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

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ABSTRACT

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

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domestic-gas-boiler $CO_{2.eq}$ emissions) are also presented. The findings of the present work: 1) are compared with the literature and good agreement is observed, 2) verify that considerably higher impact can be avoided by utilizing the vacuum-tube/BIST instead of the flat-plate/BIST system.

Keywords: Life Cycle Analysis (LCA); Building-integrated solar thermal collectors; Rainwater harvesting; Embodied energy, embodied carbon; Energy payback time (EPBT), greenhouse-gas payback time (GPBT) and energy return on the investment (EROI); USEtox and ecological footprint

1. INTRODUCTION

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

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

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

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

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

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

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

The present investigation aims at: 1) presenting a review about BIST with vacuum-tube collectors, LCA about solar thermal systems based on vacuum-tube technology, etc. and identifying critical issues related to vacuum-tube applications, 2) providing information about the environmental profile of a patented BI active solar thermal system with vacuum tubes [29] in comparison to another patented BI active solar thermal configuration with flat-plate collectors [29] which has been studied by the authors from environmental point of view [22, 23]. Both systems produce hot water for domestic applications and regard integration into building gutters. For the comparison, Embodied Energy (EE) and Embodied Carbon (EC) along with USEtox and ecological footprint are adopted. Multiple scenarios are examined, based on several databases. Additional environmental indicators in comparison to authors´ previous studies [22, 23] are presented, providing a comprehensive picture of the environmental performance of the proposed BI solar thermal systems.

Moreover, the present investigation offers useful information within the field of «energy and buildings» given the fact that: 1) it includes a specific literature review, highlighting crucial factors related to BIST applications with vacuum-tube collectors and the environmental profile of vacuum-tube collectors; 2) there are few LCA studies about the promising for the building sector technologies of vacuum-tube and BIST; 3) it refers to a double-function (production of hot water and rainwater harvesting) BIST system which has multiple advantages for the building from energetic as well as from environmental point of view.

The paper is separated into two parts: i) literature review and critical discussion with emphasis on vacuum-tube/BIST and ii) a case study, based on LCA, about two BIST systems: vacuum-tube vs. flat-plate. In this way, the theoretical part (i) is combined with the practical application of part (ii).

In part (i) selected literature studies related to the systems which are studied in part (ii) are presented. The scope of part (i) is to provide a critical literature review, revealing the importance of BIST systems based on vacuum-tubes as well as the importance of a study which provides information about the ecological profile of vacuum-tube/BIST systems in comparison to BIST configurations based on flat-plate collectors. In the frame of this scope, section 2 presents literature studies regarding: vacuum-tube solar-thermal systems (in general), vacuum-tube/BIST systems, the environmental performance of vacuum-tube collectors, issues related to solar thermal systems, critical comments. In section 2, a subsection about rainwater harvesting in buildings is also presented given the fact that the proposed BIST systems which are evaluated in part (ii) (section 3) combine into a single unit solar thermal collector and rainwater harvesting.

2. LITERATURE REVIEW AND CRITICAL ISSUES

2.1. General studies about vacuum-tube solar thermal collectors

In the present section, investigations about vacuum-tube collectors are presented, identifying crucial aspects related to this type of solar systems.

Tang et al. [30] investigated the optimal tilt-angles of all-glass evacuated tube solar collectors. A detailed mathematical procedure was developed in order to estimate the daily collectible radiation on a single tube of all-glass evacuated-tube solar collector (based on solar geometry, knowledge of two-dimensional radiation transfer). The findings revealed that the annual collectible radiation on a tube is affected by several factors such as collector type, central distance between tubes, size of solar tubes, tilt and azimuth angles, use of Diffuse Flat Reflector (DFR). For the case of collectors with identical parameters, T-type collectors (with solar tubes tilt-arranged) collect annually slightly more radiation than H-type collectors (with solar tubes horizontally arranged). The utilisation of DFR can considerably improve the energy collection of the collectors. Unlike the flat-plate collectors, all-glass evacuated-tube solar collectors should be (generally) mounted with a tilt-angle less than the site latitude in order to maximize the annual energy collection. For most of the areas with site latitude higher than 30° in China, T-type collectors should be installed with a tilt-angle about 10° less than the site latitude, while for H-type collectors without DFR, the reasonable tilt-angle should be around 20° less than the site latitude [30].

Nalamwar et al. [31] presented a work about a vacuum-tube solar thermal collector for water heating. It was noted that a critical point is the fact that most of the common transparent insulating materials cannot withstand high temperatures because they consist of plastics. Thereby, temperature resistive collector covers combining a high-transitivity with a low U-value are needed. One possibility is to utilise capillaries made of glass instead of plastic materials. Based on the same radiation intensity, a comparison of the heat gain of a flat-plate with a vacuum-tube solar collector (having the same capacity tank, mass flow rate and absorber area) showed that vacuum-tube collector is 16.12% more efficient than the flat-plate one [31].

The performance of water-in-glass evacuated-tube solar water heaters was evaluated by Budihardjo and Morrison [32], by using experimental measurements of optical and heat loss characteristics and a simulation model of the thermosiphon circulation in single-ended tubes. The performance of water-in-glass evacuated-tube solar collector configurations was compared with flat-plate solar collectors (in a range of locations). The performance of a typical 30-tube evacuated-tube array was found to be lower than a typical 2-panel flat-plate array for domestic water heating applications in Sydney [32].

Ma et al. [33] performed a thermal performance analysis of a glass evacuated-tube solar collector with U-tube. The configuration includes a two-layered glass evacuated tube, and the absorber film is deposited in the outer surface of the absorber tube. The heat loss coefficient and the heat efficiency factor were evaluated by means of one-dimensional analytical solution. The influence of the air layer between the absorber tube and the copper fin on the heat efficiency was also investigated. The results revealed that the function relation of the heat loss coefficient of the glass evacuated-tube solar collector with temperature difference between the absorbing coating surface and the ambient air is nonlinear. It was also verified that the surface temperature of the absorbing coating is an important factor for studying the thermal performance of the glass evacuated-tube solar collector [33].

Patel and Patel [34] presented a review study about evacuated-tube collectors and it was noted that glass evacuated-tube collectors present more advantages (lower convection losses, etc.) compared to flat-plate collectors. The review article [34] also revealed that, within the field of evacuated-tube collectors, CFD (Computational Fluid Dynamics) analysis about evacuated-tube collectors is a good tool for comparison with experimental results for validation purposes.

In addition, there is an investigation about BI solar systems and it refers to multiple configurations including ultra-high-vacuum evacuated-tube collectors [35]. It was mentioned that solar thermal collectors with a very low pressure vacuum can reduce the thermal losses of the collector, resulting in more efficient operation at higher temperatures. It was also noted that such collectors should be further studied and evaluated against traditional evacuated-tube collectors, in the frame of future developments [35].

Bosselaar et al. [36] conducted a study about the integration of solar water heating into residential buildings. The study [36] included useful information about evacuated-tube collectors. Some crucial aspects related to this type of solar thermal collectors are following presented:

- Since evacuated tube collectors can be manufactured in large scale in automated production lines with a relatively low material demand compared to flat-plate collectors, this type of collectors (in combination with a well-insulated hot water storage tank) has great potential not only in China, but also for export to countries of hot and moderate climate [36].
- The main market for evacuated-tube collectors refers to single-family houses in suburban and non-urban areas. In [36] it was mentioned that the possibilities for building integration of this type of systems are limited due to the nature of their design.

The main advantages are the high degree of prefabrication, the fact that they can be easily installed (with limited skills). The challenges include the improvement of the quality and durability of the evacuated-tube systems. At the moment, many evacuated tubes have problems to pass European quality tests (for example the temperature shock test). It was noted that not only in this test procedure but also in normal operation, broken evacuated tubes have been observed. Another weak point is related with the sealing between glass and storage tank. Certainly, it is highly recommended to solve these problems as quickly as possible and to test the new products in authorized test institutes before selling the products on the market [36].

- In China, vacuum-tube collectors are mainly classified into two types: 1) all-glass vacuum-tube and 2) glass-metal vacuum-tube. Most manufacturers produce all-glass vacuum-tube collectors. In recent years, some manufacturers have started to produce U-type vacuum-tube and heat-pipe vacuum-tube configurations. U-type vacuum tube has a copper U-tube which is constructed in the all-glass vacuum tube and in which the fluid medium circulates (for heat exchange). A heat-pipe vacuum tube consists of a heat tube which is constructed in the all-glass vacuum tube (so that the heat produced by the vacuum tube can be transferred). This helps to solve problems related to leakage and forced circulation [36].

- Since the second half of the 1990's, all-glass vacuum-tube solar water heating systems have become the predominant type of household solar water heating. A number of manufacturers have introduced different types of solar water heating configurations with forced circulation vacuum tubes (in the last two years). Moreover, in the last two years, the sales volume of heat-pipe vacuum tubes has gradually increased; however, their cost is still relatively high [36].

For the above mentioned comments it should be taken into account that the study of Bosselaar et al. [36] was conducted in 2004.

According to another study [37], the advantages of the vacuum-tube collectors are related to:

• Their higher solar yield in comparison to flat-plate collectors (with the same absorber area).

• The fact that they are 30% more effective and they have little thermal losses (only through some radiation).

• Their ability to work in cold, windy and humid conditions.

• The function that allows to the individual tubes to be rotated in order to optimize the ideal orientation.

• The achievement of high temperatures.

• The fact that dirt or moisture cannot get into the collector (since the tube is sealed).

Moreover, based on the above mentioned study [37], the disadvantages of the vacuum-tube collectors are associated with:

• Their cost.

• The fact that they are not easily integrated into the fabric of the building (for example in the frame of roof-integrated or façade-integrated applications).

In terms of the aesthetics, it was noted that some people like the tubes from aesthetical point of view while others they do not like [37].

Ayompe et al. [38] conducted a study about a comparative field performance of flat-plate and heat-pipe evacuated-tube collectors for domestic water heating systems in a temperate climate. Year-round energy performance monitoring results of two solar water heaters with 4 m^2 flat-plate and 3 m^2 heat-pipe evacuated-tube collectors (operating under the same weather conditions in Dublin, Ireland) were presented. The energy performance of the two configurations was compared on daily, monthly and yearly basis. The results demonstrated that for an annual total in-plane solar insolation of 1087 kWh/m^2, a total of 1984 kWh and 2056 kWh of heat energy were collected by the 4 m^2 flat-plate collector and by the 3 m^2 evacuated-tube, respectively. The annual average collector efficiencies were found to be 46.1% and 60.7% while the system efficiencies were 37.9% and 50.3% for the flat-plate and evacuated-tube, respectively [38].

Additional studies within the field of vacuum-tube solar thermal collectors are those of:

- Hayek et al. [39]: an experimental investigation on the performance of evacuated-tube solar collectors (under eastern Mediterranean climatic conditions) was presented.

- Chen et al. [40]: a non-glass vacuum-tube collector (based on acrylic) was investigated (the study included fabrication of the system, experiments and modelling).

- Qiu et al. [41]: about evacuated-tube collectors as a notable «driver» behind the solar-water-heating industry in China.

- Iranmanesh and Mehrabian [42]: optimization of a lithium bromide–water solar absorption cooling system with evacuated-tube collectors (by means of the genetic algorithm) was conducted.

- Ayompe and Duffy [43]: regarding thermal performance analysis of a solar water heating system with heat-pipe evacuated-tube collector by utilising data from a field trial.

- Arkar and Medved [44]: optimization of latent-heat storage in solar air-heating system with vacuum-tube air solar collector was conducted.

- Rad et al. [45]: a combined solar thermal and ground source heat pump system was investigated and the use of vacuum-tube solar thermal collectors (as more efficient collectors in comparison to the flat-plate ones) was proposed as a future prospect.

Furthermore, Paulus [46] conducted a work about solar district heating in France, proposing several configurations of solar thermal collectors, including an evacuated-tube collector with heat pipe made of aluminium (roll-bond).

In Table 1, selected studies about evacuated-tube collectors are presented, summarizing important issues related to this type of technology. From Table 1 it can be seen that: 1) vacuum-tube solar collectors have been examined for several climatic conditions, with emphasis on domestic-water-heating applications; 2) multiple critical issues have been identified (possibilities for building-integration, distance between the tubes, size of the tubes, use of reflectors, temperature of the absorbing coating, vacuum, alternative materials for the collector, heat storage, etc.); 3) several works give emphasis on the comparison of a vacuum-tube collector with a flat-plate one (for most of the studied cases, vacuum-tube collectors present more advantages and better performance comparing to flat-plate configurations).

Table 1. Selected studies about vacuum-tube solar collectors.

Studies	Comments/findings	Additional information
Tang et al. [30]: optimal tilt-angles of all-glass evacuated-tube solar collectors	The annual collectible radiation on a tube is influenced by collector type, central distance between tubes, size of solar tubes, tilt/azimuth angles, use of reflector	
Nalamwar et al. [31]: vacuum-tube solar thermal collector for water heating	Comparison of heat gain: flat-plate vs. vacuum-tube collector; vacuum-tube is 16.12% more efficient than flat-plate	Most of the common transparent insulating materials cannot withstand high temperatures since they consist of plastics
Budihardjo and Morrison [32]: performance of water-in-glass evacuated-tube vs. flat-plate collectors (for several locations)	The performance of a typical 30-tube evacuated-tube array is lower than a typical 2-panel flat-plate array (domestic water heating, Sydney)	
Ma et al. [33]: thermal performance analysis of glass evacuated-tube collector with U-tube	The surface temperature of the absorbing coating is an important factor for studying the thermal performance of the glass evacuated-tube solar collector	
Patel and Patel [34]: review about evacuated-tube collectors	Glass evacuated-tube collectors have more advantages compared to flat-plate	CFD is a useful tool for the evaluation of evacuated-tube collectors
[35]: BI solar systems (multiple configurations, including ultra-high-vacuum evacuated-tube collectors)	Solar thermal collectors with a very low pressure vacuum can reduce thermal losses, resulting in more efficient operation at higher temperatures	Such collectors should be further studied and evaluated against traditional evacuated-tube collectors
Bosselaar et al. [36]: the integration of solar water heating into residential buildings (emphasis on China)	The main advantages of evacuated-tube collectors: high degree of prefabrication, easy installation	Several issues were presented (about building-integration of evacuated-tube collectors, etc.)
[37]: evacuated-tube vs. flat-plate collectors	The advantages of the vacuum-tube collectors: higher solar yield in comparison to flat-plate collectors; achievement of high temperatures, etc.	Disadvantages of vacuum-tube collectors: cost; they are not easily integrated into the fabric of the building
Ayompe et al. [38]: comparative field performance study of flat-plate and heat-pipe evacuated-tube collectors (domestic water heating, Ireland)	System efficiencies were found to be 37.9% and 50.3% for the flat-plate and the evacuated-tube, respectively	An economic analysis revealed that both solar water heating systems are not economically viable
Hayek et al. [39]: experiments on evacuated-tube solar collectors (water-in-glass vs. heat-pipe)	Heat-pipe configurations are better than water-in-glass designs	The experiments were carried out November to January (Mediterranean climatic conditions)
Chen et al. [40]: fabrication and testing of a non-glass vacuum-tube collector	The evacuated-tube collector was fabricated from acrylic for improved resistance to shattering	Comparing to a glass-tube collector at a much higher vacuum level, the heat loss of the non-glass collector with natural convection in the continuum-flow regime is around 15% higher
Qiu et al. [41]: evacuated-tube collectors (emphasis on China)	Evacuated-tube collectors: a notable «driver» for solar-water-heating industry in China	
Iranmanesh and Mehrabian [42]: optimization of a lithium bromide–water solar absorption cooling system with evacuated-tube collectors	The optimum mass flow rate of hot water passing through the generator and collector plays an important role for the reduction of the auxiliary energy	Genetic algorithm was adopted
Ayompe and Duffy [43]: thermal performance analysis of a solar-water-heating system with heat-pipe evacuated-tube collector	Maximum recorded collector outlet fluid temperature: 70.3^{o}C	Data obtained from a field trial installation over a year (Dublin, Ireland)
Arkar and Medved [44]: optimization of latent heat storage in air-heating system with vacuum-tube air solar collector	The optimal mass of PCM (phase change material) in the latent heat storage and the optimal air flow rate were evaluated	
Rad et al. [45]: a combined solar thermal and ground source heat pump system	The adoption of vacuum-tube solar thermal collectors was proposed as a future prospect (instead of flat-plate)	

2.2. Studies about vacuum-tube/BIST systems

The present section focuses on studies about BIST systems based on vacuum-tube technology. Representative works are cited, highlighting critical aspects related to this specific category of BIST configurations.

A façade system with evacuated-tube collectors can achieve high temperatures during summer and thus, it can be ideal for solar thermal cooling. A façade collector with vacuum tubes was presented in [47]. The system consists of window-integrated evacuated tubes which gain solar heat, provide shade and distribute light for the indoor areas. It was noted that a vacuum-tube collector can be combined with a CPC (compound parabolic concentrator) aluminium mirror behind the tubes. In this way, high temperatures can be achieved in the solar circuit even during winter (with low outside temperatures) [47].

Li et al. [48] presented a work (experimental investigation and simulation analysis) about the thermal performance of a balcony wall-integrated solar water heating system (for high-rise buildings). An evacuated-tube solar collector (U-type, glass) is vertically fixed on the balcony wall and the water (heated in the solar collector) flows through the exchanger coil in the water tank and then it flows back to the solar collector. Based on the experimental findings, the mean daily collector efficiency is about 40%.

In the study of Zhang et al. [27], a comprehensive review about active solar thermal façades was presented and the proposed configurations were classified according to the:

1) Element (wall, window, balcony, sunshield, roof).

2) Collecting typology (evacuated-tube collector, flat-plate collector, unglazed flat-plate collector).

3) Façade transparency.

4) Application (ventilation or heat recovery, hot water production, heating/cooling, electricity/heat).

5) Heat transfer medium (air, water, heat-pipe filling liquid, PCM).

In addition, in [27] it was noted that evacuated tubes are especially recommended for balcony-integration. The high-level vacuum insulation minimizes the heat losses in order to achieve higher working efficiency. The standard arrangement consists of several glass tubes with manifold tubes (at top and bottom). The tubes are standardized products with easy joining and the number of the tubes can be flexible (according to the heat demand or construction size). The balcony-based active solar thermal façades are usually translucent (with heat transfer medium: air or heat-pipe fluid). It was also noted that the flat-plate configurations are promising for roof-based active solar thermal façades [27].

Wu et al. [49] examined the technical feasibility of a façade-integrated solar cooling system for commercial buildings. The studied solar cooling system consists of evacuated-tube solar collectors installed in the cavity of double-skin façades to collect solar energy and transferred to be used in an organic Rankine-cycle turbine (which drives the compressor of the vapour compression cycle). The collected solar energy during the weekends is stored in a hot water storage tank for using during the operating hours of the office building. The system is backed up by means of a gas-fired water heater. The technical feasibility of the system for cooling of office buildings in the tropical climate zones was studied. TRNSYS was utilized in order to determine the size of each component and to evaluate the technical performance of the integrated system. It was mentioned that the system is able to meet the cooling demand for the operating hours selected. Moreover, it was found that the annual solar fraction of the system is around 13% [49].

Goodman [50] proposed building interior evacuated tubes and reflectors, active solar thermal collector building type for mid-temperature applications in non-seismic snow accumulation regions. A walk-in architectural solar collector includes interior fixed non-imaging CPC type E-W line troughs, augmenting transverse evacuated tubes with monolithic glazing building envelope collector cover [50].

Additional studies which refer to BIST based on vacuum-tube collectors are those of:

- Weiss [51] about façade-integrated and roof-integrated configurations.
- References [28] and [52] about BIST applications general.
- Krippner [53] regarding façade-integrated systems.
- Reference [54] about façade-integrated configurations for high-rise buildings.
- Reference [55] concerning façade-integrated concepts with CPC reflectors.
- Reference [56] with respect to façade-integrated and roof-integrated applications.

Finally, it should be noted that in the study [57] several BIST concepts with vacuum-tube collectors were presented: solar pergolas, horizontal building shading, balcony eaves, façade system (window) and collectors in front of a metal cladding [57].

In Table 2, selected references about evacuated-tube collectors in the frame of building-integrated applications are presented. From Table 2 it can be noted that: 1) most of the cases refer to façade-integrated configurations and water heating, 2) few references present configurations for balconies, roofs, high-rise buildings, solar cooling applications, systems with reflectors and air heating applications.

Table 2. Selected studies about vacuum-tube collectors in the frame of building-integrated applications.

Studies	Medium	Systems	Comments/findings
[47]	Water	Façade-integrated (windows)	Ideal for solar thermal cooling
Li et al. [48]	Water	Balcony wall-integrated (water heating, high-rise building)	Mean daily collector efficiency: about 40%
Zhang et al. [27]	Water Air	Review about active solar-thermal façades (several configurations)	Evacuated tubes recommended for integration into the balcony (flat-plate configurations: promising for roof-based applications)
Wu et al. [49]	Water	Façade-integrated solar cooling system (commercial buildings)	The system is able to meet the cooling demand for the operating hours selected
Goodman [50]	Water	Building interior evacuated tubes and reflectors	Mid-temperature applications in non-seismic snow accumulation regions
Weiss [51]		Façade-integrated and roof-integrated configurations	
Krippner [53]	Water	Façade-integrated systems	
[54]	Air	Façade-integrated configurations for high-rise buildings	
[55]	Water	Façade-integrated concepts with CPC reflectors	
[56]	Water	Façade-integrated and roof-integrated applications	
[57]	Mainly about water heating	Several BIST with vacuum-tube collectors: solar pergolas, horizontal building shading, balcony eaves, façade system (window), collectors in front of a metal cladding	

2.3. Studies about the environmental performance of vacuum-tube collectors

The present section focuses on the studies which examine the ecological profile of vacuum-tube collectors by means of multiple methodologies.

A Product Carbon Footprint (PCF) study for a selected evacuated-tube collector including an implementation process map into GaBi 5 LCA software was presented

[58]. It was mentioned that the utilization of software allows for a structured and modular implementation of a process map. The functional unit of 1-year hot-water supply for a 4-person household in Germany was adopted. A carbon footprint of 237 kg CO_2 per functional unit was found [58].

Hoffmann et al. [19] compared the environmental impact (in terms of process production) of flat-plate and evacuated-tube solar collectors. SimaPro and EI99 were adopted. The results demonstrated that the manufacturing phase of the flat-plate solar collectors has higher environmental impact and carcinogen is the major category which causes environmental impact in both types of collectors (because of the consumption and emission of arsenic and cadmium ions). In the conclusions, it was noted that from environmental point of view, the evacuated-tube solar collectors are the best choice, considering the least impact generated during their manufacture phase (among the analysed categories).

Carlsson et al. [7] examined the suitability of solar-collector systems in which polymeric materials are used versus those in which more traditional materials are utilized. A solar heating system based on polymeric solar collectors was compared with two equivalent (but more traditional) solar heating systems: one configuration with flat-plate solar collectors and one configuration with evacuated-tube solar collectors. With respect to climatic and environmental performances, the results clearly demonstrated that the polymeric solar-collector system is the best. It should be noted that for the environmental study, the methodologies of EI99, IPCC 100a and CED were adopted [7].

Additional studies which include information about the environmental performance of vacuum-tube solar thermal collectors are those of:

- Reference [18]: based on IMPACT 2002+ and ReCiPe methodologies.

- Reference [59]: concerning the use of aluminium, e.g. in evacuated-tube solar thermal collectors.

- Reference [60]: life-cycle energy, life-cycle emissions and cost analysis of a typical one-storey detached house (Montreal, Canada) were presented, including a life-cycle cost and life-cycle energy use of a solar combi-system based on flat-plate and evacuated-tube solar collectors.

- Hernandez and Kenny [61]: a work which included information about embodied energy and EPBT of solar thermal collectors (evacuated-tube and flat-plate) for domestic solar water heating.

- Reference [62]: the reduction of CO_2 emissions by using an evacuated-tube solar collector instead of utilizing non-renewable energy sources was presented.

- Greening and Azapagic [63]: about the life-cycle environmental sustainability of solar water heating systems (based on flat-plate and evacuated-tube collectors) in regions with low solar irradiation, such as the UK.

In addition, Hang et al. [17] evaluated solar water heating systems for the U.S. typical residential buildings, from energetic, economic and environmental points of view, including two different types of solar collectors (flat-plate and evacuated-tube), two types of auxiliary systems (natural gas and electricity) and three different locations (Los Angeles, Atlanta and Chicago) [17].

Allouhi et al. [64] conducted an economic and environmental assessment of solar-air conditioning systems (Morocco). The installation includes solar collectors (evacuated-tube technology) connected to a heat storage tank. The results demonstrated that solar air-conditioning systems in hot climates can be an attractive solution to mitigate CO_2 emissions and increase energy savings. Nevertheless, the high installation cost is a main obstacle.

In the frame of an investigation about solar air-conditioning and refrigeration, LCA of solar cooling systems was conducted [65]. Several configurations were examined, including evacuated-tube solar thermal collectors. Based on a functional unit of 1 m^2 (evacuated-tube collector), a global energy requirement of 1.71 GJ and a GWP (global warming potential) of 101.2 kg $CO_{2.eq}$ were presented.

Finally, it should be noted that Peuportier [66] presented a work about the benefits (environmental, etc.) of solar thermal collectors in the building sector, including several solar thermal configurations (vacuum-tube, etc.).

In Table 3, selected works about the ecological profile of evacuated-tube collectors are presented. From Table 3 it can be mentioned that: 1) there are few investigations which examine the ecological profile of solar thermal systems based on vacuum-tube technology, 2) most of the references are based on CO_2 emissions and embodied energy while there are few studies which adopt single-score/eco-point methodologies and life-cycle cost analysis, 3) the investigations have been conducted under different climatic conditions, 4) the major part of the works includes a comparison of a vacuum-tube collector with a flat-plate one and the results reveal that (for most of the studied cases) the vacuum-tube system is more eco-friendly than the flat-plate one, 5) the largest number of references are about domestic hot water heating.

Table 3. Selected studies about the environmental profile of vacuum-tube collectors.

Studies	Medium	Methods, indicators, etc.	Comments/results
[58]	Water	Product Carbon Footprint (PCF) (functional unit: 1-year hot water supply, 4-person household, Germany)	Carbon footprint: 237 kg CO_2 per functional unit
Hoffmann et al. [19]	Water	EI99 (comparison of the impact in terms of process production of flat-plate and evacuated-tube solar collectors)	From environmental point of view, the evacuated-tube collectors are the best choice
Carlsson et al. [7]	Water	EI99, IPCC 100a, CED (a solar heating system with polymeric collectors was compared with two traditional solar systems (one flat-plate, one evacuated-tube))	Regarding climatic and environmental performances, the polymeric solar system is the best
[18]	Water Air	IMPACT 2002+, ReCiPe (solar thermal systems for small-scale applications)	Several configurations were studied, including flat-plate and vacuum-tube collectors
[59]	Water Air	CO_2 abatement potential of renewable-energy technologies that utilize aluminium as a key component	Multiple renewable-energy systems were examined, including evacuated-tube collectors; emphasis was given on the impact related to the use of aluminium
[60]	Water	Life-cycle energy use, life-cycle emissions and life-cycle cost analysis (typical one-storey detached house, Montreal; the study includes a solar combi-system based on flat-plate and evacuated-tube collectors)	Due to the higher efficiency of evacuated-tube in cold climates, smaller solar collectors and storage tank are needed; thus, less materials are required for the same level of performance
Hernandez and Kenny [61]	Water	Embodied energy, EPBT (domestic solar water heating, Ireland)	The studied evacuate-tube collectors have lower embodied energy (per m^2 collector area) than the flat-plate ones
[62]	Water	Embodied carbon, reduction of CO_2 emissions	When offsetting electricity usage, each evacuated tube [62] installed is equivalent to planting 32 trees
Greening and Azapagic [63]	Water	Life-cycle environmental sustainability (CML 2 Baseline 2001 methodology) of solar water heating systems (regions with low solar irradiation): flat-plate vs. evacuated-tube collector	The flat-plate system shows on average 7% lower impacts than the evacuated-tube for 7 of the 11 categories examined due to the energy-intensive manufacture of the evacuated-tube system (the production of the glass tubes is the main contributor to this high energy consumption); evacuated-tube is a better option for freshwater, marine, terrestrial and human toxicity potentials
Hang et al. [17]	Water	Energetic and environmental payback periods, life-cycle cost (U.S. typical residential buildings, solar water heating): flat-plate vs. evacuated-tube (several configurations: with natural gas, etc.)	The flat-plate system with natural gas shows the best energetic, economic and environmental performance in all of the three representative cities (Atlanta, Chicago, Los Angeles)
Allouhi et al. [64]	Water	Economic and environmental assessment of solar-air conditioning systems (Morocco): the installation includes evacuated-tube solar collectors	Solar air-conditioning systems in hot climates can be an attractive solution to mitigate CO_2 emissions and increase energy savings (however, the high installation cost is a main obstacle)
[65]	Water	Global energy requirement, GWP (solar heating and cooling systems)	Based on the functional unit of 1 m^2 evacuated-tube collector, global energy requirement is 1.71 GJ and GWP is 101.2 kg $CO_{2.eq}$
Peuportier [66]	Water Air	Primary energy, CO_2 emissions	Several configurations of solar water heating systems (including vacuum-tube collectors), buildings, etc.

2.4. Issues related to solar thermal systems

In this section, multiple factors associated with solar thermal configurations are briefly presented. These factors refer to:

- Glazing materials, collector absorbing plates, minimum entropy generation rate, optimum collector temperature, collector incidence angle, combination of components and subsystems to create a wide variety of building solar heating and cooling systems (which are some of the issues presented by Kalogirou [67] in a comprehensive study about solar thermal collectors and applications).
- The manufacture of a solar thermal collector by means of copolymer material: a study was conducted by Cristofari et al. [68].
- The concept of drain water recovery: Tanha et al. [69] conducted a study about simulation and experimental testing of two hybrid solar domestic water heating systems with drain water heat recovery.
- The utilization of nanofluids: Al-Shamani et al. [70] presented a review about the use of nanofluids in solar collectors; in addition, reference [71] is about an experimental analysis on the thermal efficiency of an evacuated-tube solar collector by adopting nanofluids.
- Wall-integrated PCMs: a state-of-the-art was presented by Memon [72] (PCMs can be adopted in the frame of solar thermal/heat storage applications).
- Performance enhancement of solar thermal collectors: a review study was conducted by Suman et al. [73].
- Design criteria of solar thermal energy storage systems (technical issues (materials, etc.); cost-effectiveness; environmental aspects) [74].
- Solar and daylight availability e.g. for façades and roofs of active or passive solar heating [75].

- The effect of colour (of certain components) on the thermal performance of BI solar collectors [76].

The above mentioned issues could be also taken into account for the specific case of vacuum-tube/BIST applications, indicating crucial aspects which can influence the energetic as well as environmental performance of vacuum-tube/BIST systems.

Furthermore, the avoidance of glare is another factor which is associated with the construction of façades [77] and it should be taken into account. Additional critical issues related to BIST configurations such as complexity in terms of system installation into the structure of the building, need of special training for the installation, requirements of building industry/private users and quality of building integration/architectural quality, have been presented in the review study of Lamnatou et al. [1].

2.5. Rainwater harvesting in buildings

Given the fact that many urban areas in Mediterranean climates have problems of water scarcity, rainwater harvesting can offer multiple advantages. In the literature there is a study which identified the most environmentally friendly strategy for rainwater utilization in Mediterranean urban environments of different densities [78]. Based on an LCA about several rainwater harvesting systems, it was found that the environmentally optimal infrastructure (regardless of urban density) locates the tank on the roof in an integrated design extended across the top of the building that evenly distributes the weight on the structure. It was noted that the crucial factor is the reduced need for structural components; moreover, the absence of catchment components, the use of the gravity flow to distribute the water supply and the adjustability of the tank to the shape of the roof are additional critical issues [78].

The case of rainwater harvesting in Spain has been investigated by Farreny et al. [79] by integrating quantitative and qualitative data of rooftop storm-water runoff in an urban Mediterranean-weather environment. The objective was to provide criteria for the roof selection in order to maximize the availability and quality of rainwater. Four roofs were monitored over 2 years (2008–2010): three sloping roofs – clay tiles, metal sheet and polycarbonate plastic – and one flat gravel roof. A model for the estimation of the runoff volume and the initial abstraction of each roof and assess the physicochemical contamination of roof runoff was presented. Big differences in terms of the runoff coefficient were observed, depending mainly on the slope and the roughness of the roof. It was mentioned that the inclusion of criteria related to roof slope and roughness in city planning may be useful in order to promote rainwater as an alternative water supply while preventing flooding and water scarcity [79].

However, except of the case of Mediterranean climate, rainwater harvesting also shows interest for other cases. Li et al. [80] conducted a study about rainwater harvesting and greywater treatment systems for domestic applications in Ireland. It was noted that: 1) water shortage has been recognized as one of the key issues facing many countries, 2) there are relatively abundant water resources available in Ireland due to its plenty of rainfall; nevertheless, Ireland will encounter water-shortage problems in the future, especially in urban areas. It was also noted that water consumption per capita per day in Ireland is one of the highest in Europe and water demand is still increasing (because of population growth and higher standards of living). The utilization of domestic rainwater harvesting and greywater treatment systems has the potential to supply around 94% of domestic water in Irish households [80].

In addition, rainwater harvesting is beneficial for the case of rural communities. Mwenge Kahinda et al. [81] conducted a study about domestic rainwater harvesting to improve water supply in rural South Africa. In South Africa there are people which do not have access to adequate water supply. Domestic rainwater harvesting which provides water directly to households has the potential to supply water even in rural and peri-urban areas that conventional systems/technologies cannot supply [81]. The importance of rainwater harvesting for the developing countries has been also highlighted by Helmreich and Horn [82]. Harvested rainwater can be utilized for agriculture or water supply for households. Given the fact that rainwater might be polluted by bacteria and hazardous chemicals, treatment is necessary before usage. Slow sand filtration and solar technologies can be utilized in order to reduce pollution. Membrane technology can also be a potential disinfection technique in order to achieve a safe drinking-water supply [82]. The benefits of rainwater harvesting for rural areas have been also investigated by Sturm et al. [83].

In the frame of the concept of rainwater harvesting in combination with renewable-energy systems, Chong et al. [84] presented a BI wind, solar and rainwater harvester for urban high-rise applications.

Godefroy et al. [85] conducted an LCA study for the specific case of gutters, in order to identify the most environmentally friendly configuration. The goal of [85] was a comparative LCA study. Three different gutters, based on different materials, were evaluated. The functional unit «ability to collect rainwater from a roof in a temperate zone over 30 years, considering one meter of gutter» was utilised. All the phases of the cycle were considered. The environmental impact was evaluated by means of ecoinvent 2.0 database and CML method (midpoint approach). Several scenarios were examined. It was found that the production phase (including raw material extraction and fabrication) has the highest environmental impact [85].

Additional studies about rainwater harvesting in urban systems have been presented by:

- Domènech and Saurí [86]: a comparative appraisal of the use of rainwater harvesting in buildings (with respect to social experience, drinking water savings and economic costs) in the Metropolitan Area of Barcelona (Spain) was presented.
- Morales Pinzón [87]: a model to study technical, economic and environmental issues of rainwater harvesting systems for domestic urban use was presented.
- Spinks et al. [88]: a study about water quality treatment processes in domestic rainwater harvesting systems was presented (in [88] it was noted that rain harvesting in the urban environment produces valuable yields of water and research into treatment processes is needed to ensure that in a future prospect, this resource can be fully utilized).

Furthermore, Villarreal and Dixon [89] investigated a rainwater collection system for domestic water supply in Ringdansen, Norrköping, Sweden. Several scenarios for utilizing rainwater in a dual water-supply system to supplement drinking water were analysed. A computer model was developed to quantify water savings potential of the rainwater collection scheme [89].

Based on the above mentioned studies, multiple critical issues related to rainwater-collection systems are highlighted (the importance of rainwater harvesting in: urban and rural areas, Mediterranean climate, domestic applications, etc.; disinfection techniques for safe drinking-water supply (e.g. by means of solar technologies); innovative concepts which combine rainwater harvesting with renewable-energy systems, etc.), revealing the benefits of rainwater-collection systems for building and environment.

2.6. Critical comments and introduction about the proposed BIST system

Taking into account that:

- Within the field of BIST there is a need for innovative designs [90]
- Architectural integration is a major issue in the development and spreading of solar thermal technologies [52]
- Multiple crucial factors which were highlighted in 2.1-2.5 (advantages of vacuum-tube collectors e.g. in Mediterranean regions for domestic water heating; benefits of vacuum-tube collectors in the frame of BI applications; positive aspects of rainwater harvesting; etc.) can play an important role for a sustainable built environment,

in the present work, a vacuum-tube/BIST system is proposed and it is investigated from environmental point of view in comparison to a counterpart flat-plate/BIST configuration (both systems are gutter-integrated). In this way, useful information about the ecological profile of two BIST configurations is provided (in the literature there are few LCA studies about vacuum-tube collectors as well as about active BIST systems).

Given the fact that the proposed system combines vacuum-tube solar thermal collectors with rainwater harvesting and building-integration, the first part of the present work (section 2), based on a critical literature review, highlights important factors related to the proposed system. In this way, a complete picture of the BIST configurations studied in the second part of the paper (section 3) is provided.

3. ENVIRONMENTAL COMPARISON OF TWO BIST SYSTEMS: VACUUM-TUBE VS. FLAT-PLATE

3.1. Materials and adopted methods

For the LCA implementation, according to ISO 14040:2006 [91] and ISO 14044:2006 [92], the phases of goal and scope definition, life-cycle inventory, life-cycle impact assessment and interpretation are adopted.

3.1.1. Functional unit and boundaries of the system

The whole system which consists of: 1) 14 solar collectors for the configuration with flat-plate collectors (System I: flat-plate/BIST) and 16 collectors for the configuration with vacuum tubes (System II: vacuum-tube/BIST), 2) additional components (storage tank, pump, external tubes with their insulation, glycol), is the functional unit. For both systems, the boundaries refer to the whole system in terms of the phases of: material manufacture (collectors and system additional components), manufacture of the collectors, system installation, use/maintenance, transportation and disposal.

3.1.2. Definition of the studied systems

Technical characteristics

The BIST configurations which are evaluated have been developed and tested at the University of Corsica, in France. Both systems (System I Fig. 1a and System II Fig. 1b) are solar thermal collectors for water heating patented by Cristofari [29] and refer to integration into building gutters with no visual impact. Each installation contains several connected modules. For System I, one module has around 1 m length and 0.1 m width for individual houses. In Fig. 1a, the components of one unit of System I are illustrated. It can be seen that System I is based on flat-plate collectors consisting of a highly-selective absorber, a glass cover, one tube for the flow of the cold water (lower insulated tube), one tube for the flow of the hot water (in thermal contact with the absorber), thermal insulation, external casing and gutter (Fig. 1a). On the other hand, System II (Fig. 1b) is based on vacuum-tube technology. Each main tube consists of two concentric copper tubes. The vacuum tubes are interconnected by means of the copper tubes. The heat transfer fluid enters from the larger copper tube and comes out from the smaller copper tube. There are 8 rows of 2 tubes inside the gutter (16 m total length). It should be noted that System I as well as System II have the same length (16 m) as common reference.

In Table 4, information about the basic technical characteristics and the performance of the studied gutter-integrated configurations (System I and System II) are presented. More details about the systems can be found in references [29, 93-97]. In the frame of the present work, System I is considered as the reference configuration (System I is System 2 of authors´ previous LCA studies [22, 23]). System I consists of flat-plate collectors connected in parallel and the tubes (cold-water tube and hot-water tube) are at different levels (Fig. 1a). Among the previous studied systems [22, 23][1], System I has been selected because: 1) it can be commercially available and 2) it presented considerably higher environmental performance in comparison to the system with collectors in series connection and tubes at different levels (System 1 in references [22, 23]).

In Fig. 2, the outputs of System I and System II in terms of the thermal energy produced (per month) are illustrated, revealing the considerably better performance of the vacuum-tube technology (System II) in comparison to the flat-plate configuration (System I).

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[1] In [22, 23], three configurations were studied: System 1 with collectors in series connection and tubes (for cold and hot water flow) at different levels, System 2 (System I of the present work) with collectors in parallel connection and tubes at different levels, System 3 (theoretical system) with collectors in series connection and tubes at the same level).

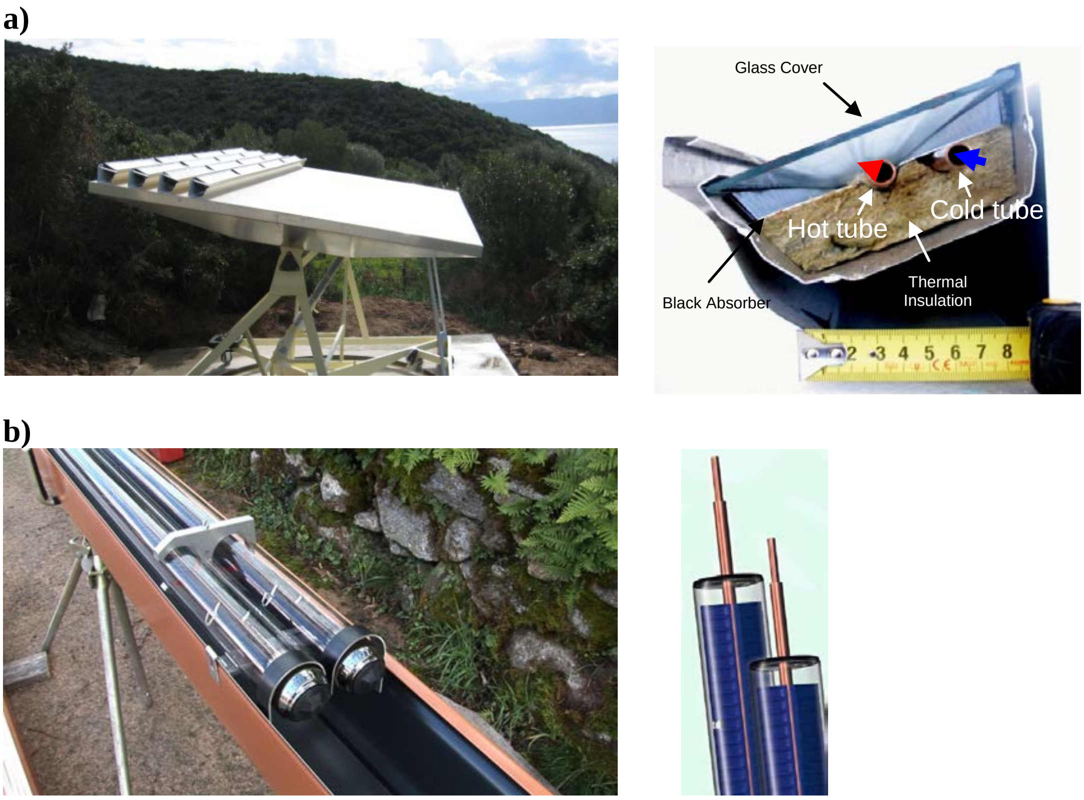


Figure 1. a) The solar gutter of System I (left) and details about the flat-plate collectors of System I (right), b) the solar gutter of System II (left) and the vacuum-tube technology of System II (right) (Source: authors´ archive of pictures).

Table 4. System I (flat-plate/BIST) and System II (vacuum-tube/BIST): basic technical characteristics, thermal energy production and electricity consumption (for pumping and auxiliary heating).

Systems	**Technical characteristics**	**Thermal energy production (kWh/year)**	**Electricity consumption for pumping (kWh/year)**	**Electricity consumption for auxiliary heating (kWh/year)**
I (Reference system)	Flat-plate collectors of parallel connection; Tubes at different levels	811.21	61.54	815.93
II	Vacuum-tube collectors interconnected with copper tube	1693.92	48.76	370.02

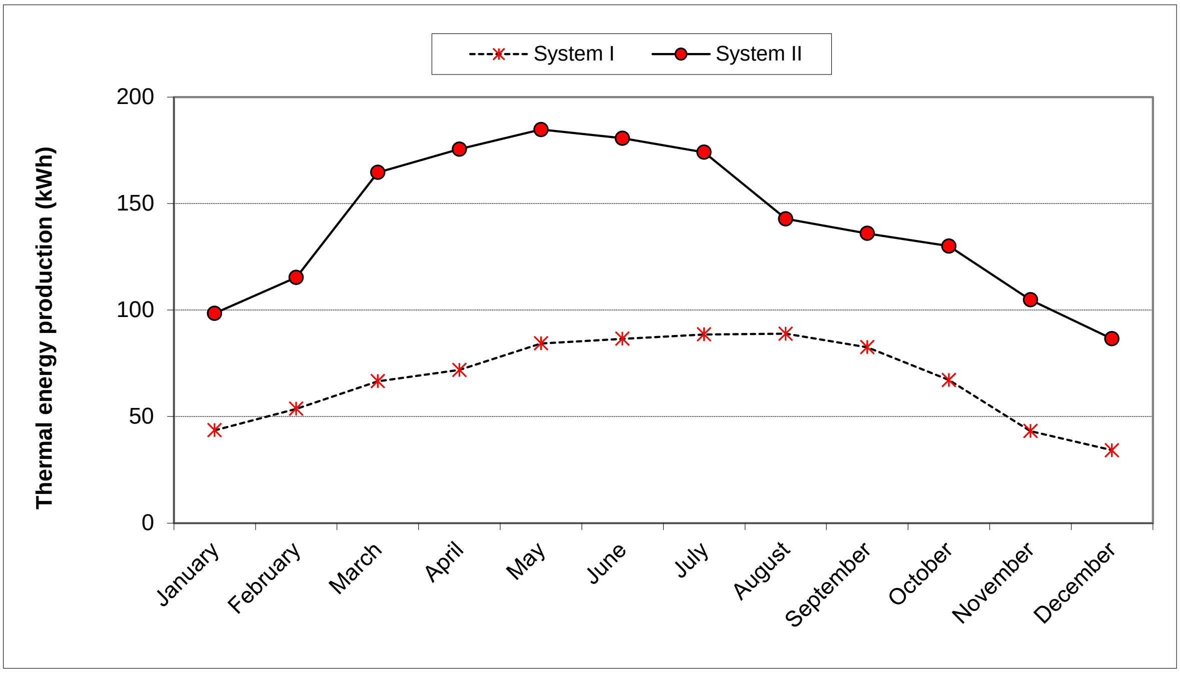


Figure 2. Annual thermal energy production (in kWh) of System I and System II.

Assumptions

- The calculations for System I refer to 14 flat-plate solar collectors (approximately 2 m^2 total absorber surface) and one 100 l tank (suitable for two persons). On the other hand, the calculations for System II concern 16 vacuum-tube collectors (around 1.8 m^2 total absorber surface). Both configurations have a total length of 16 m.

- Glycol is utilized as anti-freeze protection fluid with a proportion of 20% glycol in the glycol-water mixture [22, 23] given the fact that in Corsica the temperatures during winter are not very low.

- The impact of the processes for collector manufacturing is considered to be 27% of the impact which is related to the manufacturing of collector materials. Moreover, the impact of system installation is assumed to be 3% of the total impact for the manufacturing of collector/additional components [22, 23].

- For both systems, the use phase includes electricity for pumping/auxiliary heating, replacement of some parts of the system over its lifetime and general maintenance of the system (cleaning, etc.). The impact of the general maintenance is assumed to be 10% of material manufacturing of the collectors [22, 23].

- The optimistic scenario of 30-years system lifetime is used for the calculations (for both systems) since the life-cycle of solar thermal installations ranges from 20 to more than 30 years [98]. For some cases, one additional scenario is also adopted: 20-years lifespan (pessimistic scenario).

- Regarding the substitution of some components over system lifespan, for System I there is one replacement of the glass components, one replacement of the storage tank and five replacements of the glycol. For System II, except of the above mentioned substitutions regarding storage tank and glycol, two additional components are also replaced: a) vacuum tubes (once for the 20-years lifetime scenario and twice for the 30-years lifetime scenario) and b) polyethylene insulation (four times for the scenario of 20-years lifespan and six times for the scenario of 30-years lifespan). The assumptions about the vacuum-tube and polyethylene substitutions are based on the fact that their lifetime can be 10 years [99] and 2-15 years [100], respectively.

- A total distance of 50 km is considered for the phase of transportation (by a truck from the factory gate to the building and from the building to the disposal site) and landfill is assumed as waste treatment [22, 23].

- For the scenario of recycling, material recycling refers to glass, aluminium and copper (for the collectors, system additional components as well as for the parts of the system that are replaced over system lifespan).

- As it has been explained in authors´ previous LCA studies [22, 23], France electricity mix is adopted due to the lack of available data for Corsica´s electricity impact.

3.1.3. Life-cycle inventory

For the present study, the Life Cycle Inventory (LCI) is based on the following sources: 1) ecoinvent database/SimaPro 8 [101] for USEtox and ecological footprint, 2)

ICE [102] and ALCORN [103] databases for EE and EC. In Table 5, the materials/components of the studied systems are presented. It should be noted that the LCI also includes the gutter, even if it could not be considered as part of the collector itself. If a classic BA flat-plate collector is used, the building may also include gutters.

Table 5. LCI of the studied BIST systems: a) System I, b) System II and c) System additional materials/components (the same for System I and System II).

a)

Materials for System I	**Mass (kg)**
Materials/components for the whole system (14 collectors):	
Black absorber (aluminium)	2.74
Cover (glass)	19.84
Tube 1 for cold water (copper)	3.54
Tube 2 for hot water (copper)	3.54
Thermal insulation (rockwool)	3.23
External casing (aluminium)	8.61
Two blades (polycarbonate)	0.67
Polyester 1 (at the casing)	0.09
Gutter (aluminium)	10.19
Polyester 2 (at the gutter)	0.14

b)

Materials for System II	**Mass (kg)**
Materials/components for the whole system (16 collectors):	
Vacuum tubes (glass)	20.23
Flat-plate black absorber (aluminium)	1.88
Support for the black absorber (aluminium)	0.03
External tube/vacuum tube (copper)	4.50
Internal tube/vacuum tube (copper)	2.25
Collector in the gutters (copper)	7.88
Collector insulation (polyethylene)	1.14
External case/gutter (aluminium)	10.58
Gutter lacquer (polyester)	0.15

c)

System additional materials/components:	**Mass (kg)**
Storage tank (stainless steel)	12.48
Storage tank (rockwool insulation)	4.08
Tubes (copper)	5.64
Tubes (polyurethane insulation)	1.80
Propylene glycol	1.40
Pump (stainless steel)	3.00

3.1.4. Life-cycle impact assessment methodologies and equations

In the present study, EE, EC, USEtox and ecological footprint are adopted. USEtox (default) V1.03 / Europe 2004 results with characterization (in CTU: comparative toxic units) as well as Ecological footprint V1.01 / Ecological footprint results (in Pts) (Source: [101]) are presented.

The indicators of EPBT and Energy Return on the Investment (EROI) [104], adapted for the case of solar thermal systems, are utilized. Based on the interpretation of the EPBT for photovoltaics [104], in the same concept, the EPBT (measured in years) for a solar thermal system shows how long it takes for the system to produce enough energy to offset to the cumulative primary energy required to build (and decommission) the system. On the other hand, EROI shows how easy (in energy terms) is to exploit the available primary energy sources by investing a given amount of energy which one already has at one’s disposal [104].

For the calculation of the EPBT, the following equation [22] is adopted:

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

where,

E_{in} is the total input for material manufacturing (materials and collector manufacturing and system additional components), system installation, material disposal and transportation.

$E_{out.a}$ represents the annual output of the solar system (converted into primary energy having as reference the impact of a conventional boiler (gas or oil [8, 10]): as in reference [22]).

$E_{O\&M.a}$ refers to the annual energy inputs during the use phase of the system (for the present study, the inputs for pumping/auxiliary heating, replacement of system components and general maintenance are taken into account, distributed on an annual basis).

E_{mat} is the total EE for material manufacturing (materials of collectors and system additional components) and for collector manufacturing.

E_{inst} stands for the energy needed for the installation of the system.

E_{disp} represents the EE for components/materials disposal at the end of their life.

E_{transp} refers to the EE for materials/components transportation from the factory gate to the building and from the building to the disposal site.

It should be noted that all the above mentioned *E* quantities are primary energy.

For the calculation of EROI, the following equation [104] is used:

$$EROI = \frac{system\ \ lifetime}{EPBT} \tag{2}$$

In addition, Greenhouse-gas Payback Time (GPBT) [12] is evaluated:

$$GPBT = \frac{life-cycle\ \ CO_{2.eq}\ emissions}{annual\ \ avoided\ \ CO_{2.eq}\ \ emissions} \tag{3}$$

In the frame of the present study, GPBT is calculated by using three different ways. According to these three options of Eq. (3), the life-cycle $CO_{2.eq}$ emissions are: i) material manufacturing (only for the collectors), ii) life-cycle emissions[2] except inputs for pumping/auxiliary heating, iii) life-cycle emissions including inputs for pumping/auxiliary heating. For all the above mentioned cases, the annual avoided $CO_{2.eq}$ emissions are calculated based on the annual output of each system and having as reference the gas oil emissions [105].

[2] The phases of material/collector manufacturing, manufacturing of the materials for the additional components, installation, use phase (general maintenance and replacement of some components), transportation and disposal, are included.

3.1.5. Sensitivity analysis and adopted scenarios

The influence of multiple parameters on the environmental profile of the proposed BIST systems is examined by means of the following scenarios: 1) "No Recycling" vs. "With Recycling" and 2) 20-years vs. 30-years system lifespan.

3.1.6. Limitations related to the proposed BI systems

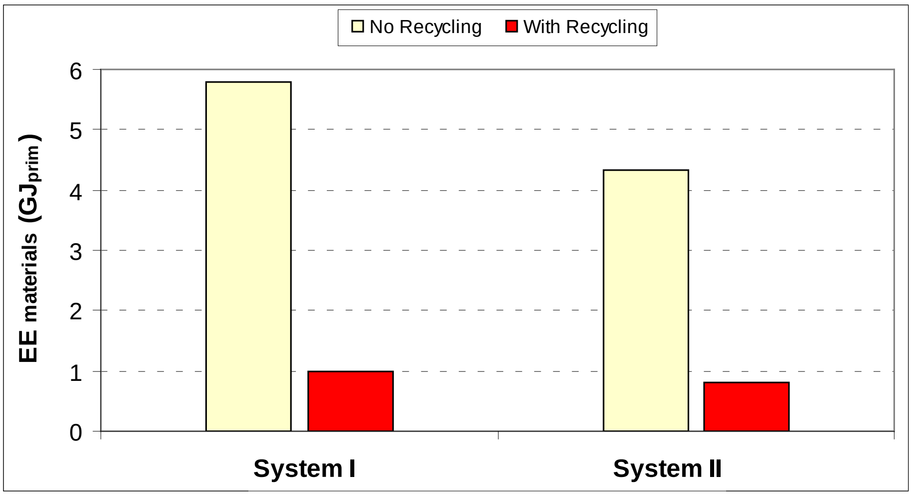
For some cases building integration, apart from the important advantages that provides is associated with a reduction of system efficiency. For gutter-integrated applications, the relatively small area of the gutter (Fig. 1) limits collector surface and in this way collector output decreases. The relatively high consumption of electricity during use phase (Table 4) is a limitation especially for System I. However, System II is based on the same concept with System I (integration into building gutters) while it offers higher thermal/energetic performance (Table 4). In the following sections, it is proved that System II (vacuum-tube/BIST) shows considerably better environmental profile in comparison to the reference configuration (System I: flat-plate/BIST).

3.2. Results and discussion

3.2.1. Embodied energy and embodied carbon: material manufacturing

The results in terms of EE and EC for the phase of material manufacturing of the collectors (Fig. 3: System I vs. System II; scenarios: No Recycling vs. With Recycling) reveal that there is a difference of 1.45 GJ_{prim} between System I and System II (without recycling) while this difference becomes 0.19 GJ_{prim} for the case with recycling. Moreover, EC findings show that EC of System I is 0.06 and 0.02 t $CO_{2.eq}$ higher (for the scenario without and with recycling, respectively) than EC of System II.

a)



b)

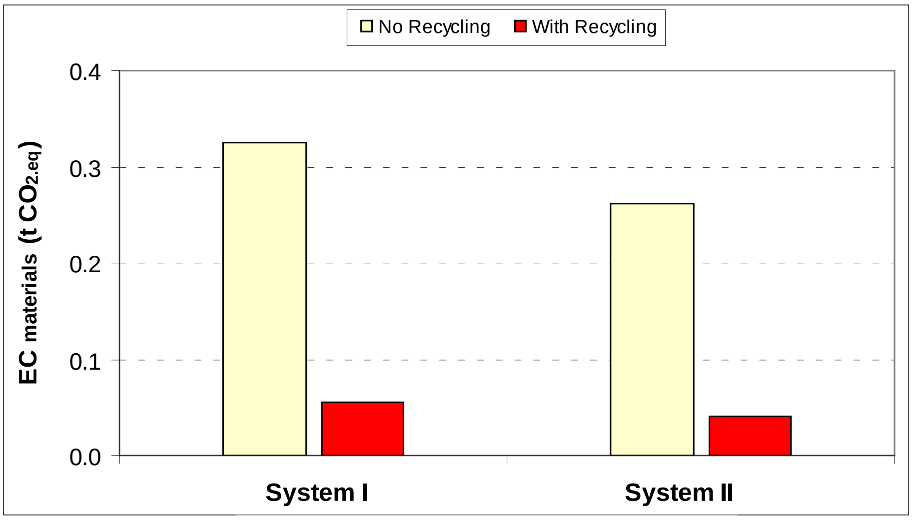


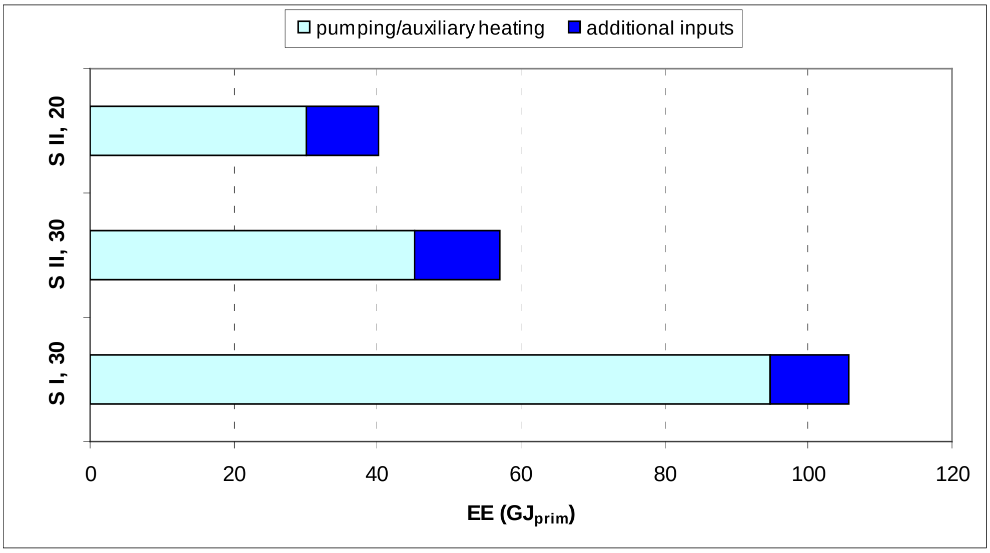
Figure 3. a) EE ($GJ_{primary}$) and b) EC (t $CO_{2.eq}$) for material manufacturing of the collectors: System I vs. System II. Scenarios: No Recycling vs. With Recycling. Average values between ICE and ALCORN databases.

3.2.2. Life-cycle inputs

In Fig. 4, the life-cycle inputs (in terms of pumping/auxiliary heating and additional inputs) are presented. The additional inputs include manufacturing of materials/collectors, manufacturing of materials for the additional components, system installation, use phase (replacement some parts of the system over its lifespan; general maintenance), transportation and disposal. It should be noted that for the auxiliary heating, the electricity mix of France, which has low CO_2 emissions and high penetration of nuclear energy [106], has been considered. For the cases of Fig. 4, the calculations have been also conducted for the scenario with recycling and the findings reveal that by adopting recycling the impact of the additional inputs shows a reduction of 6.1-7.2 GJ_{prim} and 0.4-0.5 t $CO_{2.eq}$.

By comparing the two systems (Fig. 4) based on the scenario of 30-years lifespan, it can be observed that the footprint of pumping/auxiliary heating is almost double for System I (in comparison to System II). On the other hand, by focusing on the additional inputs (scenario: 30-years lifespan), System II shows 0.8 GJ_{prim} and 0.1 t $CO_{2.eq}$ higher impact than System I. This is mainly attributed to the replacement of the vacuum tubes (glass, copper, aluminium) over System II lifetime. Nevertheless, on a long-term basis (as it is discussed in 3.2.3) System II, since it has considerably better efficiency comparing to System I (Table 4), it is proved to be more eco-friendly than the reference configuration.

a)



b)

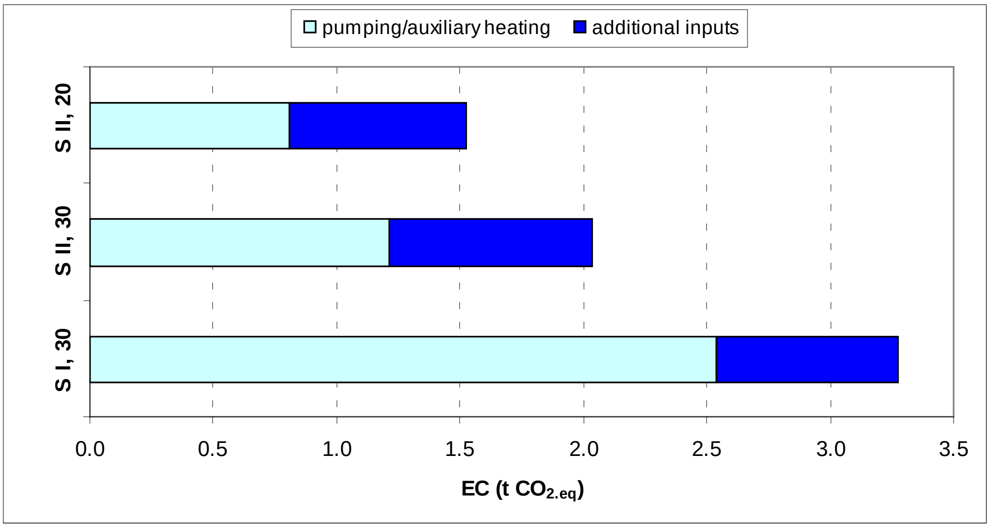


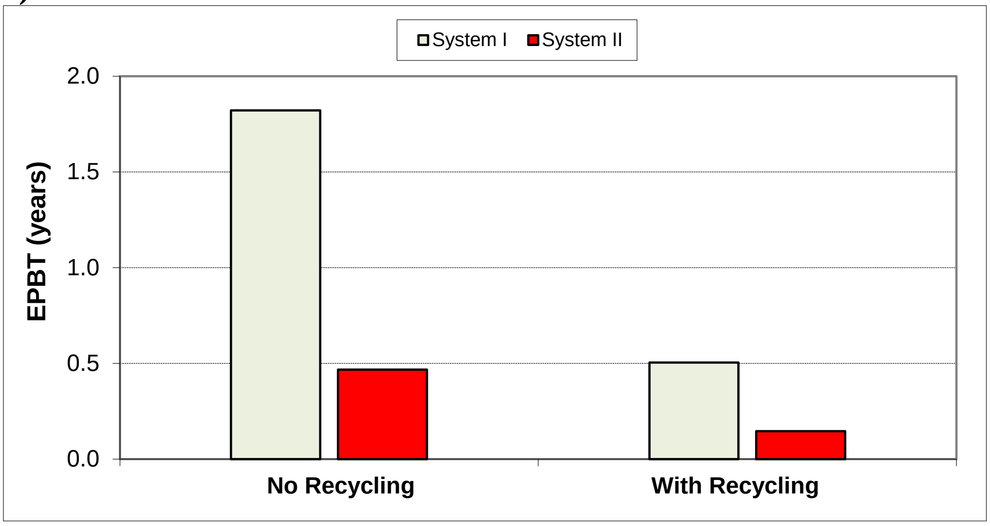
Figure 4. Life-cycle inputs (pumping/auxiliary heating and additional inputs) in terms of: a) EE ($GJ_{primary}$) and b) EC (t $CO_{2.eq}$): System I (S I) vs. System II (S II). Scenarios: No Recycling; 20-years (20) vs. 30-years (30) system lifespan (for System II). Average values between ICE and ALCORN databases.

3.2.3. Energy payback time, energy return on the investment and greenhouse-gas payback time

From Fig. 5(a) it can be noticed that EPBT of System I is 1.4 and 0.4 years higher (for the scenarios without and with recycling, respectively) than EPBT of System II. Moreover, Fig. 5(a) shows that recycling results in an EPBT reduction of 1.3 and 0.3 years for System I and System II, respectively. Fig. 5(b) illustrates EROI for both systems (scenario without recycling). It can be seen that for 30-years lifespan, System I EROI is 16.5 while System II EROI is 64.2. By taking into account the fact that a high EROI of an energy-production process is crucial for its long-term viability [104], EROI findings reveal that System II presents remarkably higher long-term viability in comparison to System I.

Considerable differences between the two systems can be also seen by focusing on GPBT (Fig. 6). For the case without recycling, System I presents GPBT values ranging from 1.4 to 13.7 years (based on the three options of Eq. 3) while for System II these values range from 0.5 to 4.1 years. Thus, for the scenario without recycling, the differences between the GPBTs of the two systems vary from 0.8 to 9.6 years. Moreover, Fig. 6 demonstrates that by adopting material recycling there is an impact reduction of 0.4-1.8 years.

a)



b)

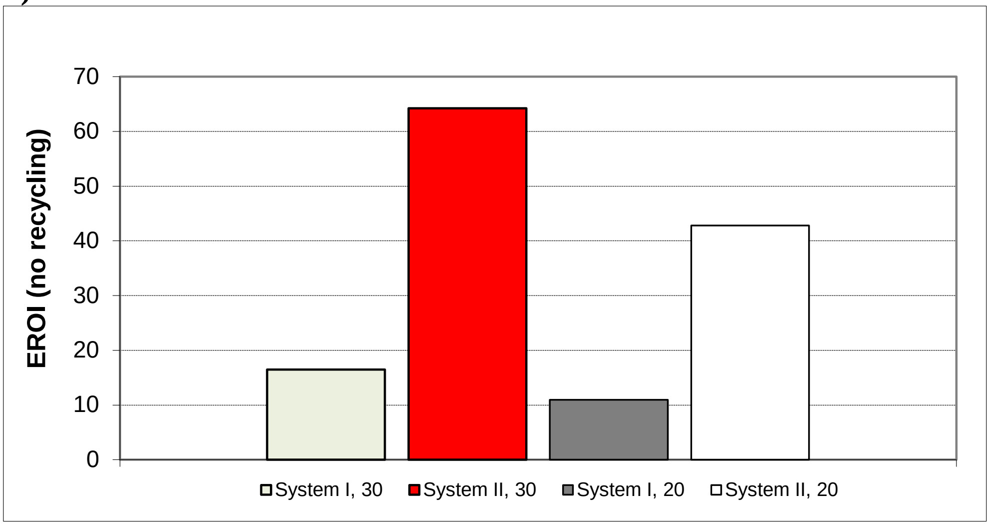


Figure 5. a) EPBT (in years) and b) EROI (without recycling). System I vs. System II. Scenarios: No Recycling vs. With Recycling (for EPBT); 20-years (20) vs. 30-years (30) lifespan (for EROI).

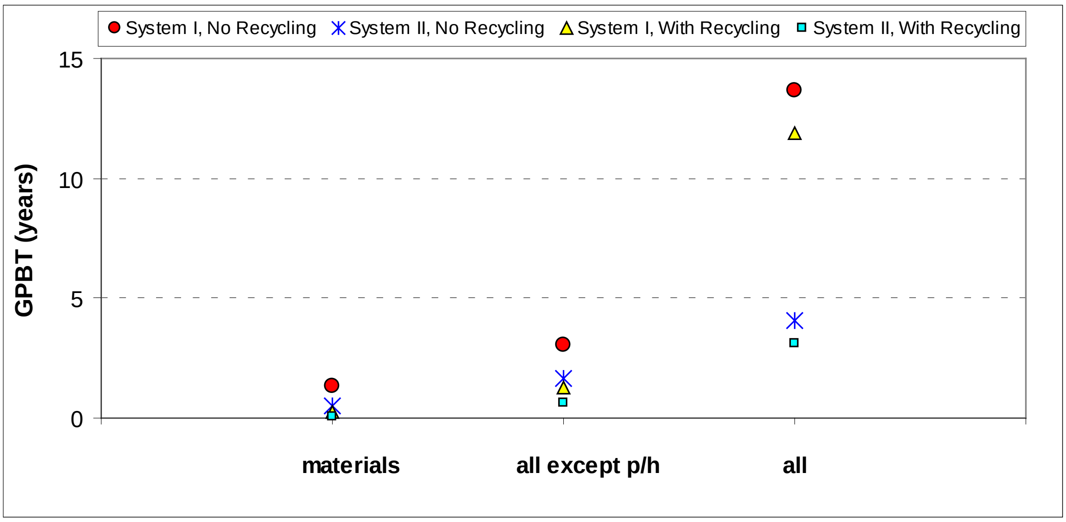


Figure 6. GPBT (years): System I vs. System II. Scenarios: No Recycling vs. With Recycling. GPBT is calculated based on the three options of Eq. (3) (presented in 3.1.4), by adopting as life-cycle $CO_{2.eq}$ emissions: i) materials (= only material manufacturing for the collectors), ii) all except p/h (= all the phases except of pumping/auxiliary heating (p/h)), iii) all (= all the phases (including p/h)). Average values between ICE and ALCORN databases.

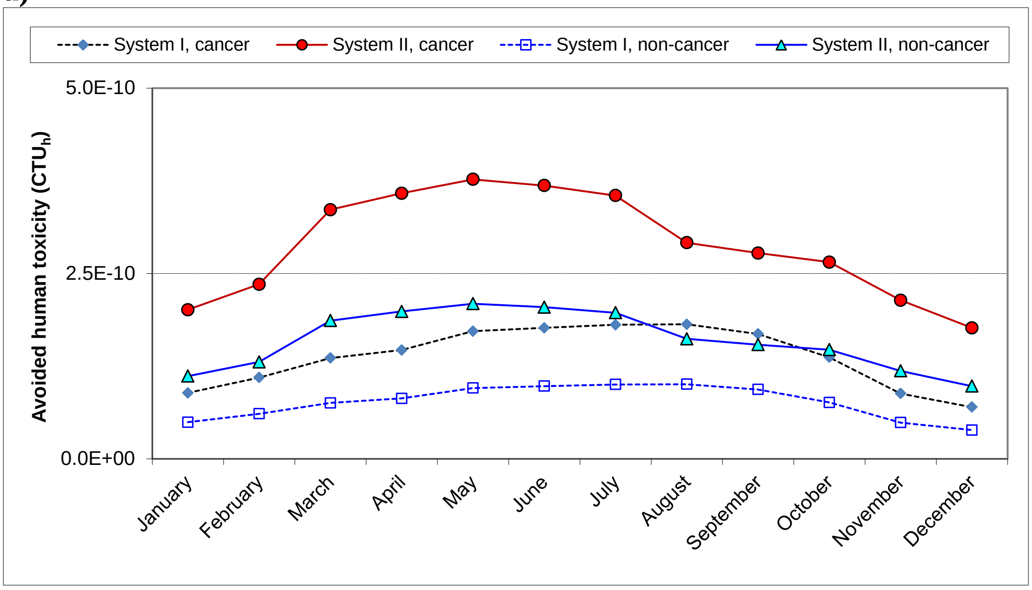
3.2.4. Avoided impact during use phase

In Fig. 7, the avoided impact because of the use of the proposed solar systems instead of using electric-resistance heater and France´s electricity is illustrated. Fig. 7(a) refers to human toxicity (cancer and non-cancer) and Fig. 7(b) regards ecotoxicity. It can be seen that by utilizing System II (instead of System I) considerably higher impact can be avoided (for example in terms of ecotoxicity (Fig. 7b), System II achieves 1.1 CTU_e higher avoided impact (annually) comparing to System I). For the calculations, it has been adopted as reference an electric-resistance hot water heater with efficiency 95% [107] and use of France´s electricity (Source: [101]).

Moreover, in Fig. 8 the avoided ecological footprint in terms of carbon dioxide and nuclear, based on the use of electric-resistance heater and France´s electricity, is presented. As it can be seen from Fig. 8, System II achieves remarkably higher avoided nuclear impact in comparison to System I (more specifically, there is a difference of 743 Pts (annually) between the two systems). On the other hand, the annual avoided carbon dioxide (Fig. 8) is low for both systems and this is mainly related to the low CO_2 emissions of France´s electricity mix [106].

Finally, it should be noted that for the conversions from thermal to electrical energy, a coefficient of 38% (= electric power generation efficiency of a conventional power plant [108]) has been used.

a)



b)

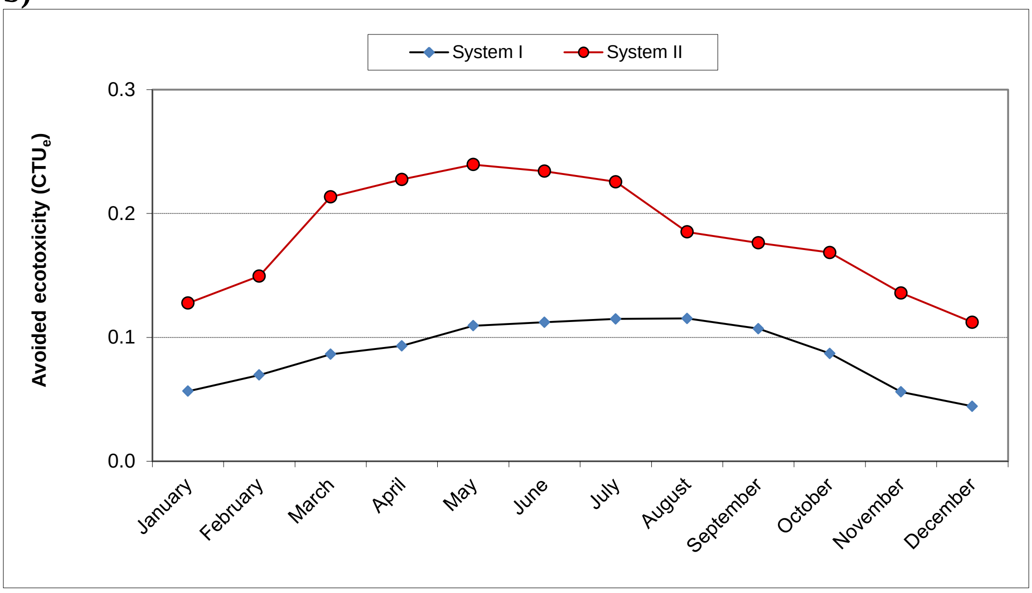


Figure 7. Avoided impact during use phase in terms of: a) Human toxicity (in CTU_h: cancer and non-cancer) and b) Ecotoxicity (in CTU_e). System I vs. System II. Reference: electric-resistance hot-water heater and France´s electricity.

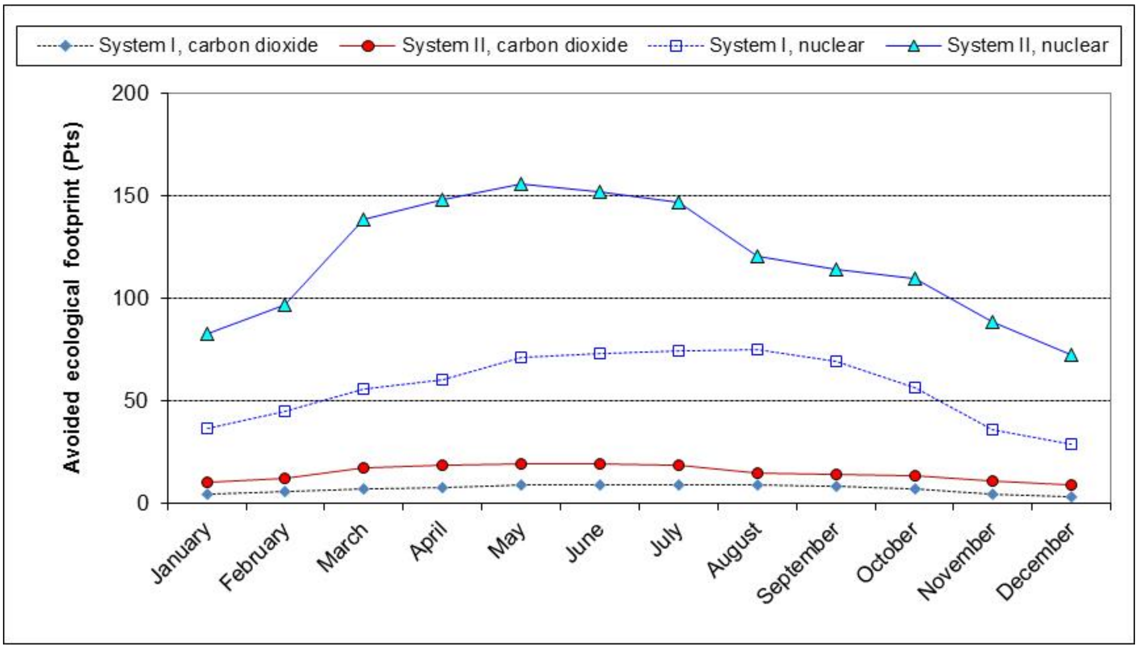


Figure 8. Avoided impact during use phase in terms of ecological footprint (carbon dioxide and nuclear: in Pts). System I vs. System II. Reference: electric-resistance hot-water heater and France´s electricity.

3.3. Comparison with the literature

By taking into account the $CO_{2.eq}$ emissions of a domestic gas boiler [10] the annual savings of System II are 401 kg $CO_{2.eq}$ while the annual savings of System I are 192 kg $CO_{2.eq}$. The results for System II are close to the findings of Ardente et al. [10] (407 kg $CO_{2.eq}$ annual savings; BA solar thermal collector; domestic hot water production; 180-l capacity water tank).

According to another study of Ardente et al. [9], a global energy consumption of 11.5 GJ_{prim} was calculated for a BA flat-plate solar thermal collector (2.13 m^2 total net surface) for domestic hot water applications. In the present work, the life-cycle[3] EE is 10.9, 11.7 and 10.1 GJ_{prim} (average values between ICE and ALCORN; scenario without recycling) for System I (30-years lifespan), System II (30-years lifespan) and System II (20-years lifespan), respectively.

Carnevale et al. [13] conducted a study about a BA flat-plate solar thermal collector (2.13 m^2 surface; 160 l water tank capacity) for domestic hot water

[3] Except the inputs for pumping/auxiliary heating.

applications, showing EPBT and $CO_{2.eq}$-payback time values from around 0.6 to 1.2 years, depending on the adopted scenario [13]. The results of the present work show: EPBT (without recycling) 1.8 and 0.5 years, for System I and System II, respectively; GPBT (only for material manufacturing; scenario without recycling) 1.4 and 0.5 years, for System I and System II, respectively.

For all the above mentioned cases it can be noticed that there is quite good agreement between the present results and those of the literature [9, 10, 13], taking into account that there are some differences between the present systems and those of [9, 10, 13] (for example, the present system is BI while the systems of [9, 10, 13] are BA). Finally, it should be noted that additional information about the comparison of the environmental profile of System I with literature data can be found in authors´ previous LCA studies [22, 23].

3.4. Benefits for building and environment

A solar gutter such as the proposed system with vacuum-tubes (System II) combines the benefits of: 1) BIST concept [1, 2] and vacuum-tube technology [19] for the production of hot water, 2) rainwater collection by means of a renewable-energy rainwater harvester [84]. Thus, the same system has two different functions: i) production of energy to cover all (or a part) of building energy needs in terms of hot water and ii) rainwater harvesting. A rainwater collection system in combination with a water-reuse system can be useful for various applications: for example irrigation of green roofs [109] or photovoltaic-green roofs [109], indoor water use [78] and home landscape irrigation [78]. Given the fact that rainwater harvesting is a co-function of the studied BIST systems, as a future prospect it could be included in the LCA model.

Since domestic hot water production by using conventional sources of energy involves a considerable footprint while irrigation and indoor water use require certain amounts of water (which also includes a footprint), remarkable impact can be avoided by using a vacuum-tube solar gutter.

4. CONCLUSIONS

Taking into account the fact that architectural integration of solar thermal systems provides multiple benefits, in the present work a vacuum-tube/BIST system is proposed and it is investigated from environmental point of view, in comparison to a counterpart flat-plate/BIST configuration. Both systems are gutter-integrated and have been developed and tested in the University of Corsica, in France.

Since the proposed system combines vacuum-tube solar thermal collectors with rainwater harvesting and building-integration, the first part of the present investigation (section 2), based on a literature review, highlights critical factors related to the proposed system. In this way, a complete picture of the BIST configurations studied from ecological point of view in the second part of the paper (section 3) is provided.

The literature review (section 2) reveals that there are studies which compare a vacuum-tube collector with a flat-plate one and for most of the cases the vacuum-tube system shows better performance than the flat-plate configuration. In addition, most of the works which propose vacuum-tube collectors for BIST applications refer to façade-integrated systems and water heating. On the other hand, there are few LCA studies about vacuum-tube collectors and most of them are based on EE and CO_2 emissions.

With respect to the findings of the LCA study (section 3), System II (vacuum-tube/BIST) shows considerably better environmental profile than System I (flat-plate/BIST). More specifically:

- System I shows EPBTs 1.4 and 0.4 years higher (for the cases without and with recycling, respectively) than System II.

- Concerning EROI (scenario without recycling and 30-years lifespan), the calculations show values of 16.5 and 64.2 for System I and System II, respectively.

- With respect to GPBT (case without recycling), System I shows GPBTs 1.4-13.7 years (based on the three options of Eq. 3) while these values for System II are 0.5-4.1 years. On the other hand, by adopting recycling for the evaluation of the GPBT, there is an impact reduction of 0.4-1.8 years.

- Calculations about the avoided impact during system use phase are also presented, based on USEtox, ecological footprint and France´s electricity mix as well as by having as reference the $CO_{2.eq}$ emissions of a domestic gas boiler. The results demonstrate that considerably higher impact can be avoided by utilizing System II instead of System I.

It should be noted that the conclusions (especially for certain environmental indicators) are influenced by the fact that France´s electricity has been adopted (since it is an electricity mix which has some special characteristics such as low CO_2 emissions and high penetration of nuclear energy [106])[4].

Conclusively, the present work: 1) presents critical aspects related to vacuum-tube/BIST applications and a case study about the environmental performance of a flat-plate/BIST and a vacuum-tube/BIST, 2) along with authors´ previous LCA studies [22, 23] offer useful information about the environmental performance of flat-plate/BIST and vacuum-tube/BIST systems and verify the benefits of a vacuum-tube solar gutter for building and environment.

[4] Certainly, as a future prospect of the present study, a sensitivity analysis in terms of the electricity mix (the systems can be compared/evaluated for different countries and thus, under different climatic conditions and electricity mixes) could provide interesting information about the ecological profile of the proposed systems.

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