. ReCiPe endpoint with characterization

In Fig. 3 the results based on ReCiPe endpoint with characterization (material manufacturing phase of the 35 collectors) in terms of: a) DALY (Fig. 3a) and b) (species.yr) (Fig. 3b) are illustrated. From Fig. 3a it can be seen that the tubes (copper) are responsible for the

highest DALY (impact related to human health). On the other hand, Fig. 3b demonstrates that the aluminium-based parts (absorber, casing, gutter) and the PCM component show the highest (species.yr) (impact related to ecosystems). In addition, from Fig. 3 it can be noted that the PCM component presents considerably higher value for (species.yr) than for DALY.

It should be clarified that the graph of (species.yr) (Fig. 3b) includes the impact categories of Climate change/ecosystems, Terrestrial acidification, Freshwater eutrophication, Terrestrial ecotoxicity, Freshwater ecotoxicity, Marine ecotoxicity, Agricultural land occupation, Urban land occupation and Natural land transformation. The graph of DALY (Fig. 3a) includes the impact categories of Climate change/human health, Ozone depletion, Human toxicity, Photochemical oxidant formation, Particulate matter formation and Ionising radiation.

3.2.2. ReCiPe midpoint with characterization

In Table 3 the environmental profile of the 35 collectors (material manufacturing phase) according to ReCiPe midpoint categories (with characterization) is presented. The two components based on polyester (Table 2) have not been included in Table 3 (because they show very low impact). Based on the findings of Table 3, Table 4 indicates which components/materials present the highest impact (total value in the cases where the same material refers to more than one component) in each ReCiPe midpoint category. From Tables 3 and 4 it can be seen that:
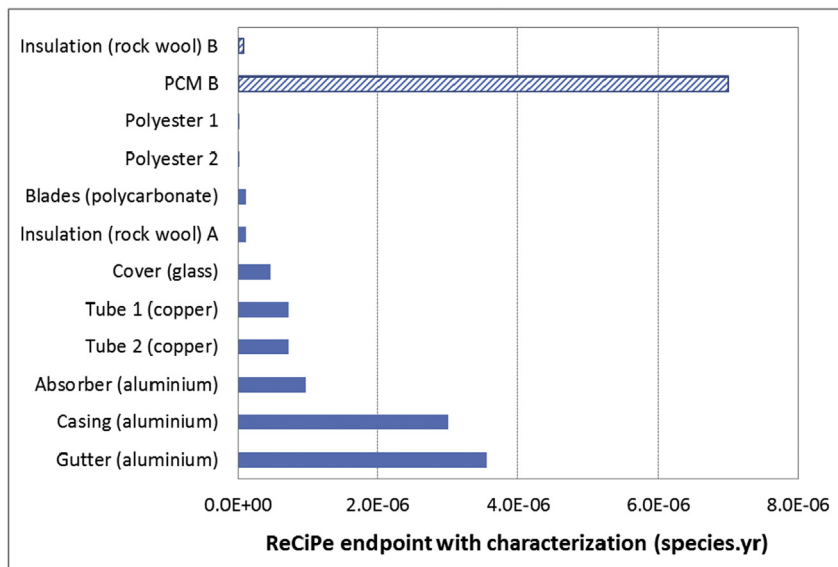
a)
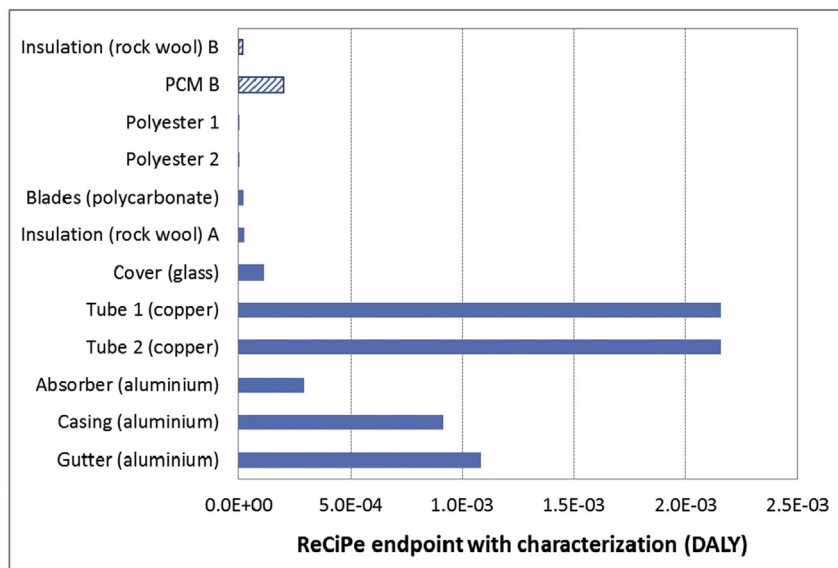
b)

Fig. 3. Results based on ReCiPe (endpoint approach, with characterization) for the components/materials of the 35 collectors (material manufacturing), according to: a) DALY, b) (species.yr).

1) Aluminium, copper and PCM are the three materials with the highest values in terms of the total impact of the 35 collectors (material manufacturing phase) based on the midpoint categories of ReCiPe (midpoint with characterization).

2) For Climate change, Ozone depletion, Terrestrial acidification, Photochemical oxidant formation, Particulate matter formation, Ionising radiation, Water depletion, Fossil depletion, the aluminium components (absorber, casing, gutter) show the highest values. It can be noted that many of the midpoint categories cited above are related to air pollution and damage to human health (endpoint).

3) For Freshwater eutrophication, Marine eutrophication, Human toxicity, Freshwater ecotoxicity, Marine ecotoxicity, Urban land occupation, Metal depletion, the tubes (copper) present the highest impact. Most of the midpoint categories mentioned above are about freshwater and marine ecosystems and are responsible for damage to ecosystems (endpoint).

4) For Terrestrial ecotoxicity, Agricultural land occupation, Natural land transformation, the PCM component shows the highest values. It can be seen that the midpoint categories cited above are related to land.

3.2.3. USEtox with characterization

In Fig. 4 the environmental profile of the 35 collectors (material manufacturing phase) according to USEtox (with characterization) is illustrated. Fig. 4 presents: 1) Human toxicity (Fig. 4a), 2) Ecotoxicity (Fig. 4b). From Fig. 4 it can be seen that:

1) For all the components/materials, Human toxicity/cancer presents higher CTU_h values than Human toxicity/non-cancer (Fig. 4a).

2) The PCM component and the aluminium-based parts (absorber, casing, gutter) are responsible for the major part of Human
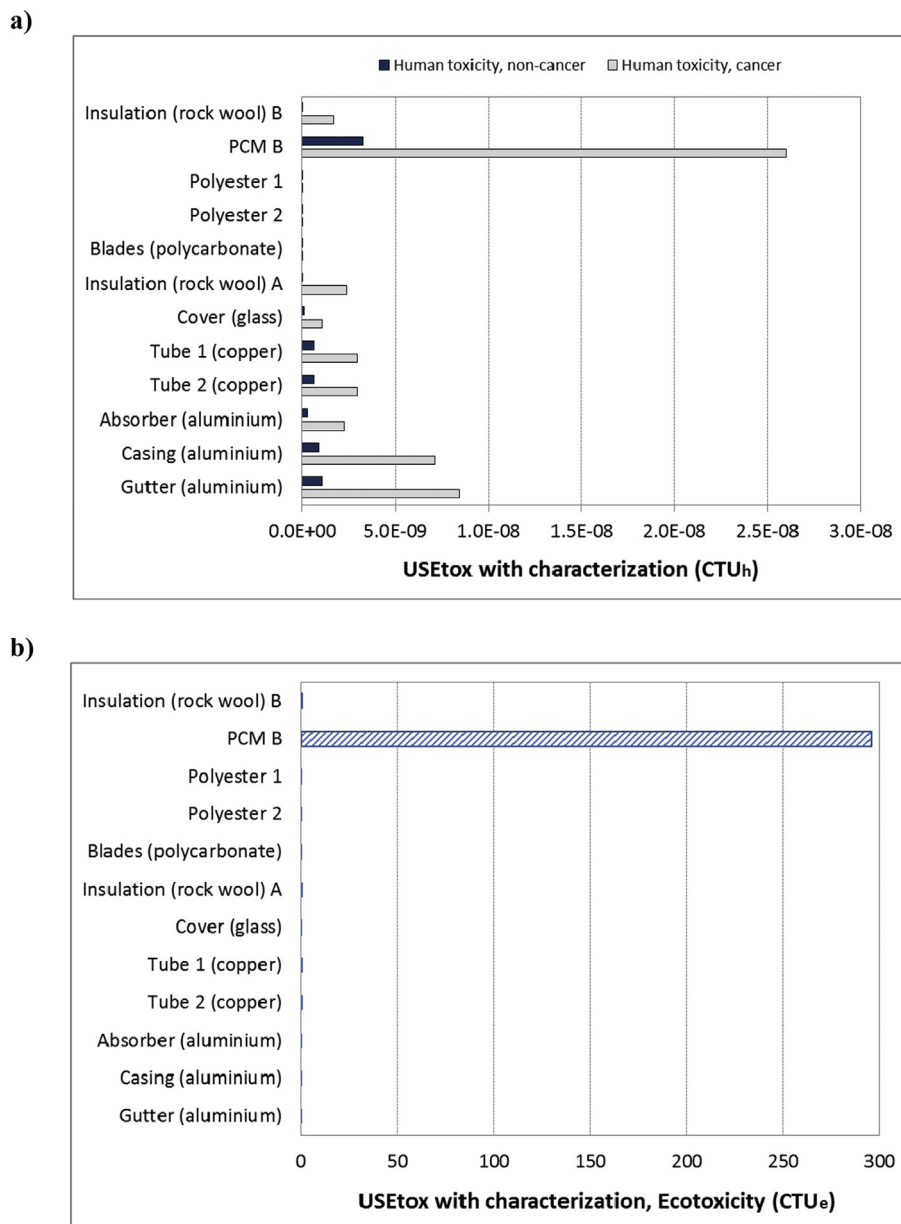
a)

b)

Fig. 4. Results based on USEtox (with characterization) for the components/materials of the 35 collectors (material manufacturing), according to: a) Human toxicity (non-cancer and cancer) in CTU_h, b) Ecotoxicity in CTU_e.

toxicity (total values of CTU_h, including cancer and non-cancer) (Fig. 4a).

3) Among all the components/materials, the PCM component presents the highest CTU_h values (for Human toxicity/cancer and Human toxicity/non-cancer) and the highest CTU_e values (for Ecotoxicity). Especially, in the case of Ecotoxicity (Fig. 4b) there is a remarkable difference between the PCM component and the other materials: PCM shows 296 CTU_e while the other components/materials present values ranging from 0.1 to 0.9 CTU_e.

3.2.4. Ecological footprint single-score

The results about the environmental profile of the 35 collectors (material manufacturing phase) according to Ecological footprint (Fig. 5) reveal that:

1) Carbon dioxide shows considerably higher scores in comparison to Land occupation and Nuclear.
2) Among all the components/materials, the aluminium-based parts (absorber, casing, gutter) present the highest impact. More specifically, according to Carbon dioxide, the aluminium components show a total value of 2196 Pts.

3.3. Impact per m^2, impact per kWh, impact related to pumping/auxiliary heating

3.3.1. Impact per m^2 of thermal absorber

In Table 5, the results based on ReCiPe Pts (endpoint, single-score including Human health, Ecosystems and Resources) per m^2 of thermal absorber are presented. It should be noted that these results refer to the phase of the manufacturing of the materials/collectors and the scenario «without recycling». In addition, it
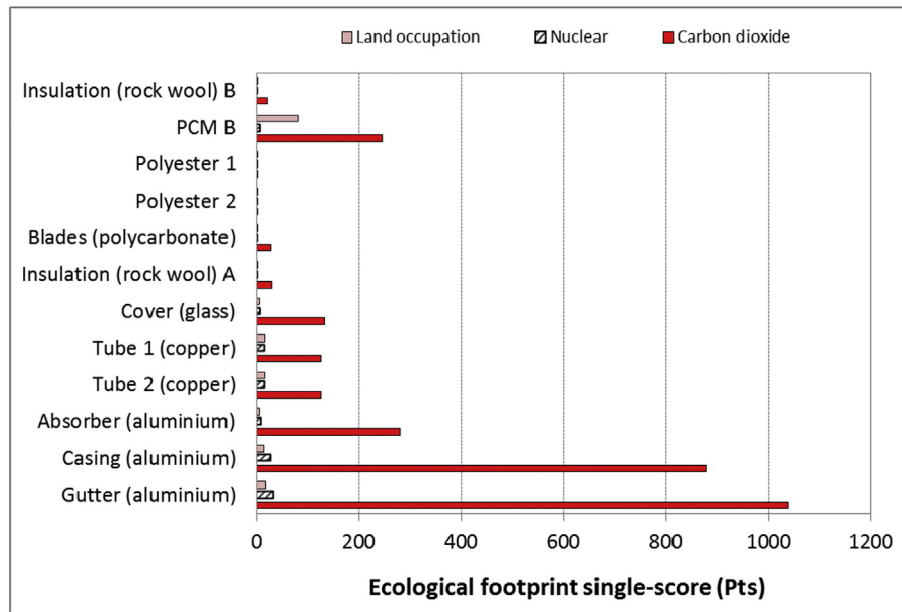
Fig. 5. Results based on Ecological footprint (single score: Pts) for the components/materials of the 35 collectors (material manufacturing).

Table 3
Results based on ReCiPe (midpoint approach, with characterization) for the components/materials of the 35 collectors (material manufacturing): 18 midpoint impact categories.

		Insulation (rock wool) B	PCM B	Blades (polycarbonate)	Insulation (rock wool) A	Cover (glass)	Tube 1 (copper)	Tube 2 (copper)	Absorber (aluminium)	Casing (aluminium)	Gutter (aluminium)
Climate change	kg CO2 eq	8.4	101.8	13.3	11.9	51.6	53.4	53.4	113.1	355.7	420.7
Ozone depletion	kg CFC-11 eq	3.5E-07	2.1E-06	4.4E-06	5.0E-07	3.7E-06	2.8E-06	2.8E-06	3.6E-06	1.1E-05	1.3E-05
Terrestrial acidification	kg SO2 eq	6.4E-02	3.5E-01	3.9E-02	9.1E-02	4.3E-01	1.0E+00	1.0E+00	7.9E-01	2.5E+00	2.9E+00
Freshwater eutrophication	kg P eq	2.8E-03	1.9E-02	3.8E-04	3.9E-03	7.0E-03	1.6E+00	1.6E+00	6.4E-02	2.0E-01	2.4E-01
Marine eutrophication	kg N eq	1.9E-03	3.5E-01	9.1E-04	2.6E-03	1.3E-02	2.0E+00	2.0E+00	2.4E-02	7.6E-02	9.0E-02
Human toxicity	kg 1,4-DB eq	2.9	18.4	1.0	4.2	8.5	2679.0	2679.0	60.5	190.2	224.9
Photochemical oxidant formation	kg NMVOC	4.0E-02	3.2E-01	3.3E-02	5.7E-02	2.7E-01	6.9E-01	6.9E-01	3.9E-01	1.2E+00	1.5E+00
Particulate matter formation	kg PM10 eq	2.2E-02	1.7E-01	2.0E-02	3.1E-02	1.3E-01	8.1E-01	8.1E-01	3.5E-01	1.1E+00	1.3E+00
Terrestrial ecotoxicity	kg 1,4-DB eq	4.1E-04	2.1E+00	2.3E-04	5.8E-04	1.8E-03	2.3E-02	2.3E-02	3.6E-03	1.1E-02	1.3E-02
Freshwater ecotoxicity	kg 1,4-DB eq	0.1	0.8	1.2E-02	0.1	0.2	52.6	52.6	1.6	5.2	6.1
Marine ecotoxicity	kg 1,4-DB eq	0.1	0.5	1.1E-02	0.1	0.2	48.0	48.0	1.6	5.1	6.0
Ionising radiation	kBq U235 eq	0.5	3.5	1.9E-02	0.7	4.0	8.0	8.0	5.0	15.8	18.7
Agricultural land occupation	m²a	0.5	160.2	5.7E-03	0.7	2.6	2.8	2.8	1.4	4.5	5.4
Urban land occupation	m²a	0.1	1.3	1.1E-02	0.2	0.3	5.4	5.4	1.0	3.3	3.9
Natural land transformation	m²	2.9E-03	1.5E+00	4.9E-05	4.2E-03	1.3E-02	1.8E-02	1.8E-02	1.1E-02	3.5E-02	4.2E-02
Water depletion	m³	11.9	75.5	3.1E-01	16.9	66.0	990.1	990.1	1000.5	3145.8	3720.4
Metal depletion	kg Fe eq	0.5	4.6	1.6E-02	0.7	5.8	945.8	945.8	2.2	7.0	8.2
Fossil depletion	kg oil eq	2.2	10.8	3.7	3.1	13.8	13.7	13.7	25.6	80.5	95.2

should be clarified that the case «without gutter» has been examined given the fact that the gutter (aluminium) could not be considered as a part of the solar system. The gutter is an additional component (mainly a component of the building itself) and may exist with any type of solar thermal system (for example, with a system based on BA flat-plate collectors). The results (Table 5) reveal that:

1) By taking into account all the cases that have been studied, the impact ranges from 58 to 73 Pts/m².
2) For both configurations (with/without PCM), the exclusion of the gutter (aluminium) from the calculations leads to an impact reduction of 10 Pts/m², verifying that the gutter considerably influences the total impact of the BIST system.
3) The configuration with PCM presents 5 Pts/m² higher impact (in comparison to the configuration without PCM).

Table 4
Indications (with X) of the components/materials with the highest impact for each of the midpoint ReCiPe categories (Table 4 is based on the data of Table 3).

	PCM B	Tube 1 and Tube 2 (copper)	Absorber, casing and gutter (aluminium)
Climate change			X
Ozone depletion			X
Terrestrial acidification			X
Freshwater eutrophication		X	
Marine eutrophication		X	
Human toxicity		X	
Photochemical oxidant formation			X
Particulate matter formation			X
Terrestrial ecotoxicity	X		
Freshwater ecotoxicity		X	
Marine ecotoxicity		X	
Ionising radiation			X
Agricultural land occupation	X		
Urban land occupation		X	
Natural land transformation	X		
Water depletion			X
Metal depletion		X	
Fossil depletion			X

Table 5
ReCiPe (endpoint, single-score) Pts per m^2 of absorber surface. Scenarios: Without recycling; With/without PCM; With/without gutter.

Configuration	Life-cycle stages considered	Results
Without PCM (scenario A)	Only manufacturing of the materials/collectors	68 Pts/m^2 (including the gutter (aluminium)) 58 Pts/m^2 (without the gutter (aluminium))
With PCM (scenario B)	Only manufacturing of the materials/collectors	73 Pts/m^2 (including the gutter (aluminium)) 63 Pts/m^2 (without the gutter (aluminium))

3.3.2. Life-cycle impact per kWh of produced thermal energy and impact related to pumping/auxiliary heating

In Table 6, ReCiPe Pts (endpoint, single-score including Human health, Ecosystems and Resources) per kWh of produced thermal energy (based on the 25-year output of the solar system) are presented. It should be mentioned that in this case the following life-cycle stages have been taken into account: Manufacturing (materials, collectors and additional components); installation; use/maintenance (lifespan); transportation; disposal. Furthermore, these results are for the following scenarios: With gutter; With/without recycling. From Table 6 it can be seen that:

1) By taking into account all the cases that have been examined, the values vary from 0.014 to 0.020 Pts/kWh.
2) The configuration with PCM presents 0.003 Pts/kWh higher impact (in comparison to the configuration without PCM).
3) Recycling results in an impact reduction of 0.003 Pts/kWh (for both configurations with/without PCM), verifying the environmental benefits of recycling for these types of systems.

The life-cycle impact per kWh of produced energy is an indicator that is influenced by the climatic conditions. The present LCA is based on the Mediterranean climatic conditions of Ajaccio (France). Certainly, different climatic conditions could affect the environmental performance of the system (according to the indicator mentioned above as well as according to other indicators which take into account the energy output of the system).

It should be clarified that the impact for use/maintenance phase (Table 6) refers to all the inputs during this phase, except of the inputs for pumping/auxiliary heating (a discussion about this issue has been presented in subsection 2.2.1). With respect to the impact related to pumping/auxiliary heating (Table 1), according to ReCiPe endpoint (single-score) and based on France's electricity mix (Sources: SimaPro; ecoinvent), it has been calculated to be 10.56 Pts

for the configuration without PCM and 10.04 Pts for the configuration with PCM. Certainly, this reduction of the impact (around 0.5 Pts) is related to the fact that the option with PCM has lower flow rate (and, therefore, lower inputs for pumping) as well as lower needs in terms of auxiliary heating (Table 1).

The effect of the inputs for pumping/auxiliary heating on the life-cycle impact of the proposed system has been presented in the authors' previous LCA study (Lamnatou et al., 2018): Evaluation of the same system (with/without PCM) based on cumulative energy demand and global warming potential. The findings according to energy payback time (EPBT) demonstrated that if the inputs for pumping/auxiliary heating are not taken into consideration, both configurations (with/without PCM) present almost the same EPBT (approximately 1.3 years). If the inputs for pumping/auxiliary heating are taken into account, EPBT is lower for the configuration with PCM. More analytically, the EPBT was found to be 4.24 years for the option without PCM and 3.68 years for the scenario with PCM. Therefore, it was demonstrated that PCM offers an EPBT reduction of approximately 0.6 years and this is mainly associated with the fact that PCM allows the use of lower flow rate. Additional life-cycle results based on cumulative energy demand and global warming potential (per kWh of produced thermal energy) can be found in the authors' previous LCA study: Lamnatou et al. (2018).

Finally, it should be noted that comparisons of the proposed BIST (without PCM) with the literature (based on multiple methods and environmental indicators: EPBT, $CO_{2.eq}$ emissions, embodied energy, Eco-indicator 99, etc.) can be found in the authors' previous articles: Lamnatou et al. (2014, 2015d, 2016, 2018). In the references cited above, in general, a good agreement with the literature has been observed.

3.4. Limitations and discussion about the PCM component

By taking into account several critical issues which have been

Table 6
ReCiPe (endpoint, single-score) Pts per kWh of produced thermal energy. Scenarios: With gutter (aluminium); With/without recycling.

Configuration	Life-cycle stages considered	Results
Without PCM (scenario A)	Manufacturing (materials, collectors, additional components); installation; use/maintenance (lifespan); transportation; disposal	0.017 Pts/kWh WITHOUT RECYCLING 0.014 Pts/kWh WITH RECYCLING
With PCM (scenario B)	Manufacturing (materials, collectors, additional components); installation; use/maintenance (lifespan); transportation; disposal	0.020 Pts/kWh WITHOUT RECYCLING 0.017 Pts/kWh WITH RECYCLING

presented in the studies of Lamnatou et al. (2016) and Lamnatou and Chemisana (2017), it can be seen that, in certain cases, BI solar systems (apart from the advantages that provide) present reduced efficiency. Certainly, this reduced efficiency influences the environmental profile of a BI solar system. For example, certain environmental indicators such as EPBT and energy-return-on-investment (since they take into account the energy output of the system) are influenced by this reduced efficiency. Moreover, parameters such as the latitude (of the place where the system is installed), the type of building-integration, the colour of certain components, the energy produced (for example, only thermal or both electrical/thermal), the lifespan of the components, the use (or not) of recyclable materials and the working fluid, influence the environmental performance of a BI solar system (Lamnatou et al., 2016; Lamnatou and Chemisana, 2017).

Related to the BIST system that has been investigated in the present study, it should be taken into account the issue that it was previously discussed (in subsection 3.3.1) about the gutter (that it could not be considered as part of the solar system itself).

In addition, it should be noted that in the specific case of gutter integration, the fact that the area of the gutter is limited (Fig. 1) limits the surface of the solar collector and, therefore, the collector output decreases. Furthermore, the relatively high consumption of electricity during the use phase of the system (Table 1) is another limitation. At this point it should be highlighted that except of the present study which focuses on heat storage/insulation options, other scenarios for the increase of the output of the BIST system have been investigated. In the frame of this goal, the use of vacuum-tube (instead of flat-plate) collectors has been examined and it was found that the BIST configuration based on vacuum-tube technology presents better environmental performance than the BIST configuration based on flat-plate collectors (Lamnatou et al., 2016).

Furthermore, it should be mentioned that there are uncertainties since LCA results can be affected by different sources of uncertainty (assumptions, life-cycle impact assessment methods, quality of the data, etc.). The experts should estimate the extent of the sources of uncertainty so as to improve the reliability of the obtained eco-profiles (Cellura et al., 2011). An extension of the present article could be a study which focuses on the effect of different sources of uncertainty.

Moreover, it is necessary to define some issues regarding the material that has been used for the calculations of the PCM impact. The material that has been adopted is fatty acid (Sources: SimaPro; ecoinvent). The production of the fatty acid which has been selected includes vegetable oils (e.g. palm oil) which remarkably influence the total impact of the production phase. Certainly, the inputs related to the production of the vegetable oils (fertilizers and energy for the cultivation of the related crops, etc.) considerably affect the total impact of the fatty acid. In the study of Noël et al. (2015), information about the adoption of palm oil in fatty-acid PCM production can be found. Noël et al. (2015) mentioned that dodecanoic acid produced from palm kernel oil for use in a solar thermal hot water system is a viable PCM with payback times (based on energy and carbon emissions) less than 3 years.

With respect to the present findings about PCM, based on

USEtox human toxicity/cancer (Fig. 4a) and USEtox ecotoxicity (Fig. 4b) the PCM component shows an impact considerably higher in comparison to the other components/materials. Moreover, according to ReCiPe endpoint with characterization (Fig. 3b), the PCM component has (species.yr) remarkably higher than the other parts of the collectors. However, based on ReCiPe midpoint with characterization (Tables 3 and 4) the components with the highest impact in terms of Human toxicity are the copper-based ones. In addition, by focusing on DALY (ReCiPe endpoint with characterization: Fig. 3a) it can be noted that the parts of the collectors with the highest impact are the copper- and aluminium-based ones. Certainly, there are differences between the findings mentioned above but it should be taken into account the fact that ReCiPe is a totally different method in comparison to USEtox (PRé, 2014).

4. Conclusions

The present article assesses the environmental profile of a BIST system (climatic conditions: Ajaccio, France). Two configurations have been evaluated (as basic scenarios): 1) Without PCM (scenario A), 2) With PCM (scenario B). The goal of the present LCA is the evaluation of the effect of the PCM component on the environmental profile of the proposed BIST system, based on ReCiPe, USEtox and Ecological footprint.

The results according to ReCiPe endpoint with characterization (for the 35 collectors and the phase of material manufacturing) reveal that: 1) the tubes (copper) are responsible for the highest DALY (impact related to human health), 2) the aluminium parts (absorber, casing, gutter) and the PCM component show the highest (species.yr) (impact related to ecosystems).

The results based on ReCiPe Pts (endpoint, single-score including Human health, Ecosystems and Resources) per kWh of produced thermal energy (25-year output) for manufacturing (materials, collectors and additional components), installation, use/maintenance (lifespan), transportation, disposal and based on the scenarios «With gutter (aluminium); With/without recycling» show that: 1) By taking into account all the cases that have been examined, the values vary from 0.014 to 0.020 Pts/kWh, 2) The configuration with PCM presents around 0.003 Pts/kWh higher impact (in comparison to the option without PCM), 3) Recycling offers an impact reduction of 0.003 Pts/kWh (for both configurations with/without PCM).

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