# Characterisation of BISTS

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**1.1 Introduction**

The Energy Performance of Buildings Directive (EPBD) requires that Renewable Energy Systems (RES) are actively promoted in offsetting conventional fossil fuel use in buildings. A better appreciation of solar thermal system (STS) integration in buildings will directly support this objective, leading to an increased uptake in the application of renewables. This uptake of RES in buildings is expected to rise dramatically in the next few years. A solar thermal system is considered to be building integrated, if a component (in most cases the collector) is a prerequisite for the integrity of the building's functionality. If the building integrated STS is dismounted, dismounting includes or affects the adjacent building component which will have to be replaced partly or totally by a conventional/appropriate building component. The members of the Cost Action TU1205 propose a systematic characterization of BISTS (Fig.1): technological/performance characterization of BISTS, architectural integration characterization of BISTS, aesthetic characterization of BISTS, functional characterization of BISTS and environmental characterization of BISTS.

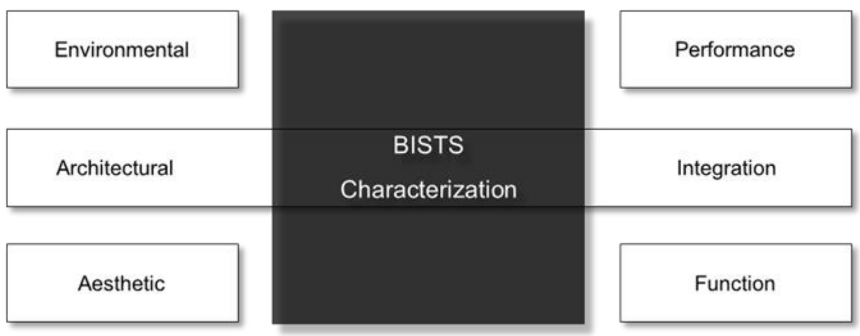


Figure 1: Main considerations for the systematic characterization of BISTS

Characterisation is defined as the act of describing distinctive characteristics or essential features. In most solar thermal collecting systems the performance characterisation is commonly used as the most important criteria by which the system (or component) is represented. Building Integrated Solar Thermal Systems (BISTS) however are typically classified across a range of operating parameters and system features and mounting configurations and in many cases the performance could be a secondary consideration in their application. Therefore BISTS characterisation most also account for the architectural integration based on structural, functional and aesthetical features. A comprehensive characterisation of BISTS is necessary to give designers, installers and end users confidence that the final solution selected is appropriate to the specific building requirements. In simplistic terms BISTS characterisation can be expressed as:

- Technological aspects (system and components, performance, services connection, etc)

- Architectural aspects as constructive element (aesthetics, functionality, weather proofing and durability, noise attenuation, health and fire safety, etc)
- Environmental aspects (embodied energy, LCA, toxicity, etc)

Moreover, there are many contextual aspects that must be considered that have location specific characteristics. The following figures illustrate many of the external / internal and design / construction / operation relationships that influence the final characteristics adopted by any BIST system.

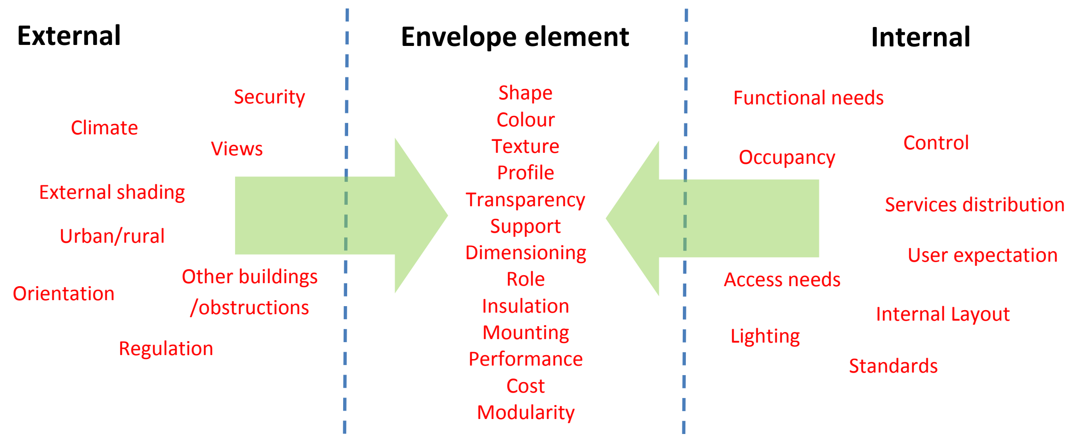


Figure 2: External/internal relationships that influence BIST system characteristic

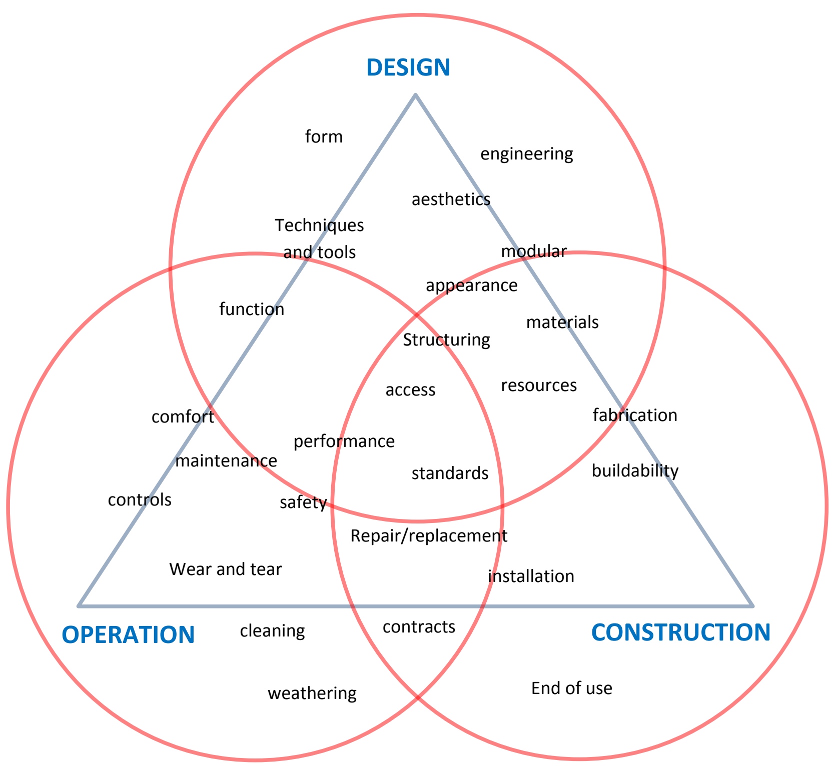


Figure 3: Interdependent design/construction/operation relationships that influence BIST system characteristics

## 1.2 Technological/Performance Characterisation of BISTS

### Solar thermal systems performance characterisation

The performance characterisation of solar thermal systems is necessary to give designers, installers and end users confidence in the capabilities of the solar heating technology. Depending on the required accuracy, easier of more complex characterizations can be used.

The European Committee for Standardisation (CEN) following a proposal from the European Solar Industry Federation (ESIF) established CEN/TC 312 which was tasked to developing European Standards that covered the terminology, general requirements, characteristics and test methods of thermal solar systems and components (Table 1). Solar thermal systems were classified according to their mode of design, manufacture and/or installation: factory made systems and custom built systems. This division was necessary so that the whole spectrum of thermal solar systems used in Europe could be accounted for, spanning small compact systems (thermosiphon and Integrated Collector Storage systems) to large complex individually designed systems. The 12976 series and particularly 12976-2, which is based on ISO 9459-5 was developed for factory made solar thermal systems and the 12977 series more for custom made systems.

Table 1: Overview of standards for testing and rating of solar thermal components and systems.

| Standard | Specification |
|---|---|
| EN 12975-1 | Thermal solar systems and components - Solar collectors - Part 1: General Requirements |
| ASHRAE 93 | Methods of Testing to Determine the Thermal Performance of Solar Collectors |
| EN ISO 9806 | Solar Energy - Solar thermal collectors - Test methods |
| EN 12976-1 | Thermal solar systems and components - Factory made systems - Part 1: General requirements |
| EN 12976-2 | Thermal solar systems and components - Factory made systems - Part 2: Test methods |
| EN 12977-1 | Thermal solar systems and components - Custom built systems - Part 1: General requirements for solar water heaters and combi-systems |
| EN 12977-2 | Thermal solar systems and components - Custom built systems - Test methods for solar water heaters and combi-systems |
| EN 12977-3 | Thermal solar systems and components - Custom built systems - Part 3: Performance test methods for solar water heater stores |
| EN 12977-4 | Thermal solar systems and components - Custom built systems - Part 4: Performance test methods for solar combi-stores |
| EN 12977-5 | Thermal solar systems and components - Custom built systems - Part 5: Performance test methods for control equipment |
| EN ISO 9488 | Solar energy - Vocabulary |

The thermal performance of factory made systems is determined according to EN 12976-2 either by applying the DST (Dynamic System Test) or by using the CSTG (Complete System Testing Group). In the Dynamic method, the operation of a solar thermal system can be described by a partial differential equation, each term of which represents a certain sub-process of the system. The aim is to calculate the coefficient of each term of the equation (system parameters). This is accomplished by operating the system in a wide range of conditions (in order to reduce standard deviations of the identified system parameters) and by a computer software that uses appropriate mathematical tools to fit the parameters on the basis of the measurement data. The identified parameters are used for the prediction of the long-term performance of the system being tested, for any climatic and load condition using local input data.

Table 2: Overview of standards for testing and rating of solar thermal components and systems (Qaist, 2012)

| **Solar Thermal Standards** | | |
|---|---|---|
| **Standard** | **PF** | **Definition** |
| EN 12975-2 | $\eta$ | The collectors thermal efficiency is the ration of the energy removed by the heat transfer fluid over a specified of a defined collector area (gross, absorber or aperture) and the solar irradiation incident on the collector for the same period, under steady or non-steady state conditions (according to ISO 9488). |
| ISO 9806 | $\eta$ | Same as EN12975 |
| ASHRAE 93 | $\eta_g$ | Collector thermal Efficiency: defined as the actual collected useful energy to the solar energy by the collector gross area. |
| EN12976, EN12977 | $f_{sol}$ | Solar Fraction is the energy supplied by the solar part of a system divided by the total system load. The solar part of a system and any associated losses need to be specified, otherwise the solar fraction is not uniquely defined (according with ISO 9488). |
| | $f_{sav}$ | Fractional Energy Savings is the reduction of purchased energy achieved by the use of the solar thermal system calculated as 1-[(auxiliary energy used by solar heating system)/ (energy used by conventional heating system)] in which both systems are assumed to use the same kind of conventional energy to supply the user with the same heat quantity giving the same thermal comfort over a specified time period (according to ISO 9488). |
| | Thermal performance | The thermal defined is defined as a set of performance indicators. For solar system without auxiliary energy sources, there are: the heat delivered by the solar heating system, QL; solar fraction, fsol; the parasitic energy, Qpar, if ant is available. For systems including auxiliary energy resources: the net auxiliary energy demand, Qaux, net; the fractional energy savings, fsav; the parasitic energy, Qpar. |
| ISO 9459 | Thermal performance | Comparable definition to EN 12976 and EN 12977 |
| EN15316-4-3 | | Same nomenclature as in EN 12977 |

In the CSTG method an input–output approach is used to consider the system operation as a single process rather than a sum of individual thermal processes. It involves a series of one-day outdoor tests on the complete system. The long-term performance can be calculated, using the short term characterization parameters with the relevant equations/parameters using a simulation model and the results presented in the form of an input/output diagram in figure 4.

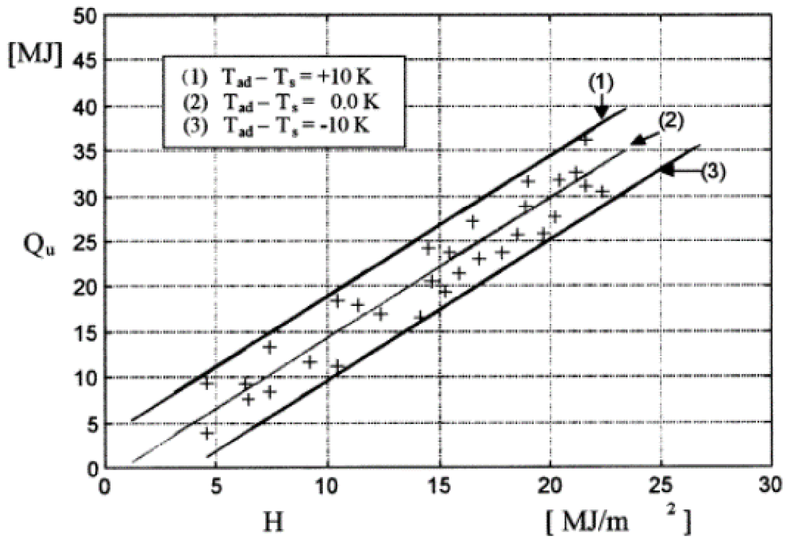


Figure 4: A typical Input/output line diagram for a solar thermal system (Zerrouki et al, 2002)

Another method commonly used in determining the thermal performance of active solar heating systems (using either liquid or air as the working fluid) and solar domestic hot water systems is the f-Chart method. Developed by Klein and Beckman (2005), the f-Chart method is essentially a correlation of the results of hundreds of simulations of solar heating systems. The conditions of the resulting correlations give F, the fraction of the monthly heating load (for space heating and hot water) supplied by solar energy as a function of two dimensionless variables involving collector characteristics, heating loads, and local weather. Typically, solar thermal standards assume one ambient temperature around the whole collector. In the case of BIST collectors, the room temperature also influences the collector performance. The building envelope typically provides a better back insulation to the collector than testing the collector alone. Therefore the building envelopes in association with BISTS can either be physically tested as part of the whole building envelope or the effect of the increased back insulation calculated. BISTS models including room temperature can be used to achieve a higher accuracy of collector performance along with the associated heating and cooling loads of the building. Custom built solar heating systems are either uniquely designed/fabricated or assembled by putting together a system from an assortment of components. Systems classified under this grouping are regarded as a set of components. Using the CTSS (Component Testing and System Simulation), the (most important) components are separately tested and test results are integrated to give an assessment of the whole system. The thermal performance of the complete system is normally predicted by using a component based system simulation program such as TRNSYS. Belessiotis et al. (2010) proposed a new method which allows for an assessment of the performance of a Large Solar Thermal Systems (LSTS), considering the system as a black box with input-output parameters that are determined by all-day tests. This method is based on a linear relationship which correlates the total amount of heat Q [MJ] stored during the day with the total daily solar irradiation at the collector level and the operating temperature level of the system. Babalis and Nielsen (2012) conducted a review the modelling methods/tools available for the thermal performance prediction and/or verification of large custom-built solar thermal systems (as defined in the EN 12977 Standard series).

**BISTS performance characterisation**

The accurate energy (performance) characterization of BISTS presents a potential problem. Considering the widely presented definition of a BISTS – 'A solar thermal system is considered to be building integrated, if for a building component this is a prerequisite for the integrity of the building's functionality' makes one realize that the current methods for solar thermal characterization are based on independent, non-integrated components, and thus are inadequate in covering the extensive range of BISTS deployed. Only when the BIST components or systems are independent of the building elements (i.e., factory made and integrated later on-site), then the methodologies previously stated can be employed as the components/systems can be characterized without the need for the building. However a collector integrated in a wall has different heat loss than the same collector just attached to the wall. Wherever the components/systems are embedded in the building, it is difficult to accurately determine the BISTS without considering the wider influence of the building. One example for BISTS performance characterization is illustrated in Figure 5.

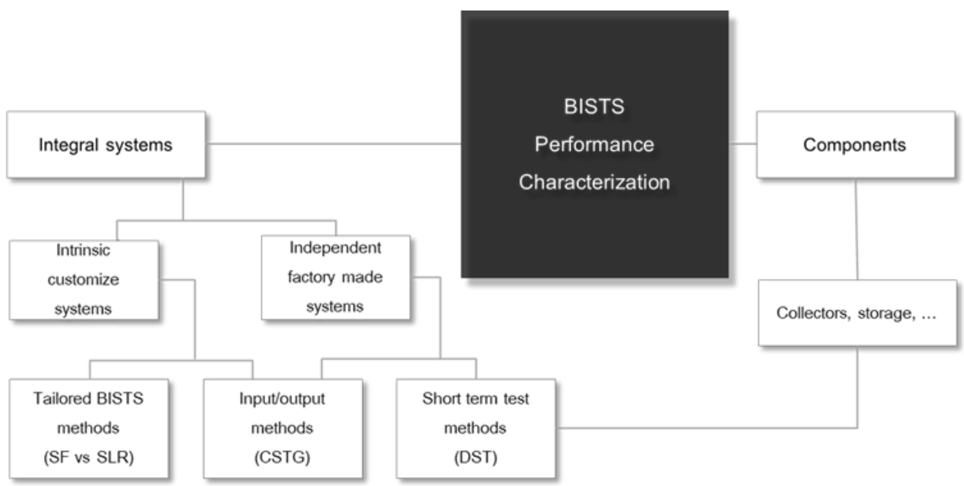


Figure 5: Classification of BISTS Performance Characterization methods.

Several authors have attempted to address the issue of an integrated solar system's contribution to a building's thermal energy needs using a range of methodologies. Oliveira Panão et al. (2012) presented a study that reviewed and analyzed a simplified empirical method based on the Solar Load Ratio (SLR) and ISO 13790 methodologies.

During the 1980s, the SLR (Solar Load Ratio) method (Balcomb and McFarland RD, 1978; Wray et al, 1979) developed at the Los Alamos Scientific Laboratory, was widely used to quantify monthly heating energy needs of passive solar houses with direct and indirect gains. This method compares the collected solar gains ($Q_{sol}$) with a reference heating load ($Q_{ref}$) and the ratio between them is the (Monthly) Solar Load Ratio (SLR) parameter.

$$SLR = \frac{Q_{sol}}{Q_{ref}} \qquad (1)$$

In practice ($Q_{ref}$) is an energy demand and therefore can theoretically range from zero to infinity. When monthly solar gains are higher than the reference heating load, the SLR > 1. For real buildings, some of the total solar gains are not useful because the thermal storage capacity of the building is limited, so that any extra solar gain is not immediately beneficial, unless some form of thermal storage is utilized. The solar heating fraction (SHF) (or solar saving fraction (SSF)), quantifies the portion of solar gains that are useful to the reference heating load. In the SLR method, the SHF is obtained by empirical correlations and heating energy needs ($Q_{hn}$) are calculated from:

$$Q_{hn} = (1 - SHF)\, x\, Q_{ref} \qquad (2)$$

SHF correlation coefficients are obtained by fitting different mathematical functions to the known results obtained by running experiments or simulations. It is noteworthy that correlation functions are strongly dependent on the predefined conditions, such as orientation, building materials, insulation, glazing type, ventilation, etc.

The ISO 13790 base method developed by van Dijk and Spiekman (2004) consists of a numerical estimative of the physical quantities of the monthly heat transfer and heat sources, which differs from a mere comparison between gains and losses in a building. Indirect gains are included and consist of the gains collected in an adjacent, but unconditioned zone, including solar systems, such as opaque elements with transparent insulation, ventilated solar walls (Trombe-Michel walls) and ventilated envelope elements for the heating energy needs of buildings as detailed in Annex E of the ISO 13790 standard details with reference to the calculation procedure. Similarities among Load Ratio methods and ISO 13790 are found in Sander and Barakat (1993) and Oliveira and Oliveira Fernandes (1992) when the utilization factor concept is introduced, referred to utilization factor for solar gains and utilization efficiency of solar gains, respectively. Another method that has applications for BISTS is the Un – utilizability design method used in predicting the long term performance of collector / storage walls. It relies on solar radiation statistics to determine the non-useful fraction of solar gain that must be eliminated to prevent overheating. More parameters can be considered than compared to the SLR method, but it requires more calculations involving radiation data. It is, therefore, not so widely used as the SLR method. The calculations are also done on a monthly basis, with the annual amount of auxiliary energy needed for a passively heated structure being determined.

**BISTS performance challenges**

The main challenges for characterizing the BISTS lie in the coupling between different subcomponents and physical effects, in the large number of possible variants and in the definition of the boundary conditions.

While standards are available for conventional facades and for conventional solar thermal collectors, some questions still remain e.g. how exactly does a BISTS facade needs to be tested for fire safety? Sometimes one company provides an absorber and a craftsman implements the absorber in a BISTS façade together with several other materials. This same façade could be tested in a laboratory, too. However, there are infinite possible systems and not all of them can be tested in laboratory. Innovative BISTS facades can offer large advantages for specific cases. It is important to allow boundary conditions which make it possible to prove these advantages. However, this results in a large number of boundary conditions which make it difficult to compare different BISTS.

**1.3 Architectural Integration Characterisation of BISTS**

When solar thermal collector systems are integrated in a building shell they become part of the general building design and also often become general building elements (Hestnes, 1999). In addition to their contribution to thermal considerations, these systems may reduce the total cost of construction by replacing conventional building envelope components, resulting from a holistic approach to building design that should occur early on in the design development phase.

In principle, BISTS can be used in all aspects of the building envelope, including facades, which have enormous potential in northern latitudes where the sun angle remains comparatively low throughout the year and roofs, which offer advantageous irradiation values. Into consideration should also be taken the ratio of façade surface area to roof surface area, which increases along with the building height. This is important when considering that the available roof area is often reduced due to the installation of mechanical and other building infrastructure, which translates advantageously for the incorporation of BISTS in façades in high-density and high-rise urban cores (Odersun, 2011).

Indeed, when considering building and also architectural integration, the active solar elements have to address the same building performance criteria as those of a traditional building envelope and including the incorporation of wall, window or roof cladding elements they replace (Roberts & Guariento, 2009). Some of the requirements that BISTS need to fulfil are colour, image, size, weather-tightness, wind loading, durability, maintenance, safety during construction and while in use (fire, electrical, stability) and last but not least cost.

Considering the above, a differentiation may then be drawn between the terms ‘building’ and ‘architectural’ integration (Basnet, 2012). In the first instance, for a designer, the aesthetic aspect of architectural integration rather than the physical aspect is a principal factor for consideration when talking about building integration. In the second instance, building integration is primarily concerned with the physical integration of BISTS in the building envelope. The optimal condition is therefore achieved when a system is both aesthetically pleasing and effectively articulated in terms of its physical practicality and functionality.

Indeed, many cases of good physical integration do exhibit a lack of aesthetic integration. Moreover, a ‘visual’ analysis of BISTS shows that the ‘look’ of a poorly designed building does not improve, simply by adding a well-designed BIST system. On the other hand, a well-designed building with an aesthetically synthesized BIST system has an easier time being accepted by urban design review boards in general (Reijenga & Kaan, 2011).

Consequently, a designer needs to examine many different types of integration techniques. Most often, BISTS are either architecturally integrated or building integrated or both. In the first instance, BIST systems do not have to be building integrated to achieve architectural integration. Indeed, it may be said that building integration is architectural integration, but architectural integration is not necessarily building integration (Probst & Roecker, 2012). It is usually possible to integrate BISTS in a physically appropriate manner, so that the overall system functionality is enhanced. However, it may not always be as easy to achieve architectural integration. It is only when the process of integration enhances the architectural qualities of a building that the term architectural integration may become more appropriate to use.

In residential building refurbishment, Golic et al (2011) present a general model for SWHS integration that considers several basic phases in order to facilitate problem-solving and to enable the individual optimization processes for various BISTS designs. Measurable criteria such as Building Potential and Degree of Feasibility are introduced in order to estimate the suitability of SWHS integration. The Building Potential is defined by an appropriate set of criteria including climatic and urban planning criteria, characteristics of existing building technology systems and architectural criteria. A multi-criteria compromise ranking method, is recommended for a comprehensive evaluation of design variants and for the selection of the optimal SWHS integration Design Variant.

The architectural integration of active solar systems was a main parameter examined by the IEA Photovoltaic Power Systems Programme (PVPS) in Task 7. According to the PVPS programme, the factors of solar suitability are "the relative amount of irradiation for the surfaces depending on their orientation, the inclination and location, as well as the potential performance of the photovoltaic system integrated in the building. The IEA PVPS Task 7 defined a kit of indicators to evaluate:

- natural integration
- designs that are architecturally pleasing
- good composition of colours and materials
- dimensions that fit the 'gridula', harmony, composition
- PV systems that match the context of the building
- well-engineered design
- use of innovative design

Jo and Otanicar (2011) developed a methodology for assessing the potential capacity and benefits of installing rooftop solar integrated systems in an urbanized area. Object oriented image analysis and geographical information systems were combined with remote sensing image data to quantify the rooftop area available for solar energy applications and therefore predict the potential benefits of urban scale photovoltaic system implementation. Zanetti et al (2010) present various methods of utilization in order to find a proper balance between technical and aesthetic requirements to formalize a set of criteria and recommendations which allow the defining of a suitable procedure when using solar technologies in the urban environment, especially on buildings whose architectural, historical or cultural features need to be considered most carefully.

In addition a number of standards are available that can be used to determine measurable criteria relating to façade elements of solar collectors that can easily be adapted/applied to BISTs and their architectural integration.

- Acoustic
    - ASTM E 966 Standard Guide for Field Measurements of Airborne Sound Insulation of Building Facades and Facade Elements
    - ASTM E90 - 09 Standard Test Method for Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions and Elements
- Fire Safety
    - Building Regulations Approved Document B 2006. Volume 2 and European classifications based on BS EN 13501 Part 1: 2002
- Durability and reliability (and weather-tightness)
    - BS EN 12975-1 is a European Standard which specifies requirements on durability (including mechanical strength), reliability and safety for liquid heating solar collectors.

**1.4 Aesthetic Characterization of BISTS**

Within the Task 41, criteria for the aesthetic building integration were developed and published by Probst and Roeker (2012). In this study it allows e.g. communities to define a required quality of building-integration for certain districts and can lead manufacturers to develop more successful new BIST elements. Two other subjective methodologies employed to characterize the aesthetic integration of solar systems on buildings are based on subjective interpretation of the visual integration of the solar absorbing elements into the building elements/fabric. Although both methods do not directly refer to building integrated solar thermal systems, the wording can be interpreted to encompass features that are equally representative of BISTS. Reijenga and Kaan (2011) present a methodology to assess the aesthetic integration of building integrated PV. Rush (1986) also uses five categories to characterize the level of visual integration of building services systems in buildings. These services are interconnected, and the nature of the connection identifies the level of integration which permits the designer to investigate alternative levels of integration to conserve space, material, and time. Probst and Roeker (2012) proposed a new method, to help authorities preserve the quality of pre-existing urban areas while promoting solar energy use. The method is based on the concept of architectural “criticity” of building surfaces, "criticity" level of a surface is defined by the sensitivity of the urban context and by the visibility of the integrated system from the public domain.

Table 3: Aesthetic characterization methodologies

| Reference | Methodology | |
|---|---|---|
| Reijenga and Kaan (2011) | assessment of the aesthetic integration of building integrated PV | Applied invisibly<br>Added to the design<br>Added to the architectural image<br>Determining architectural image<br>Leading to new architectural concepts |
| Rush (1986) | characterize the level of visual integration of building services systems in buildings | Level 1- Not visible, no change<br>Level 2 - Visible, no change<br>Level 3 - Visible, surface change<br>Level 4 - Visible, with size or shape change<br>Level 5 - Visible, with location or orientation change |
| Probst and Roeker (2012) | Quality-Site-Visibility | Context sensitivity<br>System visibility |

Rush (1986) also uses five categories to characterize the level of visual integration of building services systems in buildings. These services are interconnected, and the nature of the connection identifies the level of integration which permits the designer to investigate alternative levels of integration to conserve space, material, and time.

### 1.5. Functional Characterization of BISTS

Solar thermal collectors integrated into roofs or facades, whether transparent or non-transparent, substantially change the physical functionality of the building. Light and direct solar transmittance, vapor diffusion, thermal bridges and insulation level as well as sound transmission may change dramatically. The solar thermal component might enhance the building performance as well as the building element might enhance the energy or functional performance (e.g. mechanical stability) of the solar component. Conversely misplaced and wrong installations might deteriorate the overall performance and user comfort. Therefore these aspects have to be thoroughly planned in all detail and the installation work supervised. The main function of BISTS is to produce thermal energy. In the case of hybrid systems BIPV/T electricity will also be produced. A whole range of additional functions related to building physics and constructional requirements can be addressed by BISTS: thermal insulation, acoustic insulation, humidity regulation, rain and wind tightness, solar protection, daylighting, structural functions, fire resistance, security protection. There are different levels of building integration depending on the number of functions being delivered by BISTS. While partially integrated solar thermal systems have a poor scope of functionality, fully integrated systems are characterized by functional complexity. Moreover, external layers of the building envelope STC can influence the aesthetic potential and design options. STC systems can be used to replace normal building components with their multifunctional potential as an external skin similar to that exhibited by integrated PV systems. Clearly the multi-functionality of the collector makes it applicable to integration and can provide the advantage for the designer to use fewer building elements, as the collector fulfils several functions. For example application of building integrated solar thermal façade collectors may remove the need for conventional cladding materials which will be reflected in investment costs. In terms of functions, light permeability and visual contact to the ambient requires a new type of semi-transparent collectors. Various light transmission grades and interesting lighting effects can be produced inside a building. For example the variation of profiles, partial use of absorber and transparent areas in the aperture, redirection of light by slats, different arrangements and distances between vacuum tubes can result in different effects achieved by the shadows and light. Achieving functional requirements must be accompanied by fulfilling aesthetic requirements. This requires that the functional and aesthetic aspects are considered simultaneously, taking into account the various building aesthetics, building physics and STC mounting criteria categories.

**1.6 Environmental Characterisation of BISTS**

A critical review on Life Cycle Analysis (LCA) about solar systems with emphasis on BIST installations has been presented (Lamnatou et al., 2015a). Several issues such as BISTS influence on building ecological profile, ongoing standardization and environmental indicators were discussed. It was demonstrated that in the literature there are few studies about real BIST (and solar thermal/electrical) installations and there is a need for more LCA investigations which evaluate the BISTS itself and/or in conjunction with the building. Active systems that can provide energy for the building would be interesting to be evaluated from ecological point of view. Studies about BISTS influence on building life-cycle performance could also offer useful information in the frame of sustainable built environment (Lamnatou et al., 2015a).

In the same way as LCA implementation on multiple systems and products, LCA implementation on BIST installations should also follow ISO 14040:2006 and ISO 14044:2006. More specifically, the phases of goal and scope definition, life-cycle inventory, life-cycle impact assessment and interpretation should be adopted (Lamnatou et al., 2015a). Modelling BISTS life-cycle can be conducted e.g. by focusing on the system itself (Lamnatou et al., 2014; Lamnatou et al., 2015b) or by integrating the system in the whole life-cycle assessment of the building (Lamnatou et al., 2015a).

In order to assess the whole life-cycle footprint and BISTS contribution to the environmental impacts and benefits, the following processes/factors are crucial for the life-cycle calculations (Lamnatou et al., 2015a):

- Materials used for BISTS components (the materials utilized for construction elements could be also taken into account): phases of manufacturing, maintenance, etc.
- Materials added (or replaced) over lifespan
- Energy consumed by the BISTS
- Energy delivered inside and outside of the building system and produced by the BISTS

On the other hand, with respect to the adopted methodologies/environmental indicators about BIST installations, according to the literature, it can be observed that the proposed BIST LCA models are based on:

- Life-cycle cost analysis (Nowzari and Atikol, 2009: Trombe wall; Agrawal and Tiwari, 2010: Building-Integrated Photovoltaic/Thermal (BIPVT) systems)
- CML 2007, primary energy (Lenz et al., 2012: transparent solar thermal collector for façade integration)
- IPCC 2001 GWP 100a, CED (cumulative energy demand) (Stazi et al., 2012: Trombe wall)
- CED, GHG (greenhouse gas) emissions, EPBT (energy payback time), GHG PBT (greenhouse-gas payback time) (Chow and Ji, 2012: PVT systems, including BIPVT)
- Embodied energy, embodied carbon, EPBT, CO2.eq emissions during system operational phase, indicator of sustainability in terms of embodied carbon (Lamnatou et al., 2014: BISTS gutter-integrated)
- Embodied energy, EPBT, primary energy consumption (operational phase), life-cycle primary energy use, energy ratio in terms of embodied-energy use (Bojić et al., 2014: buildings without/with Trombe walls)
- Embodied energy, EPBT, electricity production factor, life-cycle conversion efficiency, CO2 emissions, CO2 mitigations, carbon credit (Kamthania and Tiwari, 2014: semi-transparent hybrid PVT double-pass façade)
- Eco-indicator 99, IMPACT 2002+, embodied energy, embodied carbon, primary energy and CO2 savings (Lamnatou et al., 2015b: BISTS gutter-integrated and comparison with other systems)
- Embodied energy, embodied carbon, operational energy, life-cycle energy and carbon balances (Pomponi et al., 2015: double-skin façades)

From the above mentioned references it can be seen that (in the literature) there are few LCA studies about BIST (including passive and active systems) and regarding the adopted methodologies/indicators, most of the investigations are based on embodied energy and embodied carbon whilst there are very few works based on single-score/eco-point life-cycle impact assessment methodologies.

Therefore, there is a need for more LCA studies within the field of BIST systems, especially based on multiple life-cycle impact assessment methodologies and environmental indicators in order to provide a complete picture of the ecological profile of the proposed systems. Moving in this direction, LCA models which are based on a newly-developed method (for example ReCiPe) along with other methodologies such as IPCC 2013 GWP (for different time horizons), ecological footprint and USEtox, can offer useful information about the environmental performance of a solar system (Lamnatou and Chemisana, 2015).

Regarding the above mentioned methodologies, more detailed information is presented. For an LCA study in an energy context, it is crucial the evaluation of the primary-energy inputs to produce a given product. In such a way, the least energy-intensive industrial option among alternative configurations can be determined. Thus, the concept of embodied energy arises showing the quantity of energy required to process (and supply to the construction site) a material. In order to evaluate the magnitude of this embodied energy, an accounting methodology is necessary for summing the energy inputs over the major part of the material supply chain or life-cycle. In the same concept with embodied energy, the emissions of energy-related pollutants (e.g. CO2 which is a concern in the frame of global warming and climate change) may be studied over the life-cycle (e.g. of a product). In this way, the notion of embodied carbon arises (Hammond and Jones, 2008).

IPCC 2001 is a methodology developed by the Intergovernmental Panel on Climate Change (IPCC) and it lists the climate change factors of IPCC with a timeframe of 20, 100 and 500 years. Characterization factors (IPCC) for the direct GWP of air emissions are available while normalization and weighting are not a part of this methodology. IPCC 2007 is an update of IPCC 2001 and IPCC 2013 is an update of IPCC 2007 (PRé, 2014).

For CED, characterization factors are given for the energy resources divided into 5 impact categories: non-renewable, fossil; non-renewable, nuclear; renewable, biomass; renewable, wind, solar, geothermal; renewable, water. Normalization is not a part of this methodology (in order to get a total (cumulative) energy demand, each impact category is given the weighting factor 1) (PRé, 2014).

Eco-indicator 99 is the successor of Eco-indicator 95 and both methodologies utilize the damage-oriented approach. For example for the characterization of the emissions, multiple impact categories (carcinogens, respiratory organics, respiratory inorganics, climate change, radiation, ozone layer, ecotoxicity, acidification/eutrophication) are taken into account. In terms of the damage assessment, the damages of the impact categories result in 3 types of damages (human health, ecosystem quality, resources). Normalization is conducted on damage category level and also weighting is performed at damage category level. The hierarchist option of Eco-indicator 99 with average weighting is chosen as default. In general terms, value choices made in the hierarchist option are scientifically and politically accepted (PRé, 2014).

IMPACT 2002+ is acronym of IMPact Assessment of Chemical Toxics and it proposes a feasible implementation of a combined midpoint/damage approach, linking all types of life-cycle inventory results via 14 midpoint categories (human toxicity, respiratory effects, ionizing radiation, ozone layer depletion, photochemical oxidation, aquatic ecotoxicity, terrestrial ecotoxicity, aquatic acidification, aquatic eutrophication, terrestrial acidification/nutrification, land occupation, global warming, non-renewable energy, mineral extraction) to 4 damage categories (human health, ecosystem quality, climate change, resources). Characterization, normalization and weighting can be conducted (PRé, 2014).

ReCiPe is successor of Eco-indicator 99 and CML-IA. The purpose (at the start of the development) was to integrate the problem-oriented approach of CML-IA and the damage-oriented approach of Eco-indicator 99. The problem-oriented approach refers to the impact categories at a midpoint level. ReCiPe includes 2 sets of impact categories with associated sets of characterization factors. At the midpoint level, 18 impact categories are addressed (ozone depletion, human toxicity, ionizing radiation, photochemical oxidant formation, particulate matter formation, terrestrial acidification, climate change, terrestrial ecotoxicity, agricultural land occupation, urban land occupation, natural land transformation, marine ecotoxicity, marine eutrophication, fresh water eutrophication, fresh water ecotoxicity, fossil fuel depletion, minerals depletion, fresh water depletion). At endpoint level, most of these midpoint impact categories are multiplied by damage factors and aggregated into 3 endpoint categories (human health, ecosystems, resource surplus costs). The three endpoint categories are normalized, weighted and aggregated into a single-score (PRé, 2014).

Ecological footprint is the biologically productive land and water a population needs to produce the resources it consumes and to absorb part of the waste generated by fossil and nuclear fuel consumption. With respect to characterization, in the frame of LCA, the ecological footprint of a product is the sum of time integrated direct and indirect land occupation, related to nuclear energy use and to CO2 emissions from fossil energy use. Normalization is not a part of this method and (in order to get a footprint) each impact category is given weighting factor 1 (PRé, 2014).

USEtox model is an environmental model for characterization of human and eco-toxicological impacts in LCA and comparative risk assessment. USEtox describes the fate, exposure and effects of chemicals. Characterization and normalization are available (PRé, 2014).

### 1.7 Conclusion

In the past the inclusion of a solar thermal system onto a building envelope was in many cases due to the isolation of the building or a simple techno-economic calculation; if the performance of the unit yielded a sufficient return on investment then the installation was approved. Today, however, the inclusion of a solar thermal unit requires much greater assessment and the development of BISTS has proven that the choice is not purely an economic exercise. Therefore, methods to fully assess and characterise the technological/performance, architectural integration, aesthetics, functional and environmental features of BISTS should be given important consideration.

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