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# Solar Thermal Systems – Towards a systematic characterization of building integration

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**Abstract**

Characterization is defined as the act of describing distinctive characteristics or essential features. In most solar thermal collecting systems the energy performance characterization 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, system features and mounting configurations, and other criteria are similarly important to be considered. Therefore BISTS characterization should also account for the architectural and building physics integration based on structural, functional and aesthetical features. A comprehensive characterization of BISTS is necessary to give designers, installers and end users confidence that the final solution selected is appropriate to the comprehensive building requirements.


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*Keywords:* solar systems, integration, characterization methods

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## 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 authors of this paper, members of the Cost Action TU1205 [1], 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.

**Nomenclature**

| | |
|---|---|
| BISTS | Building Integrated Solar Thermal System |
| CEN | European Committee for Standardisation |
| CSTG | Complete System Testing Group |
| CTSS | Component Testing and System Simulation |
| DST | Dynamic System Test |
| EPBD | Energy Performance of Buildings Directive |
| ESIF | European Solar Industry Federation |
| IEA | International Energy Agency |
| IS | Indicator of Sustainability |
| LCA | Life Cycle Analysis |
| LCIA | Life Cycle Impact Assessment |
| LSTS | Large Solar Thermal Systems |
| PVPS | Photovoltaic Power Systems Programme |
| RES | Renewable Energy System |
| SHF | Solar Heating Fraction |
| SLR | Solar Load Ratio |
| SSF | Solar Saving Fraction |
| STS | Solar Thermal System |
| SWHS | Solar Water Heating System |
| $Q_{sol}$ | Collected solar gains |
| $Q_{ref}$ | Reference heating load |
| $Q_{hn}$ | Heating energy needs |

## 2. Solar thermal system performance characterization

The performance characterization 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, the easier of more complex characterizations can be used. The European Committee for Standardization (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 from small compact systems (thermosiphon and Integrated Collector Storage systems) to large complex individually designed systems.

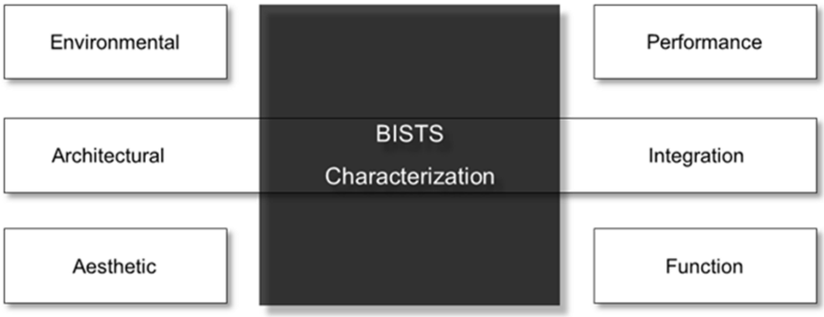


Fig. 1. Main considerations for the systematic characterization of BISTS.

The EN 12976 series and particularly EN 12976-2, which is based on ISO 9459-5 was developed for factory made solar thermal systems and the EN 12977 series more for custom made systems [2].

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.

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 [3] using a simulation model and the results presented in the form of an input/output diagram [4], Fig.2.

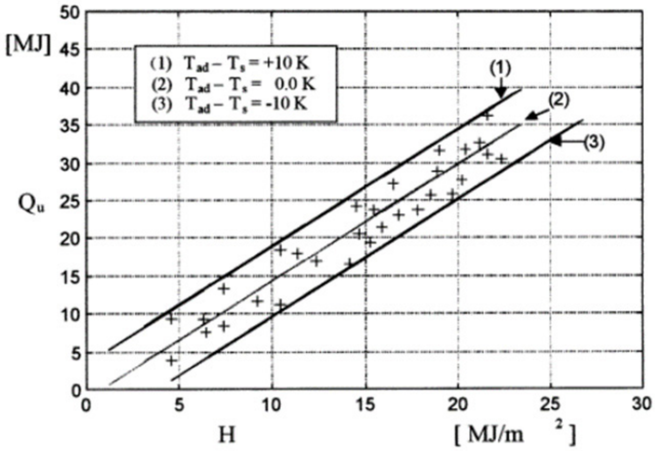


Fig. 2. A typical Input/output line diagram for a solar thermal system [4].

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 [5], 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 [6] or the effect of the increased back insulation calculated [7]. 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 [8]. 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 [9]. Belessiotis et al. [10] 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 [11] 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).

## 3. Technological/performance characterization of BISTS

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 Fig. 3.

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 [12–15]. Oliveira Panão et al. [16] presented a study that reviewed and analyzed a simplified empirical method based on the Solar Load Ratio (SLR) and ISO 13790 [17] methodologies.

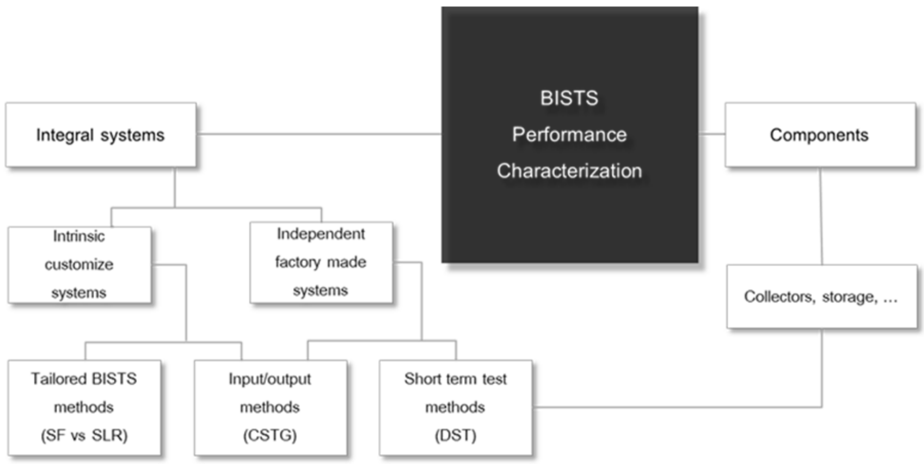


Fig. 3. Classification of BISTS Performance Characterization methods.

During the 1980s, the SLR (Solar Load Ratio) method [12,18] 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.

$$SLR = \frac{Q_{sol}}{Q_{ref}} \tag{1}$$

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:

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

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 [19] 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 [15] and Oliveira and Oliveira Fernandes [20] 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.

## 4. Architectural integration characterization of BISTS

The usual practice of the implementation of SES has been the installation of PV and STC panels on flat and tilted roofs in buildings. The architectural integration of active solar systems is one of the main parameter examined for example by the International Energy Agency (IEA) programs. 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. Zanetti et al. [21] tried 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. Fuentes [22] proposed a classification integration method, where both PV and STC systems can be incorporated into buildings by either superimposition - where the system is attached over the existing building envelope, or integration - where the system forms a part of the building envelope. Superimposed – a simple method well suited in case of existing buildings. The solar modules are mounted on a structure; for e.g.: roof, on the building envelope and in parallel with them. There are no savings in substituting elements as the materials underneath the solar modules are not replaced [22]. With superimposition, architectural integration can still be achieved as the buildings can be made elegant. If this is the case, it may also be called architectural integration but is certainly not building integration. Integrated – The PV and STC systems are used both as an architectural element as well as a means of energy generation. This method is most likely to be suitable for new buildings. The traditional constructive elements are substituting for PV and STC materials. Savings are possible where the cost of the substituted elements is below that of the traditional elements.

Golic et al. [23] present a general model for SWHS integration in residential building refurbishment 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 gradual, harmony, composition, PV systems that match the context of the building, well-engineered design and,use of innovative design. Jo and Otanicar [24] 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.

## 5. Aesthetic characterization of BISTS

Within the Task 41 [25], criteria for the aesthetic building integration were developed and published [26]. 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 [27] present a methodology to assess the aesthetic integration of building integrated PV. Rush [28] 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 proposed a new method [29], 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 2. Aesthetic characterization methodologies

| Reference | Methodology | |
|---|---|---|
| Reijenga and Kaan [27] | assessment of the aesthetic integration of building integrated PV | Applied invisibly |
| | | Added to the design |
| | | Added to the architectural image |
| | | Determining architectural image |
| | | Leading to new architectural concepts |
| Rush [28] | characterize the level of visual integration of building services systems in buildings | Level 1- Not visible, no change |
| | | Level 2 - Visible, no change |
| | | Level 3 - Visible, surface change |
| | | Level 4 - Visible, with size or shape change |
| | | Level 5 - Visible, with location or orientation change |
| Probst and Roeker [29] | Quality-Site-Visibility | Context sensitivity |
| | | System visibility |

Rush [28] 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.

## 6. 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 [29]. 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 [22]. 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 [30–32]. 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.

## 7. Environmental characterization of BISTS

In respect of environmental characterization methods for BISTS, various has been used as a methodology to define environmental characteristics through a life cycle analysis (LCA), Life Cycle Impact Assessment (LCIA) methodologies and the impact of a product is evaluated based on “eco-points”. ISO 14040-43 [33] has been used as a methodology to define environmental characteristics through a life cycle analysis (LCA) of a patented building-integrated solar thermal collector developed at the University of Corsica [34]. The methodology was based on calculating the embodied energy and embodied carbon from which an indicator of sustainability (IS) was calculated and used to critically evaluate the system designs. Life Cycle Impact Assessment (LCIA) methodologies such as EPS 2000, EI99, IMPACT 2002+, the impact of a product is evaluated based on “eco-points”. For example the total eco-points per produced kWh for a solar and a conventional system can be compared by adopting several scenarios e.g. in terms of solar system output under various climatic conditions [34]. Tsoutsos et al. [35] presents an overview of an environmental impact assessment that assesses the potential environmental intrusions of solar energy systems. The analysis process utilises a simplistic grading system based on energy technology indicators and covers the construction, installation and the demolition phases, as well as noise and visual intrusion, greenhouse gas emissions, water and soil pollution, energy consumption, labour accidents, impact on archaeological sites or on sensitive ecosystems, negative and positive socio-economic effects.

## 8. Conclusions

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 assess the technological/performance, architectural integration, aesthetics, functional and environmental features and characterization of BISTS should be given important consideration. A review of BISTS characterization methods has been presented to give designers, installers and end users confidence that the final solution selected is appropriate to the comprehensive building requirements.

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