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Analysis of solar technology life cycles, with a focus on integrated solar thermal systems for buildings, and some thoughts on the topic

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A B S T R A C T

This study aims to provide a critical overview of solar system Life Cycle Analysis (LCA) research. Here we highlight the BI solar thermal systems. To round up the literature review, we also include studies on BA designs and systems that generate electrical (or electrical/thermal) energy. Additionally, we look at how BI solar thermal systems affect the environmental profile of buildings. Ongoing standardisation and environmental indicators are among the important topics covered. According to the findings, there is a knowledge vacuum in life cycle assessment (LCA) about actual BI solar thermal (and solar thermal/electrical) systems. Therefore, further life cycle assessment (LCA) studies should be conducted to investigate the BI solar thermal system, either independently or in combination with the building. It would be fascinating to study active systems that might power the building. A more sustainable built environment may benefit from studies that examine how BI solar thermal systems affect the life-cycle performance of buildings.

Keywords:
Life Cycle Analysis (LCA) Building-integrated solar thermal systems Building life-cycle environmental performance, Critical issues,

Introduction

Solar thermal systems are a game-changer when it comes to lowering building energy consumption. A new trend toward zero or nearly zero energy buildings, known as Building-Inte-grated (BI) systems, offers several benefits over Building-Added (BA) solar thermal configurations, including increased aesthetic value, and should be encouraged [1].
While there are a few papers on BI solar systems in the literature, the vast majority focus on BI PVs [2]. Research on practical BI solar thermal systems is limited. Integrating into a building's façade [3] or gutters [4,5] is the focus of these experimentally-and/or model-based investigations [4e6]. When it comes to the modelling studies, some focus on the system independently [4,5], while others look at the system in relation to the building [6].
However, most Life Cycle Assessment (LCA) studies pertaining to BI solar thermal systems focus on passive solar walls, also known as Trombe walls [7]. Furthermore, BA solar thermal configurations have only been the subject of a handful of life cycle assessment studies. As an example of a solar water heating and solar space/water heating system, see Kalogirou [8]. For comparisons between nanofluid solar collectors and conventional collectors, see Otanicar and Golden [9]. For information on passive solar collectors, see Ardente et al. [10,11]. However, the majority of these research focus on DHW applications, and embodied energy and carbon are the most used approaches for life-cycle effect assessments.
This article provides a critical overview of life cycle assessment (LCA) research on solar systems. Solar thermal installations by BI are the main subject of this evaluation. For a more comprehensive understanding of the studies that are currently available in the literature, we also reference studies that deal with BA configurations and solar systems that generate electrical (or electrical/thermal) energy. Along with important topics like continuing standardisation and environmental indicators, we also talk about how BI solar thermal systems affect the environmental performance of buildings.
The current investigation fills a gap in the literature by reviewing the research on LCA's function in solar thermal systems, particularly in relation to BI solar thermal arrangements. This study addresses a knowledge

vacuum in the literature and draws attention to important topics like how BI solar thermal systems affect the LCF of buildings. We provide a critical analysis of the references given and suggest certain BI setups that may be worth investigating in the future from an LCA perspective. Thus, future BI solar thermal systems/buildings can benefit from the knowledge gained from this study, which contributes to their reduced environmental impact.

Solar thermal systems

Building-integrated solar thermal systems

Building-integrated solar thermal collectors

So far, the sole LCA study involving a genuine BI active solar thermal system is the one conducted by Lamnatou et al. [12] in their most recent investigation. Developed and tested at the University of Corsica in France, the system under study has a patent [13] and is designed to be integrated into building gutters [4,5,14,15]. We looked at three different setups:
First, a system with collectors connected in series to tubes at various levels (for hot and cold water flow), second, a system with collectors connected in parallel to the same two tubes at different levels, and third, the theoretical configuration with collectors connected in series to the same two tubes at the same level. All stages were considered, including production of materials and collectors, production of system additional components, installation of the system, use/maintenance, transportation, and disposal. Two databases, ICE [16] and Alcorn [17], were used to form the basis of the embodied energy and embodied carbon approaches utilised in life-cycle impact assessments. The following scenarios were implemented: "No Recycling" vs. "Recycling," "France's vs. Spain's electricity mix," and so on. The findings proved that: Approximately 3 GJprim/m2 of absorber surface constituted the embodied energy of the systems for both databases. This value was decreased to approximately 0.4e0.5 GJprim/m2 through the use of recycling. According to both databases, the systems' embodied carbon was about 0.16 t CO2.eq/m2, and recycling reduced it to about 0.02e0.03 t CO2.eq/m2. Energy Payback Time (EPBT) for System 1 was around 1.5 years while recycling was in place, but it dropped to about 0.5 years when System 2 was used. - The CO2 emissions were much lower in France's power mix compared to other countries'. This was due to the country's adoption of a more renewable energy source.the same amount of emissions as a power plant that uses natural gas or the electricity mix in Spain. The large penetration of nuclear power in France's electrical grid is connected to this [18]. The scenario 'France's power' had the least effect on CO2.eq emissions compared to all the systems that were considered. Nonetheless, when compared to the other two power sources, nuclear energy's high penetration causes France's cumulative energy demand to be greater [18]. System 1-3's CO2.eq emissions were significantly reduced (28.96%) by using their respective thermo-retical systems, which had a twofold collector surface and produced twice as much thermal energy. - Indicator of Sustainability (IS) values for System 2 were 0.78 and 1. The 'ideal' System 3 has an IS value of 1, while System 2 is a practicable system. Because it is not yet available for purchase, System 3 was only ever studied in theory [14].

Finally, the findings showed that the suggested BI solar thermal system with minor adjustments, such parallel-connected collectors, significantly improved its efficiency and, by extension, its environmental profile. Environmentally, the system is clearly more effective in areas that have

substantial sun radiation and electrical mixtures with a significant influence. Research is presently underway at the University of Corsica that is focused on developing the investigated BI system further, using the same principle (integration into the gutters)—for example, by enhancing heat transfer mechanisms. The suggested BI solar thermal system has the potential to significantly enhance its heat output and, by extension, its environmental performance in the future [12].

Trombe walls

In order to optimise solar wall systems, Stazi et al. [19] performed an LCA research. Ancona, Italy served as the site of the case study evaluation of a Trombe wall integrated into a solar residential building prototype. The system's constituent parts were an outside window with a single pane of glass and an aluminium frame, and an inside concrete wall covered with plaster measuring 40 cm. Black, vertical metal strips insulated with polyurethane were also a part of the system. We made use of the Ecoinvent database and the Simapro program. The solar wall in the constructed case demonstrated that the system has a significant influence on the environment during both the pre- and post-use stages. Aluminium and concrete posed significant environmental challenges during production, while energy consumption and carbon dioxide emissions were high during operation because of cooling in the summer. From the conventional setup (40 cm thick concrete, aluminium frame, single glazing) to the optimised setup (20 cm thick aerated concrete blocks, wood frame, double glazing), the optimisation showed that CO_2 emissions and energy demand of solar walls (during production and use) can be reduced by up to 55 percent.

In their study, Nowzari and Atikol [20] used TRNSYS to model and simulate the temperature behaviour of a two-story structure with a total floor area of 120 m2. The south façade of the ground level was adorned with a vented Trombe wall, while the south façade of the top floor included a direct gain window of 6.5 m2. The location of the model building was thought to be in the Larnaca region of Cyprus. In comparison to installing a 3 kW gas heater, the study's Life Cycle Cost Analysis (LCCA) found that building a 15 m2 thermal storage wall in Cyprus was more economically feasible, with a saving-to-investment ratio of 2.3.

In addition, the energy and environmental performance of buildings with and without Trombe walls was examined by Bojíc et al. [7]. Together, the annualised embodied energy consumption from the Trombe walls and the main operational energy used for heating in the winter made up the environmental performance indicator. A "Mozart" house in Lyon, France, which complied with French thermal regulation, had two Trombe walls on its south side. We looked at how well various Trombe wall structures worked. In order to model the thermal behaviour of these homes, the EnergyPlus software was utilised. The authors pointed out that dwellings with Trombe walls may have lower annualised life-cycle energy usage if the core material had reduced density and embodied energy. When comparing electric and natural gas heating methods, the ideal core layer thickness and primary energy consumption numbers were much greater for the former. An annual savings of around 20% in heating energy was discovered when the building with Trombe walls was used. The energy ratio was about 6, and the EPBT was about 8 years, for the optimal core thickness and electrical heating. These figures were close to three and eighteen years, respectively, for natural gas heating.

Lastly, it's worth mentioning that Chel [21] investigated a number of building-integrated renewable energy technologies, including Trombe walls. Building design, low energy building standards, and energy efficiency are the three primary factors that the author cited as crucial to a building's ability to save energy.

products and the use of renewable energy sources for a range of purposes. Sunspace, Trombe walls, and other solar passive heating and cooling configurations can result in significant energy savings when these are incorporated into building designs. In addition, to lessen the impact on the environment during construction, it is recommended to use building materials with low embodied energy, such as stabilised mud blocks, fly ash bricks, and fibre reinforced bricks. Renewable energy sources, such as photovoltaics (PVs) and solar thermal systems, may lessen the amount of energy that buildings use.

Sun thermal systems that are incorporated into buildings: key concerns 2.1.3

With supplementary information regarding the methods used, results, etc., Table 1 presents the studies about actual BI solar thermal systems that are currently available in the literature. Lamnatou et al. [12] is the only research that has examined a BI active solar thermal system, as shown in the table. Most of the research also targeted systems in the Mediterranean region, with an emphasis on embodied energy and carbon dioxide emissions. In order to analyse the influence on the system's environmental profile, many parameters were examined, including alternative configurations/system output effects and alternative materials (which have a lesser environmental impact compared to reference/traditional materials).

So, there is a lack of information in the literature regarding life cycle assessment investigations of BI solar thermal installations, particularly active systems. In particular, there is a lack of research on active BI solar thermal designs that might meet the energy needs of buildings by providing hot water and/or air, as just a single LCA study has focused on these systems. Since active solar thermal systems typically use less components to meet a building's energy demands (in terms of DHW and other metrics), they are projected to have a smaller environmental effect.

Solar thermal systems integrated into buildings (2.2)

Due to the paucity of literature on life cycle assessment (LCA) studies involving actual BI solar thermal systems, the following sources are cited regarding LCA of BA solar thermal configurations.

2.2.1. Solar thermal collectors with flat plates; active systems integrated into buildings
In Nicosia, Cyprus, Kalogirou [8] studied solar water heating systems and solar space/water heating systems. About 1.2 years passed before the energy used in production and installation was returned. In terms of emissions, the payback period varied from a few months to 9.5 years.
Two DHW systems that were identical in design but used different materials were investigated by Streicher et al. [22]. The first system's EPBT was determined to be 1.4 years, whereas the second system's EPBT was 2.1 years. In their comparison, Otanicar and Golden [9] looked at both traditional and nanofluid solar collectors. Application submitted by DHW of Phoenix, Arizona, USA. Compared to a traditional collector, the nanofluid one had a reduced embodied energy of z9% and pollution offsets that were around 3% greater.
A solar thermal facility in Valladolid, Spain, that used flat-plate collectors for the generation of district heating water (DHW), was investigated by Rey-Martínez et al. [23]. We used the EPS 2000 technique. We compared the solar installation's financial and environmental benefits to those of a natural gas boiler system. The resources reduction indicator had a higher value due to the solar installation's higher component count compared to a conventional one. However, the conventional system had a higher operation-related resources reduction indicator than the solar one.

A 2.8 m2 solar hot water system with a freeze-tolerant flat-plate collector was investigated by Allen et al. [24] for the residential sector in the UK. The amount of alternative fuel or electricity that was displaced determined the environmental benefits of using the system. The major influence on the system's production came from the aluminium used in its construction. Recycling more aluminium would be a good thing.
Contrarily, solar water heating systems for cold areas were the subject of an LCA research by Burch et al. [25]. Using the gly-col, drainback, and thermosiphon systems, LCA was performed using the hypothesised lower-cost components. The system was simplified and traditional metal components were replaced with polymeric ones as part of the balance-of-system measures. A low-cost, selectively-coated, glazed polymeric collector may lower the cost of saved energy by little over 50% according to the data, whereas either a standard selective metal-glass or a non-selective glazed polymer collector might reduce it by slightly under 50%. When traditional pressurised solar storage tanks and metal heat exchangers were substituted with unpressurised polymer tanks and immersed polymer heat exchangers, the cost of saved energy was found to be the most reduced by the biggest percentage.
The lack of research on BA active flat-plate solar thermal collectors is evident from the points raised above. Few of these studies additionally looked at the financial implications of the suggested configurations; most focused on the systems' embodied energy and CO_2 emissions. On top of that, every single investigation focused on DHW uses, and the systems were examined in a variety of hot and cold climates, including those in the UK, Cyprus, Germany, and Spain.

2.2.2. Passive solar thermal collectors with flat plates for use in buildings

Thermosiphon solar water heaters for homes were studied by Kalogirou [26] at Nicosia, Cyprus. The energy that was used for manufacturing and installation was returned in around thirteen months. Many months to 3.2 years was the range of the payback period.
A passive solar device for home use was investigated by Ardente et al. [10] in Palermo, Italy. Approximately 11.5 GJ of primary energy was calculated. Ardente et al. [11] performed a research with many scenarios based on [10]; the results showed a great deal of uncertainty with respect to galvanised steel, thermal fluid, copper, and aluminium.
It follows that there are less investigations on BA active flat-plate collectors than on BA passive flat-plate collectors in the literature. The focus of these studies was DHW in the context of the Mediterranean (Cyprus, Italy). In terms of methodology, the majority of these research looked at the CO_2 emissions and embodied energy of the suggested systems.

2.2.3. Solar collectors using evacuated tubes

Using Pebble Bed Heat Storage (PSSP) in a passive solar heating system, Jang et al. [27] evaluated the system's environmental impact (China). The passive solar heating system of the PSSP type relied on natural heat circulation and consisted of a glass evacuated tube collector (ETC) for solar energy collection and a pebble bed for heat storage. We also looked at CCHSs, or conventional coal-heating systems. The projected total life cycle costs for the PSSP and the CCHS, over a 40-year period, were $1,431.50 and $2,740.00, respectively. A further consideration is that the PSSP had an estimated payback period of about six years. Research on the net energy analysis of operational household solar water heating setups (flat-plate and ETC collectors) was carried out by Hernandez et al. [28]. A well functioning installation often results in energy savings over its lifetime, with embodied energy making up a modest portion of that total. Even in a maritime climate like Ireland, paybacks as short as three years are quite feasible.

Environmental and financial life cycle assessments (LCAs) of solar hot water systems, including ETC and flat-plate collectors, were carried out by Hang et al. [29] (for residential buildings). Natural gas and electricity were the two auxiliary systems that were explored, along with three different locations: Los Angeles, Atlanta, and Chicago. Across all kinds and locations, the flat-plate/natural gas auxiliary heater systems performed the best. When compared to conventional electrical water heating systems in each city, the energy and environmental payback periods for solar water heating systems were less than six months, while the life-cycle cost payback varied between four and thirteen years. In areas with low sun irradiation, like the UK, Greening and Azapagic [30] looked studied the environmental sustainability of solar water heating systems throughout their whole life cycle. According to the findings, compared to evacuated-tube systems, flat-plate collectors have a little less effect on the environment. Given the above, it is clear that the area of ETCs likewise has a limited number of references. The majority of these research looked at embodied energy and CO_2 emissions from ETCs compared to flat-plate collectors; a small number of studies also examined LCCA. The climates of the four countries studied (the United States, the United Kingdom, China, and Ireland) were as varied as the DHW applications.

2.2.4. Systems that combine collecting and storing data

In their study, Smyth et al. [31] looked at a solar water heater with a reflector that could retain heat and had an integrated collector and storage system (Ireland, Northern Europe). The materials were determined to have a primary embodied energy of 2.94 GJ. With a total of 3.81 GJ, the unit embodied energy. It took less than two years for the energy that went into making the unit to pay for itself. Figure 1 is a schematic depicting the parameters taken into account in the life cycle assessment (LCA) research conducted by Smyth et al. [31].

Battisti and Corrado [32] also looked at a storage/collector system that worked together (for nations in the Mediterranean). The EPBT and CO2 PBT for the system varied between five and nineteen months. An energy storage solar collector (SOLARSTORE) was examined by Masruroh et al. [33]. A thermochemical storage unit and a universal solar heating unit were components of the SOLARSTORE system. A total of 6.3e10 kg CO_2, 46.6e70 g SO_2, 2.1e3.1 g phosphate, and 0.99e2.2 g C2H4 were determined to represent the environmental impacts associated with producing 1 GJ of energy using that innovative system. The majority of the environmental effect throughout the product's lifecycle (99%) was caused by the procedures involved in acquiring raw materials and producing components. Thus, it is clear that there is a dearth of research on active solar collectors in general and a dearth of research on this particular type of collectors in particular. In every instance, DHW was used, and the systems were tested in various climates (Mediterranean, etc.). Several approaches were used for life-cycle impact evaluation.

Photovoltaics

In Sections 3 and 4, systems which produce electrical and electrical/thermal energy are cited in order to have complementary information (along with the solar thermal) and thus, a more comprehensive review of the current literature. Given the fact that the present study gives emphasis on the BI solar thermal systems, PV (photovoltaic) and PVT (photovoltaic/thermal) technologies are briefly presented.

Building-integrated photovoltaics

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The studies about BIPVs are also few; however, are more in comparison with the BI solar thermal systems. Following repre-sentative studies are cited according to the PV cell technology.

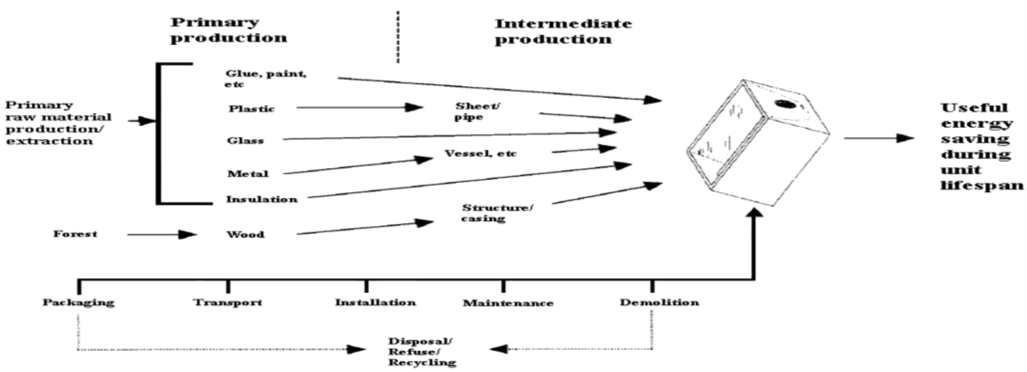

Fig. 1. A schematic illustrating the factors considered for the LCA of the integrated collector/storage solar water heater of Smyth et al. (Source: [31]).

Crystalline silicon

Crystalline silicon (Si) PVs have been the focus of the majority of the research so far [2,34–e43]. In a few of these studies, crystalline Si PVs were compared to amorphous Si cells, although the majority of the cases involved residential buildings. The systems were integrated with the building's roof and façade, and several configurations were tested for various climates (e.g., Spain, France, UK, Italy, India, Australia, Thailand, etc.). When looking at the approaches that were used, the majority of the research focused on embodied energy, CO2 emissions, and economic difficulties.

Amorphous silicon (3.1.2).

Regarding amorphous Si cell BIPVs, Keoleian and Lewis [44] looked at two potential alternatives to traditional construction materials and utility-generated electricity: the preservation of fossil fuels and environmental advantages. Compared to the traditional grid and the materials that were formerly used in construction, the energy and environmental performance of BIPVs were described using a life-cycle inventory model. In several parts of the United States, the created model was tested on an amor-phous silicon PV roofing shingle.

3.2. Photovoltaics integrated into buildings (different PV cell technologies)

Here are few references that are typical in the area of BA PVs: [45e56]. Crystalline silicon photovoltaics (PVs), roof-added/grid-connected systems, and residential structures were the primary foci of these investigations. Even though most of these studies looked at the installations' embodied energy and CO_2 emissions, a few of them also included LCCA. The suggested methods were tested in a variety of climates, including those of Hong Kong, Singapore, Italy, Switzerland, and Spain. Following is a presentation of some of the aforementioned references that can help paint a picture of PV's environmental profile.

The authors Fthenakis and Alsema [47] determined the EPBT, GHG emissions, and external environmental costs of commercial PV technologies by analysing production data from twelve businesses in the US and Europe. Under typical insolation conditions in Southern Europe (1700 kWh/m2/yr), full rooftop PV systems based on multicrystalline Si emitted 37 g CO_2eq/kWh over their lifetime. The figures were determined to be 30 g/kWh for Si ribbon technology and 45 g/kWh for monocrystalline Si technology. Ribbon, multi-, and mono-Si systems had EPBTs of 1.7, 2.2, and 2.7 years, respectively. The systems located on top were estimated to have a Performance Ratio of 75%.

With 850 polycrystalline modules and a rated output of 200 kWp, the roof-integrated, grid-connected (without solar tracking) plant was investigated by Sumper et al. [52]. While this research focused on Catalonia, sensitivity analyses were also conducted in other areas of Spain. Out of the entire primary energy consumption of the PV system, the manufacture of the PV modules accounted for more than 84%. There was a clear downward trend in the EPBT as radiation levels rose, and a little upward trend when solar radiation levels reached very high levels, according to the data. The polycrystalline PV modules' LCA for the present site indicated an EPBT of 4.36 years. Between 3.67 and 4.94 years was the EPBT for the modules in Santander when polycrystalline technology was used. The outcomes for Almería and Santander, in relation to monocrystalline technology, ranged from 7.08 to 9.57 years, respectively. Almería had a thin-film technology EPBT of 3.43 years and Santander had 4.45 years.

Thermoelectric and photovoltaic

4.1. Photovoltaic and thermal systems incorporated into buildings (using crystalline silicon)

Roof and façade integration of BIPVT has been the subject of several investigations [57–59]. The climates of India and Hong Kong were used to compare crystalline Si PVs with other technologies of PV cells. Cases involving embodied energy and CO_2 emissions from planned systems were most often found in residential constructions. The outcomes of one such study are detailed in the paragraph that follows.

It was the performance of several semi-transparent PVT double-pass façades (India) that Kamthania and Tiwari [59] studied. While a-Si and CdTe systems had EPBTs of 1.57 and 1.34 years, respectively, the m-Si system had an EPBT of

2.3 years. In contrast to the a-Si and CdTe systems, which demonstrated CO2 mitigation values of 321.41 and 49.32 t, respectively, the m-Si configuration exhibited 260.62 t CO2 mitigation over the lifetime of the system.

Structure-integrated photovoltaic and thermal

References [60–64] examined BA PVTs. Crystalline Si cells, systems attached to roofs, and residential structures were the primary foci of these investigations. Embodied energy and carbon dioxide emissions were the primary foci of the system evaluations conducted across a range of climates (e.g., Greece, India, etc.). Economic factors were also considered in some research.

5. Concentrating solar systems that are added to buildings or integrated into them

Menoufi et al. [65] is the sole LCA study that discusses BI Concentrating PV (CPV). Copper cooling lines (linked to a water pump) ran underneath the PV cells in this installation, which was a genuine BI (façade). An experimental building at Spain's University of Lleida served as the site for the installation's development and testing. The results were compared to those of a standard BIPV system that was purely imaginary. We employed the EI99 and EPS 2000 techniques for life-cycle impact assessments. The complete concentrating system could produce a maximum concentration ratio of 10× (suns) using 22 flat coated reflectors measuring 2 × 0.16 × 0.006 m. The reflectors served as blinds for the windows. In order to hold the reflectors in place, a steel framework was chosen. Sun tracking was also a part of the system. There were two receiver units, each with a 250 Wp CPV module. A layer of single-crystalline Si PV cells, with dimensions of 48 × 36 mm apiece, was included in every CPV module, with a thickness of 300 mm. An aluminium frame box with a layer of translucent white glass covered the entire structure. Since the CPV only accounted for 10% of the overall impact points in the BICPV system, the findings demonstrated that the use of CPV technology had a very low environmental effect. The following result was reached by both methodologies: by switching from traditional BIPV schemes to BICPV ones, the environmental effect was significantly reduced. In addition, the environmental impact of the CPV system was reduced as the concentration factor was increased. I should remark that there is also the LCCA of Valan Arasu and Sornakumar [66] in the subject of CPVT systems for buildings. In any case, the setup was BA. The system was operational, and it was used to heat water at an Indian restaurant.

6. Systems for shading buildings using solar energy

A similar dearth of life cycle assessment (LCA) research [67–73] applies to solar cooling systems. The majority of the approaches that were used dealt with embodied energy and their ability to cause climate change. The weather was all over the place (Cyprus, USA, Italy, Switzerland, Brazil, Thailand, China), and the structures were all different kinds (residential, commercial, offices, etc.). We see one of these citations in the paragraph that follows.

Traditional plants that were helped by PVs and small-scale solar thermal cooling systems were also studied by Beccali et al. [72]. Solar thermal + absorption with hot back-up (natural gas burner) and solar thermal + absorption with cold back-up (the same as with 5), as well as conventional + PV grid, conventional + PV stand alone (full load), conventional + PV stand alone (partial load), and conventional + grid were the systems that were examined. Rio de Janeiro, Palermo, and Zurich all had their systems tested. System 2 was the only one with low EPBT and emission PBT values (around 3 years each) when looking at the Rio de Janeiro payback indices. In contrast, the EPBTs of the other systems varied from twelve years for System 6's cold backup to thirty-five years for System 5's hot backup. This final figure, the authors pointed out, was highly dependent on how well the country's energy mix performed.

7. How on-site solar thermal systems affect the efficiency of a building over its useful life

7.1. Environmental indicators and ongoing standardisation

Life cycle assessment (LCA) can be used for both individual products and larger groups of products, like a building. Since the early 1970s, LCA methods have been used to assess energy flows in buildings. Some researchers in the late

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1980s came up with a more thorough and rigorous method for evaluating a building's life-cycle environmental impacts [74].

Environmental impact assessment (LCA) is a crucial tool for comparing various design options that achieve the desired performance but have different effects on the environment. Throughout a building's lifespan, concerns about the building materials' environmental performance, the building's effect on the surrounding landscape, and the building's biodiversity tend to take center stage. The use of energy for heating and cooling is largely responsible for the environmental impacts of building life-cycle, which includes both commercial and residential structures. According to estimates, the operational phase of a typical building consumes around 80% to 94% of the total energy consumed throughout its lifetime. Raw material extraction, transportation, and production consume about 6% to 20%, and end-of-life scenarios consume less than 1% [75]. Because of this, design teams should prioritise eco-efficiency in materials for dams and bridges and look for more energy-efficient choices for buildings. In the future, the manufacturing and end-of-life phases of each material will contribute less to the entire life-cycle effect of buildings due to the development of energy efficient structures and the use of less polluting energy sources.

Buildings contain hundreds—if not thousands—of individual products, and there may be dozens of companies involved in a construction project, making the adoption of environmental life cycle assessment (LCA) a labour-intensive and complicated process. The typical building also has a very lengthy lifespan, lasting hundreds of years at the very least. Another limitation is the lack of standardisation in building design, which means that each structure is often constructed to be distinctive [76].

The LCA is a favoured approach for analysing the environmental pressures created by materials, construction elements, and the building's lifecycle, according to experts in the area of Building Sustain-ability Assessment. Stakeholders in the life-cycle of buildings, including those who design, construct, purchase, or use them, do not make considerable use of the recognised LCA tools. There is a lack of consistency between the LCA method and most instruments used to evaluate building sustainability and sustainability certification systems. Typical criteria used to assess environmental performance in these systems and tools include material attributes, recycling potential, and distances between the production and construction sites, among others [77]. The intricacy of the LCA approach means that it is mostly utilised and developed by experts, who are typically from academic institutions.

The most widely used sustainability certification systems have simplified the process of quantifying environmental performance in order to address this issue and encourage its practical application. Although the sustainability certification's present environmental performance quantification methodologies are at odds with the LCA approach, they have been helpful in bringing sustainability into the construction industry. The findings of an assessment are not same or comparable since the mechanism for quantifying environmental performance is not common across the various instruments and systems. In order to determine for sure whether the project truly achieved the performance predicted by the specification, it is crucial to use more accurate methodologies for assessing environmental performance. On top of that, this solution becomes crucial for interpreting and comparing findings from various certification methods [78]. An approach to voluntarily providing environmental information to support sustainable works on construction is being developed as part of the CEN/TC 350 standardisation mandate's efforts to address this issue at the European level. European building sustainability assessment techniques were established by this technical committee's environmental indicators. Throughout its entire lifecycle, the object of assessment causes a number of affects on the environment. This quantifiable picture is intended to be conveyed by the list of impact categories. Both newly constructed and preexisting structures may be evaluated using the criteria laid forth by the CEN standards. This technique of computation encompasses the whole building life cycle, from construction to operation and disassembly. It was designed to maximise the use of LCI data obtained from Environmental Product Declarations (EPDs).

Parameters describing impacts on the environment, parameters describing use of resources, and other environmental information describing various waste categories and output flows make up the three main types of environmental parameters that must be declared in an EPD, as per EN 15804:2012 [79]. The environmental factors that are required to be stated in accordance with this standard are listed in Table 2.

Steps for Life Cycle Assessment in Structures 7.2

Since the second part of the 1990s, the International Organization for Standardisation (ISO) has standardised the LCA technique (ISO 14040:2006) [80]. At present, two distinct sets of regulations govern the parameters and necessities of a life cycle assessment (LCA): the Environmental Management Life Cycle Assessment (ELCA) Princi-ples and Framework (ISO/FDIS 14040:2006 [80]) and the Related Requirements and Guidelines (ISO/FDIS 14044:2006 [81]). After four previous standards—ISOD 14040:2006[80], ISO14041:1998[82], ISO 14042:2000[83] and ISO 14043:2000 [84]—were superseded on July 1, 2006, by these standards.
In accordance with ISO 14040:2006 [80] and ISO 14044:2006 [81], as shown in Figure 2, the execution of an LCA study consists of four stages that are basically iterative:
Definition of Goal and Scope;
Life-Cycle Inventory;
Life-Cycle Impact Assessment;
Interpretation.

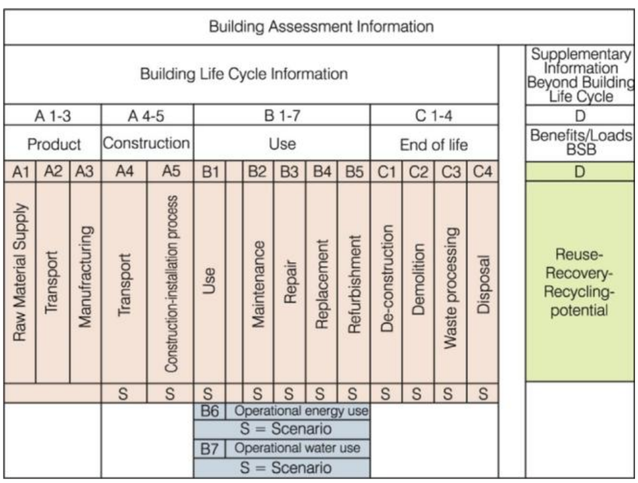

Fig. 3. Schematic representation of building life cycle break down into elementary stages [85].

dismantling, disassembling, and destroying the structure; recycling and reusing building materials and assemblies; transporting and storing demolition debris; and finally, disposing of the debris. It is possible to provide further information beyond the building life cycle when communicating the findings of an environmental performance evaluation. Energy recovery, in-situ energy generation that is exported beyond the system boundary, additional recycling and reusing, and other recovery procedures not included in the building life cycle may all contribute to this supplemental data. The following sections provide a high-level overview of the LCA process.

7.2.1. Purpose and extent

A key point to keep in mind while working with any model is that it is inherently biased since it is a simplified version of reality. Consequently, the difficulty for LCA practitioners lies in creating models that are sufficiently complex to ensure that the distortions and simplifications do not substantially impact the outcomes. The anticipated application, reasons for carrying out the research, target audience, or persons to whom the findings will be presented must be exposed explicitly in the assessment study of the life-cycle, according to ISO 14040:2006 [80]. It is imperative that the scope

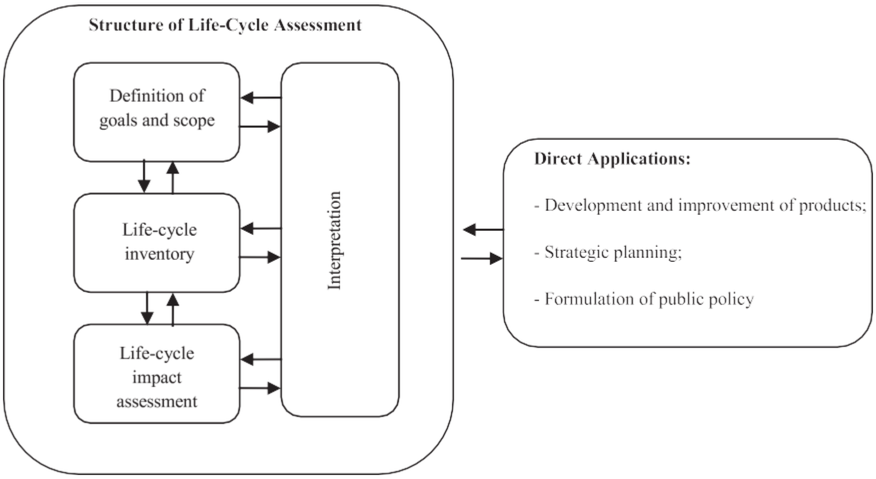

Fig. 2. Phases of LCA method (adapted from ISO 14040:2006 [80]).

be sufficiently well defined to ensure that the extent, depth and detail of the study are consistent and sufficient for achieving the planned objectives.

Inventory analysis

Quantifying the flows into and out of a product system is an integral part of inventory analysis. Typical life-cycle environmental impact assessments include raw material, water, and energy inputs and air, land, and water outflows as inventory flows. The goals of this method necessitate that the inventory also cover the creation and end destination of trash.

Data related to the manufacturing system has to be gathered from the firms, which may be a time-consuming process. Therefore, it is vital to create a questionnaire (or questionnaires) to gather the data needed for the life-cycle analysis at this point.

It is unnecessary to undergo the arduous process of gathering all the data through questionnaires because around 80% of the data required for a typical LCA analysis is already accessible [86]. Databases, literature, or the internet may provide this data. Nevertheless, existing data must be utilised with caution, particularly data originating from unidentified sources or lacking further details, as utilising data unsuitable for the product and the specifications established in the prior stage will lead to significant biases in the outcomes.

According to LCA specialists, the Ecoinvent database is a reliable source of information [87]. Energy supply, resource extraction, materials supply, chemicals, metals, waste management systems, transportation services, and more are all part of more than 4000 industrial processes that are covered by the most recent version of Ecoinvent, which includes life-cycle inventory data.

For LCIA, especially on a European scale, Gabi datasets [88] provide useful average LCI statistics. The statistics in question are derived from patent, technical, and scientific publications in addition to Gabi's collaborations with other industries. More than 8,000 entries, including metals (steel, aluminium, non ferrous metals), plastics, mineral materials, energy supply (power grid mixes, steam, thermal energy), end-of-life, coatings, manufacturing, electronics, construction, renewable materials, textile processing, and more are included in the most recent version of the Gabi datasets. Data on average LCI for PVs and solar thermal collectors, specifically at the BA system and component level, is available in the Ecoinvent and Gabi databases.

7.2.2. Evaluation of the long-term effects

One part of life cycle assessment (LCA) is determining the possible environmental consequences on a product's system at various points in time and how big they are. This is done in accordance with EN ISO 14044:2006 [81]. In addition to resource depletion, impact assessments should include human and environmental health implications. In order to determine how a product or procedure could affect the environment, a life cycle impact assessment looks for connections between the two. Consequently, the objective of this assignment is to use one or more normalised LCIA methods to transform the acquired LCI data into potential environmental effects.

An item's material inputs and outputs, energy consumption, and emissions to the environment are all factors that may be considered when calculating its life-cycle effect. Midpoint and endpoint evaluations are the two main categories of life-cycle assessment tools. Human health, species extinction, and the availability of resources for future generations are

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examples of environmental concerns that fall under the second type's broad consequences, while the first type reflects the environmental mechanism and allows for the acquisition of indicators for the environmental impact. The CML Baseline 2000, the Cumulative Energy Demand, and the TRACI are all examples of midpoint techniques. However, Eco-Indicator 99, EPS 2000, and EDIP 2003 are examples of endpoint methods. To illustrate the point, the characteristics representing environmental consequences are given in Table 2, and Table 3 shows the LCIA methodologies and the declared unit that are often used to measure them.

7.2.3. How to Understand

The most important part of the process is usually thought to be the last step, interpretation. Finding the procedures and components that have the greatest influence on a product's effects is the main goal of this phase. It encompasses uncertainty and sensitivity analysis as well. It is important that LCA's primary function aligns with the study's aims and parameters. Based on the results, we can determine where the impacts came from, make sense of the observed differences, compare solutions, define limitations, and offer suggestions. During this stage, an LCA analysis is conducted and its findings are reviewed by an impartial expert. This is particularly important when the comparison results are meant to be made public.

3.2. Simulating the lifespan of solar thermal systems incorporated into buildings

It is common practice to incorporate BI solar thermal system life-cycle modelling into a building's overall life-cycle assessment. As shown in Figure 4, the foundation of the Life-Cycle Analysis is the quantification of the materials and energy flux, as well as the physical boundary:

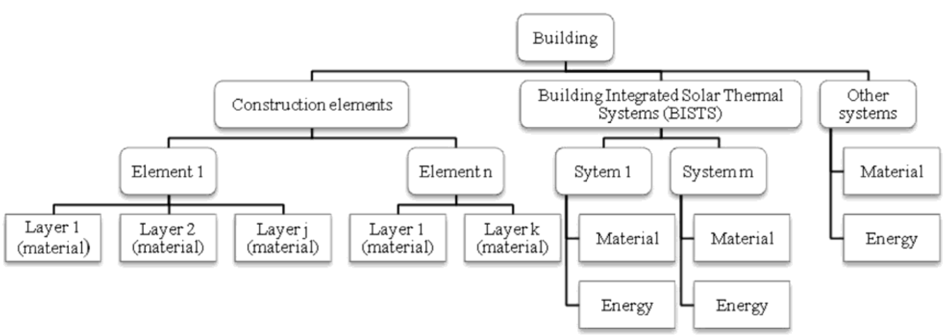

Fig. 4. Structure of the building model used for LCIA.

The materials used for the exterior (roof, windows, etc.) and interior (interior walls, etc.) building fabrics make up the construction element. One or more materials are used to make a building piece. A material layer is associated with each material. Building components include things like roofs, exterior walls, windows, and interior partitions. BI solar thermal systems include many systems, including heating and ventilation systems. Every system has its own set of parts, or components, such as a boiler or a pump, and those parts are made of materials and may use energy. This context encompasses both PV systems and solar thermal collectors. In addition to the BI solar thermal system, other building systems include the technological equipment that is installed to assist with a building's operation, as described in EN 15978:2011 [85] (such as artificial lighting and lifts).

The LCIA must include the following procedures to evaluate the environmental effects and benefits across the product's entire life cycle, as well as the BI solar thermal system's contribution to these outcomes:

Components of the BI solar thermal system and materials used in its manufacture. The building materials that are added to or replaced during a structure's construction or refurbishment should be included. The calculation must incorporate the stages that correspond to the production, upkeep, replacement, and removal of these materials. Solar collectors, photovoltaics, heat pumps, and other energy-generating and

collecting components are also a part of it. Defining the specifications of the construction materials' service life and the BI solar thermal component is important since they impact the LCIA. Having a longer lifespan can make up for a greater influence on the environment; The energy that the BI solar thermal system uses to meet its needs (heating, cooling, domestic hot water production, etc.) while the building is in operation is included in the energy that the system consumes.
It is essential to determine the advantages and loadings at and beyond the system boundary by considering the energy that is provided inside and outside the building system as well as the energy that is generated at the building scale by the BI solar thermal system. When a building incorporates an in-situ energy production system that exports energy outside the system boundary, the benefits and loadings beyond the boundary are calculated.

Figure 5 shows the typical life-cycle assessment (LCA) steps for a building-integrated (BI) solar thermal system. These steps include raw material extraction, component production, system assembly, operation (including energy delivery inside and outside the building boundary), maintenance, disposal, and all transportations undertaken throughout the life-cycle. database of life-cycle inventory items and EPDs 7.3.1 The goal of LCI is to ensure that datasets are used correctly in LCA case studies and that suitable datasets are chosen for each individual LCA study. BI solar thermal system life-cycle inventory data is hard to come by. The majority of the LCI data utilised in LCA studies pertaining to BI and BA systems originate from the Ecoinvent database, according to a literature review on the subject [89]. However, EPDs are not widely used or available, and we were unable to locate any public EPDs for BI solar thermal systems.
Data from BA solar thermal, BA, and BIPV systems are all part of Ecoinvent's LCI database [90]. We could not locate any data pertaining to PVT.
To illustrate the environmental impacts and energy used in the production of various BA solar collectors and integral systems, Tables 4e7 provide the quantification, or life-cycle impact assessment (LCIA), of the embodied environmental parameters.
Table 3 lists the environmental indicators that were taken into consideration, along with the units and LCIA approach that were then utilised to quantify them.

Using the SimaPro 7.3 software and the Ecoinvent 2.2 database, this study completed a life cycle impact assessment for various solar collectors and systems. The assessment included the following steps: production, transportation (by truck), installation (on top of the system), and disposal (excluding auxiliary heat-ing), but it did not include auxiliary heat-ing. The data shown in Table 4 is not sourced from any particular installation or manufacturer of BA solar thermal collectors. These numbers reflect the average state of the art in technology since they are derived from the average LCI of collectors and complete systems sold in Switzerland each year. While the LCI statistics originate from Switzerland, it is reasonable to believe that they are applicable on a European scale due to the fact that technology employed in European nations is quite similar. Table 4 shows the functional units of the values that reflect the usual system technology available in the Swiss market. One square metre for collectors and one piece for solar thermal systems are used. Domestic hot water generation and indoor space heating are accomplished simultaneously via the use of a combination system. The results of the study in Table 4 show that compared to a flat-plate collector system, the average potential life-cycle impacts of an evacuated-tube system are less severe. This distinction is mostly

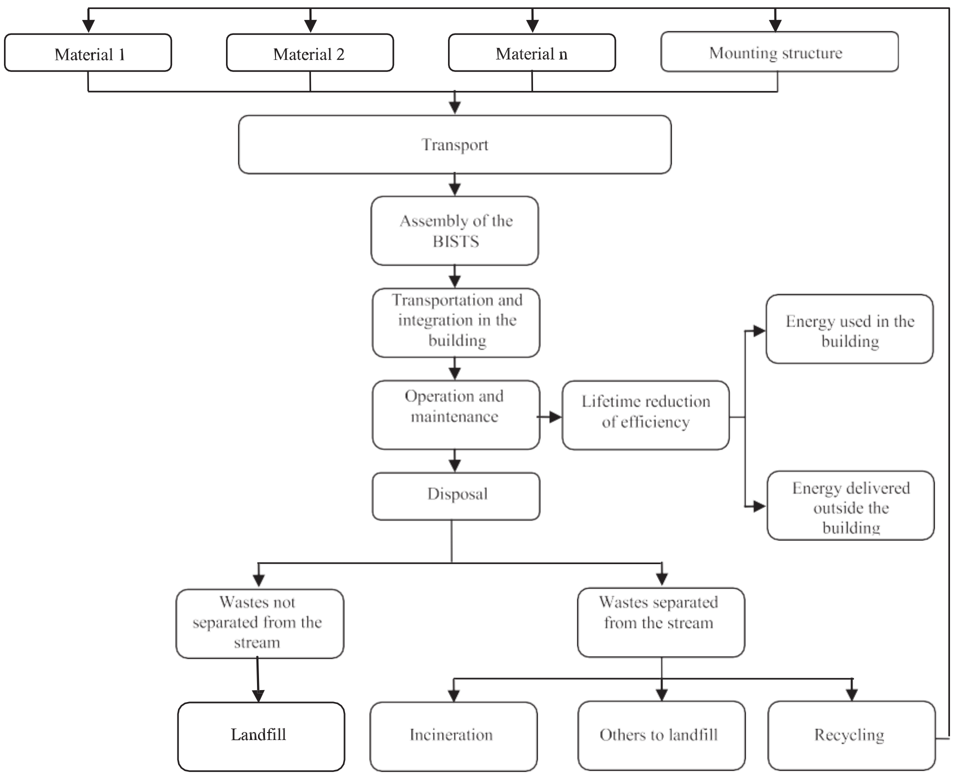

Fig. 5. Typical stages of an LCA study applied to a building-integrated solar thermal system.

related with the higher impacts due to the quantity of aluminium used in the flat plate collector.
The Ecoinvent database also includes LCI data related with the delivery of heat by a solar system. This includes the allocation, in each MJ of delivered heat, of the impacts resulting from the pro-duction of the system, its maintenance and the electricity used for the operation of the recirculation pumps, but it excludes the required auxiliary heating. presents the results from the LCIA of the delivery of heat of different solar thermal collector technologies and the results are for each MJ of delivered heat. In the same way with the results presented in gkti6the information provided by Table 5 is not for specific systems or installations since it is based on the average LCI resulting from the operation of the systems sold in Switzerland during a year. Therefore, the scope is the presentation of the average technical specification of the sys-tems in operation in Switzerland and as referred and it can be extrapolated to European scale.

Conclusions

A lack of life cycle assessment (LCA) research pertaining to BI solar thermal systems has been identified in the existing literature. This is due to the fact that BI solar thermal systems have recently become popular in the construction industry. While passive solar walls (also known as Trombo walls) have been the subject of few studies, one life cycle assessment (LCA) study focused on a BI active solar thermal system. While most research has focused on concentrated heat and water (DHW), there is a dearth of literature on BA solar collectors such as flat-plate (active and passive), evacuated-tube, and integrated collector/storage. Regarding BI systems that generate both thermal and electrical energy, PVT and CPVT systems have received less attention. Solar thermal systems, particularly BI active configurations—which are simple systems with few components and high building-integration potential—need additional life cycle assessment (LCA) studies. These configurations have the potential to supply thermal energy to buildings, either with or without parallel electricity production. Since these systems both replace a building component and meet some or all of the structure's energy demands, they should have short payback periods. Potentially less impactful alternatives to crystalline Si cells for configurations that include electricity generation (in tandem with heat production) should be considered. It would be fascinating to study the impact of storage and/or supplemental heating on the overall installation's environmental profile in relation to the modes of operation, particularly in the long run throughout the building's operating period. When it comes to approaches for life-cycle impact assessments, it would be great if other environmental indicators could be used to help understand the effect of the proposed solar systems at the midway and terminus, in addition to embodied energy and carbon. Considering that the majority of the research has concentrated on residential buildings, it would be beneficial to conduct life cycle assessments of solar systems for larger-scale applications, such as commercial multi-story structures. Lastly, future solar building designs and academic/research endeavours could benefit from LCA studies that take a holistic approach by analysing the solar system in relation to the building.

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