SECTION 2

DESIGN PROCESS OF BISTS

CONTENTS

2.1 ARCHITECTURAL PLANNING/INTEGRATION

Aleksandra Krstic-Furundzic, Andreas Savvides, Gerald Leindecker, Constantinos Vassiliades

The energy problem is at the forefront of current discussions. After the first oil crisis in the early seventies, the use of renewable sources, especially solar energy integrated with architectural design, is an important parameter in reducing a building's carbon footprint (Tombazis, 1994). Also, as the stock of fossil fuels is depleted, countries like Cyprus look to exploit local climatic conditions – extended sunlight periods – to lessen reliance of the current building stock on the national grid which relies on fossil fuel combustion. Indeed, solar energy is viewed as one of the main alternative sources of energy to deal with fossil fuel dependency (Yang et al., 2013), especially as the operational costs of buildings account for 40% of energy use in the EU context.

The sun is a renewable energy source whose usage exerts influence on architectural design and building concepts (Krstic-Furundzic, 1996). Concepts of energy efficient buildings are developed producing new building envelope structures and components to reduce consumption of pollutant energy sources and thereby reduce CO_2 emissions. Influence of solar thermal systems on building and settlement appearance is significant and, therefore, design of building integrated solar thermal (BIST) collectors, as well as building integrated PV (BIPV) modules, presents a specific challenge to architects.

Reaching the agreed 2020 target can only be achieved by combined measures to increase the share of building parts producing energy in an integrated manner (Leindecker, 2007).

The increasing use of renewable energy sources means that building integrated solar thermal systems (STSs) and photovoltaics (PVs) have a key role in the provision of electricity, domestic hot water and in the heating and cooling of buildings (Kalogirou, 2013). Previously, implementation of these systems in new buildings has been commonly treated in the literature. For some time in the literature, the debate on renovation of existing buildings is dominant, with the field of building integrated technologies moving in that direction – the integration of solar panels to existing buildings in order to produce energy required for the building's operation without occupying any land. In the ongoing discussion, PVs are seen to be generally benign in terms of environmental impact, making use of one of the most viable renewable energy technologies by replacing existing building cladding materials (Tsoutsos et al., 2005). The same can be stated for building integrated solar thermal collectors.

Due to functional complexity, building envelopes with integrated STC and PV modules can be treated as multifunctional structures. Development of multifunctional solar facades and roofs that produce electrical and thermal energy, and provide protection against inclement weather, light and noise is actual (Krstic-Furundzic, 2007). This is indicated by the European regulations, according to which new buildings must be nearly zero energy. This confirms the necessity of the application of solar thermal collectors and PV modules to the building envelope. The design of multifunctional building envelopes is a particularly complex task asking for a multidisciplinary approach.

The design of solar thermal collectors (STCs) integration is a very complex process because of a large number of constraints, related to the building architecture and construction, building placement and surroundings, climate, characteristics of the existing heating system, together with conflicting energy, aesthetic and economic requirements (Golic et al., 2011).

At the Training school 3 of COST TU1205 Action, it was stated (Krstic-Furundzic, 2016) that from an architectural viewpoint the design process of building integrated solar thermal systems (BISTS) should include the following research steps:

- Prediction of amount of energy demands that should be covered by STC.
- Evaluation of building potential for STC integration based on climatic data, urban layout and building technology system characteristics.
- Discussion of location and position of STC on the building envelope taking into account functional and aesthetic aspects, as well as mounting options (creation of design scenarios).
- Calculation of energy benefits of different design scenarios.
- Estimation of environmental benefits of different design scenarios.
- Multi-Criteria comparative analysis of different design scenarios (aesthetic, energy, ecological, economic, etc. criteria).
- Selection of optimal STC integration scenario.

Predicting the amount of energy demands to be covered by solar thermal collectors, indicates the required area of building envelope surfaces appropriate for STC integration. Assessment of the buildings feasibility for solar thermal integration, in other words the 'Building Potential' is based on an appropriate set of criteria including (Krstic-Furundzic et al., 2012b; Golic et al., 2011):

i. Climatic and urban planning criteria.
ii. Characteristics of building technology systems.
iii. Architectural criteria relevant for STC integration.

When it comes to climatic and urban planning entries, the following parameters have to be analyzed (Krstic-Furundzic et al., 2012b; Golic et al., 2011):

1. Global solar irradiance on building location (kWh/m^2)
2. The number of favourably (south, south-west or south-east) oriented roof sides.
3. The number of favorably (south, south-west or south-east) oriented facade walls.
4. Shading effect on roof caused by the surroundings (other buildings, trees, etc.).
5. Shading effect on facade walls caused by the surroundings (other buildings, trees, etc.).

System efficiency is strongly influenced by orientation and inclination of the solar thermal collector's absorbing surface. A favourable orientation is facing the equator, while the choice of inclination is influenced by latitude. Dr. Farrington Daniels gives a simple rule of thumb for domestic hot water systems in his book 'Direct use of the Sun's Energy' (Farrington, 1964): "In the northern hemisphere they are faced south and tilted at angle with the horizontal equal to the latitude. In the winter it is recommended that the flat-plate collectors be tilted at the angle of latitude plus 15°, and in the summer at the angle of latitude minus 15°" (Appleyard and Konkle, 2007). Deviation to southeast and southwest up to 30° is also acceptable. For heating applications, the solar yield is optimized with stronger inclination, with a 60° to 90° inclination recommended. Inclination may be also important in areas with high snow loads. The larger the inclination angle, the easier it is for snow to slide off flat-plate collectors. Some studies and observations indicate that evacuated tubes, because of their shape and heat retention, take longer to shed snow (Appleyard and Konkle, 2007).

It is not recommended to apply solar thermal panels on periodically shaded surfaces of building envelope because it results in a lower system efficiency and may cause damages such as glass cracks.

A neighborhood shading analysis should be conducted in order to confirm the correct pitch and shading. An example GIS photograph with symbols indicating a good solar potential is shown in Figure 2.1.1 for individual residences in an Ann Arbor settlement, Michigan, USA (Appleyard and Konkle, 2007).

Figure 2.1.1. Neighbourhood mapping. (Key: full sun=optimal orientation, no shade; green tree=good orientation, little to no shade; yellow tree=medium orientation, some shade; red tree=east-west facing orientation, some shade; red octagon=no exposure).

Characteristics of building technology systems are related to building construction concept, materials and installation systems. Position of the boiler and piping for the inlet and outlet of the working fluid should be planned in accordance with the structural characteristics of the building and applied materials. In that sense attention should be paid to the design of floors, walls and ceilings. Likewise, the structures and materials affecting the mounting possibilities for integration of STC into building envelope. It is clear that it is necessary to achieve sophisticated and compromise integration of urban planning and design, building form and construction design, material selection and solar thermal system design in order to create optimal solution in terms of functional, energy, economical and architectural viewpoint.

The quality and aesthetic characteristics of STCs (e.g., dimensions, shape, material type, colour, surface texture, etc.) have a considerable effect on the building aesthetics and they have a great influence on the economics, energy performance and functional aspects (Krstic-Furundzic et al., 2012b).

From an architectural aspect, different specifications can be required regarding: Placement possibilities, Application possibilities, Function possibilities, Light permeability, Dimensions and form, Colour and appearance of modules, Construction possibilities (Krstic-Furundzic, 2007).Various possibilities for fulfilment of listed specifications result in a large variability of building envelopes with BISTS. Main possibilities as key to architectural planning/integration and design process of BISTS are discussed and structured in following relevant parameters:

- Position on the building envelope.
- Function possibilities.
- Aesthetical possibilities.
- Constructional mounting options.

Architectural implications in the building integration of photovoltaic and solar thermal systems are discussed at the end of this chapter, taking into consideration a number of case studies.

2.1.1 Position on the Building Envelope

The addition of building integrated solar thermal devices, as well as PV modules, onto a building envelope requires them to be physically integrated directly into the building constructional elements or in the form of an add-on. In different ways they each strongly influence the building appearance, as shown in Figure 2.1.2. In the latter case they are independent devices applied on roof or facade structure. In the former, building-integrated solar thermal systems are building components which can be substituted for conventional roof or facade cover materials (Krstic-Furundzic, 2007). Development of technologies, materials, support systems and coatings is continuous, giving freedom to architectural design.

Moreover, to be considered as building integrated these systems should be a functional part of a building's structure or should be architecturally integrated into its design (Peng et al., 2011).

Figure 2.1.2. "Standoff" (left) and "building-integrated" (right) STC influence on building appearance.

The two usual positioning locations for a PV or an STS system are the roof and facade, with all other locations being known as building components (Reijenga, 2003; Gajbert, 2008).

Considering the building envelope structure and geometry, solar collecting elements can be integrated into:

i. facades – vertical walls, sawtooth wall (vertical or horizontal direction), sloping wall,
ii. roofs – skylights, sawtooth roof, sloping roof,
iii. facade and roof shading devices – horizontal, vertical, tilted,
iv. overhangs – horizontal and sloped,
v. balcony railings – vertical and tilted,
vi. curved/flexible facade and roof surfaces.

Building envelope geometry exerts influence on BISTS and BIPV position, integration design and construction solutions. For skillful design of form of new building, advantages and obstructions of facade and roof form types regarding integration of BISTS and BIPV should be well known.

STC can be applied onto transparent and/or opaque facade and roof surfaces both of which require completely different design and construction approaches in the creation of:

i. semi-transparent solar thermal collectors and

ii. non-transparent solar thermal collectors.

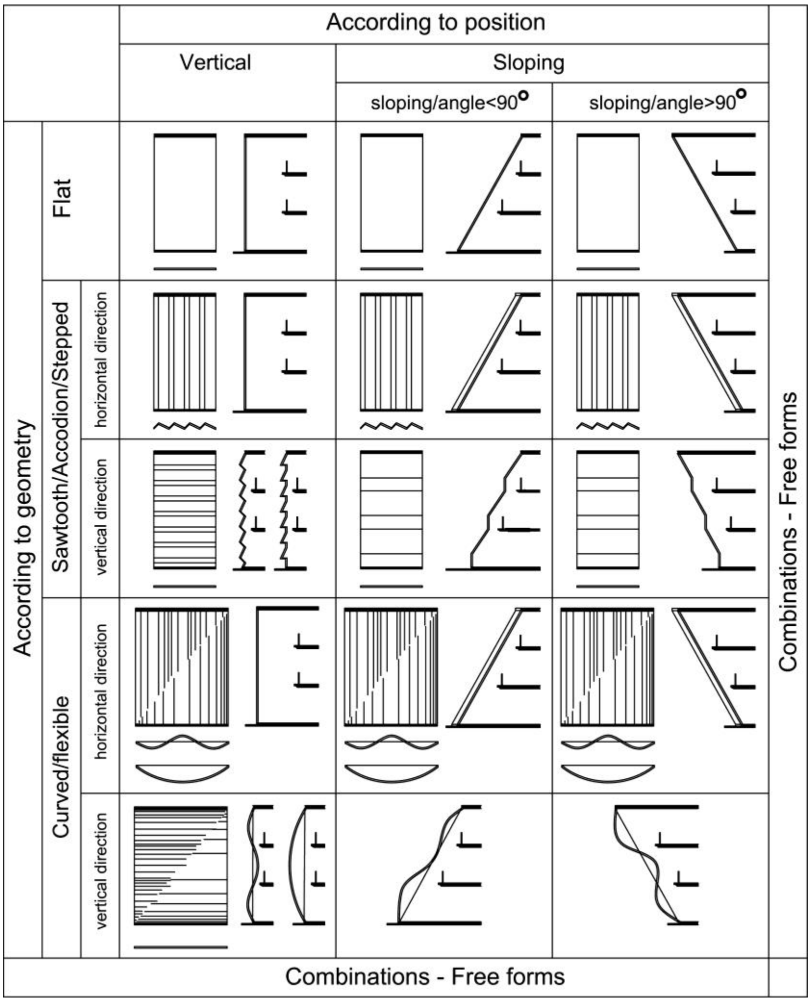


Figure 2.1.3. Form types of facades according to position and geometry of surface (Krstic-Furundzic et al., 2012a).

Facade vertical and sloping with angle < 90° surfaces (Figure 2.1.3), are convenient for STC integration and existing mounting options are suitable. In case of sawtooth facade surface, sunlit planes have to be identified for STCs integration and situation is more complex if step line is horizontal. It is necessary to take into account the mutual shadowing between the surfaces. The situation is similar in the case of curved facade surface and directly depends on the direction and radius of curvature of planes. Sloping facade surfaces with angle > 90° are not appropriate for STC integration as they are hardly sunlit.

Solar thermal systems can be integrated in single and double skin facades. For single skin facades, they are integrated into a parapet or wall structure as a specific building component, whilst a ventilated double skin facade in itself is already a solar thermal collector (Figure. 2.1.4). Design and functional variability of both facade types, as challenges to and obligation of contemporary architectural design, could be achieved by transparent and non-transparent solar thermal collector structures.

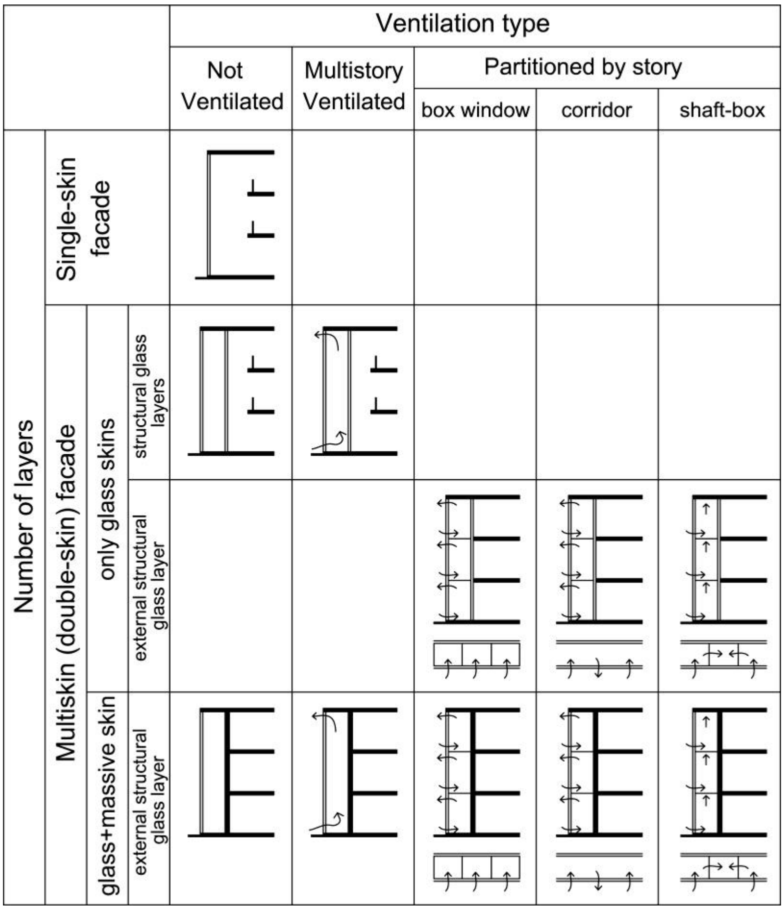


Figure 2.1.4. Assembly types of facades according to number of layers and ventilation type (Krstic-Furundzic et al., 2012a).

Flat horizontal roof surfaces are not appropriate for STC integration (Figure 2.1.5) as they get limited solar exposure in the winter period and water tightness can be difficult to achieve. Also, the glass surface can get considerably dirty, which is a problem because it reduces the efficiency of the collector. Roof sloping surfaces are convenient for STC integration and existing mounting options are suitable. In the case of a sawtooth roof surface, solar exposed planes have to be identified for STCs integration and mutual shading between the surfaces must be considered. The situation is similar in the case of curved roof surfaces and directly depends on the direction and radius of curvature of planes.

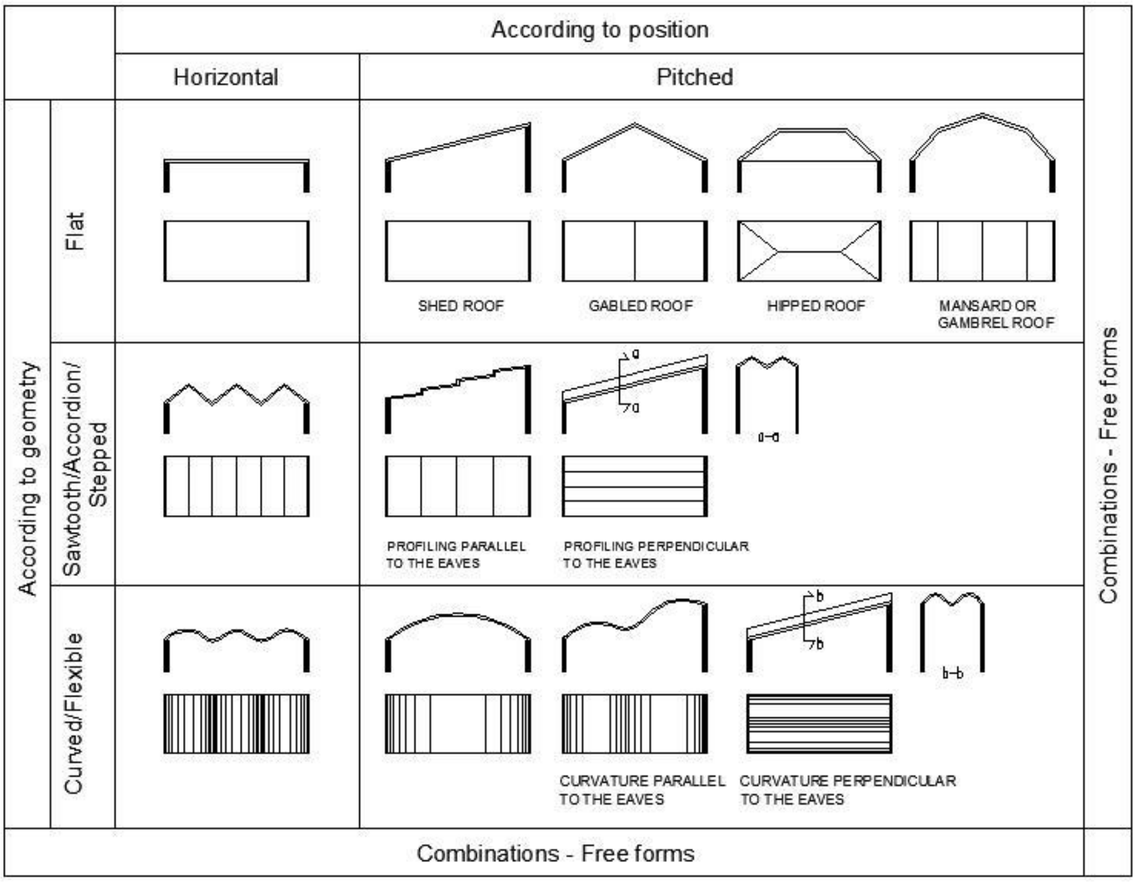


Figure 2.1.5. Form types of roofs according to position and geometry of surface (Krstic-Furundzic et al., 2013).

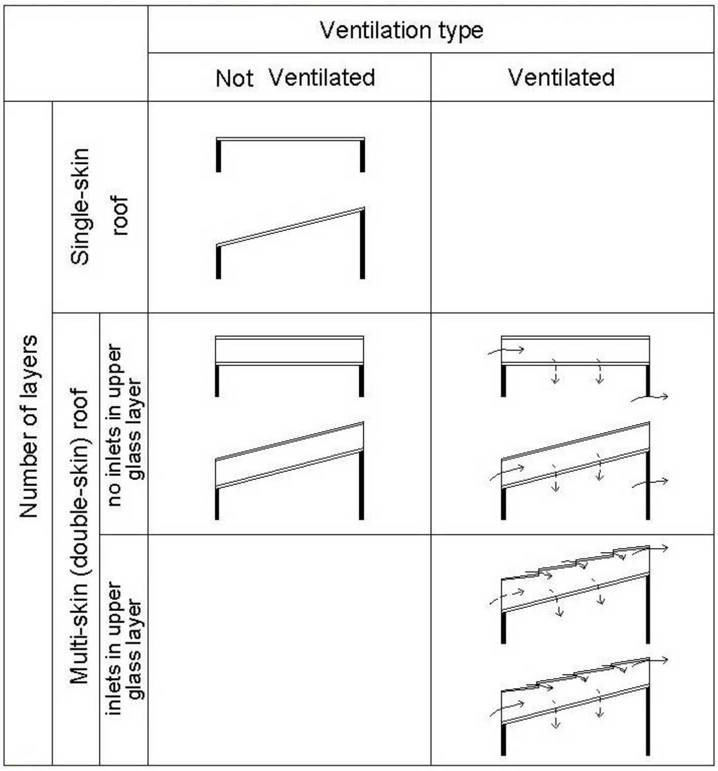


Figure 2.1.6. Assembly types of roofs according to number of layers and ventilation type (Krstic-Furundzic et al., 2013).

Solar thermal systems can be integrated in single and double skin roofs. For single skin roof, they are integrated as a specific building component, whilst a ventilated double skin roof in itself is already a solar thermal collector (Figure. 2.1.6). In the case of a ventilated double skin roof regarding air inlets two options are available: no inlets in upper glass layer (inlets are under the eaves) and inlets are in upper glass layer created as special roof components for air inlet or air inlet is between roof tiles. Design and functional variability of both roof types, could be achieved by transparent and non-transparent solar thermal collector structures.

The area of building integrated STC depends on building utilization, thermal energy demands and available area of facade and roof surfaces. Also, the building geometry can produce limitations which, in some cases, can be solved by skillful design and appropriate features/devices as shown in Figure 2.1.7.

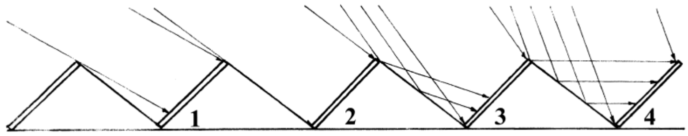


Figure 2.1.7. Effect of booster reflectors to collectors regarding the direction of solar rays (Tripanagnostopoulos et al., 2000).

2.1.2 Function Possibilities

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 as STC can influence the aesthetic potential and design options (Krstic-Furundzic, 2007). 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 (Fuentes, 2007).

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 (Table 2.1.1).

Table 2.1.1. Connection between functional and aesthetic aspects (Krstic-Furundzic et al., 2012b).

Aspects		Criteria function groups	Individual criteria functions
Functional and Aesthetic aspects	Class of Criteria for Building Aesthetics	Compatibility of physical characteristics of STCs in relation to building envelope	Compatibility of dimensions of STCs in relation to building envelope
		Compatibility of material appearance of STCs in relation to building envelope	Compatibility of color of STCs in relation to building envelope
			Compatibility of surface characteristics (texture, fracture, surface relief, warmth to touch) of STCs in relation to building envelope
			Compatibility of glossiness – reflection of STCs in relation to building envelope
			Compatibility of transparency level in relation to building envelope * refers only to glazed STCs
		Compatibility of physical and aesthetic characteristics of STC sealing-joints in relation to building envelope	Compatibility of physical and aesthetic characteristics of STC sealing-joints in relation to building envelope
		STCs' fitting in building envelope	Naturalness of STC integration
			Relationship between composition of STC colors and materials and colors and materials on building envelope
			Design harmony
			STCs' fitting in building context
			Design innovation
		Success of visualization concept of STC integration	Success of visualization concept of STC integration simultaneously in relation to building and in relation to building context
	Class of Criteria for Building Physics	Physical–mechanical characteristics	Mechanical characteristics of STCs (material strength, friction resistance, resistance to force impact)
			Behavior in relation to liquids (water absorption, capillary absorption, moistening/non-moistening, permeability of water, frost resistance
			Behavior in relation to air – steam of STCs
			STC characteristics in relation to deformations and destruction (behavior in relation to wind, fire, earthquake; deformations caused by changing of moisture level, temperature change, dynamic loads)
			Thermal characteristics of STCs (size modifications caused by temperature change, thermal capacity of materials, thermal resistance, thermal insulation in winter and summer)
			Acoustic characteristics of STCs
	Class of Criteria for Mounting	Ease of STC mounting and joint quality	Easy for mounting
			Joint quality (construction stability aspect, building physics aspect, maintenance aspect)

Weather proofing is another consideration in the integration of PVs and STSs acting as the shell of the building as rain-screens. In this case the system modules act as an outer screen for the building, protecting an inner leaf from the deleterious effects of heavy wetting, solar radiation and the effects of thermal expansion and contraction (Roberts and Guariento, 2009). It is also important to consider the effect of noise reduction as the system panels in double-skin facades or vertical flat surfaces make a positive contribution in this aspect (Scholes and Sargent, 1971; Arons, 2000).

Clearly the multifunctionality 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, the 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 requires a new type of semi-transparent collectors (Giovannetti et al., 2014; RitterXL, 2014). 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 (Figure 2.1.8).

Figure 2.1.8. Semi-transparent collector encapsulated into a double skin facade, Social housing, Paris, France.

Also, by shading a façade system panels provide a passive way to limit excessive solar gains and the good opportunities of the combination of system modules into shading devices, gives both reduced cooling loads and utilization of solar energy which are a palpable expressions of the conservation of energy (Roberts and Guariento, 2009).

2.1.3 Aesthetical Possibilities

The aesthetical possibilities like dimensions, form, jointing, colours, texture etc. of a solar thermal collector can all be influenced by the materials and constructional elements of the collector that are used. Even the type of fluid used (liquid for solar water heating systems or gas for solar air heating systems) may affect the eventual appearance. Passive solar collectors like the Trombe wall or Translucent/transparent insulation use the thermal mass of the wall directly as absorbing element and thus some aspects are already dictated by the building structure (Chan et al., 2010; Platzer, 2000). Structural characteristics of such collectors as solar structure are shown in Figure 2.1.9.

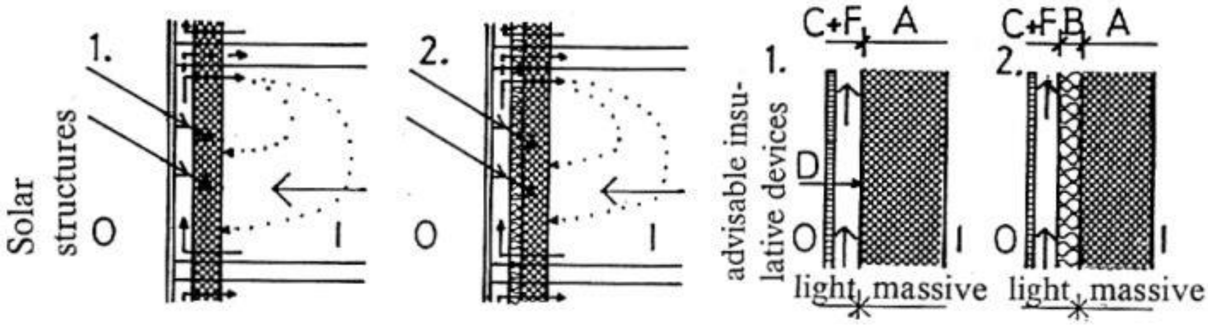


Figure 2.1.9. Structural characteristics of solar structures (Krstic-Furundzic, 2000).

1. Trombe wall and 2. Solar wall with transparent insulation (A-thermal storage area, B-thermal insulation area, C-heated air area, F-external protection area, D-dark coloured surface, O-outside, I-inside

Variations in the dimensions of glazed solar thermal collector usually are limited and the production is not as flexible as it is for windows. Variations in the form of curved STC or non-rectangular shapes may be only produced with extra effort (Probst and Roecker, 2007). For uncovered STC in conventional roof and facade claddings however, various systems are available and designers must have greater flexibility (SolarWall, 2014; Wall et al., 2012). The visibility or invisibility of joints, surface colours and textures also varies and depends very much on the STC selected.

Another important aspect of these systems is the flexibility in the application of these systems to allow a multitude of building integrated options, e.g. BIPV foil products which are lightweight, flexible and can be curved, as well as being easy to install given prevailing weight constraints for roofs (Jelle and Breivik, 2012).

2.1.3.1 Dimensions

For STC some problems can be identified in relation to dimensions:

- Most suppliers in the collector industry produce their modules with fixed sizes. This would force the designer to adapt the whole building to a standard collector size.
- Alternatively, if non-standard sizes are needed, relatively few companies are able to produce these on an individual production basis. For example, triangular collectors may be produced by trimming the absorber-fins of collectors individually. This implies that architects are forced to design its application in favour of certain products before the call for tender. This is contrary to the approach accepted by the building industry that elements being specified by size become part of the tendering process.

The building industry needs an "open" STC system approach and thus the production of variable size and shape of collectors that will fit in with other industries. As standardized products are often not available, the situation calls for innovative approaches with custom made products (Hermannsdorfer and Rub, 2005). However, the associated cost for bespoke products needs to be reduced, which requires an adaptation of the production processes.

Polymer collectors have been suggested as an alternative option (Lang, 2012). Polymer components could be manufactured more cheaply and flexibly thanks to the well-established process of extrusion, which could easily produce the exact dimensions needed to integrate collectors with buildings of all shapes and sizes. Components would be lighter to transport and easier to install, and could potentially come in a variety of attractive hues to do away with the ‘any colour as long as it is black′ approach of conventional collectors (Lee, 2005). A transparent polycarbonate (PC) twin wall sheet or hardened glass could be used as cover sheet (Figure 2.1.10). Advanced plastic materials such as polycarbonate sustain itself at high temperatures and retains excellent properties under humid conditions. The twin wall absorber sheet of 10 cm thickness contains a large number of channels filled with ceramic particles which provide good thermal contact between the carrier fluid and the energy absorbing surface of the absorber plate. This is obtained by means of the capillary effect (SolarNor AS, 2014). The polycarbonate sheet is supplied in widths of 60cm, and standard lengths of 170, 255, 340, 510cm. A specific appearance can be obtained by the colour of the ceramic particles and structure of the transparent layer.

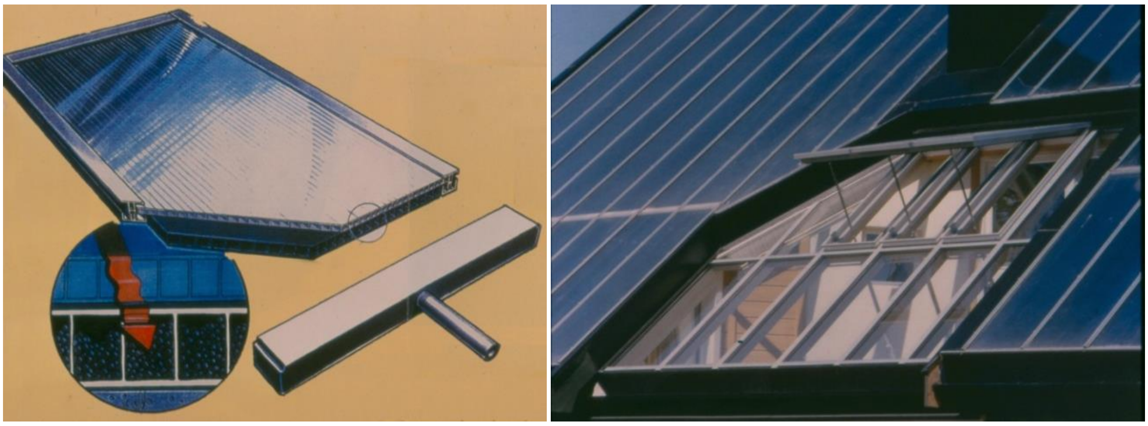


Figure 2.1.10. Transparent polycarbonate (PC) twin wall sheet filled with ceramic particles.

The unique qualities of prefabricated facade wall panels and roof panels with BISTC can be achieved by producing at the factory. Mounting is easier and less time is needed (Figure 2.1.11). Dimensional (modular) coordination is essential.

Figure 2.1.11. Prefabricated facade wall panels and roof panels with BISTC.

2.1.3.2 Form

Flat collector formats represent the most common form due to the availability of flat glazing products, but concave and convex shapes are also available and can be necessary as these forms are commonly present in contemporary architecture.

In general, the following solar thermal collector types and therefore forms can be selected:

i. Flat-plate collectors – rectangular, triangular, other shapes (Figure 2.1.11).
ii. Curved collectors.
iii. Evacuated (vacuum) tubes.

Due to high prices of curved glass, if the curved surface of the building envelope is covered with solar collectors, the curve is usually formed by an appropriate number of flat plate collectors (Figure 2.1.12).

Figure 2.1.12. Curved surface of the building envelope formed by an appropriate number of flat plate collectors, AEE-Institute for Sustainable Technologies (AEE INTEC).

In order to achieve a comprehensive architectural expression of the building, there is also a need for dummy elements with the same appearance as the STC but with no solar collecting capability. The use of these dummy elements is usually on the non-solar exposed surfaces of the facade or roof enabling the singularity of the visual appearance of all facade and roof surfaces, if expected from design concept and/or urban planning regulations.

The fact that dummy elements have not been provided up to now, even by manufacturers aware of the problem, is due to the characteristics of the collector to be imitated. To have an appearance compatible with the system, dummies would require glazing and an added metal sheet similar to the absorber used in the proper collectors. These complex, unproductive elements would clearly be too expensive in terms of cost and grey energy to be successful (Probst et al., 2007).

2.1.3.3 Colour and surface texture

The colour of the BISTS collector depends primarily on the absorber colour (Figure 2.1.13) or selective filter colour (Figure 2.1.14), but also to some extent on the cover material.

Figure 2.1.13. The colour of the BISTS collector depends on the absorber colour.

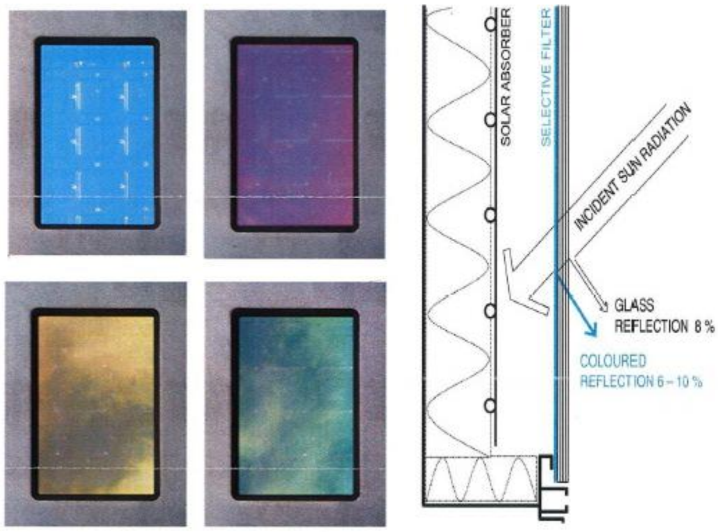


Figure 2.1.14. The colour of the BISTS collector depends on the selective filter colour.

Regarding performances of solar systems employing collectors with coloured absorbers, Tripanagnostopoulos et al., (2000) concluded the following: "Flat plate solar collectors are of black appearance because of the colour of the absorber, which is employed to maximize the absorption of solar spectrum. Generally, to avoid the monotony of the black colour we can use collectors with absorbers of blue, red–brown, green or other colour". These collectors are of lower thermal efficiency than that of the usual black type collectors, because of the lower collector absorbance, but they are of more interest to architects for applications on traditional or modern buildings.

The application of solar collectors with coloured absorbers is a new concept and regarding the total solar system, it is noticed that the increase in cost (by using larger area of collectors to overcome the lower efficiency of the coloured absorber) is balanced by the achieved aesthetic harmony with the building architecture (Kalogirou et al., 2005). The research by Tripanagnostopoulos et al., (2000), on the applications of solar collectors with coloured absorbers in a large solar water heating system suitable for a multi-flat residential or office buildings, a house space heating and an industrial process heat also noticed: The results show that although the coloured collectors present lower efficiency than the typical black type collectors, the difference in energy output is at an acceptable level considering the improvement in aesthetics. For a medium value of the coefficient of absorbance ($\alpha = 0.85$), the coloured collectors give satisfactory results regarding the drop of the amount of collected energy (about 7–18%), compared to collectors with black absorbers ($\alpha = 0.95$). This implies the use of proportionate larger collector aperture areas to have the same energy output as that of typical black coloured collectors. In the case of the PVs more colours can be obtained by the variation of the thickness of the anti-reflection coating, although by doing this, the efficiency will decrease by 15–30% depending on the colour, due to the increase of the overall reflection (Roberts and Guariento, 2009).

Despite an Austrian survey showing that 85% of architects would like to make use of coloured collectors, even with a slightly reduced efficiency (Figure 2.1.15); the integrated black collectors are still in the majority (Probst, 2008). This of course does not mean that coloured collectors are not being integrated, but it demonstrates that integration issues are much more complex than just choosing an appropriate collector colour. Polymer STC can potentially offer greater choice as they are available in a larger variety of attractive hues with acceptable performances (Lee, 2005).

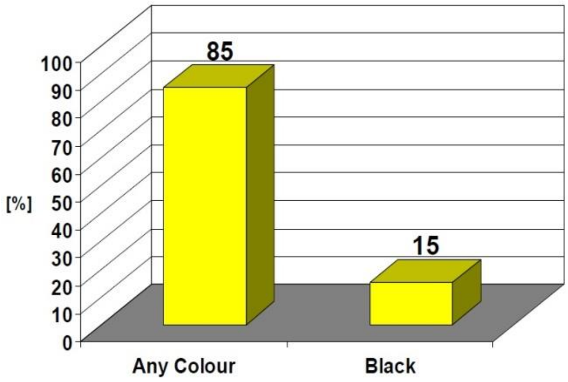


Figure 2.1.15. Austrian survey related to declaration of architects for coloured collectors (Werner, www.aee-intec.at).

In the case of unglazed STC, the absorber surface texture and finish is clearly visible and hence can be an option for differing envelope and surface patterns. The absorbers of uncovered STC have large variations in terms of surface texture and finish such as corrugated, embossed, perforated, etc. The surface can have a matt, glossy or structured finish (Probst and Roecker, 2011a).

In glazed STC systems, a clear glazing above the absorbers can reflect light secularly and glare could be a problem. Surface textured glass was used more extensively in the 1990's in order to avoid glare and to an extent to hide absorber features. Variations in the surface texture and finish beneath the glass covering may also be hidden. Since the market introduction of full plate absorber sheets however clear glass dominates the market. Clear glass collectors can be suitably integrated to complement the glass surfaces of a façade or roof.

In general, opaque solar thermal collectors are normally integrated into opaque elements of a façade or roof (Probst and Roecker, 2011). STC systems that are architecturally pleasing, have good material and colour composition, that adapts well to overall modularity, creates a satisfactory composition that will result in good integration and renders high architectural quality (Roberts and Guariento, 2009).

2.1.3.4 Joints and jointing

The design and construction of joints between STC modules has a significant impact on the quality of integration.

The jointing is usually visible and hence must be similar to the jointing of other cladding elements to maintain surface continuity. However, to achieve an appearance similar to that of the facade or roof cladding, custom designed modules need to be used in most cases (Basnet, 2012).

A major problem relating to the total lack of adequate jointing options for facades using flat plate technologies still exists (Probst, 2008). Only one manufacturer offers an alternative to the standard rubber jointing mechanism which uses a continuous, wide, aluminium frame.

For evacuated tubes the situation is different since the manufacturer supplying facade modules provides a level of jointing flexibility compatible with the facade application (Probst, 2008).

2.1.4 Constructional Mounting Options

Different construction options are available for integrated STC. There are three mounting options for integrating STC into buildings; roofs, facades and extruding building components (such as balcony railings, sunshades, sunscreens and awnings) (Reijenga and Kaan, 2011). Solar collectors should be designed with reference to the normal construction practices within the building industry. The following construction options for integrated STC modules within the building envelope are commonly used:

i. glazing layer (glazed flat STC),
ii. conventional facade and roof cover,
iii. mounted as a projected external element or device.

Flat STC are applicable for both integral glazing and conventional elements in all structural parts of the building envelope, whilst vacuum tube collectors, because of the shape and tube spacing tend to be suitable for solar thermal shading devices, overhangs, balcony railings, etc.

2.1.4.1 Glazing layer (glazed flat STC)

Integral glazed systems offer multifunctional options but this very much depends on the architect's creativity, rather than the availability of specific products. However, no major manufacturers offer multifunctional elements or provide dummies as standard options (Probst, 2008). Facade integrated systems include vertical and tilted positions of glazed ST collectors-modules (Figure 2.1.16). Glazed solar thermal integrated facades are a type of curtain wall. ST collectors-modules can be integrated into most of the contemporary suspended facade systems. Suspended facades (curtain walls) are light structures which are leaned against the building structure and are suspended in front of it (Krstic-Furundzic, 2007).

Figure 2.1.16. Vertical and tilted positions of glazed ST collectors-modules.

With respect to available design options for the integration of active solar systems into curtain walls, Krstic-Furundzic (2007) presents the following observations: Glazing layers consist of principally two kinds of structural components: profile sections and glass sheets. Figure 2.1.17 illustrates the simple prefabricated components which can be assembled and erected on site using scaffolding; when the frame structure, the glass panels can be joined directly and indirectly. Wooden, metal and plastic profile sections are commonly used (Figure 2.1.18). Regarding section characteristics, Krstic-Furundzic (2007) concludes the following: metal and plastic profile sections are light and have smaller dimensions than wooden sections. Metal sections are separated in two parts to create a thermal break to prevent thermal bridging and condensation. Using the diversity of dimensions, shapes, colours and materials of frames available it is possible to make different facade designs. Joints can also be hidden, providing a frameless appearance.

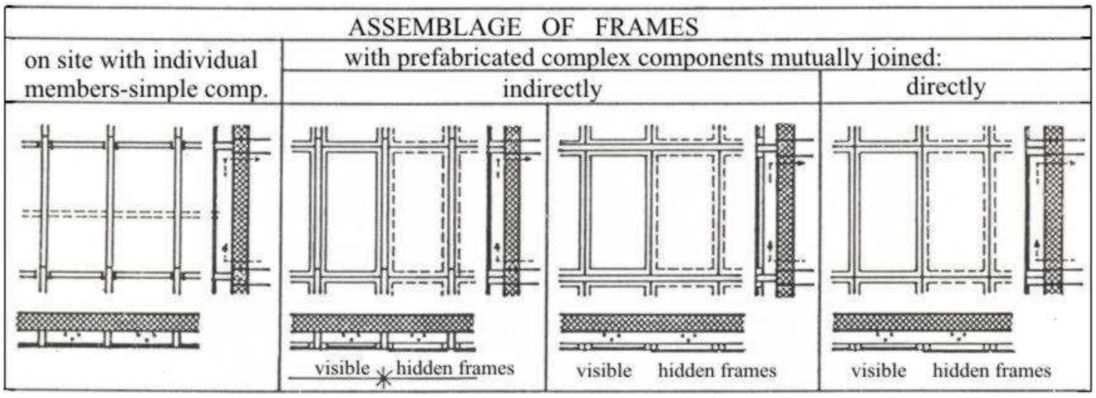


Figure 2.1.17. Suspended facade assemblage possibilities (Krstic-Furundzic, 2007).

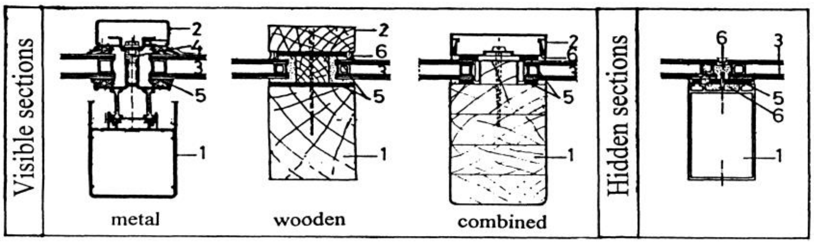
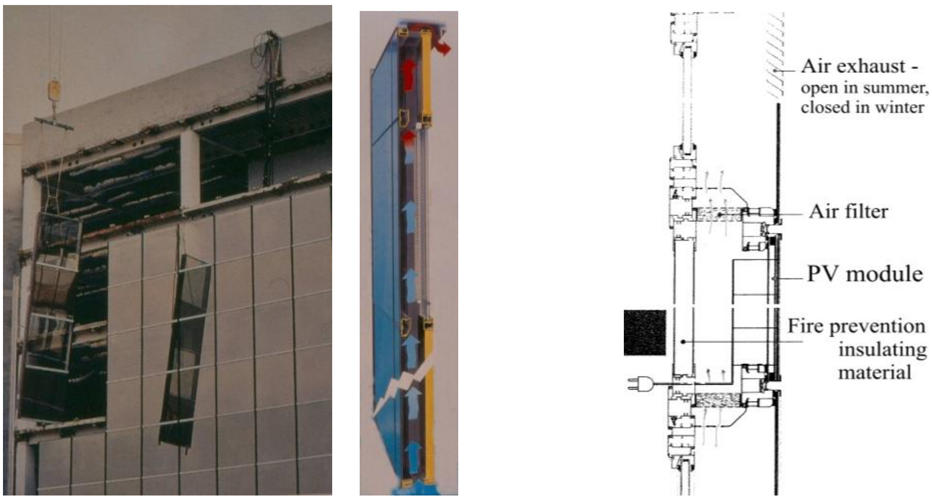


Figure 2.1.18. Types of sections regarding material and appearance (Krstic-Furundzic, A., 2007). 1. Supporting section, 2. Covering sections, 3. Double-glazing (or single), 4. Heat-bridge break, 5. Rubber profile, 6. Putty or silicone.

Hybrid PV/T solar facades consisting of three layers: an external glazed layer (in which the PV modules are encapsulated), an internal insulating layer and separating gap layer in between intended for air flow are available. The heated air from the ventilated middle layer can be used in building heating applications. Assembly of multifunctional modules (M-modules) by using curtain wall technologies is acceptable as shown in Figure 2.1.19.



School of Architecture, University College Dublin "Environmental facade" Alumil Milonas S.A.

Figure 2.1.19. Hybrid Photovoltaic/Thermal facade constructed of prefabricated glass modules.

Mounting system of glazed roof STC consists of frameworks of extrusions which provide support for the modules, a watertight seal, and tubes or air channels. Air gap is placed between external glazed layer and internal solid, light or massive, roof construction which have to be well insulated to prevent heat losses. Such structure with opaque modules is customary solution in the case of solid, not transparent, roof concepts. Prefabricated solar thermal collectors are preferable for application on roof surfaces (Figure 2.1.20) as the mounting process is easier with less installation time needed. In addition, the quality of the collector finish achieved in the factory can be of a higher standard.

Figure 2.1.20. Roof integrated solar thermal collectors.

Generally, the production of preformed panels at the factory provides a high quality of all products, which is consistently present for each component. It is more difficult to accomplish in the case of handicraft production of the collectors at the site.

The parameters outlined above may be incorporated in pre-fabricated and customized units and PV and STS modules -especially the flat-ones- may be used as "filling" panels, integrated into curtain wall systems or double facade systems either in the vision area or in the spandrel area of the facade (Roberts and Guariento, 2009).

2.1.4.2 Conventional facade and roof cover

Contemporary facade cladding technology utilizes facade cladding panels placed over a load-bearing substructure where the air gap between the panel and the wall is ventilated. In these façade structures, air heated in the air gap is usually ejected and thus a significant amount of potentially useful heat is lost. But such structure can function as solar collector (as BISTS) with minimal disruption whilst maintaining a conventional building appearance. A solar wall provides pre-heated fresh air required in the building. The bare wall is covered with a layer of insulation having a vapour barrier (Krstic-Furundzic, 1996). Dark coloured vertical corrugated metal cladding is then applied which becomes the solar absorber. One product is perforated to allow outside air to travel through thousands of tiny perforations/holes on the metal surface, but others are also on the market. The air absorbs the heat and rises to the top of the wall by virtue of thermal buoyancy, where it is directed into a canopy plenum and via an active fan, ducted to supply (Figure 2.1.21). The fan augments the natural buoyancy effect, inducing a negative pressure in the wall cavity to draw air through the holes. In systems with a low air flow rate, the top plenum can be incorporated within the cladding.

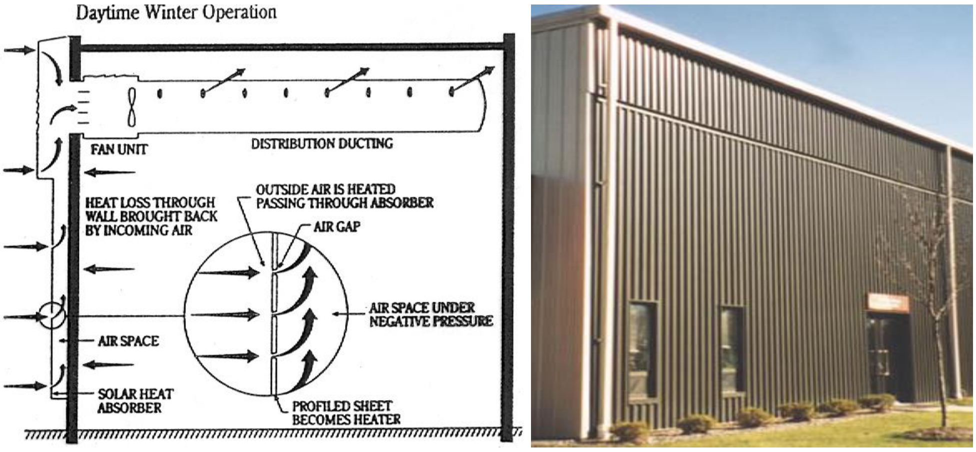


Figure 2.1.21. Construction as conventional facade cover (SolarWall, 2014).

Various metal panel profiles are available from deep grooved shapes which have sufficient internal air space capacity to much shallower profiles. Aluminium panels have the best properties regarding corrosion resistance. This type of solar thermal collector is easy to integrate into most building forms and very architecturally versatile. They can be styled, shaped, and designed in a variety of colours.

Contemporary roofing technology refers to placement of roofer over the substructure. The air gap between the roof tiles and underlay is ventilated and can function as solar collector with conventional roof appearance (Figure 2.1.22). Preheated fresh air is provided for the building. Usually dark coloured roofs become the solar absorber. Air picks up heat and rises to the top of the roof by stack effect, where upon it is ducted to the nearest fan and distributed into the building. In the summer period gap layer is ventilated, the air is exhausted into outer space preventing the roof to be overheated.

Figure 2.1.22. Construction as conventional roof cover – unglazed flat STC, Berwickshire, Scotland.

Roof ceramic tiles can be with integrated solar thermal collectors simulating the appearance of traditional roofs (Figure 2.1.23).

Figure 2.1.23. Ceramic tiles can be with integrated solar thermal collectors. (Techtile Therma STC systems on the roof. http://www.remenergies.it/).

Interesting roof appearances can be created by construction as conventional roof cover with glazed roof tiles under which the tubes/channels are integrated (Figure 2.1.24). They resemble and replace a normal roof tiles, providing weather protection. The assembly can be simplified to such an extent that it can be mounted by regular craftsman.

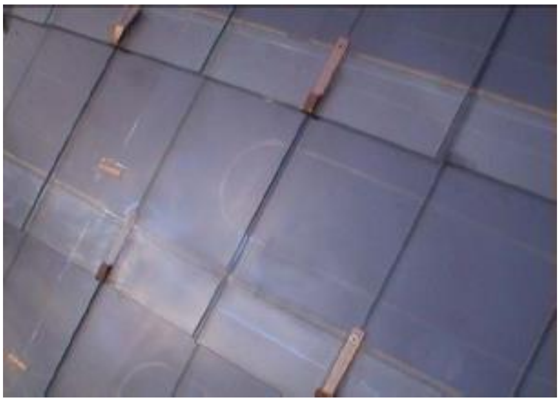


Figure 2.1.24. Conventional roof cover with glazed roof tiles under which the tubes/channels are integrated.

2.1.4.3 Mounted as a projected external element or device

Shading devices with integrated STC convert solar energy into thermal energy and at the same tame prevent admittance of sun rays and overheating of a room in summer. BISTCs as shading devices are placed in front of the glazed surfaces in such a manner to provide sufficient lighting of the room, operable windows and ventilation and according to need to allow passing of sun rays into room in winter.

Regarding structure and geometry following solar thermal shading devices can be selected (Figure 2.1.25):

- flat STC as sloped or horizontal overhang above window,
- vacuum STC as horizontal overhang above window or like shading screen with horizontal, vertical or sloped arrangement of vacuum tubes.

Figure 2.1.25. Solar thermal collector as shading device.

Flat STC are preferable for overhangs as they can protect from rain and snow. If constructed of vacuum tubes it is just a shading device. For balcony railings construction both types are suitable, but vacuum tubes enable better view of the surroundings (Figure 2.1.26), although issues relating to their physical strength must be considered.

Figure 2.1.26. Solar thermal overhang and balcony railing.

In the case of movable shading elements building envelope becomes changeable structure adaptable to day and season changes - "a living" structure.

2.1.5 Architectural Implications in the Building Integration of Photovoltaic and Solar Thermal Systems – A taxonomy and assessment methodology

Taking into consideration a number of case studies, integration of photovoltaic and solar thermal systems in new and existing buildings are discussed in terms of types of systems, building physics, construction, integration options and the appearance of buildings. Different classifications are taken into account and in this regard examples reviewed. Since the assessment methodology created, comparison in the application of BIPV and BISTS in new and existing buildings is carried out.

2.1.5.1 Assessment methodology

The proposed methodology relies on literature review and precedent analysis to formulate a classification and taxonomy of various existing applications of the building integrated PV and solar thermal systems. The forty-two case studies selected and featuring both BIPV and BISTS, provide a sample for a taxonomy that delves on the investigation, assessment and categorization of existing system applications. In each case, system functions are examined in order to identify the specifications of the various applications and juxtapose them in a Table format according to new buildings and extensive renovations. PVs and STSs are dealt in parallel to provide a holistic approach to an evaluation of the architectural implications in case of building integrated systems.

Consequently, it is important to define the geometry and performance of BISTS and BIPV and to examine their applicability to new or existing building shells. Identified systems may fall into the following groups: *BIPV foil products*, *BIPV tile products*, *BIPV module products* and *solar cell glazing products* (Jelle and Breivik, 2012). The STSs available for integration in the market are: the *Glazed Flat Plate Hydraulic Collectors*, the *Unglazed Flat Plate Hydraulic Collectors*, the *Unglazed Plastic Hydraulic Collectors*, the *Unglazed Flat Plate Air Collectors*, the *Vacuum Tube Hydraulic Collectors* and the *Concentrating Hydraulic Collectors* (Probst and Roecker, 2007). These technologies take the solar irradiation and convert it into solar thermal energy - for air or water heating, in the case of BISTS (Probst and Roecker, 2011b) and electricity in the case of BIPV.

2.1.5.2 Comparative Assessment and Critical Evaluation of Building Integrated Systems

In order to cover all the possible applications regarding building integrated PV and ST systems, 42 case studies were examined. In these case studies, 7 types of different technologies are applied on new or existing buildings. Some technologies are more "popular" while others are seen in a limited number of examples. Various types of integration were observed for new and existing buildings.

In the case of new buildings, building integrated solar thermal systems and photovoltaics are fully integrated into the shell and form an integral part of the building design concept (Figure 2.1.27).

Figure 2.1.27. Views of integrated systems in four newly constructed buildings (Available online from www.bio-tecture.net, www.fondazionerenzopiano.org, www.jetsongreen.com, www.archdaily.com [Accessed 25 May 2014]).

Similarly, there are examples of applications in renovated buildings which form part of the building envelope, while improving the building's energy performance (Figure 2.1.28).

Figure 2.1.28. Views of integrated systems of four renovated buildings (Available online from www.projects.pilkington.com, www.solarwall.com, www.ecda.co.uk [Accessed 25 May 2014]).

Comparison in the application of BIPV and BISTS in new and existing buildings is presented in Table 2.1.2. The organization of this Table is based on the differentiation of these two categories, which thereafter, are organized according to the system technologies mentioned above.

Subsequently, each system is examined according to its architectural integration merits, such as a system's integration on the building shell, e.g. on the roof, in a façade or as part of another building integrated component. Then, issues of system flexibility are covered both in terms of unit geometry and mounting ease – rated from low to high – both of which affect the viability of a system's integration on new or existing buildings.

Subsequent categories include architectural aspects, beginning with "transparency", which is rated again from low to high and addresses the extent to which system panels allow for effective insolation from the outside and visibility from the inside of a building facade. Thermal insulation is also examined, which addresses the "weather proofing" performance of the system panels constituting the building shell, which indicates the technologies that can provide protection from the weather to the building and also illustrate contributions with regards to noise protection and facade shading.

There follows an estimate with regards to the shell structural system contribution inherent in the panel assembly, as a result of its integration in the building facade. Two further issues are examined: the extent to which the "collector profile is visible" after building integration; and the variations in "surface colour or texture" beyond the base case. Next, the comparative Table looks at issues of pre-fabrication and the customization potential of the systems examined in order to fulfill individual case study specifications; and lastly it indicates whether the system examined forms part of a curtain wall or double-skin facade.

Table 2.1.2. Comparison of BIPV and BISTS applications in new and existing buildings.

			Applicability on New Buildings							Applicability on Existing buildings						
			BIPV				BISTS			BIPV				BISTS		
			Modules	Solar Cell Glazing	Foil	Tiles	Unglazed Flat Plate Air Collectors	Unglazed Flat Plate Hydraulic Collectors	Vacuum tube hydraulic collectors	Modules	Solar Cell Glazing	Foil	Tiles	Unglazed Flat Plate Air Collectors	Unglazed Flat Plate Hydraulic Collectors	Vacuum tube hydraulic collectors
System	Application	Air Heating					16							16		
		Water Heating						4	1						4	1
		Electricity Production	5	13	1	2				5	12	1	2			
Architectural	Application	Replacement of a building component	3	12		2		4		3	12		2		3	
		On Façade	3	9			16	2	1	3	8			16	1	1
		On Roof	4	4	1	2		1	1	4	4	1	2			1
		On Building Component		1				2			1				2	
		Flexibility														
		Ease on application														
	Building Physics	Transparency														
		Thermal Insulation		2							2					
		Weather proofing	5	11		2		2		5	11		2		1	
		Noise Reduction	3	3			16	1		3	2			16	1	
		Shading	2	12				3	1	2	11				3	1
		Structural														
	Integration	Visible Collector Profile	5	5				1		5	5				1	
		Surface Colour Texture		1		1	16	1			1		1	16		
	Construction	Pre - Fabricated Units	5	8		2		1		5	8		2		1	
		Customised Design		5	1		16	3	1		4	1		16	2	1
		Curtain Wall	2	3						2	3					
		Double Envelope Structure		3			16	1			2			16	1	

1 – 16   Low – High

In the context of the discussion above, it is also important to quote the work of Tjerk H. Reijenga (Reijenga, 2003), on the integration of PV systems in architecture and their subdivision into five categories: 1. applied invisibly; 2. added to the design; 3. adding to the architectural image; 4. determining architectural image; and 5. leading to new architectural concepts. However, it must be said, that the challenge for architects, is the proper PV modules building integration, and it must be noted that the invisible apply of PV modules to a project does not necessarily mean that this project has lesser quality (Reijenga, 2003). The selected 42 case studies may be reclassified and organized according to Reijenga's classification as shown in Figure 2.1.29.

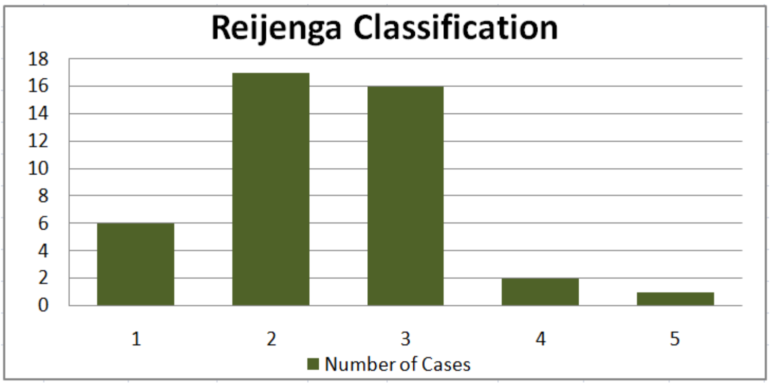


Figure 2.1.29. Dominant trends with regards to the integration of PV and STS in new and existing buildings.

2.1.6 Conclusion of comparative assessment

The results above indicate that building integration is equally possible in new and existing buildings. Also, the comparison reveals that the most popular method for integration is BISTS with the Unglazed Flat Plate Air Collectors, followed by BIPV technology of Solar Cell Glazing. Another important finding is that in a majority of the selected case studies, a number of compatible building façade components are readily interchangeable with solar panels indicating the relative ease of integration, while at the same time weather proofing, noise reduction and shading are also significant.

An important characteristic of a properly integrated technology has also emerged, in the ability of the Unglazed Flat Plate Air Collectors to be colourized. In relation to the construction of an integrated system, apart from the Unglazed Flat Plate Air Collectors, construction methods available do not determine the popularity of appropriate integration. On the other hand, it is significant that technologies which can be applied easily are not popular. It is also remarkable that no technology offers high system panel transparency, both in their application to new or existing buildings. It is also shown that although foil is flexible and relatively easy to apply, it is not a popular application. Finally, it is clear that no technology yet makes significant contributions to a building’s structure.

In both cases of existing and new buildings, the two technologies that offer themselves for building integration are the BIPV, Solar Cell Glazing and the BISTS, Unglazed Flat Plate Air Collectors. Although they are not the easiest to integrate within a building facade, they are widely used due to their superiority in many of the categories illustrated above. However, it is significant that in the case of Cyprus, where cooling loads are about six times larger than the heating loads (Florides et al., 2002) - probably also true of several other Mediterranean locales - the preferred technology is Solar Cell Glazing, due to the shading it offers, which can be used as part of a passive cooling strategy. Electricity generation may then be used as an energy source for cooling. Similarly, BISTS contribute to the production of hot air or water.

Finally, the utilization of the Reijenga classification analysis indicates that according to that categorization method the prevailing entries were the panel systems: "Added to the design" and also "Adding to the architectural image". From this to occur, system panel designs need to be innovative in the way in which they allow for it to coexist symbiotically and be part of the architectural concept of each building.

Given the results of this research, future work should be carried out in terms of prototyping of various assemblies of building integrated solar systems based on the parameters outlined above. The prototyping phase will be concurrent with a simulation phase that will attempt to examine the combination of parameters available to the design team, as well as the construction of scaled versions of building shell scenarios in order to conduct field measurements and for simulation model verification purposes on the road to a holistic approach with regards to the examination of the architectural implications in the building integration of photovoltaic and solar thermal systems.

REFERENCES

Appleyard, W. and Konkle D., Making solar thermal fit in, Ann Arbor's 5000 solar roofs programme. Renewable Energy World, 2007; Volume 10, No. 5, pp. 80-86.

Arons, D. M., Properties and applications of double-skin building facades. Thesis (S.M.), Massachusetts Institute of Technology, Boston, 2000.

Basnet, A., Sustainable Architecture. Master's Thesis. Norwegian University of Science and Technology, Trondheim., Faculty of Architecture and Fine Arts, Department of Architectural Design, History and Technology, 2007.

Farrington Daniels Direct use of the Sun's Energy, Yale University, 1964, reprint Ballantine Book, 1974.

Florides, G. A., Kalogirou, S. A., Tassou, S. A., Wrobel, L. C. Modelling and simulation of an absorption solar cooling system for Cyprus. Solar Energy, 72(1), 2002, pp. 43-51.

Fuentes, M., Integration of PV into the built environment, 2007. Available: http://www.brita-in-pubs.eu/bit/uk/03viewer/retrofit_measures/pdf/FINAL_12_Integration_of_PV_red_kth_rev1.pdf [Accessed 15 March, 2012].

Gajbert, H., Solar thermal energy systems for building integration. Licentiate Dissertation, University of Lund, Sweden, 2008.

Golic, K., Kosoric, V., Krstic-Furundzic, A., General model of solar water heating system integration in residential building refurbishment-Potental energy savings and environmental impact. Renewable and Sustainable Energy Reviews, 2011; 15 (3), pp. 1533–1544.

Hermannsdorfer, I. and Rub, C., Solar Design, Berlin, Jovis Verlag GmbH, 2005.

Jelle, B. P. and Breivik, C. State-of-the-art building integrated photovoltaics. Energy Procedia, 20, 2012, pp. 68-77.

Kalogirou, S. A., Building integration of solar renewable energy systems towards zero or nearly zero energy buildings. International Journal of Low-Carbon Technologies, ctt071, 2013.

Kalogirou, S., Tripanagnostopoulos, Y., Souliotis, M., Performance of solar systems employing collectors with coloured absorber. Energy and buildings 37, Elsevier science Ltd, 2005, pp. 824-835.

Krstic(-Furundzic), A., Application of solar collectors and photovoltaic devices in buildings. In: Proceedings of International Conference Architecture and Urbanism at the Turn of the III Millennium, Faculty of Architecture, University of Belgrade, Volume 2, Belgrade, 1996, pp. 181–186.

Krstic-Furundzic, A., PV Integration in Design of New and Refurbishment of Existing Buildings: Educational Aspect. Journal of the Association of Arab Universities for Basic and Applied Sciences 4 (Supplement), 2007, pp. 135–146.

Krstic(-Furundzic), A., Measures and Techniques for Improvement of Thermal Performances of Inherited Buildings External Walls. In: Proceedings of the World Renewable Energy Congress-VI, Renewable Energy - Renewables: The Energy for 21th Century, Pergamon, UK, 2000, pp. 356-361.

Krstic-Furundzic, A., Kosic, T., Terzovic, J., Architectural Aspect of Structural Design of Glass facades/Glass Skin Applications. In: L. Bos, V. Nijsse (Eds.): Challenging Glass 3, Proceedings of the Conference on Architectural and Structural Applications of Glass. Faculty of Civil Engineering and Geosciences, Delft University of Technology. The Netherlands: IOS Press BV, 2012a, pp. 891-900.

Krstic-Furundzic, A., Kosoric, V., Golic, K., Potential for reduction of CO_2 emissions by integration of solar water heating systems on student dormitories through building refurbishment. Sustainable Cities and Society 2 (1), 2012b, pp. 50–62.

Krstic-Furundzic, A., Kosic, T., Terzovic, J., Architectural aspect of structural glass roof design. In: J. Belis, C. Louter, D. Mocibob (Eds.), Proceedings of the Conference on structural glass, Taylor&Francis Group, London, UK, 2013, pp. 45-52.

Krstic-Furundzic, A., Architectural aspects of BISTS, lecture at the Training school 3 of COST TU1205 Action, Warsaw, 2016. http://www.tu1205-bists.eu/2016/09/19/training-school-3/ and http://www.tu1205-bists.eu/wp-content/uploads/sites/13/2016/09/2-2-Architectural-aspects-of-BISTS.pdf [Accessed 30 October, 2016].

Lee, A., Move up on new material, Renewable Energy World Magazine, Vol.14, No. 4, 2005, pp. 14-15.

Leindecker, G. Austria- Case study 1. In: European Carbon Atlas, The Welsh School of Architecture, Cardiff, 2007, pp. 1-11.

Peng, C., Huang, Y., Wu, Z., Building-integrated photovoltaics (BIPV) in architectural design in China. Energy and Buildings, 43(12), 2011, pp. 3592-3598.

Probst, M., Architectural integration and design of solar thermal systems, PhD thesis, EPFL, Lausanne, Switzerland, 2008.

Probst, M. C. M. and Roecker, C., Architectural Integration and Design of Solar Thermal Systems, Oxford, UK, Routledge Taylor and Francis Group, 2011a.

Probst, M. C. M., and Roecker, C. Architectural integration and design of solar thermal systems. Lausanne. EPFL Press, 2011b.

Probst, M., and Roecker, C. Towards an improved architectural quality of building integrated solar thermal systems (BIST). Solar Energy, 81(9), 2007, pp. 1104-1116.

Probst, M. C., Schueler, A., De Chambrier, E., Roecker, C., Facade Integration of Solar Thermal Collectors: Present and Future. CISBAT International Conference. Lausanne, Switzerland, 2007.

Reijenga, T. H., PV in architecture. In: A. Luque and S. Hegedus (Eds.), Handbook of Photovoltaic Science and Engineering, Wiley, Chichester, 2003.

Reijenga, T. H. and Kaan, H. F., PV in Architecture. In: LUQUE, A. & HEDEDUS, S. (eds.) Handbook of Photovoltaic Science and Engineering. Second ed.: John Wiley & Sons, 2011.

Roberts, S. and Guariento, N., Building integrated photovoltaics: a handbook. Basel. Walter de Gruyter, 2009.

Roberts, S. and Guariento, N. Building Integrated Photovoltaics / a handbook [Online]. Available: http://www.springerlink.com/content/978-3-7643-9948-1/?MUD=MP&sort=p_OnlineDate&sortorder=desc&o=10 [Accessed 12 March, 2012].

Scholes, W. E. and Sargent, J. W. Designing against noise from road traffic. Applied Acoustics, 4(3), 1971, pp. 203-234.

SolarNor AS advertising material, Integrated Solar Systems.

Tombazis, A. N., Architectural design: A multifaceted approach. Renewable energy, 5(5), 1994, pp. 893-899.

Tripanagnostopoulos, Y., Souliotis, M., Nousia, Th., Solar collectors with coloured absorbers, Solar Energy, Vol. 68, No. 4, Elsevier Science Ltd, 2000, pp. 343–356.

Tsoutsos, T., Frantzeskaki, N., Gekas, V., Environmental impacts from the solar energy technologies. Energy Policy, 33(3), 2005, pp. 289-296.

Werner Weiss, Building integration of solar collectors, AEE-Institute for Sustainable Technologies (AEE INTEC), Austria, www.aee-intec.at

Yang, Y., Wang, Q., Xiu, D., Zhao, Z., Sun, Q., A building integrated solar collector: All-ceramic solar collector. Energy and Buildings, 62, 20013, pp. 15-17.

2.2 SOLAR SYSTEM DESIGN

Mirco Blagojević, Soteris A. Kalogirou, Ivan Miletić, Aggelos Zacharopoulos, Christoph Maurer

2.2.1 Mechanical Design

There are basically two types of solar flat plate collectors, water-based and air-based, which are basically distinguished according to the type of heat transfer fluid used. In this section the basic design of these two systems is presented.

A water based flat plate collector is shown in Figure 2.2.1.

Figure 2.2.1. Photos of water based flat-plate collector.

The collector plate absorbs as much of the irradiation as possible through the glazing, while losing as little heat as possible upward to the atmosphere and downward through the back of the casing. The collector plates transfer the retained heat to the transport fluid. To maximize the energy collection, the absorber of a collector should have a coating that has high absorptance for solar radiation (short wavelength) and a low emittance for re-radiation (long wavelength). Such a surface is referred as selective surface. The absorptance of the collector surface for shortwave solar radiation depends on the nature and colour of the coating and on the incident angle. Usually black colour is used, whereas various shapes have been proposed by various researchers as shown in. Figure 2.2.2.

Figure 2.2.2. Various designs of riser-absorbing tube assembly.

When solar radiation passes through a transparent cover and impinges on the blackened absorber surface of high absorptivity, a large portion of this energy is absorbed by the plate and then transferred to the transport medium in the fluid tubes to be carried away for storage or use. The underside of the absorber plate and the two sides are well insulated to reduce conduction losses. The liquid tubes can be welded to the absorbing plate, or they can be an integral part of the plate. The liquid tubes are connected at both ends by large diameter header tubes. The header and riser collector is the typical design for flat plate collectors.

The useful energy produced by the collector is given by:

$$Q_u = A_c\left[G_t(\tau\alpha) - U_L\left(T_p - T_a\right)\right] = \dot{m}c_p\left[T_o - T_i\right] \tag{2.2.1}$$

Where: A_c is the total collector area, G_t is the solar radiation falling on the area of the collector, $(\tau\alpha)$ is the effective transmittance-absorptance product, U_L is the collector heat loss coefficient, Tp is the absorbing plate temperature, Ta is the ambient temperature, T_o is the collector outlet temperature and T_i is the collector inlet temperature.

Replacing T_p, which is not easy to obtain, with T_i, this becomes:

$$Q_u = A_c F_R\left[G_t(\tau\alpha) - U_L\left(T_i - T_a\right)\right] \tag{2.2.2}$$

Where: F*R* is the heat removal factor given by:

$$F_R = \frac{\dot{m}c_p}{A_c U_L}\left(1 - \mathrm{Exp}\left[-\frac{U_L F' A_c}{\dot{m}c_p}\right]\right) \tag{2.2.3}$$

The efficiency of the collector is obtained by dividing Q_u by the incoming solar energy, which gives:

$$\eta = F_R\left[(\tau\alpha) - \frac{U_L(T_i - T_a)}{G_t}\right] \tag{2.2.4}$$

In Eq. (2.2.3) the factor F´ is the collector efficiency factor, which for a header and riser type of collector, shown in Figure 2.2.1, is given by:

$$F' = \frac{\dfrac{1}{U_L}}{W\left[\dfrac{1}{U_L\left[D + (W - D)F\right]} + \dfrac{1}{C_b} + \dfrac{1}{\pi D_i h_{fi}}\right]} \tag{2.2.5}$$

Where D is the riser tube diameter, W is the distance between successive riser tubes, C_b is the conductance of the weld between the riser tube and the absorbing plate, D_i is the riser tube internal diameter, hfi is the convective heat transfer coefficient inside the riser tube and F is the fin efficiency given by:

$$F = \frac{\tanh\left[m(W - D)/2\right]}{m(W - D)/2} \tag{2.2.6}$$

The major difference between air and water based collectors is the need to design an absorber that overcomes the heat transfer penalty caused by lower heat transfer coefficients between air and the solar absorber. Air or other gases can be heated with flat-plate collectors, particularly if some type of extended surface is used to counteract the low heat transfer coefficients between metal and air. Metal or fabric matrices or thin corrugated metal sheets or porous absorbers may be used, with selective surfaces applied to the latter when a high level of performance is required. The principal requirement of these designs is a large contact area between the absorbing surface and the air. The thermal capacity of air is much lower than water hence larger volume flow rates of air are required, resulting in higher pumping power. The typical assembly just crates duct passages for air to pass through the collector and heated by the solar radiation.

The same relations are used for the evaluation of air-based flat plate collector. The only difference is with respect to the collector efficiency factor, which for an air collector is given by:

$$F' = \frac{1/U_L}{(1/U_L)+(1/h)} = \frac{h}{h+U_L} \qquad (2.2.7)$$

Where h is the convective heat transfer coefficient between the air and the air flow channel walls.

Much more details about the design of these collectors can be found in the book Solar Energy Engineering: Processes and Systems, written by the Action Chairman, published by Academic Press.

2.2.2 Optical Design

2.2.2.1 Optical design approaches for BISTS

Reflective and/or refractive optical components can be part of BISTS to provide a combination of the following benefits:

- Increase the average concentration of solar flux onto the absorber surface of the system (Figure 2.2.3). For a given absorber surface area, this results in higher outlet fluid temperatures. Depending on the employed concentration ratio the BISTS can operate in the medium temperature range providing heat output suitable for process heat applications (Figure 2.2.4). Increased solar flux concentration can also increase PV efficiency in PVT BISTS however this will require low operating temperatures.

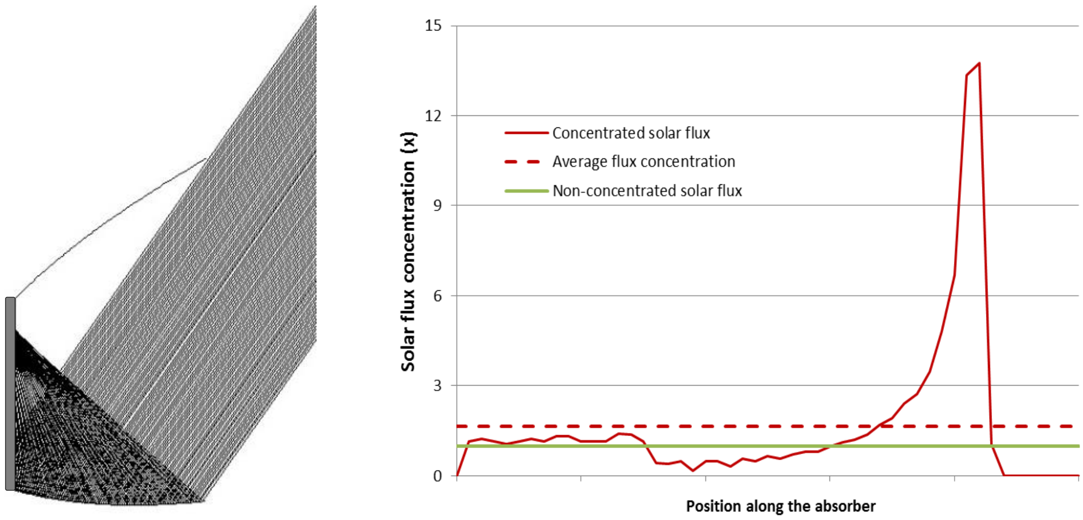


Figure 2.2.3. Ray trace diagram for an asymmetric CPC designed for BISTS with light incident at 55° from the horizontal (left). For a given absorber surface area the concentrator increases the intensity of the collected beam solar flux compared to a non-concentrating BISTS which has a solar flux intensity of 1x (right). The flux becomes highly non-uniform with a maximum intensity of 13.8x and an average value of 1.64x (for a 90% reflectivity).

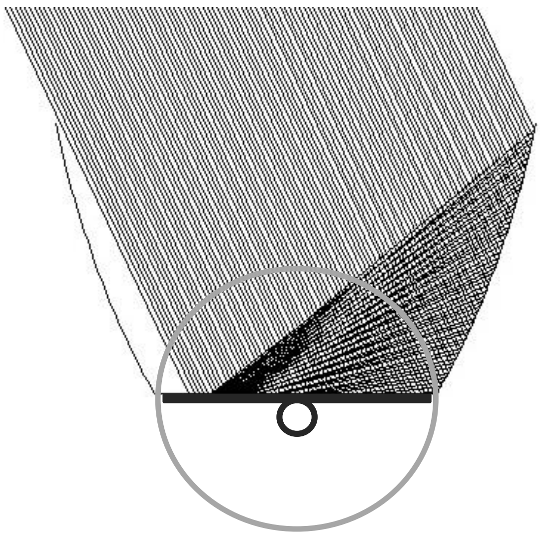


Figure 2.2.4. An evacuated tube SWH integrated with a symmetric CPC (30° half acceptance angle). The concentrator provides higher solar flux distribution on the absorber surface enabling medium temperature output suitable for process heat applications (Nchelatebe and Smyth, 2012).

- Reduce absorber surface area and associated material costs whilst sustaining the required levels of collected solar radiation (Figure 2.2.5). This is an effective approach when absorber costs are a considerable part of the overall system costs (e.g.

PV material costs in PVT BISTS) and the achieved savings outweigh the costs of the employed optical component (Zacharopoulos et al., 2000).

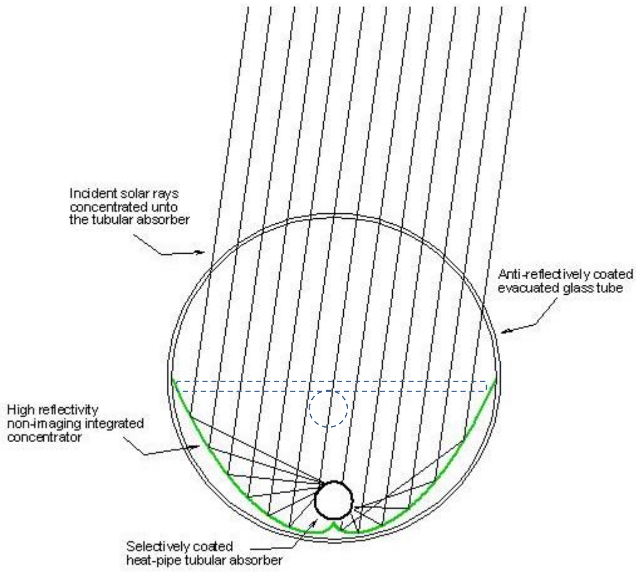


Figure 2.2.5. Cusp CPC profile designed to replace the fin tube absorber (dash outline) in an evacuate tube SWH with a tube one.

- Enhance performance of the system in given conditions such as specific time of the day or season. In this case the optical component is designed to capture and redirect increased amounts of solar radiation onto the absorber for a desired range on incidence angles of solar radiation.

- Provide control of daylight penetration into the building or control the nature (e.g. wavelengths) of the solar radiation that is captured by the system. This approach can provide multifunctional BISTS where heat and/or electricity and and/or daylight is provided to the building with the proportions of them depending on the incidence angle of solar radiation (Figure 2.2.6).

When any of the above benefits are achieved by using an optical component, the acceptance angle of the BISTS is restricted. For static systems integrated onto facades or roofs, this results in curtailed hours of diurnal or seasonal operation. BISTS with tracking optical components can overcome this problem but have increased size, weight, complexity and maintenance requirements and when operating in arrays they need to be spaced carefully to avoid loss of performance due to shading (Chemisana and Zacharopoulos, 2015).

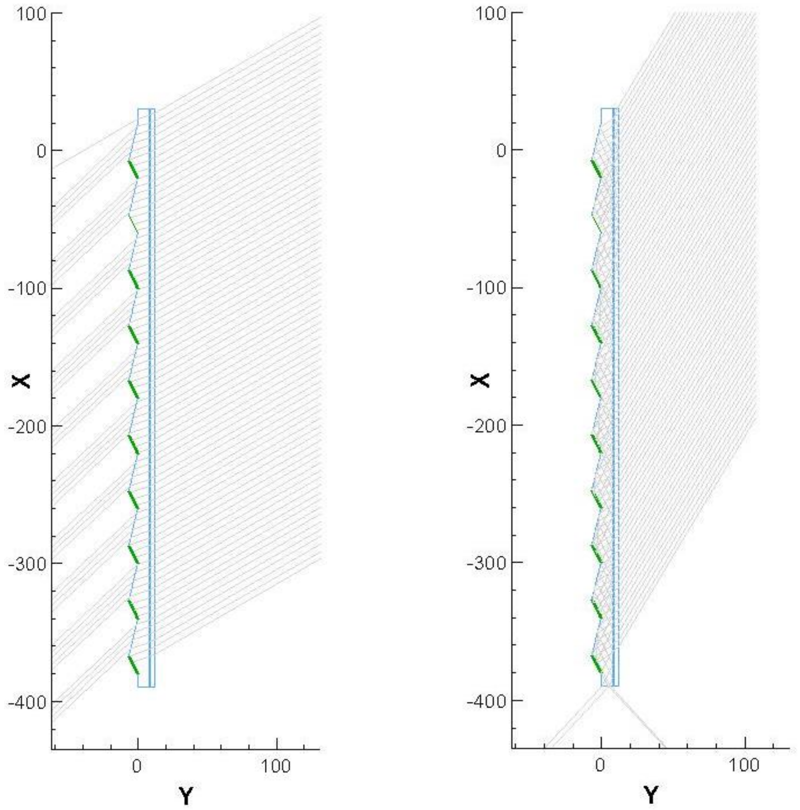


Figure 2.2.6. Glass prisms designed to transmit part of the beam solar radiation into the building at low incidence angles (left) and concentrate it onto PVT absorbers for high incidence angles using Total Internal Reflection (TIR) of light (right) (Zacharopoulos et al., 2015).

Depending on the material type of the components optical losses are also expected. Reflectors operate at lower than 100% efficiency whilst refractive type components made out of glass (typically low-iron) suffer from reflective losses at the air-component interface and absorption losses when light travels through them. For the same system geometry reflective components can be scaled up or down without any effect on their optical efficiency or angular acceptance characteristics. Refractive components offer the advantage of wider acceptance angles due to the refraction of sunlight on their aperture. However, they suffer from large absorption losses the bigger they are. Ray trace was used to compare the optical efficiency and angular acceptance (Figure 2.2.7) of the same concentrating geometry – an asymmetric CPC designed for building façade integration – when reflective (95% reflectivity) or refractive (low iron glass with extinction coefficient $a=0.004mm^{-1}$ and refractive index of 1.52) and two different concentrator depths- 332mm and 33.2mm (10x scaled down). Concentrator depth has no effect on the optical efficiency or angular acceptance of the reflective system. Optical efficiency reaches 97% and all light incident within its design acceptance limits (0°-40°) reaches its absorber. The refractive system has a wider acceptance angle but it suffers from light absorption losses which depend on its depth. For a 332mm system depth the maximum achieved optical efficiency is 23%. For a 10x scaled down system with a depth of 33.2mm, light paths inside the glass body are reduced dramatically and a maximum optical efficiency of 83% is achieved.

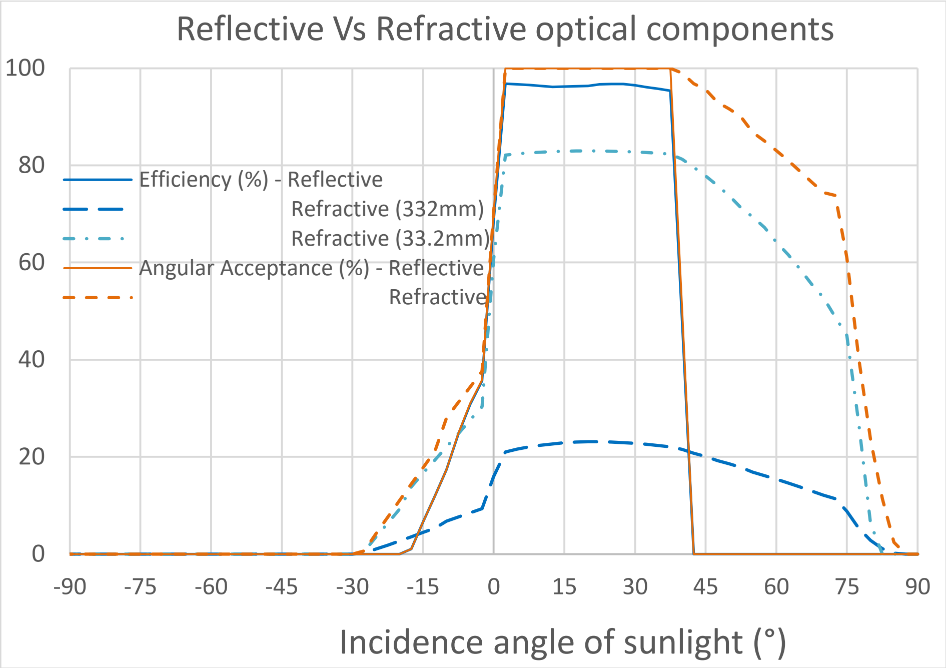


Figure 2.2.7. Optical efficiency and angular acceptance of an asymmetric CPC when made out of reflective material and when made out of low-iron glass (two concentrator depths examined).

2.2.2.2 BISTS with optical components

A building integrated transpired air heater developed by the Dublin Institute of Technology (DIT) used a combination asymmetric CPC with a semi-circular geometry to collect and concentrate solar radiation onto a flat absorber. The employed optical component provides a geometric concentration ratio of 2.3 and allows a minimum of 8 hours of collection of solar radiation per day over the summer (93 days) in Dublin (53º latitude), from 8am to 4pm. This means that all incoming direct solar rays at incident angles between 17° and 60° from the horizontal reach the absorber of the collector during that period (Figure 2.2.8).

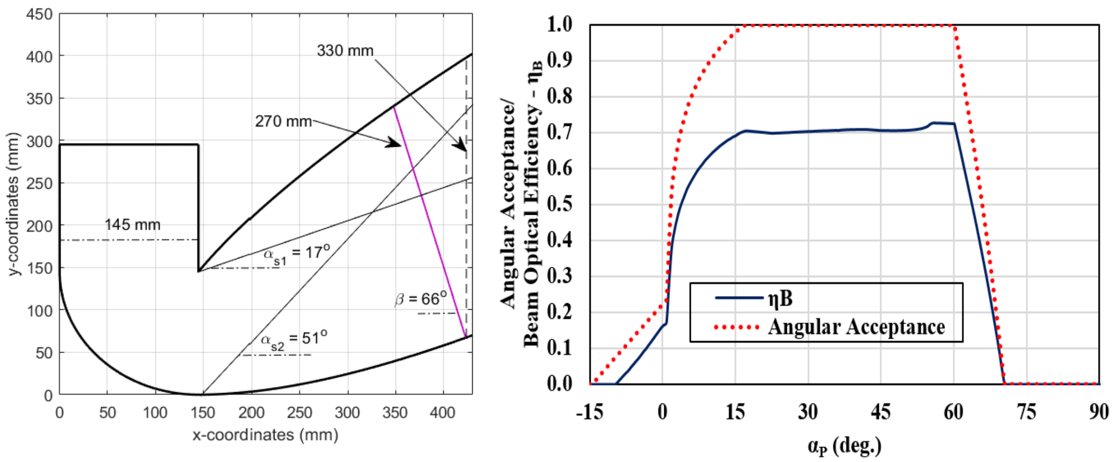


Figure 2.2.8. The geometry of the building integrated transpired air-heater developed by DIT (left) and the modelled beam optical efficiency and angular acceptance (right).

Fieber et al. (2003) developed a BISTS which combined active and passive heating, PV electricity and control of daylight penetration into the building. The solar wall element used a PV/T hybrid absorber with tracking insulated parabolic reflectors integrated into a window. The tracking reflectors offered an effective concentration ratio of 2.55 while they also acted as sun-shades. To maximise the fraction of solar radiation that reaches the PV/T absorber highly transparent glass with anti-reflective coating was used for the window (Figure 2.2.9).

The tracking reflectors could be set to achieve a range of combinations of solar radiation concentrated onto the PV/T absorbers and light penetrating the building interior. With the reflectors fully closed, all the incident solar radiation is concentrated onto the absorbers maximising electricity or heat generation and minimising solar gains. With the reflectors fully opened all incident solar radiation penetrates the building to provide maximum natural lighting and solar gains.

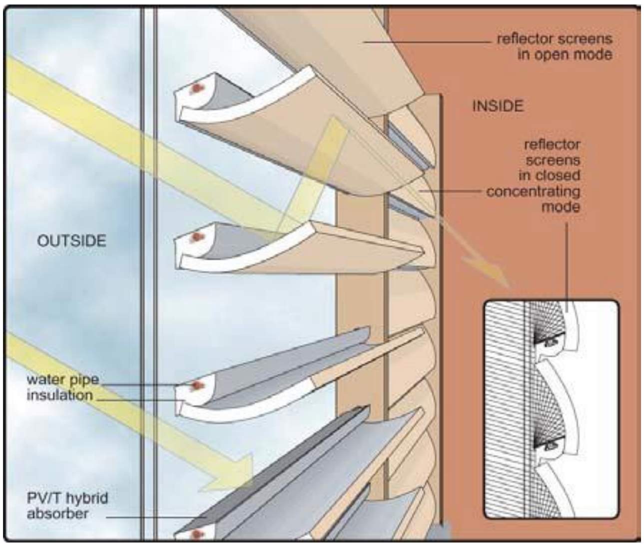


Figure 2.2.9. The Hybrid Solar Wall Element.

The Applied Solar Energy group (APSE), at the University of Lleida, designed a BISTS which made use of a stationary wide angle optical concentrator. The concentrator was designed to transmit the incident solar radiation onto a small moving focal area, which in turn was tracked by a PVT absorber (Figure 2.2.10) (Chemisana 2011).

a) b)

Figure 2.2.10. a) Architectural design of the Fresnel PVT collector, b) the prototype system built using a structure of metallic profiles which supports the Fresnel lenses and the PV/T absorber.

The optical system combined a linear Fresnel lens (5×) with a secondary CPC reflector (2×) to maximise concentration ratio and obtain mainly homogeneous solar flux onto the PVT absorber focal area. The optical performance of the system was found to be consistent throughout the year (Figure 2.2.11).

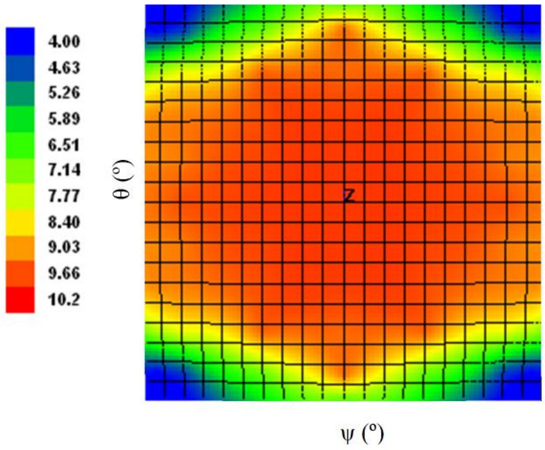


Figure 2.2.11. The concentration ratio as function of the relative angles in the direction perpendicular to the focal plane (θ) and in the direction of the focal plane (ψ). The lens was placed at the latitude plane and the angles variation was: θ (-25º, 25º) and ψ (-70º, 70º) (Chemisana 2009).

The Concentrating PhotoVoltaic/Thermal Glazing (CoPVTG), developed at the Centre for Sustainable Technologies at Ulster University is a BISTS which incorporates refractive optical components to passively control sunlight collection and penetration into the building (Zacharopoulos et al., 2015). The optical components have a prismatic shape and made out of low-iron glass. Depending on their, a part of the incident solar radiation can reach the PV/T absorbers generating electricity and waste heat while the rest can travel through the unit to provide daylight to the building interior. Using total internal reflection (TIR), the lens design can produce a seasonal effect with more light allowed into the building at low incidence angles (i.e. in the winter months) and less light at high incidence angles (i.e. in the summer). Figure 2.2.12 shows how the collection efficiency and acceptance of the lens is influenced by the incidence angle of the sunlight. Beam solar radiation incident above 37° from the horizontal undergoes TIR and is concentrated onto the PVT absorbers. Below that critical angle, most of the incident solar radiation is transmitted through the glass concentrators to provide daylight to the building. Only the radiation that is directly incident onto the PVT absorbers is collected.

2.2.3 Materials for Solar Systems

Typical glass materials are commonly used in the production of the flat plate collectors, because it has high transmittance (high transparency) for shortwave solar radiation. For glass with a small content of iron, transmittance is equal to 0,85-0,9 with angle of incidence of 90°. On the other hand, glass is almost impermeable for low temperature longwave radiation with wavelengths of 5-50 μm. In a defined wavelength range (longwave infrared radiation), glass practically behaves as absolutely black body.

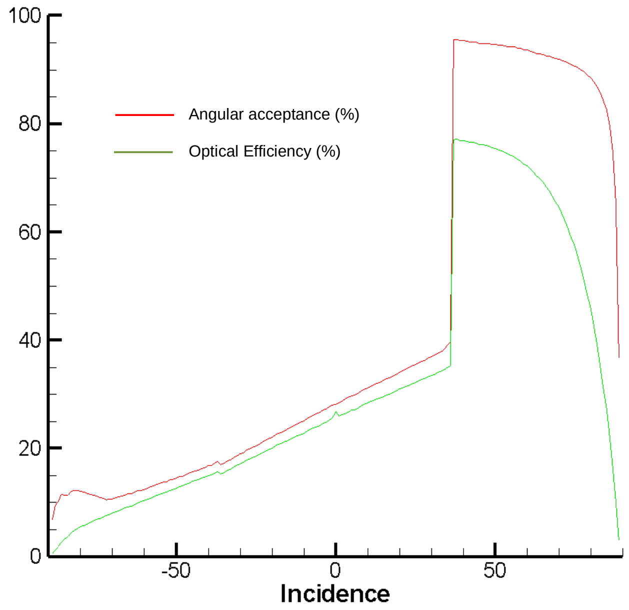


Figure 2.2.12. Optical efficiency and angular acceptance of the CoPVTG.

Glass also has bad characteristics as glazing for flat solar collectors. Glass has high density, which significantly increases the overall weight of the collector. It is expensive and fragile, which creates problems on the eventual impact of the collector plate. By absorbing longwave radiation, glass heats up and emits it back to ambient, which increases the heat losses from the solar collector.

In practice, plastic materials are also used for glazing in the flat solar collectors. Types and properties of plastic films and other cover materials for solar collectors is given in Table 2.2.1. (Ekechukwu and Norton, 1999). Plastic materials are much cheaper than glass, not fragile and very light (ten times smaller density than glass). However, these materials have high transmittance of longwave radiation, and they are unstable due to degradation over long expose periods to ultraviolet radiation and high operating temperatures.

Anti-reflective coatings are also used and can increase transmittance (transparency). Usage of anti-reflective coatings can increase annual production of heat energy by 6,5% (Hellstrom et al., 2003).

Today, the idea of using transparent insulation materials is being investigated. Some investigations have reached acceptable efficiency levels for solar collectors, but usage of transparent insulation materials and their subsequent inclusion in STCs is still insufficiently researched.

There are some external influences that can reduce transmittance of the glass. First of all there is atmospheric dust, which in some regions (sandstorms) or micro locations (next to cement factory for example) can create significant problem. According to research (Hegazy, 2001; Elminir et al., 2015) transparency of solar collector glass can be influenced by many factors connected to deposition of dust, especially density and the amount of dust, but also the position of the solar collector. The least influence on transmittance reduction due to dust is observed on horizontally positioned collector (up to 6%), while for the other angles close to vertical position this reduction can be even higher than 20%. Some authors have the opinion that deposition of dust doesn't have a significant impact, as rain washes the dust layers away (Kalogirou, 2004).

Table 2.2.1. Properties of plastic films and other cover materials.

Material	Thickness available (mm)	Transmittance of visible light[a]	Transmittance of infrared radiation	Weather-ability[b]	Ultimate tensile straight (N/mm^2)	Propagating tear straight (N/mm)	Maximum width (mm)
Commonly available plastic films							
Polyethylene (PE) (u.v.-inhibited)	0.01 upwards	0.86	0.77	Poor	10-30	20-115	12.2
Polypropylene (PP)	0.01-0.25	0.92	No data	Fair	30-275	1-230	3.0
Polyvinyl chloride (PVC)	0.015-0.75	0.90	0.12	Poor	10-70	2-380	2.1
Polyethylene terephthalate (polyester) (PET) e.g. Mylar™	0.002-0.35	0.88	0.24	Very good	140-275	19-115	3.0
Polyvinyl fluoride (PVF) e.g. Tedlar™	0.01-0.1	0.86-0.92	0.33	Very good	50-125	45-390	3.5
Ethylene/tetra-fluoro-ethylene Copolymer (ETFE) e.g. Teflon™	0.05-0.2	0.95	0.20	Very good	50-55	230-350	1.2
Less common films							
Cellulose acetate	0.02-0.75	0.93	0.03	Fair	50-110	1.5-3.9	1.5
Cellulose triacetate	0.05-0.5	0.93	0.11	Good	62-110	1.5-11	1.2
Cellulose acetate butyrate	0.28-0.75	0.93	-	Good	35-60	1.9-3.9	2.6
Ethylene/vinyl acetate copolymer (EVA)	0.02 upwards	-	-	Poor	6-24	20-115	12.2
Ethylene chlorotriofluoro rthylene (ECTFE)	0.01-2.2	-	-	Very good	55-70	350-500	1.4
Fluoroethylene propylene (FEP)	0.01-0.75	0.93	-	Very good	17-20	50	1.2
Perfluoro-alkoxy (PFA)	0.01-0.75	-	-	Very good	27-50	15-27	1.2
Polychlorotrifluoro-ethylene (PCTFE)	0.02-0.25	-	-	Very good	34-70	1-15	1.2
Polycarbonate (PC)	0.006-0.35	0.87-0.92	-	Good	55-80	7.5-10	1.4
Polymethyl metacrylate (acrylic) (PMMA) e.g. Plexiglass™	0.05-0.25	0.87	0.01	Good	55-60	No data	2.8
Polystyrene (PS)	0.006-0.5	0.87-0.92	0.35	Fair	55-80	2	1.9
Vinyl Chloride/acetate copolymers	0.2-0.75	-	-	Fair	17-55	4-540	2.1
Other materials							
Horticultural glass	3.0	0.90	0.01	Very good	-	-	-
PVC-coated polyester cloth	-	0.10	-	Very good	150	-	-

[a]Where no data are given for visible light transmittance, the material is quoted as being “transparent”.
[b]The ageing of materials depends on many factors, and there is no overall accepted standard criterion for weatherability. In moderate climates, polyethylene rarely lasts for more than 2 years, whereas some fluoroplastics can last for more than 15 years.

Absorber materials for solar collectors should have following properties: high absorptivity of shortwave radiation, low emissivity of longwave radiation, good thermal conductivity, small mass, durable, resistance to corrosion and high operating temperature and low cost. The main absorber material is metal with high thermal conductivity (cooper, aluminium or stainless steel). Plastic materials are rarely used. The surface oriented to solar radiation is usually coated. The most common absorber coatings and properties are given in Table 2.2.2.

Table 2.2.2. Properties of absorber materials and coatings (Ekechukwu and Norton, 1999).

Coating	**Substrate**	**Absorpti-vity**	**Emissi-vity**	**Max. temp.**	**Durabi-lity**
Black nickel	Iron, copper, zinc/aluminium	0.85-0.96	0.05-0.15	288°C	Medium
Black chrome	Nickel/aluminium copper, iron	0.82-0.96	0.04-0.15	427°C	Very good
Black copper	Copper	0.85-0.95	0.10-0.15	316°C	-
Copper oxide	Copper, iron, aluminium	0.87-0.90	0.08-0.16	-	-
Anodic aluminium	Aluminium	0.90-0.96	0.10-0.23	-	-
Metal carbide	Copper, Glass	0.82-0.93	0.02-0.05	-	-
PbS paint	ANY	0.90	0.30	-	-
Selective paint (coralur)	Most	0.93	0.30	-	-
Black Paint	Any	0.95-0.97	0.95-0.97	-	-

Regarding insulation materials, mineral or glass wool is used on higher temperatures applications, whilst more compact insulation materials like polystyrene is used at lower temperatures. Compact insulation materials are more resistant to moisture than mineral wool. In practice, a combination of these 2 materials is commonly used.

Materials used to make solar collector casings should have specific strengths, durability, resistance to corrosion and other weatherable conditions, small mass and reasonable price. It is usually stainless steel or aluminum, that already have satisfactory strength and good resistance to corrosion that are preferred.

Plastic materials are cheaper than aluminum, but there is a problem with their durability and stability at higher temperatures or different weather conditions, especially to ultraviolet radiation.

The total cost of energy which is produced by a solar thermal collector is defined by the cost of materials which are used to make the system, cost of the maintenance and by the amount of solar energy which is collected by solar thermal collector over its life. From the beginning in the development of solar technology, additional focus was given to the development of polymers, due to the benficial properties of polymers for use in solar systems. These polymers are widely available with a low cost, and therefore can be used for mass production of cheaper/lightweight solar collectors which are resistant to corrosion and low temperatures. However, their reliability, durability and performance over the long term haven't been researched enough. The use of polymer materials compared to conventional metal materials can reduce the mass of the collector by around 50%, which makes the collector easier to install. (Cristofari et al., 2002).

Polymeric glazing can be used instead of glass in conventional collectors as the cover plate, but they can also be used as integral elements in polymeric systems (Tsilingiris, 2000), resulting in big potential for cost savings. However, they can degrade due to the combined effects of high temperatures and ultraviolet radiation. To reduce the effect of degradation, ultraviolet absorption additives can be used for the outside cover of the system, or through special inhibitors. Usage of these additives increases the life of the collectors with a slight negative impact on the collector cost. Use of polymers as a material for solar collectors has been extensively researched (Best, 1982; Waksman and Dawson, 1980). Thin-walled cellular polycarbonate materials in the form square honeycombs or capillary structures are commonly used as glazing cover material (Platzer, 1992). Some of the best polymers for absorbers are ones that belong to the group of polyolefins, such as polyethylene and polypropylene or those that belong to the group of propylene-diene-monomer (EPDM), such as synthetic rubbers. EPDM materials are used for flexible tubes and polyolefins are used in the production of thermally extruded flat rigid absorbers.

Polymer materials have a relatively low thermal conductivity, with acrylics and derivatives, in the range 0.17-0.23$Wm^{-1}K^{-1}$ (Kirk and Othmer, 1982). These values are around 0.35 and 0.15 $Wm^{-1}K^{-1}$, for high density (HD) and ultra-high density (UHD) polyolefin and EPDM, respectively (Tsilingiris, 1997). These two materials having a low cost and can be used for low and medium temperature applications. It can be seen that the thermal conductivity of polymers is much lower (3 times) than conventional materials like metal. This is very important for their future use in solar energy applications and calls for the redesign of conventional tube and fin metal absorbers. The design of polymer heat exchangers which can be used in high pressure and temperature application, but be compatible with potable water is the primary challenge for the future (Wu et al., 2004), needing to operate for at least 10 years without significant loss of the thermal performance.

Polymer heat exchanger have following advantages:

1. Cost of the materials and production is reduced
2. Increased resistance to corrosion and mineral build-up, with reduction of mineral build-up comes the less cost for maintenance
3. Friction coefficient are lower
4. Easier installation and reduced weight
5. Usage of polymers allows increased compatibility with other components.

Polymers like high temperature nylon (HTN), cross linked polypropylene (PEX) and polypropylene (PP) are certified for tube components and use in heat exchangers. They have good characteristics for high temperature use.

Photovoltaic conversion is the direct conversion of sunlight into electricity without any heat engine to interfere (Parida et al., 2011). Photovoltaic power generation systems consist of cells, mechanical and electrical connections and components. All solar cells have a material which absorbs light and this material is within the cell structure to absorb photons and create free electrons in the photovoltaic effect. Conversion of sunlight to electricity in photovoltaic or solar cells is based on the photovoltaic effect.

Photovoltaic cell technology has developed rapidly and is now in the fourth generation of photovoltaic cells (Lukić and Babić, 2008):

1. First generation includes classic silicon cells created from monocrystalline or polycrystalline silicon;
2. Second generation presents technology of coating semiconductors in thin film on specific surface. This include amorphous silicon, but also in many other combinations (cadmium-telluride, copper-indium-diselenide, copper-indium-gallium-diselenide, gallium-arsenide, ...);
3. Third generation presents photovoltaic cells on different principle of photo-electro-chemical effect, that implies using of polymers, organic photovoltaic cells and nanocrystals;
4. Fourth generation presents combination of polymer and nanoparticles in structures which can absorb and transform the different parts of electromagnetic spectrum (Lukić and Babić, 2008).

Multi-layered photovoltaic cells are commonly being used, in which, several photovoltaic cells placed one below the other, absorbs sunlight and converts it in electric energy. The most efficient and the most expensive multi-layered photovoltaic cells structure is made from gallium-arsenide (GaAs) with traces of other materials. Similar constructions are made from copper-indium-diselenide ($CuInSe_2$) or amorphous silicon. Multilayered GaAs photovoltaic cell gave efficiency of 35% under concentrated solar radiation.

Average values of photovoltaics cells efficiency are given in Table 2.2.3.

Table 2.2.3. Average values of photovoltaic cells efficiency (Lukić and Babić, 2008).

Material	**Laboratory Conditions Efficiency (%)**	**Applied Efficiency (%)**
Monocrystalline Si	24	14-17
Polycrystalline Si	18	13-15
Amorphous Si	13	5-7
Cadmium Telluride CdTe	16	6-8
Cooper-indium-diselenide $CuInSe_2$	18	6-8

2.2.5 Solar System Control

One of the most important components of an active solar energy system is the temperature controller, as a faulty control is usually the cause of poor system performance. Generally, control systems should be as simple as possible and should use reliable controllers. The use of reliable good quality devices is required for many years of trouble-free operation. The control system should be capable for handling all possible system operating modes, including heat collection, heat rejection, power failure, freeze protection, and activation of auxiliary heating in case that the solar system cannot satisfy the demand.

The basis of solar energy system control is the differential temperature controller (DTC). This is simply a fixed temperature difference thermostat with hysteresis. The differential temperature controller is a comparing controller with at least two temperature sensors that controls usually the solar pump. Typically, one of the sensors is located at the top side of the solar collector array and the second at the storage tank. On unpressurized systems, a different kind of differential temperature controller may control also the extraction of heat from the storage tank. Most other controls used in solar energy systems are similar to those for building services systems.

The differential temperature controller monitors the temperature difference between the collectors and the storage tank. When the temperature of the solar collectors exceeds that of the storage by the predetermined amount (usually 4-11°C), the differential temperature controller switches the circulating pump ON. When the temperature of the solar collectors drops to 2-5°C above the storage temperature, the differential temperature controller stops the pump. Instead of controlling the solar pump directly, the differential temperature controller can operate indirectly through a control relay in order to operate one or more pumps and possibly perform other control functions, such as the actuation of control valves.

The temperature differential set point of the differential temperature controller may be fixed or adjustable. If the controller set point is fixed, the controller selected should correspond to the requirements of the solar system. An adjustable differential set point makes the controller more flexible and allows it to be adjusted to the specific system or specific conditions of the solar system, such as, different settings in summer and winter. The optimum differential ON set point is difficult to calculate because of the changing variables and conditions. Typically, the ON set point is 5-9°C above the OFF set point. The optimum ON set point is a balance between optimum energy collection and the avoidance of short starts and stops of the pump. Frequent starts and stops of the pump must be minimized because it can lead to premature pump failure. The optimum OFF temperature differential should be the minimum possible, which depends on whether there is heat exchanger between the collectors and storage.

If the system does not have a heat exchanger, a range of 1-4°C is acceptable for the OFF set point. If the system incorporates a heat exchanger, a higher differential temperature set point is used so as to have an effective heat transfer and thus have a higher energy transferred between the two fluids. The minimum, or OFF temperature differential is the point at which the cost for pumping the energy costs is equal to the cost of the energy being pumped in which case the heat lost in the piping should also be considered. For systems with heat exchangers, the OFF set point is generally between 3 and 6°C.

The typical control format for solar thermal system uses the temperature of the heat transfer medium at the outlet of the collector field and the temperature at the bottom of the storage. When the temperature difference exceeds a certain start temperature, the pump is switched on to a constant mass flow. And when the temperature difference decreases below a certain stop temperature, the pump is switched off. Another option for the control of BIST is a matched-flow control. In this case, a minimum mass flow and a maximum mass flow of the heat transfer medium is defined as well a target outlet temperature of the collector field. The mass flow is then adjusted between the minimum and maximum mass flow to reach the target temperature. If the target temperature is not even reached by the minimum mass flow, the pump is switched of. And if the outlet temperature exceeds the target temperature even with the maximum mass flow, the mass flow is fixed to the maximum mass flow. Many more controls can be used e.g. to optimize the storage of the solar thermal energy for different applications.

REFERENCES

Alghoul M.A., Sulaiman M.Y., Azmi B.Z., Wahab M.A., Review of materials for solar thermal collectors, Anti-Corrosion Methods and Materials, 2005; 52: 199-206.

Best D., New plastics head for higher temperatures, Solar Age, 1982; 51-52.

Chemisana, D., Ibáñez, M., & Rosell, J. I., Characterization of a photovoltaic-thermal module for fresnel linear concentrator. Energy Conversion and Management, 2011, 52(10), 3234-3240.

Chemisana D. and Zacharopoulos A., Building-Integration of High-Concentration Photovoltaic Systems in High Concentrator Photovoltaics. Fundamentals, Engineering and Power Plants (Editors: Pérez-Higueras, Pedro, Fernández, Eduardo F.) Springer, 2015 (ISBN: 978-3-319-15039-0)

Cristofari C., Notton G., Poggi P., Louche, A., Modelling and performance of a polymer solar water heating collector, Solar Energy, 2002; 72:99-112.

Ekechukwu O.V., Norton B., Review of solar-energy drying systems III: low temperature air-heating solar collectors for crop drying applications, Energy Conversion & Management, 1999; 40: 657-667.

Elminir H.K., Ghitas A.E., Hamid R.H., El-Hussainy F., Beheary M.M., Abdel-Moneim K.M., Effect of dust on the transparent cover of solar collectors, Energy Conversion & Management, 2006; 47: 3192-3203.

Fieber A., Gajbert H., Hakansson H., Nilsson J., Rosencrantz T., Karlsson B., in Proceedings of ISES Solar World Congress, Gothenburg, 14-19 June, 2003

Hegazy A.A., Effect of dust accumulation on solar transmittance through glass covers of plate-type collectors, Renewable Energy, 2001; 22: 525-540.

Hellstrom B., Adsten M., Nostell P., Karlsson B., Wackelgard E., The impact of optical and thermal properties on the performance of flat plate solar collectors, Renewable Energy, 2003; 28: 331-344.

Kalogirou S.A., Solar thermal collectors and applications, Progress in Energy and Combustion Science, 2004; 30: 231-295.

Kirk, Othmer (Eds), Encyclopedia of Chemical Technology, Wiley, New York, NY, 1982.

Lukić N., Babić M., Solar energy, 1th ed. Kragujevac: Faculty of Mechanical Engineering; 2008.

Nchelatebe N.D. and Smyth M., Performance analysis and comparison of concentrated evacuated tube heat pipe solar collectors, Applied Energy, 2012; 98: 22-32.

Parida B., Iniyan S, Goic R., A review of solar photovoltaic technologies, Renewable and Sustainable Energy Reviews, 2011; 15: 1625-1636.

Platzer W.J., Total heat transport data for plastic honeycomb-type structures, (1992), Type Structures, Solar Energy, 1992; 49: 351-358.

Tsilingiris, P.T., Design, analysis and performance of low-cost plastic film large solar water heating systems, Solar Energy, 1997; 60: 245-256.

Waksman D., Dawson A., The influence of environmental exposure on solar collectors and their materials, Proceedings of the AS/ISES Conference, 1980; 415-419.

Wilson H.R., Transmission switching using microencapsulated liquid crystal films, Solar Energy, 1992; 49: 435-445.

Zacharopoulos A., Eames P.C., McLarnon D., Norton B., Linear dielectric non-imaging concentrating covers for PV integrated building facades, Sol. Energy, 2000, 68, 439-452.

Zacharopoulos A., McAnearney C., Hyde T., Mondol J.D., Smyth M., Experimental evaluation of a concentrating PV/Thermal glazing façade technology, Proceedings of COST Action TU1205 Symposium, Guimaraes, Portugal, 2015, 128-137.

2.3 MODELLING AND PERFORMANCE ANALYSIS OF BUILDING INTEGRATED SOLAR THERMAL (BIST) SYSTEMS

Chrysovalantou Lamnatou, Istvan Farkas, Aggelos Zacharopoulos, Annamaria Buonomano, Adolfo Palombo, Daniel Chemisana

2.3.1 Introduction

Architectural integration of solar thermal systems is important for the spreading of solar thermal technologies (Munari Probst and Roecker, 2007). Even if certain types of architecturally-integrated solar thermal systems e.g. Trombe wall (Steemers and den Ouden, 1984) exist several years ago, during the last years there is an increasing interest for this specific type of systems which are known as Building-Integrated Solar Thermal (BIST) systems. BIST, and in general BI solar systems, offer several advantages (higher aesthetic value, etc.) in comparison to the solar systems which are added (and not integrated) on the building (Kalogirou, 2013) known as Building-Added (BA) systems. For the specific case of BI solar applications, factors such as the balance between aesthetics and performance (Zomer et al., 2014) play an important role.

A literature review shows that there are some investigations about BI solar systems; however, most of these studies are about BI Photovoltaic (BIPV) (Lee et al., 2014; D´Orazio et al., 2014). There are only few investigations about BIST systems for e.g. façade-integration (Maurer and Kuhn, 2012; Maurer et al., 2013) and gutter-integration (Motte et al., 2013a, 2013b; Notton et al., 2014).

Given the importance of building integration in the spreading of solar thermal systems (Munari Probst and Roecker, 2007), in the field of BIST further investigation is necessary. Certainly, the experimental investigations are important for testing the behaviour of a system; nevertheless, modelling can be adopted in order to predict the performance of a system, saving time and cost. Thereby, further modelling investigations for the behaviour of the BIST system (Lamnatou et al., 2015a) and/or for the behaviour of the coupled building/BIST system configuration (Lamnatou et al., 2015b), along with experimental testing for BIST systems, are needed. There are also innovative components for BIST systems (Source: http://solarintegrationsolutions.org/) which need new models in order to demonstrate the benefits that they offer.

The present chapter aims to fill the gaps of the literature in BIST modelling by providing useful information about the developed codes, both thermal and optical. Emphasis is given on the codes which have been built and validated. A flow chart for the modelling and simulation procedure of BIST configurations is also presented. Furthermore, a separate section about performance analysis is included. Finally, a case study (about modelling and thermal analysis of roof-integrated solar tiles) is presented.

2.3.2 Validation of developed codes: thermal and optical

In the present section the methodology for modelling and simulating a BIST system is first introduced by reviewing the main studies available in the literature. In addition, the main differences with respect to the simulation of a solar thermal system are analysed.

2.3.2.1 Representative studies of BIST modelling and simulation

A) Opaque systems

Opaque BI systems may refer to systems which are integrated into the roof of a building. Assoa and Ménézo (2014) presented a work about a roof-integrated PVT (photovoltaic/thermal) air collector. A 2D simplified dynamic mathematical model of a solar PVT air collector with a metal absorber was proposed. The validation of the numerical model was performed by measured data obtained from a full-scale test bench located near Lyon, in France.

During cold sunny winter days, when the south wall is well insulated, a considerable amount of the solar energy falling on this façade is not transferred to the inside of the building. Ibrahim et al. (2014) presented a work about a novel closed wall-loop system to capture this wasted energy available during non-cloudy winter days and transfer it to the cooler north façade (by means of water pipes embedded in an exterior aerogel-based insulating coating). The system was presented along with all the mathematical equations and the numerical model. The model was validated against experimental data from the literature. In order to test its performance on a full-scale house, the MATLAB numerical model was coupled to the whole building energy simulation program EnergyPlus through co-simulation. The findings showed that the reduction in the annual heating load for the house using this system relative to the one without this system were between 28 and 43% for new houses and 15-20% for old houses (based on the Mediterranean climate). For other climates, the reductions varied between 6% and 26%. The heat losses through the north façade were reduced by around 60-88% for the Mediterranean climate and around 20-50% for the other climates. In Figure 2.3.1 the active embedded pipe wall loop system is illustrated. The exterior walls of the system are composed of concrete or brick layer with an outside insulating coating based on the (super)-insulating materials silica aerogels (Ibrahim et al., 2014).

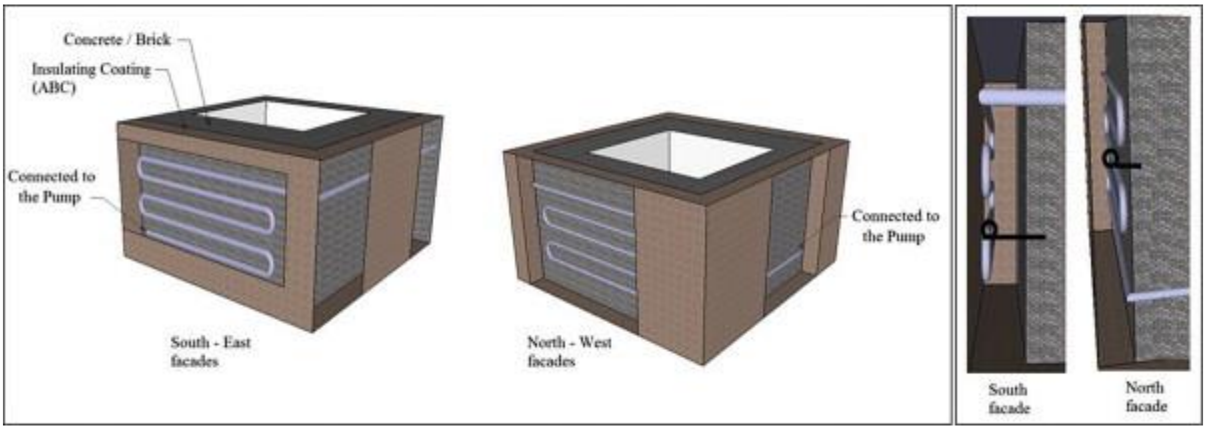


Figure 2.3.1. The active embedded water pipe wall loop system investigated by Ibrahim et al. (2014).

A dual-function solar collector system can provide passive space heating in cold winter as well as water heating in warm seasons. This system shows higher annual utilization ratio than a conventional system designed for passive space heating. A coupled numerical model was developed by Ji et al. (2011a) for such a configuration (for the case of Hefei, China). Based on experimental validation, the numerical model was proved to be able to give accurate predictions. The model was a dynamic numerical model and it was developed in order to evaluate water heating performance and solar transmission though building façade. Finite difference method was adopted for the model while the heat flow through the front glazing was one-dimensional. Moreover, Ji et al. (2011b) conducted another study related with the above mentioned configuration. Two dynamic numerical models based on the finite-difference method for two different operating modes of the testing system were developed and experimental data were utilised to validate these two models.

Li et al. (2014) developed and validated energy models for the simulation of BIPVT (building-integrated photovoltaic/thermal) systems with unglazed transpired solar collectors. The scope of the models was to predict the cavity exit air temperature and the plate surface temperature (by using weather and design parameters as inputs). The energy models were validated with measurements (outdoor test-facility) and a good agreement between model predictions and experimental data was found. The effects of significant parameters on the performance of the system were demonstrated based on literature data and simulations, by adopting CFD (computational fluid dynamics) and energy models.

Buker et al. (2014) presented a work about a BIPVT system in terms of its performance and techno-economic aspects. The study also included experimental validation. The integration of a unique polyethylene heat exchanger loop underneath PV modules was investigated. The system was designed to act as a roof element having a heat resource for solar assisted heating and cooling systems. A detailed thermal model was adapted in order to evaluate the roof-unit thermal performance. Numerical simulations were conducted by means of Engineering Equation Solver (EES) for the climatic conditions of Nottingham, UK and design parameters of the BIPVT. The experimental values showed that the water temperature difference could reach up to 16^{o}C and the system could give up to 20.25% overall thermal efficiency.

The thermal performance of a roof-integrated solar concrete collector for reducing the heat gain to a house and for providing domestic hot water was investigated by Sarachitti et al. (2011). The solar concrete collector consists of PVC pipes embedded in deck slab or concrete roof. Two test rooms were built in order to compare the energy savings. In the first room, the reinforced cement concrete slab was used as deck slab whereas the second room was equipped with a cement concrete solar collector. The experimental results showed that the cement concrete solar collector is very interesting since it can produce up to 40 *l* of hot water per day at water temperatures 40-50^{o}C. A mathematical model based on the conservation equations of energy was developed (in order to predict the performance of the cement concrete solar collector). A reasonable agreement between measured and predicted results was found.

Yang and Athienitis (2012; 2014) presented a numerical control volume method to simulate an open-loop air-based BIPVT system with a single inlet. The simulated results were validated with indoor tests data (the tests were conducted under controlled test conditions by using a solar simulator). Energy balance equations were utilized to simulate the components in the BIPVT system.

Li and Karava (2014) presented a work about energy modelling and performance analysis of BIPVT systems with corrugated unglazed transpired solar collectors. CFD and energy models were adopted for the simulation. The simulated results were validated with measured outdoor test data. A parametric analysis was performed in order to investigate the impact of the corrugation geometry and collector orientation on the thermal performance of the proposed system.

Chen et al. (2010) studied the thermal performance of a BIPVT system thermally coupled with a ventilated concrete slab. A simplified three-dimensional, explicit control-volume finite-difference thermal model was adopted for the simulation of the thermal behaviour of the system. The findings from the simulations were validated by using measured data and it was found that the accuracy of the model was lying within the acceptable range. In addition, Shan et al. (2013) presented a simulation model of a PVT collector with water heating for applications in buildings (in order to analyse PV and thermal performances).

Corbin and Zhai (2010) adopted a CFD model in order to simulate the effect of active heat recovery on cell efficiency and the performance of a BIPVT collector. The results from the simulations were verified with experimental data. A parametric analysis was performed by using the validated model. The findings demonstrated that the heat recovery lowered both average and maximum cell temperatures compared to natural convection. In Figure 2.3.2(a) the experimental test collector is presented and in Figure 2.3.2(b) the PV temperature contours are illustrated (Corbin and Zhai, 2010).

a)

b)

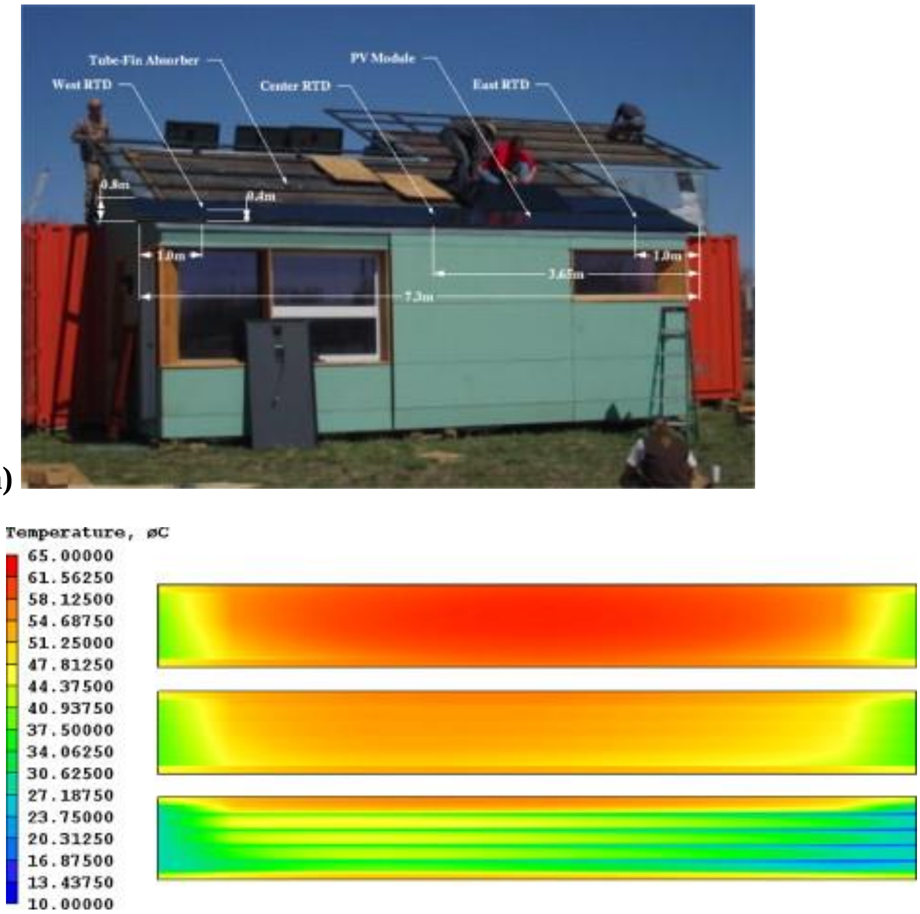


Figure 2.3.2 a) Experimental test collector and b) PV temperature contours for natural convection (top), heat recovery (middle), thermal absorber temperature contour (bottom) at 1000 W/m^2 and 10^{o}C inlet temperature (Corbin and Zhai, 2010).

Xiang and Gan (2015) conducted a study about the optimization of a BIPVT air system combined with thermal storage. PV panels combined with phase change material (PV/PCM) are hybrid solar systems which use PCM in order to reduce PV temperature and store energy for other applications. The investigation of Xiang and Gan (2015) included experiments on a prototype PV/PCM air system by using monocrystalline PVs. Transient simulations of system performance were also conducted by means of a commercial CFD package based on the finite volume method. The results from the simulations were validated with experimental findings. It was demonstrated that PCM is effective in limiting temperature rise in PV device and the heat from PCM can enhance night ventilation and decrease building energy consumption to achieve indoor thermal comfort for certain periods of time.

Anderson et al. (2009) presented a work about a BIPVT collector. The configuration was theoretically analysed based on a modified Hottel–Whillier model and it was validated with experimental data (from testing on a prototype BIPVT collector). The findings showed that key design parameters such as fin efficiency, thermal conductivity between PV cells and their supporting structure and the lamination method have a considerable influence on both electrical and thermal efficiency of the BIPVT.

Chow et al. (2008) studied computer modelling and experimental validation of a BIPV and water heating system. A dynamic simulation model for the system was developed. The numerical model was based on finite-difference control-volume method and the validity of the modelling was verified by comparing its predicted operating temperature changes and system daily efficiencies with the measured data from experiments (City University of Hong Kong). The results based on the model showed good agreement with the experimental results.

Li et al. (2015a) conducted a study based on TRNSYS simulations to investigate the thermal performance of a balcony-wall type solar water heater system. The solar collector consists of U-type evacuated glass tubes fixed vertically on the balcony wall. The collector outlet temperatures from the simulations were compared with experimental data (the mean relative deviation between the two results was found to be 9.4%).

Agrawal and Tiwari (2011) proposed a simulation model, based on Matlab, to evaluate the electrical and thermal performance of a glazed hybrid micro-channel solar cell thermal tile. Indoor tests were conducted by using a solar simulator to characterise system performance and to compare the experimental data with the theoretical findings. A good agreement between the theoretical and the experimental results was found.

A CFD model for a ventilated active façade with PCMs was presented by Diarce et al. (2014). In order to validate and calibrate the developed CFD model, real-scale experimental data were adopted. The proposed model is based on Fluent software. For the modelling of the radiation, S2S and DO sub-models were tested. RNG k–ε, standard k–ω and SST k–ω turbulence models were compared in order to simulate air flow inside the ventilated layer. It was highlighted that further research is needed to improve the accuracy of the developed model for low-Reynolds-number turbulence conditions.

A numerical and experimental investigation about the heat transfer in a BIPVT system was presented by Liao et al. (2007). A CFD study about the proposed BIPVT system aimed at evaluating the heat transfer in the BIPVT system cavity. The k-ε model was used to simulate the turbulent flow and the convective heat transfer in the cavity (buoyancy effect and long-wave radiation between boundary surfaces were included). A particle image velocimetry (PIV) system was utilized in order to investigate the fluid flow in the BIPVT cavity and for partial validation of the CFD model. The cavity temperature profiles were compared with experimental data (for different conditions) and good agreement was observed. Robust correlations for the convective heat transfer coefficients for the cavity surfaces of the system were obtained and such correlations can be utilized for the design and analysis of BIPVT systems with lumped parameter models.

Motte et al. (2013a) presented a work about the performance of a novel solar collector for water heating by adopting numerical method. The studied solar collector is integrated into building gutters. MATLAB was used for the numerical calculations (finite difference model; electrical analogy) and good agreement between numerical and experimental findings was observed (the relative root mean square errors were around 5% for the water temperatures) (Motte et al., 2013b).

Anderson et al. (2010) investigated colour effect on the thermal performance of BI solar collectors. The adopted model was: 1D, steady-state, thermal model based on Hottel–Whillier–Bliss equations. The model was validated and it was used to evaluate the fraction of a typical domestic water-heating load (based on the various theoretical coloured collectors). An F-chart was also developed for the operation of the collectors in New Zealand (Auckland).

In addition, thermal resistance-based models were developed in order to simulate the performance of direct gain, indirect gain and integrated heat-pipe passive solar systems for different locations (Albuquerque, Rock Springs, Louisville, Madison) (Albanese et al., 2012). A parametric study was conducted to determine the design features that have a considerable influence on the performance. A prototype heat-pipe wall was developed and tested for validation data. MATLAB codes were created to simulate the hourly performance of the heat-pipe system, as well as direct gain and concrete and water wall indirect gain. A thermal network approach and an anisotropic model were utilized.

Concerning BICPVT configurations, Li et al. (2015b) presented a study about outdoor overall performance of a novel air-gap-lens-walled compound parabolic concentrator incorporated with PVT system. A prototype was designed and installed on a rooftop (University of Science and Technology of China, Hefei). The optical, electrical and thermal performances of the system under outdoor conditions were analysed for the case of BICPVT applications. Simulations and experiments were carried out in order to evaluate the optical characteristics of the system for two typical days. The experimental results verified the results from the optical simulation.

With respect to agricultural applications, Nayak and Tiwari (2008) presented a work about energy and exergy analysis of a PVT system integrated with a solar greenhouse. The study included validation of the thermal model with experimental data for a typical day of August (clear weather conditions for New Delhi).

Moreover, several new and simple models have been developed by Maurer et al. (2015), in order to take into account the coupling of BIST systems to the building. Such models, based on the adaptation of the efficiency curve and the adaptation of the collector results, are less complex than detailed physical models, but more accurate than those which neglect the building integration effect. The proposed modelling approaches can be used as approximations for BIST collectors with good insulation and for cases with low insulation (towards the building interior) as well as when there is availability of monitoring data such as energy flux and thermal performance.

B) Transparent systems - Several BIST configurations

Khanal and Lei (2015) presented a numerical investigation about the buoyancy induced turbulent air flow in an Inclined Passive Wall Solar Chimney (IPWSC) attached to a room (ventilated space) for ventilation applications. The standard k–ε turbulence model was adopted in order to model the air turbulence in the solar chimney system. The numerical results revealed that the turbulent kinetic energy and the turbulent intensity in the solar chimney decrease with the increase of the inclination of the passive wall. The effectiveness of the IPWSC design for enhancing the thermally driven ventilation was confirmed. Additional simulations were performed for a standalone solar chimney model. The findings showed that the standalone model over-predicts mass flow rate compared to that predicted by the attached model. The validation of the numerical model was conducted by comparing the numerical results with the experimental results. In Figure 2.3.3, a schematic of the two-dimensional IPWSC studied is illustrated (Khanal and Lei, 2015).

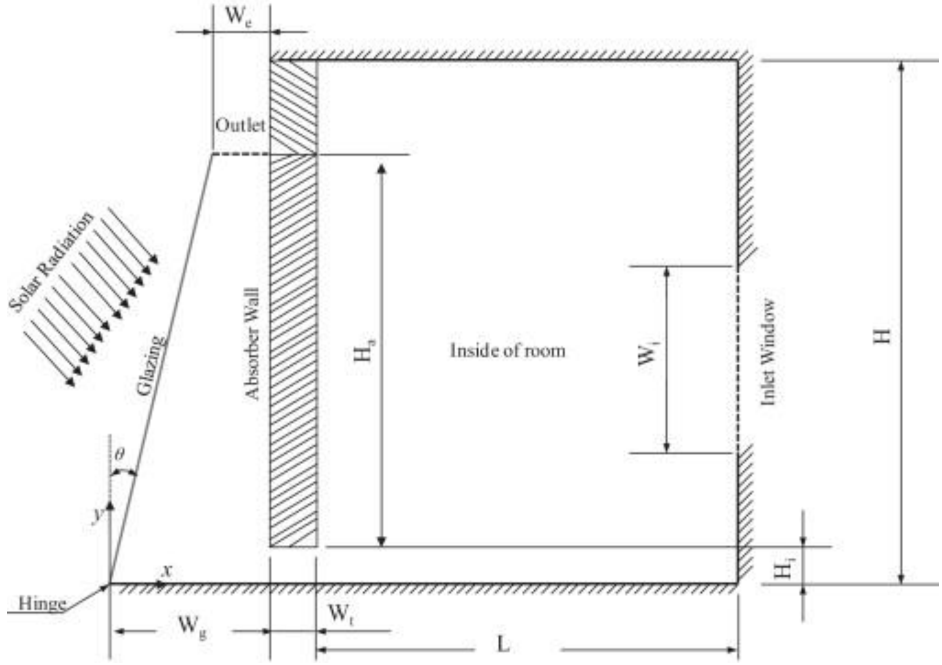


Figure 2.3.3. Schematic of the system studied by Khanal and Lei (2015): two-dimensional solar chimney (IPWSC) attached to a room.

Wang et al. (2015) proposed a simplified physical model of a built-in curtain on a glazed window. The flow and the heat transfer characteristics of the simplified model were analysed. A method for the evaluation of the additional thermal resistance of the curtain was presented. The rationality of the simplified model and the accuracy of the calculations were verified by means of experiments.

Maurer et al. (2013) investigated the performance (in terms of heating and cooling) of a high-rise building incorporating façade-integrated Transparent Solar Thermal Collectors (TSTCs). Two new TRNSYS types were developed in order to simulate the performance of the TSTC system and the passive solar gains of a glazing with venetian blinds. The simulations evaluated the overall performance including heating, ventilation and air conditioning of the building with façade-integrated TSTC system. Further investigation was also conducted in order to examine the possibility for primary energy savings by using building mass as an additional thermal storage.

A new methodology based on a «black box» model regarding building simulation programs for modelling the solar gains through complex façades was developed by Kuhn et al. (2011). The advantage of this new methodology is that it only uses measurable quantities of the transparent or translucent part of the façade as a whole. The method has been designed for complex façades such as façades with prismatic layers, light re-directing surfaces and in general, for façade properties with complex angular dependence, façades with non-airtight layers, non-flat surfaces and other complex configurations. The method was implemented in ESP-r and it was validated. Kuhn et al. (2011) noted that the method could also be implemented in other detailed simulation programs such as DOE-2, EnergyPlus or TAS thermal analysis software and it has been implemented in TRNSYS by Maurer (2012).

Maurer and Kuhn (2012) presented a work about the effect of variable *g* value of transparent façade collectors. A new Type 871 was developed and the model was successfully validated and used to calculate the primary energy savings. The model was built in such a way that new BIST elements can be also quickly modelled. A detailed model like Type 871 offers accurate prediction of the collector gain, the heating and cooling load of the building and even the indoor surface temperatures to allow detailed calculations of the thermal comfort, including an optical simulation and a thermal network. In addition, the BlackBoxType 861 provides unprecedented accuracy in modelling glazing with blinds in TRNSYS.

Chan and Tzempelikos (2012) developed a method for assessing the integrated energy performance of passive and active multi-section façade systems combined with lighting and thermal controls of perimeter building zones by utilizing open source language. A thermal network approach was adopted to predict indoor thermal environmental conditions and annual energy consumption of perimeter zones equipped with combinations of passive and active façade systems. The model adapted anisotropic sky models for accurate prediction of solar gains, variable angular glazing properties and non-linear interior and exterior convection and radiation heat transfer coefficients together with transient internal gains (obtained from transient lighting simulation). The baseline building (West Lafayette, Indiana) includes a single room with large windows facing south. Typical Meteorological Year (TMY3) data were interpolated in order to represent a typical weather pattern of this city as input value for both thermal and daylighting models. The angle-dependent glazing properties (transmittance, reflectance, absorptance) were obtained from WINDOW6 and matched with experimental data. A thermal network approach was used to predict the indoor thermal environmental conditions and the annual energy consumption on perimeter zones equipped with combinations of passive and active façade systems such as selective glazings, translucent panels, motorized shades and blinds, in conjunction with daylight-linked lighting and shading controls. Each of the components of the building system was presented as a node. In order to maintain accuracy, numerical stability and computing efficiency, a suitable time step was determined from building details, efficiency and sensitivity analysis and a modified Gauss-Siedel iteration algorithm was used to solve the iteration of equation sets. A previously developed daylighting model (Shen and Tzempelikos, 2012) was adopted in order to predict work plane illuminance levels and lighting demand. Regarding model validation, experimental measurements in full-scale outdoor test office spaces at Purdue University were conducted in order to compare them with the simulation results.

Maurer et al. (2012) presented a study which included measurements and corresponding modelling of transparent solar thermal façades. Angle-dependent spectrally resolved optical measurements of the different collector layers were used for an optical simulation in order to determine the angle-dependent absorptance of each layer and the angle-dependent transmittance of the whole collector. Perez et al. (1993) sky model with Tregenza (1987) sky patches were used for accurate treatment of the diffuse radiation. The thermal network was first modelled by means of CFD and then it was calibrated by using calorimetric measurements. The resulting detailed physical model offers multiple benefits such as predictions of the advantages, easy collector optimization and the possibility of quantifying the uncertainties of the simulation. The method to determine these uncertainties was presented.

Glória Gomes et al. (2014) conducted a numerical and experimental study about solar and visible optical properties of glazing systems with venetian blinds. Direct and diffuse fluxes of transmitted, reflected and absorbed solar and visible radiation within a multilayer glazing/shading system were considered. Net radiation method was used to solve the radiant energy exchange within a multilayer system. The numerical, analytical and experimental results were compared while design charts were developed to help designers and users in enhancing the thermal and daylighting indoor conditions by adjusting the slat orientation of venetian blinds.

Li et al. (2015c) presented a work about a novel Solar Thermal Curtain Wall (STCW) which is a solar thermal system with collectors installed as building envelope or curtain collector. The STCW combines energy production with other functional issues (architectural, structural and aesthetic). A thermal model was developed and the differential equations of the STCW were converted to numerical format through finite difference scheme and translated to TRNSYS type with FORTRAN program (which is STCW type). Except SCTW type, TRNSYS standard utility components which include type 60 detailed fluid storage tank, type 2 ON/OFF differential controller, type 3 pump and type 9 weather data reader were adopted in the frame of the simulations. In order to study the thermal performance of the proposed system and in order to validate the model, experiments were carried out on a curtain wall that was facing the south without any horizontal obstruction.

A numerical model was developed to evaluate the thermal performance of a solar collector integrated into the external louvres of buildings (Palmero-Marrero and Oliveira, 2006). The model considers steady-state heat transfer and consists of 4–6 heat balance equations, depending on the configuration. The EES software was adopted in order to model the complete water heating system, integrated-louvre collector, storage tanks and other system components. Transparent configurations were also examined.

In terms of agricultural applications of BIST, Joudi and Farhan (2014) investigated a solar air heater for heating an innovative greenhouse. The proposed greenhouse combines a traditional greenhouse with a system of solar air heaters on the roof (as one structure). The proposed configuration does not affect the required solar radiation inside the greenhouse for winter heating (when compared with a conventional greenhouse). An energy balance method was adopted in order to calculate the heating load and this differs from the previous standard method which does not include soil heat storage.

Regarding BICPVT systems, Chemisana et al. (2011) designed an advanced solar unit to match the needs of building integration and CPVT generation. The proposed unit combines three elements: a domed linear Fresnel lens (as primary concentrator), a compound parabolic reflector (as secondary concentrator) and a PVT module. The PVT generator was built, analysed and characterised while models for the electrical/thermal behaviour of the module were developed and experimentally validated. The electrical performance was analysed by means of the I–V curves measured at different temperature and illumination outdoor conditions. The numerical thermal analysis was performed in detail by utilising a CFD software package. The CFD findings were well validated by utilizing laboratory measurements.

Gupta et al. (2016) presented an exergy analysis of a BI semi-transparent PVT (BISPVT) system. Experimental validation of the theoretical model was also conducted. Based on energy balance, an analytical expression for room air, solar cell and room floor temperatures was obtained (along with solar cell electrical efficiency). An overall exergy analysis of the proposed system was conducted, by considering thermal and electrical energy and daylighting factor. An increase of 1.15% in the overall exergy was found for the number of air changes varying from 0 to 4.

Shukla et al. (2016) studied the energy, exergy and power generation of BISPV modules for roof and façade applications. Energy and exergy efficiencies and electrical and thermal energy output of an experimental setup, consisting of BISPV were assessed. The exergy efficiency of the BISPV module (low due to the irreversibility of the PV conversion) resulted to be highly affected by the solar radiation intensity, increasing with its increase. It was also found that the energy and exergy of the BISPV module at façade are better in comparison to the BISPV at the rooftop of a building.

Vats and Tiwari (2012) carried out an electrical and thermal energy and exergy analysis of a BISPVT system integrated into the building roof. Six different PV modules (m-Si, p-Si, amorphous silicon, cadmium telluride, copper indium gallium diselenide and a heterojunction comprised of a thin a-Si PV cell on top of a c-Si cell (HIT)) were taken into account. The results showed that the difference in building room temperature, calculated for all the six PV modules, was marginal. Moreover, it was found that the annual overall exergy is maximum for the HIT (834 kWh) module and minimum for the a-Si (334 kWh) module.

C) Double-skin façades

In the category of transparent BIST are also included multi-skin façades, for example DSF (double-skin façade) configurations. A multi-skin façade is a type of façade which includes different layers. Between these layers air can move. The multi-skin façades can be used to provide for example heat for the building (Lamnatou et al., 2015b). In the following paragraphs, studies about DSF modelling are presented.

Joe et al. (2014) analysed a multi-story DSF (Korea). Parametric and optimization studies on the DSF design were conducted, based on a validated model. Algorithm GenOpt was used for the optimization of the proposed system. A binary version of the Particle Swarm Optimization (PSO) algorithm was adopted. The location of the input variable for each simulation in EnergyPlus becomes a particle and each particle includes information on a value of an objective function.

Marques da Silva et al. (2015) performed tests on an outdoor air curtain DSF test cell (with a movable slat venetian blind). Measurements with no active shading as well as during night were done. Outdoor and test cell air gap temperatures were continuously measured and wind pressure coefficients were evaluated from wind tunnel tests. The experimental results were compared to those obtained by a simple model by considering both thermal and wind effects on the façade. Based on this comparison, discharge coefficients were evaluated (which can be used for characterizing DSF behaviour).

An integrated and iterative modelling for analysing the thermal performance of DSF cavities with buoyancy-driven airflow by using Building Energy Simulation Program (BESP) along with a CFD package has been presented (Pappas and Zhai, 2008). A typical DSF cavity model was established and simulated while the model and the modelling process were calibrated and validated against experimental data. The validated model was utilized to develop correlations that can be implemented in a BESP, offering the accuracy gained from CFD simulations without the required computation time. Correlations for airflow rate through cavity, average and peak cavity air temperature, cavity air pressure and interior convection coefficient were developed. The correlations are valuable for «back of the envelope» calculations and for examining the accuracy of zonal-model-based energy and airflow simulation programs.

The impact of the double-skin orientation and the impact of wind direction on the behaviour of the DSF were studied by Gratia and De Herde (2004). The TAS software package in order to simulate the natural ventilation in a multi-story DSF was used. The software was also adopted in order to study daytime natural ventilation and different strategies necessary to achieve natural cooling for buildings with the use of DSF.

Cipriano et al. (2013) presented a work about heat transfer modelling of DSF, with emphasis on free-convection operation. A methodology to analyse the valid range of the existing mathematical correlations for the convective heat transfer coefficients and for the air mass flow rate in laminar and transition to turbulent free convection (providing an evaluation of the effect of the asymmetry of the wall boundary conditions) was proposed. In order to determine the accuracy of the existing heat transfer correlations, a numerical code, based on a stabilized finite element formulation (FEM), including the validation of the adopted physical and numerical hypothesis, was utilized to solve the incompressible Navier–Stokes equations within the air gap.

Moon et al. (2014) developed an Artificial Neural Network (ANN)-based temperature control method for energy efficient indoor thermal environment in buildings with double-skin envelope systems. A parametrical optimization process was presented and the analysis of the performance tests verified predictability and adaptability of the developed ANN model for diverse background conditions (in terms of stable root mean square and mean square error values). For the validation of optimization processes set up, field measurements were performed in an actual double-skinned building (for the case of Ansan, South Korea).

In addition, von Grabe (2002) developed a simulation method to investigate the temperature behaviour of double façades. The model accuracy was tested by means of experimental data. It should be noted that the model accuracy was improved by modifying flow resistance for multiple geometries.

Park et al. (2004) developed a lumped simulation model which was calibrated for DSF systems with controlled rotating louvers and ventilation openings. A parameter estimation technique and *in situ* monitoring of a full-scale element mounted on the south-facing façade of an existing building were adopted. The new approach was based on a postulated «minimalistic» lumped model, calibrated based on *in situ* measurements.

Balocco and Colombari (2006) presented a work about a non-dimensional analysis to analyse mechanically-ventilated double-glazed façade energy performance. A comparison between Nusselt number solved by means of experimental data and Nusselt number calculated by the validated multivariable correlation function was presented. Balocco and Colombari (2006) mentioned that due to its wide validity field the proposed method can be adopted to analyse the thermodynamic performance of glass DSF with mechanical ventilation.

Jiru and Haghighat (2008) modelled a ventilated DSF system based on a zonal approach. Zonal models can provide information about airflow and temperature distribution in a ventilated space faster than CFD, but with more accuracy and details than lumped and control-volume models. In the study of Jiru and Haghighat (2008), the zonal airflow equation, power-law, was utilized to evaluate the airflow through the shading device and cavities. The zonal energy equation was used to calculate the temperature distribution in the DSF system. The predicted temperature distributions were verified by means of measured values. The case used for the development and verification of the DSF models was an experimental test cell (Torino, Italy). The results demonstrated that the zonal models can assess the performance of the DSF system with venetian blinds while the developed DSF model can further be integrated into Building Simulation tool with HVAC (heating, ventilation and air conditioning).

Blanco et al. (2014) investigated the thermal behaviour of double-skin perforated sheet-metal façade, by considering several parameters (perforation rates, colours, materials, wind penetration). A numerical model based on the fundamental laws of heat transfer through the shell was proposed and validated by experimentation (by means of a complex data capture and storage system setup). The experimental process for the validation included monitoring metallic sheets within a range of 0–35% (perforation rates), black-white (colours) and galvanized steel-aluminium (materials) in a large-scale test campaign. Excellent agreement was observed between the outputs from the numerical model and the tests.

Saelens et al. (2008) compared multiple-skin façade configurations in order to improve their energy performance. Many different zones in TRNSYS 15 were used. It was demonstrated that controlling the air flows and the heat recovery of the air between the two building skins can lead to energy savings.

A theoretical study about double-façades with integrated PVs and motorized blinds has been presented by Charron and Athienitis (2006). The study aimed at investigating the effect of various design parameters in order to maximize the conversion of solar radiation to useful energy. A one-dimensional finite-difference thermal model was proposed (in order to calculate the energy and the electrical performance of the proposed system).

Recently, the electrical, thermal and visual performances of semi-transparent thin-film PV façades for building applications have been studied by several authors, for example by Olivieri et al. (2014). Based on different window-to-wall ratios, Olivieri et al. (2014) analysed the overall energy performance of five semi-transparent PV elements, evaluating their energy saving potential compared to a conventional solar control glass compliant with the local technical standard. The optical characterization was experimentally undertaken. The data obtained were used to perform simulations for a reference office building, by adopting a package of specific software tools (DesignBuilder, EnergyPlus, PVsyst and COMFEN). The results demonstrated that the potential energy savings range between 18% and 59% compared to the reference glass.

The integration of semi-transparent PVs in DSF has been recently studied. Peng et al. (2016) investigated the annual overall energy performance and the energy-saving potential of a ventilated PV DSF for the case of a cool-summer Mediterranean climate zone. In order to perform sensitivity analysis, a numerical simulation model based on EnergyPlus was used to simulate the PV DSF overall energy performance, simultaneously considering the thermal power and the daylight.

In general, BIST elements have a variable *g* value or solar heat gain coefficient (Maurer and Kuhn, 2013). This means that heating and cooling demands depend on the irradiance and on the operation of the collector. Standard collector models consider only the ambient temperature. For BIST elements, the temperature of the interior should be also considered. The performance of a BIST collector can be higher than in BA systems due to the decreased back losses. Models which include the energetic coupling between absorber and building interior can provide accurate predictions.

2.3.3 Flow diagram for BIST modelling

By taking into account the critical issues for the simulation of BIST systems (working fluid temperature, radiation, coupling with the building, etc.) that were highlighted in the studies presented in the previous section (2.3.2), the flow chart of Figure 2.3.4. has been developed. This flow chart shows the steps of the modelling and simulation procedure that should be adopted for the specific case of BIST configurations.

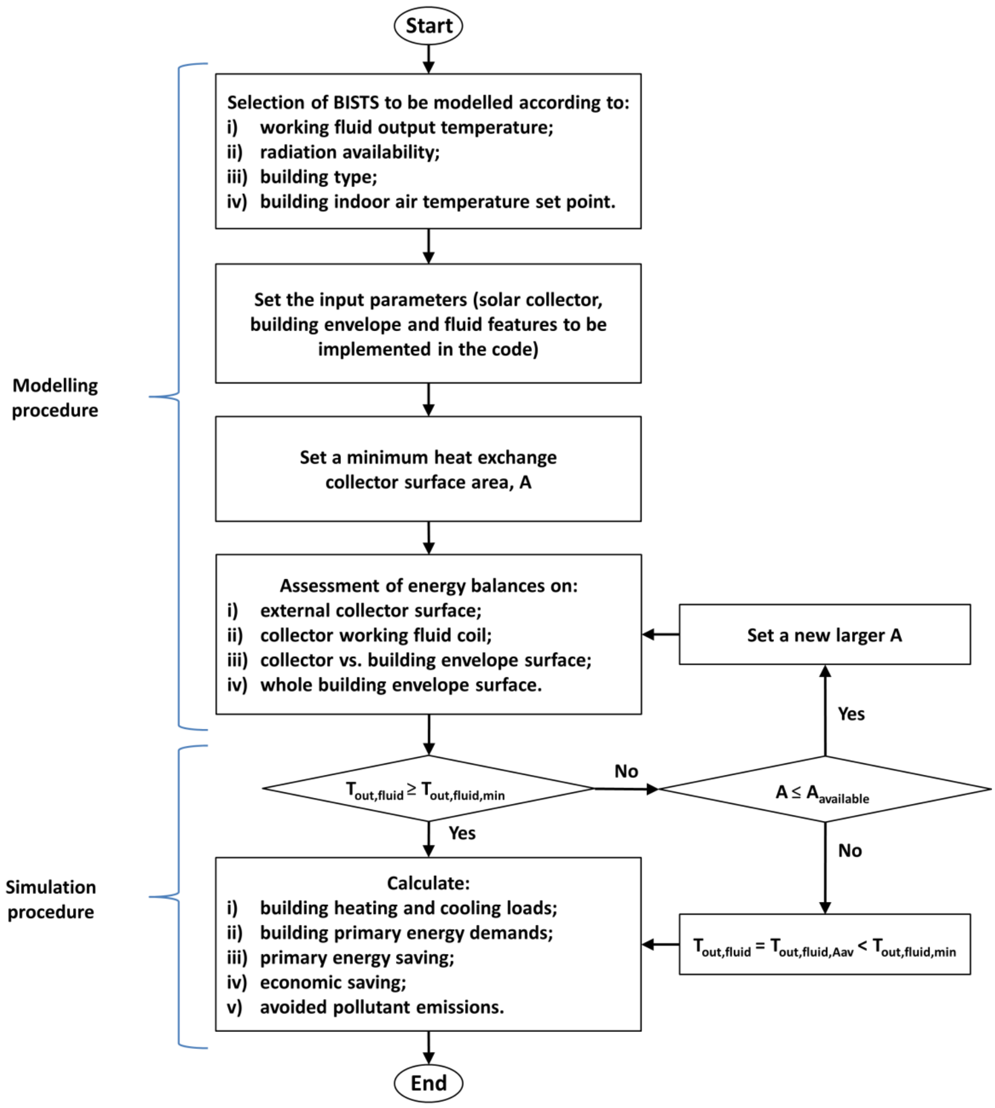


Figure 2.3.4. Flow chart for BISTS (building-integrated solar thermal system) modelling and simulation procedure.

In the flow chart of Figure 2.3.4., critical steps such as the selection of the BIST system that is going to be modelled based on certain criteria, the setting of the input parameters, the setting of a minimum heat exchange collector surface, the assessment of the energy balances and the final calculations are presented.

2.3.4 Performance analysis

2.3.4.1 Market established BIST systems

The present subsection is about market established BIST systems, presenting certain configurations along with their basic characteristics.

The WAF Fassadensysteme solar thermal façade system enables natural energy generation via the external walls of the building (WAF, 2016). The optimum thermal delivery of the WAF solar façade lies within that of low-temperature range. In order to achieve the highest efficiency of the façade, the fluid temperature should be between 35°C and 45°C. In this range of temperature, preheating of drinking water, energy provision for low temperature heating or low temperature process heat can be provided.

The unglazed flat plate collector by Energie Solaire (Energie Solaire, 2016) ideally suited to large installations requiring water up to 50°C. The collector consists of two sheets of stainless steel which are assembled back to back with their peaks and edges shifted in such a way relative to one another so the fluid can flow through the resulting voids. The lack of glazing cover allows it to achieve a maximum (optical) collection efficiency of 95%. A weather proof selective absorber coating with absorptivity of 0.94 and emissivity of 0.18 allows the system to achieve a heat loss coefficient to 9.81 W/m^2/K. The system is expected to generate 500-770 kWh/m^2/year for installations in France. Nivo (2014) reported on the performance of an «Energie Solaire» system installed on the South facing façade at the Centre d´Entretien des Routes Nationales (CeRN) in Switzerland. The total collector area was 576 m^2 and produced 288,000 kWh of hot water per year.

BIO TECture (2014) reported on a multifunctional BIST system installed on a residential building in Hollywood, USA. The BIST system consists of 5 specially designed boxed sections of horizontal oriented evacuated tubes. The system was installed in the south facing façade of the building. The 18.5 m^2 system was designed to provide water pre-heating, solar shading and natural cooling. The system provides 30% of the building hot water demand. The natural cooling concept reduces the heat gain by an average of 4.8 % and 18.9 % peak demand reduction.

SolarWall (2016) has reported a typical efficiency of over 60% for their BIST system and annual CO_2 savings 200 kg/m^2 of collector. Practically the system provides temperature lifts of 16-38°C for a conventional and 20-55°C for a 2-Stage system on sunny days in cold climates.

A Kingspan ISAC system integrated on the façade of a commercial building in Doncaster, UK provides solar pre-heating to a floor space area of 645 m^2 having a conditioned volume of 11,483 m^3. The solar-heated air flow rate for the building was calculated at 89 m^3/h per m^2 of collector panel (a total panel area of 124.8 m^2 was required). The system delivered 13.14

MWh of the total 66.32 MWh space heating demand. This provided a calculated reduction of 2.36 t CO_2 emissions per year and a 5-year payback period for the installation.

Athienitis et al. (2011) reported on a façade-integrated PVT system (with an unglazed transpired air collector) in Montreal, Canada. The 288 m^2 system has a peak electrical power output of 24.5 kW and preheated up to about 7.5 m^3/s of fresh air for the building occupants. It was noted that while the overall combined thermal efficiency for the unglazed transpired collector is higher than that of the BIPVT system, the generated energy (assuming that electricity is at least four times more valuable than heat) was found to be 7-17% higher.

2.3.4.2 Experimental BIST systems

Ramirez-Stefanou et al. (2011) reported on a BIST system based on dielectric asymmetric compound parabolic concentrator (DACPC). At slope β=30° the average optical efficiency of direct beam was 44.3% having a total energy collected of 0.758 kWh/m^2 from 9:22 to 15:15. For sloped angles of 60° and 90° the average optical efficiencies for direct beam were 93% and 86%, respectively. The total collected energy was 1.591 kWh/m^2 for β=60° and 1.266 kWh/m^2 for β=90°. For the 21st of December simulation, the system showed a 93% optical efficiency of direct beam and a total energy collection of 1.322 kWh/m^2. The optical efficiency of the diffuse beam was 54.5% for all the cases. Outdoor experimental characterization of the DACPC collector during July and August showed that the average collection efficiency is 65%. Slope angles of 45° and 60° had collection efficiencies of 61.8% and 62.5% under 675 W/m^2 and 426 W/m^2, respectively. The serpentine arrangement had a collection efficiency of 50.1%, which was 7% greater than the parallel arrangement at the same solar conditions. The maximum temperature achieved by the DACPC collector was 80.2°C under stagnation with an average solar radiation of 760 W/m^2. Under 110 W/m^2 for a period of time of about 50 minutes the maximum temperature reached was 30.3°C.

Fieber et al. (2004) reported on the performance of a building-integrated multifunctional PVT solar window which was constructed of PV cells laminated on solar absorbers placed in a window behind the glazing. A 1 m^2 prototype was evaluated in terms of its sun shading and U-value properties while its PV and active thermal outputs were monitored. For a double glazed anti-reflectively coated window an improvement in U-value from 2.9 to 1.2 W/m^2K was reported with the reflectors close. The annual transmittance through the window was estimated to 609 kWh/m^2 (of which approximately 10% is expected to be delivered by the PV modules). About 20% is delivered as active solar heat and 30% as net passive space heating. The performance of the system was analysed separately for passive gains, active thermal gains and PV electricity yield. According to a proposed regulating schedule passive gains were estimated to 210 kWh/m^2 annually. The performance of the fully concentrated PVT absorber was estimated to 79 kWh/m^2 of electricity, and at least 155 kWh/m^2 of heat for domestic hot water.

A model for the simulation of the electric and hot water production was developed and it was able to perform the yearly energy simulations for different features, such as the shading of the cells and/or the effects of the glazing (can be included or excluded). The simulation can be run with the reflectors in active, passive, up right and horizontal positions. The simulation program has been calibrated against the measurements on a prototype solar window placed in Lund, Southern Sweden and against a solar window built into a single family house at Solgarden, Central Sweden. The results obtained from the simulation showed that the solar window annually produces about 35% more electric energy per unit cell area as compared to a vertical flat PV module (Davidsson et al., 2012).

2.3.5 Case study: Modelling and thermal analysis of roof-integrated solar tile collectors

The present section aims at describing a case study where simulations and performance analysis are conducted in agreement with the previous sections of the present chapter. The new scientific achievements, methods, procedures and limits of the applicability for modelling approaches in terms of the recently developed solar tile collectors are discussed.

2.3.5.1 Introduction

It is important to carry out research/development activities in order to harness renewable energy and this resulted in the birth and using of equipment, systems and emergence commercially viable technologies (in the past decades) (Butti and Perlin, 1980). Surveys and studies show that people appreciate solar collectors, not only because of their usefulness but also because of their aesthetic advantages, and this is the basic idea of the present study taking into consideration the advanced design of roof-integrated solutions (Figure 2.3.5).

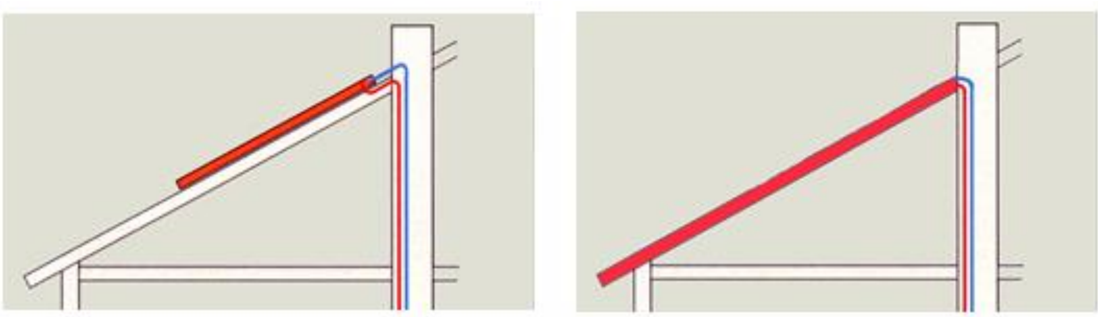
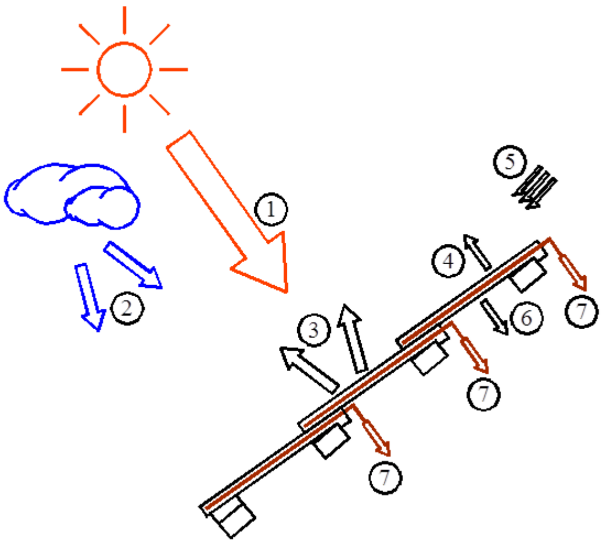


Figure 2.3.5. The traditional (left) and the advanced (right) structure design of a solar collector. (Fekete, 2015).

The roof integrated collectors convert the solar irradiance into heat energy with certain losses, which can be divided into optical and heat losses (Farkas, 2011; Fekete, 2015) as it can be seen in Figure 2.3.6.



Major energy factors:
1. Direct solar radiation
2. Diffused solar radiation
3. Reflection
4. Losses from convection
5. Wind, rain and snow convection
6. Conduction losses
7. Useful output

Figure 2.3.6. Energy balance for roof-integrated solar collectors.

In addition, another issue is how a solution is justified when the building components can be also used to capture solar energy. In terms of the energy, one can draw it less efficiently but there is more surface area available.

2.3.5.2 Modelling approach

First, the thermal behaviour of BI collector elements is analysed. In the course of this task the goal is to increase and optimize the thermal efficiency of the integrated shell-structured collector bodies. There is an opportunity to reach the technologically maximum efficiency by changing the structure and substance construction of the collectors (Kendrick, 2009).

The temperature of the solar tiles depends mainly on the radiation intensity and the size of the absorber surface (Pisello et al., 2011). Additionally, the rest of the influencing factors are the following: effective irradiation (I), ambient temperature (T_a), average temperature of the flowing working fluid (T_m), inlet temperature of the working fluid to the collector (T_{in}). During the warming course of the working fluid, in order to calculate the outlet temperature (T_{out}) and the tile temperature (T_t) according to the mass flow rate ($\dot{m}$), a differential equation based on heat and mass transfer approach is developed.

The input/output scheme of the solar tile element prepared for modelling can be seen in Figure 2.3.7 (Fekete, 2015).

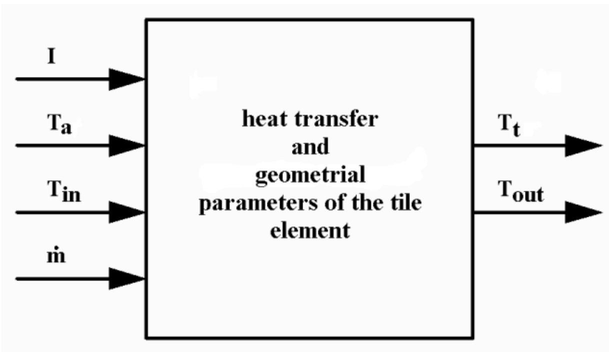


Figure 2.3.7. The input/output of the solar tile element for realization.

The heat transfer model of the tile element is given in Figure 2.3.8, where the section by section calculation method is illustrated.

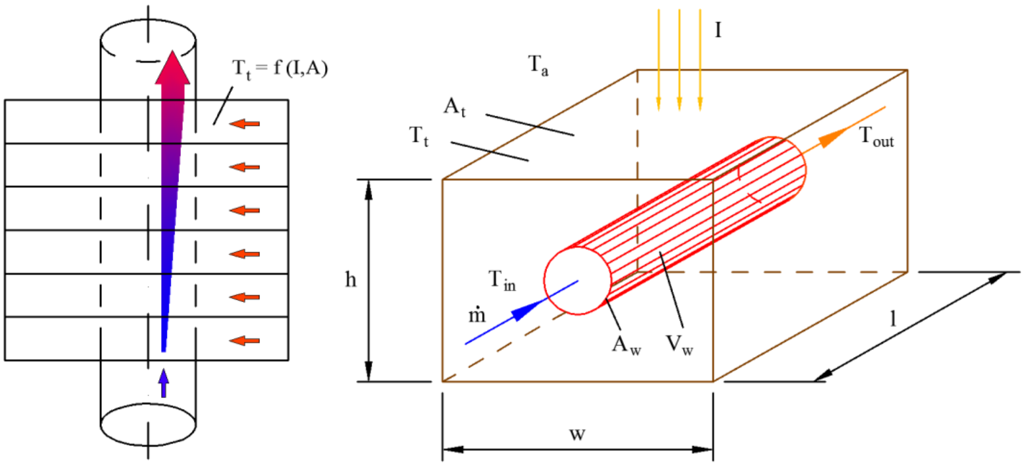


Figure 2.3.8. Structure and heat balance scheme of the tile element (Fekete, 2015).

During the simulation along with the model equations several environmental variables should be entered in addition to the geometric data and the physical characteristics of the materials used. The governing equations for the Matlab coded simulations can be written as follows (Fekete, 2015):

Surface of the tile element in the direction of the environment:

$$A_{te} = 2A_t + 2lh \tag{2.3.1}$$

Volume and mass of the tile element:

$$V_t = h\,w\,l \tag{2.3.2}$$

$$m_t = V_t\,\rho_t \tag{2.3.3}$$

The effective radiation intensity on the tile is the difference of the global and the loss intensities:

$$I = I_g - I_l \tag{2.3.4}$$

The heat balance between the water and the tile:

$$c_w\,m_w\,\dot{T}_w = k_{wt}\,A_w\,(T_t - T_w) \tag{2.3.5}$$

The heat balance between the element of the tile and the environment:

$$c_t\,m_t\,\dot{T}_t = I\,A_t + k_{te}A_t\,(T_a - T_t) - k_{wt}\,A_w\,(T_t - T_{out}) \tag{2.3.6}$$

The water temperature inside the tile:

$$c_w\,\rho_w\,V_w\,\dot{T}_{out} = k_{wt}\,A_w\,(T_t - T_{out}) - \dot{m}\,c_w\,(T_{out} - T_{in}) \tag{2.3.7}$$

By adopting equations (2.3.5) - (2.3.7) for the Matlab-coded simulations, the temperatures of the tile and the outlet fluid can be obtained:

$$\dot{T}_t = \frac{I\,A_t + k_{te}A_{te}\,(T_a - T_t) - k_{wt}A_w(T_t - T_{out})}{c_t\,m_t} \tag{2.3.8}$$

$$\dot{T}_{out} = \frac{k_{wt}A_w\,(T_t - T_{out}) - \dot{m}_w\,c_w\,(T_{out} - T_{in})}{c_w\rho_w V_w} \tag{2.3.9}$$

Based on the equations (2.3.1) - (2.3.9) the flow chart of the simulation process can be seen in Figure 2.3.9, including the following notations:

$$U[1] = T_t;\ U[2] = T_{out};\ U[3] = T_{in}. \tag{2.3.10}$$

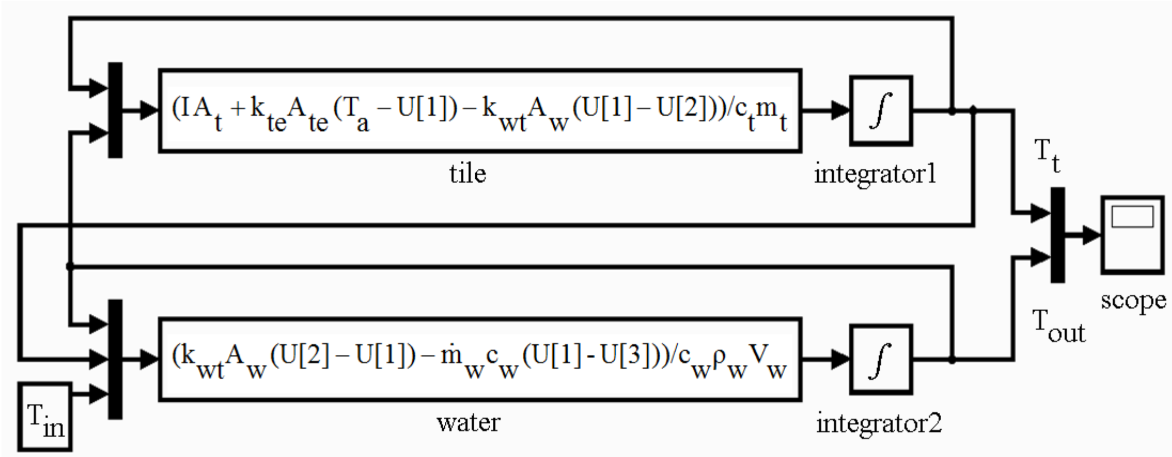


Figure 2.3.9. Matlab realization of the tile collector model (Fekete, 2015).

2.3.5.3 Calculation results and validation

Table 2.3.1 shows the values of the parameters used for the experiments and in the frame of Matlab simulations.

Table 2.3.1. The values of the parameters used for the experiments and for the simulations. Source: Fekete (2015).

Parameters	Values	Parameters	Values	Parameters	Values
l	2.6 m	c_t	900 J/kgK	$\dot{m}$	0.01 kg/s
d_w	0.005 m	c_w	4196 J/kgK	ρ_w	1000 kg/m^3
ρ_t	2000 kg/m^3	w	0.02 m	T_a	20°C
h	0.015 m	I	600 W/m^2	T_{in}	18 °C
k_{te}	20 W/m^{2}K	k_{wt}	150 W/m^{2}K		

The temperature distributions in the shell-structured tiles calculated by means of the simulations were first analysed. Figure 2.3.10 shows the warming process in some locations of the tile (A and B) until steady state is reached (the locations of A and B points are indicated in Figure 2.3.11). Based on the aforementioned parameters, the maximum available tile surface temperature difference (ΔT_t) is about 27°C, the outlet fluid temperature difference (ΔT_{out}) is about 25°C and the inlet temperature (T_{in}) is 18 °C.

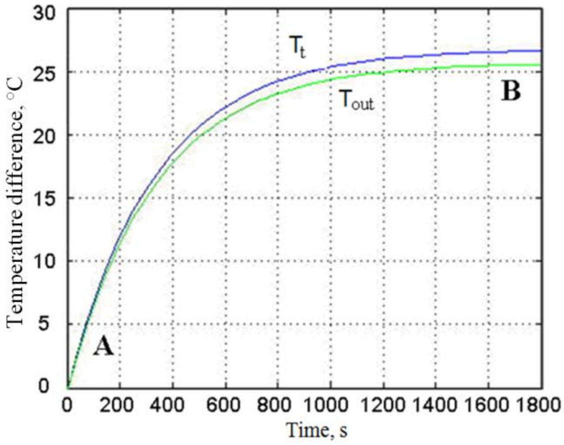


Figure 2.3.10. The calculated temperature differences for the tile and for the outlet working fluid (Fekete, 2015).

In Figure 2.3.11, the matching of the calculated and the measured temperature is illustrated. The fluid enters at point A and exits at the tile point B. Point C shows the maximum tile surface temperature. The colour scale presents the approximate temperature values, along with an accuracy of 0.1°C of the thermal imager software.

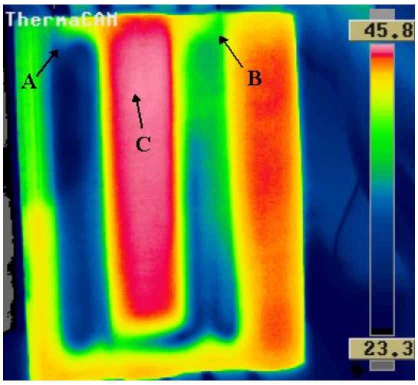


Figure 2.3.11. The temperature distribution of a tile element. (Fekete, 2015).

Another case that was studied was based on varying the pipe length built in the tile (Figure 2.3.12: the length of the pipe is 2 m (left graph) and 3 m (right graph), the radiation is 1000 W/m^2, the air temperature is 20°C and the temperature of the working fluid is 18°C). The values of the other parameters are listed in Table 2.3.1.

In addition, the findings from the simulations show the warming process when steady state is reached. The influence of the pipe length reveals that the available maximum temperature of the tile surface (T_t) is about 30°C, the outlet fluid temperature (T_{out}) is about 28°C (left side), in the other case the available maximum temperature of the tile surface (T_t) is around 32°C, the outlet fluid temperature (T_{out}) is about 30°C (right side). In the second embodiment, the built-in tube is longer; therefore, the output temperature of the fluid is consequently higher. A further increase in tube length is not economical as the tile collector reaches a maximum performance.

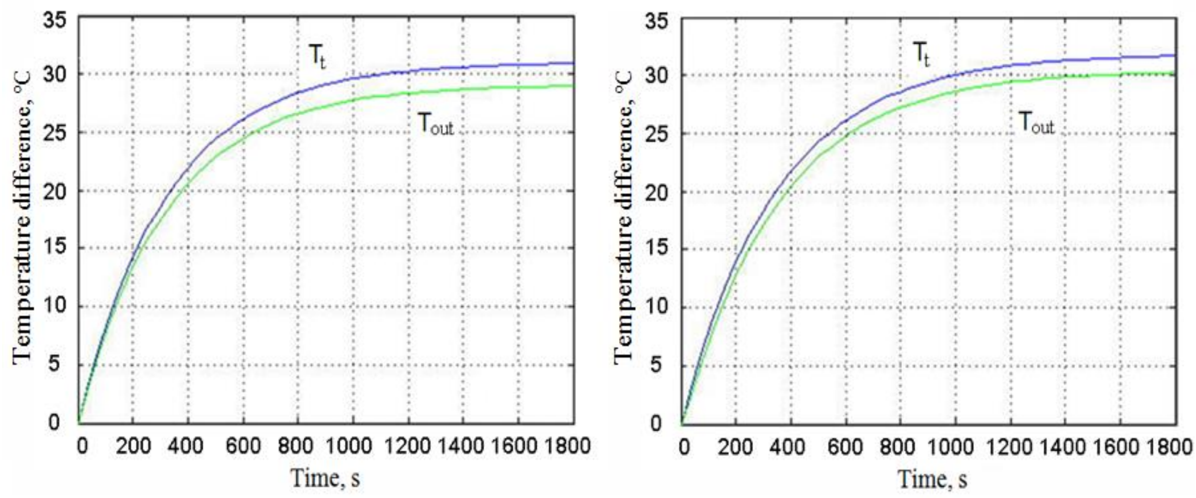


Figure 2.3.12. Simulation results with different pipe length in the tile element.

Parameter sensitivity study

The simulation results can be also used to determine the other influencing parameters and their operational values, which can be used for the development of a new collector structure. In Table 2.3.2, the most influential parameters are presented as shaded (along with some practical notes).

Table 2.3.2. The list of the influential parameters (the most influential parameters are shaded). (Fekete, 2015).

Parameters	**Notes**
Length of the tube (l)	It can be used for the optimization of the heat transfer, number of serial elements
Diameter of the tube (d_w)	It can be used for the optimization of the flow resistance, $d_w < h$; $d_w < w$; d_w max. is about $h/2$ and $w/2$
Mass flow rate of water ($\dot{m}$)	It can be used for pump optimization
Volume of the tube (V_w)	It can be used for the optimization of heat transfer
Surface of the tube (A_w)	It can be used for the optimization of heat transfer
Specific heat of the working fluid (c_w)	It can be considered other than water
Density of the working fluid (ρ_w)	It can be considered other than water

2.3.5.4 Temperature distribution measurements and evaluation

Processing and evaluation of the large amount of data originated from the performed measurements are suitable for the preparation of the subsequent analysis. For such purposes, an appropriate data acquisition system with appropriate analysis software is developed.

The collector surface temperature distribution, as the most important feature, it is rather difficult to measure exactly by using conventional temperature measuring devices. For that reason, the calculated temperature values were verified by infrared camera recordings. The accuracy of the infrared images software was about ±0.1°C. Figure 2.3.13 shows some recording features. During the evaluation of the thermal images, the temperatures are identified according to the radiation intensity levels. The modern infrared cameras setting can be chosen freely; however, for detection purposes it is recommended to use the colour scale standard settings. In addition, in Figure 2.3.13 colour classification examples are illustrated.

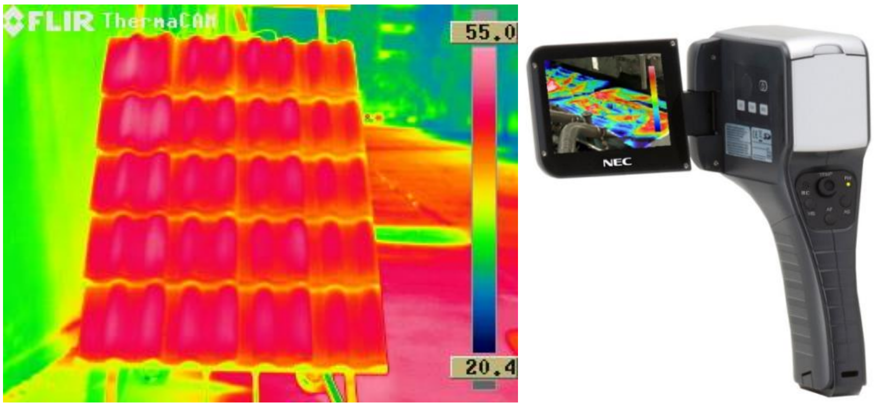


Figure 2.3.13. Measured surface temperature distribution of the elements: recording features and examples of colour classification (Fekete, 2015).

In Table 2.3.3, the symbols adopted in the frame of this case study are presented, along with explanations for each case.

2.3.6 Conclusions

The first part of the present chapter presents an overview on the validation of developed codes, thermal and optical, within the field of BIST systems. Specific requirements for BIST modelling and simulation are highlighted and representative studies are cited. Within the BI configurations the systems are presented divided into two groups: opaque and transparent systems. The second part of the chapter presents a flow chart specifically for the modelling and simulation procedure of BIST configurations. This flow chart highlights the steps needed for the modelling/simulation processes. In addition, a separate section with emphasis on performance analysis is included, presenting information about market-established and experimental BIST systems. Finally, as a continuation of the issues which are presented in the above mentioned sections of the chapter, a case study is included.

Table 2.3.3. The symbols used for the modelling of the case study.

A_t	Tile surface (m^2)
A_{te}	Surface of the tile element in the direction of the environment (m^2)
A_w	Surface of the working fluid (m^2)
c_t	Specific heat of tile material (J/kg°C)
c_w	Specific heat of water (J/kg°C)
I	Effective irradiation (W/m^2)
k_{te}	Heat transfer coefficient between tile and ambient (W/m^2°C)
k_{wt}	Heat transfer coefficient between tile and water (W/m^2°C)
$\dot{m}$	Mass flow rate of the working fluid (kg/s)
m_t	Mass of the tile (kg)
m_w	Mass of the working fluid (kg)
ρ_w	Density of water (kg/m^3)
T	Temperature (°C)
$\dot{T}$	Temperature difference (°C)
V_w	Volume of the working fluid (m^3)
w, h, l	Geometric parameters of the tile (width, thickness, length) (m)
Subscripts	
a	Ambient
in	Inlet
m	Average (mean)
out	Outlet
t	Tile
w	Working fluid (water)

The results show that there are some specific requirements such as solar gain control, daylight utilisation and indoor environment quality which should be taken into account in the frame of BIST modelling. Regarding validation methodologies, on-site validation has been conducted for several types of systems (active façades, multi-section façades, etc.). On the other hand, indoor solar simulators facilitate solar research in cold climates and in the literature there are studies about laboratory validation for multiple configurations (concentrating BIPV, façade-integrated solar systems, etc.). Moreover, test cells provide an intermediate solution between a real building and an experiment in the laboratory and they have been also adopted for some studies.

The literature review about the validated models for BIST reveals that there are studies for opaque as well as for transparent systems. Within the field of transparent BIST, several configurations have been modelled: façade-integrated collectors for high-rise buildings, complex façades, glazings with venetian blinds, curtain walls, double-skin façades, etc. Furthermore, it should be noted that there are few studies in the field of BIST in the agricultural sector and thus, it would be interesting the investigation of systems such as innovative greenhouses with BIST.

In terms of the flow chart for BIST modelling and simulation, critical steps such as the selection of the BIST system that is going to be modelled based on certain criteria, the setting of the appropriate input parameters, the setting of a minimum heat exchange collector surface and the assessment of the energy balances should be adopted.

Concerning performance analysis, several systems have been developed and studied, for example experimental BIST based on different configurations (with/without concentrators, solar windows, PVT, etc.). Moreover, there are BIST configurations from companies (for some cases in collaboration with universities) which have been established in the market.

Regarding the case study, it is about modelling and thermal analysis of roof-integrated solar tile collectors. The goal is the increase and the optimization of the thermal efficiency of the integrated shell-structured collector bodies. Matlab simulations are utilized. Furthermore, temperature distribution measurements are also included. A sensitivity study is conducted, revealing that there are some critical parameters such as the length and the diameter of the tube and the mass flow rate of water.

In this way, the present chapter provides a complete picture about modelling and performance analysis of multiple BIST configurations, highlighting issues which should be taken into account in the frame of BIST modelling.

REFERENCES

Agrawal S., Tiwari A., Experimental validation of glazed hybrid micro-channel solar cell thermal tile, Solar Energy, 2011; 85:3046–3056.

Albanese M.V., Robinson B.S., Brehob E.G., Sharp M.K., Simulated and experimental performance of a heat pipe assisted solar wall, Solar Energy, 2012;86:1552–1562.

Anderson T. N., Duke M., Morrison G. L., Carson J. K., Performance of a building integrated photovoltaic/thermal (BIPVT) solar collector, Solar Energy, 2009;83:445–455.

Anderson T.N., Duke M., Carson J.K., The effect of colour on the thermal performance of building integrated solar collectors, Solar Energy Materials & Solar Cells, 2010;94:350–354.

Assoa Y.B, Ménézo C., Dynamic study of a new concept of photovoltaic-thermal hybrid collector, Solar Energy, 2014;107:637-652.

Athienitis A., Bambara J., O'Neil B., Faille J., A prototype Photovoltaic/Thermal system integrated with transpired collector, Solar Energy, 2011;85:139–153.

Balocco C., Colombari M., Thermal behaviour of interactive mechanically ventilated double glazed façade: Non-dimensional analysis, Energy and Buildings, 2006;38:1–7.

BIO Tecture (2014), DURAND DR <http://www.bio-tecture.net/downloads/residential_casestudy.pdf> Accessed on May 2014.

Blanco J.M., Arriaga P., Rojí E., Cuadrado J., Investigating the thermal behavior of double-skin perforated sheet façades: Part A: Model characterization and validation procedure, Building and Environment, 2014;82:50-62.

Buker M.S., Mempouo B., Riffat S.B., Performance evaluation and techno-economic analysis of a novel building integrated PV/T roof collector: An experimental validation, Energy and Buildings, 2014;76:164-175.

Butti K., Perlin J., A golden thread: 2500 years of solar architecture and technology, Marion Boyars, London-Boston, 1980.

Chan Y.C., Tzempelikos A., A Simulation and Experimental Study of the Impact of Passive and Active Façade Systems on the Energy performance of Building Perimeter Zones, ASHRAE Transactions 2012;118 (2):149.

Charron R., Athienitis A.K., Optimization of the performance of double-façades with integrated photovoltaic panels and motorized blinds, Solar Energy 2006;80:482–491.

Chemisana D., Ibáñez M., Rosell J. I., Characterization of a photovoltaic-thermal module for Fresnel linear concentrator, Energy Conversion and Management, 2011;52:3234–3240.

Chen Y., Galal K., Athienitis A.K., Modeling, design and thermal performance of a BIPV/T system thermally coupled with a ventilated concrete slab in a low energy solar house: Part 2, ventilated concrete slab, Solar Energy, 2010;84:1908-1919.

Chow T.T., He W., Chan A.L.S., Fong K.F., Lin Z., Ji J., Computer modeling and experimental validation of a building-integrated photovoltaic and water heating system, Applied Thermal Engineering, 2008;28:1356–1364.

Cipriano J., Houzeaux G., Chemisana D., Lodi C., Martí-Herrero J., Numerical analysis of the most appropriate heat transfer correlations for free ventilated double skin photovoltaic façades, Applied Thermal Engineering, 2013;57:57-68.

Corbin C.D., Zhai Z.J., Experimental and numerical investigation on thermal and electrical performance of a building integrated photovoltaic–thermal collector system, Energy and Buildings, 2010;42:76–82.

D'Orazio M., Di Perna C., Di Giuseppe E., Experimental operating cell temperature assessment of BIPV with different installation configurations on roofs under Mediterranean climate, Renewable Energy, 2014;68:378-396.

Davidsson H., Perers B., Karlsson B., System analysis of a multifunctional PV/T hybrid solar window, Solar Energy, 2012;86:903–910.

Diarce G., Campos-Celador Á., Martin K., Urresti A., García-Romero A., Sala J.M., A comparative study of the CFD modeling of a ventilated active façade including phase change materials, Applied Energy, 2014;126:307–317.

Energie Solaire SA, 2016. Le capteur sans vitrage. <http://www.energie-solaire.com/wq_pages/fr/site/page-70.php> Accessed on June 2016.

Farkas I. (2011), Solar energy applications, in Hungary, Renewable Energy Handbook 2011, /ed. by Kovács R./, Poppy Seed 2002 Bt, 2011.

Fekete I. (2015), Building integrated shell-structured solar collectors, Thesis of PhD Dissertation, Szent István University, Gödöllő, Hungary, 2015.

Fieber A., Nilsson J., Karlsson B. PV performance of a multifunctional PV/T hybrid solar window, Proceedings of 19th European Photovoltaic solar energy conference and exhibition, 7-11 June 2004, Paris, France.

Glória Gomes M., Santos A.J., Moret Rodrigues A., Solar and visible optical properties of glazing systems with venetian blinds: Numerical, experimental and blind control study, Building and Environment, 2014;71:47–59.

Gratia E., De Herde A., Natural ventilation in a double-skin facade, Energy and Buildings, 2004;36:137–146.

Gupta N., Tiwari A., Tiwari G.N., Exergy analysis of building integrated semitransparent photovoltaic thermal (BiSPVT) system, Engineering Science and Technology, an International Journal, Article in press, 2016.

http://solarintegrationsolutions.org/

Ibrahim M., Wurtz E., Biwole P. H., Achard P., Transferring the south solar energy to the north facade through embedded water pipes, Energy, 2014;78:834-845.

Ji J., Luo C., Chow T.-T., Sun W., He W., Thermal characteristics of a building-integrated dual-function solar collector in water heating mode with natural circulation, Energy, 2011a;36:566–574.

Ji J., Luo C.L., Chow T.T., Sun W., He W., Modelling and validation of a building-integrated dual-function solar collector, Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 2011b;225:259-269.

Jiru T.E., Haghighat F., Modeling ventilated double skin façade - A zonal approach, Energy and Buildings, 2008;40:1567-1576.

Joe J., Choi W., Kwak Y., Huh J.-H., Optimal design of a multi-story double skin façade, Energy and Buildings 2014;76:143–150.

Joudi K.A., Farhan A.A., Greenhouse heating by solar air heaters on the roof, Renewable Energy, 2014;72:406-414.

Kalogirou SA., Building integration of solar renewable energy systems towards zero or nearly zero energy buildings, International Journal of Low-Carbon Technologies, 2013;0:1–7.

Kendrick C. (2009), Metal roofing on residential buildings in Europe: A dynamic thermal simulation study, Report 090903ECC, Oxford, September 2009.

Khanal R., Lei C., A numerical investigation of buoyancy induced turbulent air flow in an inclined passive wall solar chimney for natural ventilation, Energy and Buildings, 2015;93:217–226.

Kingspan: http://www.kingspan.com/

Kuhn T.E., Herkel S., Frontini F., Strachan P., Kokogiannakis G., Solar control: A general method for modelling of solar gains through complex facades in building simulation programs, Energy and Buildings, 2011;43:19–27.

Lamnatou Chr., Mondol J.D., Chemisana D., Maurer C., Modelling and simulation of Building-Integrated solar thermal systems: Behaviour of the system, Renewable and Sustainable Energy Reviews, 2015a;45:36-51.

Lamnatou Chr., Mondol J.D., Chemisana D., Maurer C., Modelling and simulation of Building-Integrated solar thermal systems: Behaviour of the coupled building/system configuration, Renewable and Sustainable Energy Reviews; 2015b;48:178-191.

Lawrence Berkeley National Laboratory. EnergyPlus - Engineering documentation: the reference to EnergyPlus calculations. University of Illinois & Ernest Orlando Lawrence Berkeley National Laboratory, Chicago, 2001.

Lee J.B., Park J.W., Yoon J.H., Baek N.C., Kim D.K., Shin U.C., An empirical study of performance characteristics of BIPV (Building Integrated Photovoltaic) system for the realization of zero energy building, Energy, 2014;66:25-34.

Li R., Dai Y., Wang R., Experimental investigation and simulation analysis of the thermal performance of a balcony wall integrated solar water heating unit, Renewable Energy, 2015a;75:115-122.

Li G., Pei G., Ji J., Su Y., Outdoor overall performance of a novel air-gap-lens-walled compound parabolic concentrator (ALCPC) incorporated with photovoltaic/thermal system, Applied Energy, 2015b;144:214–223.

Li R., Dai Y.J., Wang R.Z., Experimental and theoretical analysis on thermal performance of solar thermal curtain wall in building envelope, Energy and Buildings, 2015c;87:324–334.

Li S., Karava P., Energy modeling of photovoltaic thermal systems with corrugated unglazed transpired solar collectors – Part 2: Performance analysis, Solar Energy, 2014;102:297-307.

Li S., Karava P., Currie S., Lin W.E., Savory E., Energy modeling of photovoltaic thermal systems with corrugated unglazed transpired solar collectors – Part 1: Model development and validation, Solar Energy, 2014;102, 282-296.

Liao L., A. K. Athienitis, L. Candanedo, K.-W. Park, Y. Poissant, M. Collins , Numerical and Experimental Study of Heat Transfer in a BIPV-Thermal System, Journal of Solar Energy Engineering 129(4), 423-430 (May 15, 2007) (8 pages) doi:10.1115/1.2770750

Marques da Silva F., Glória Gomes M., Moret Rodrigues A., Measuring and estimating airflow in naturally ventilated double skin facades, Building and Environment, 2015;87:292-301.

Maurer C. (2012), Theoretical and experimental analysis and optimization of semi-transparent solar thermal façade collectors, Dissertation, Fakultät für Architektur, Karlsruher Institut für Technologie (KIT).

Maurer C., Baumann T., Hermann M., Di Lauro P., Pavan S., Michel L. et al., Heating and cooling in high-rise buildings using facade-integrated transparent solar thermal collector systems, Journal of Building Performance Simulation, 2013;6:449-457.

Maurer C., Cappel C., Kuhn T.E., Simple models for building-integrated solar thermal systems, Energy and Buildings, 2015;103:118–123.

Maurer C., Di Lauro P., Hermann M., Kuhn T.E., Transparent solar thermal collectors – measurements and modelling, in: Thermische Solarenergie / 22. Symposium, May 9-11, 2012, Ostbayerisches Technologie-Transfer-Institut e.V. (OTTI), Kloster Banz, Bad Staffelstein.

Maurer C., Kuhn T.E., Variable *g* value of transparent façade collectors, Energy and Buildings, 2012;51:177–184.

Maurer C., Kuhn T.E., The *g* value of building-integrated solar thermal systems, In: Energy Forum, Advanced Building Skins: 5-6 November 2013, Bressanone, Italy, pp. 65–68.

Moon J.W., Lee J.H., Yoon Y., Kim S., Determining optimum control of double skin envelope for indoor thermal environment based on artificial neural network. Energy and Buildings, 2014;69:175–183.

Motte F., Notton G., Cristofari C., Canaletti J.L., A building integrated solar collector: Performances characterization and first stage of numerical calculation, Renewable Energy, 2013a;49:1-5.

Motte F., Notton G., Cristofari C., Canaletti J.L., Design and modelling of a new patented thermal solar collector with high building integration, Applied Energy, 2013b;102:631–639.

Munari Probst M.C., Roecker C., Towards an improved architectural quality of building integrated solar thermal systems (BIST), Solar Energy, 2007;81:1104–1116.

Nayak S., Tiwari G. N., Energy and exergy analysis of photovoltaic/thermal integrated with a solar greenhouse, Energy and Buildings, 2008;40:2015–2021.

Nivo atelier, 2014. Le CeRN de Bursins <www.nivo.ch/cern.html> Accessed on May 2014.

Notton G., Motte F., Cristofari C., Canaletti J.L., Performances and numerical optimization of a novel thermal solar collector for residential building, Renewable and Sustainable Energy Reviews, 2014;33:60–73.

Olivieri L., Caamaño-Martín E., Moralejo-Vázquez F.J., Martín-Chivelet N., Olivieri F., Neila-Gonzalez F.J., Energy saving potential of semi-transparent photovoltaic elements for building integration, Energy, 2014;76:572-583.

Palmero-Marrero A.I., Oliveira A.C., Evaluation of a solar thermal system using building louvre shading devices, Solar Energy, 2006;80:545–554.

Pappas A., Zhai Z., Numerical investigation on thermal performance and correlations of double skin facade with buoyancy-driven airflow, Energy and Buildings, 2008;40:466–475.

Park C.S, Augenbroe G., Messadi T., Thitisawat M., Sadegh N., Calibration of a lumped simulation model for double-skin façade systems, Energy and Buildings, 2004;36:1117–1130.

Peng J., Curcija D.C., Lu L., Selkowitz S.E., Yang H., Zhang W., Numerical investigation of the energy saving potential of a semi-transparent photovoltaic double-skin facade in a cool-summer Mediterranean climate, Applied Energy 2016;165:345–356.

Perez R., Seals R., Michalsky J., All-weather model for sky luminance distribution - Preliminary configuration and validation, Solar Energy, 1993;50:235-245.

Pisello, A., Rossi, F., Cotana, F., Increasing roof albedo: a retrofitting strategy for buildings and environment, 48° Convegno Internazionale AiCARR Baveno, Lago Maggiore, 22-23 September 2011.

Ramirez-Stefanou M., Mallick T., Smyth M., Mondol J.D., Zacharopoulos A., Hyde T.J., (2011), Characterisation of a Line-Axis Solar Thermal Collector for Building Façade Integration, Sustainability in Energy and Buildings, Volume 7 of the series Smart Innovation, Systems and Technologies, pp. 277-287.

Saelens D., Roels S., Hens H., Strategies to improve the energy performance of multiple-skin facades, Building and Environment, 2008;43:638–650.

Sarachitti R., Chotetanorm C., Lertsatitthanakorn C., Rungsiyopas M., Thermal performance analysis and economic evaluation of roof-integrated solar concrete collector, Energy and Buildings, 2011;43:1403–1408.

Shan F., Cao L., Fang G., Dynamic performances modeling of a photovoltaic–thermal collector with water heating in buildings, Energy and Buildings, 2013;66:485–494.

Shen H., Tzempelikos A., Daylighting and energy analysis of private offices with automated interior roller shades, Solar Energy, 2012;86:681–704.

Shukla A.K, Sudhakar K., Baredar P., Exergetic analysis of building integrated semitransparent photovoltaic module in clear sky condition at Bhopal India, Case Studies in Thermal Engineering, 2016;8:142–151.

SolarWall, 2016. How the SolarWall® Technology Provides Fresh Air & Free Heat <http://solarwall.com/en/products/solarwall-air-heating/how-solarwall-works.php> Accessed on September 2016.

Steemers T.C. and den Ouden C. (ed.) (1984), Solar Energy R&D in the European Community, Series A, Vol. 4, Solar Energy Applications to Dwellings, Proceedings of the EC Contractors´ meeting held in Bruseels 1-3 June, 1983, kluwer the language of science, The Netherlands.

Tregenza P.R., Subdivision of the sky hemisphere for luminance measurements, Lighting Research Technology, 1987;19:13-14.

Vats K., Tiwari G.N., Energy and exergy analysis of a building integrated semitransparent photovoltaic thermal (BISPVT) system, Applied Energy, 2012;96:409–416.

von Grabe J., A prediction tool for the temperature field of double facades. Energy and Buildings, 2002;34:891–899.

WAF (2016), Solar Thermal Façade by WAF (WAF, 2016, Solar Façade, http://www.waf-solarfassade.at/ Accessed on September 2016.)

Wang D., Liu Y., Wang Y., Zhang Q., Liu J., Theoretical and experimental research on the additional thermal resistance of a built-in curtain on a glazed window, Energy and Buildings, 2015;88:68–77.

Xiang Y., Gan G., Optimization of building-integrated photovoltaic thermal air system combined with thermal storage, International Journal of Low-Carbon Technologies, 2015;10:146–156.

Yang T., Athienitis A.K., A study of design options for a building integrated photovoltaic/thermal (BIPV/T) system with glazed air collector and multiple inlets, Energy Procedia, 2012;30:177-186.

Yang T., Athienitis A.K., A study of design options for a building integrated photovoltaic/thermal (BIPV/T) system with glazed air collector and multiple inlets, Solar Energy, 2014;104:82-92.

Zomer C., Nobre A., Cassatella P., Reindl T., Rüther R., The balance between aesthetics and performance in building-integrated photovoltaics in the tropics, Progress in Photovoltaics: Research and Applications, 2014;22:744–756.

2.4 RAY TRACING MODELLING TECHNIQUE FOR CONCENTRATED COLLECTOR

Fernando Guerreiro[1], Brian Norton, Michael McKeever, David Kennedy

2.4.1 Methodology

The methodology developed here comprises of the optical modelling and simulation of the proposed solar collector in order to define its dimensions to be used for air heating purpose. The details of the system are presented in Chapter 4.6 in Section 4.

The collector designed is a combination of an inverted perforated (transpired) absorber and asymmetric compound parabolic concentrator (ACPC), as shown is Figure 2.4.1.

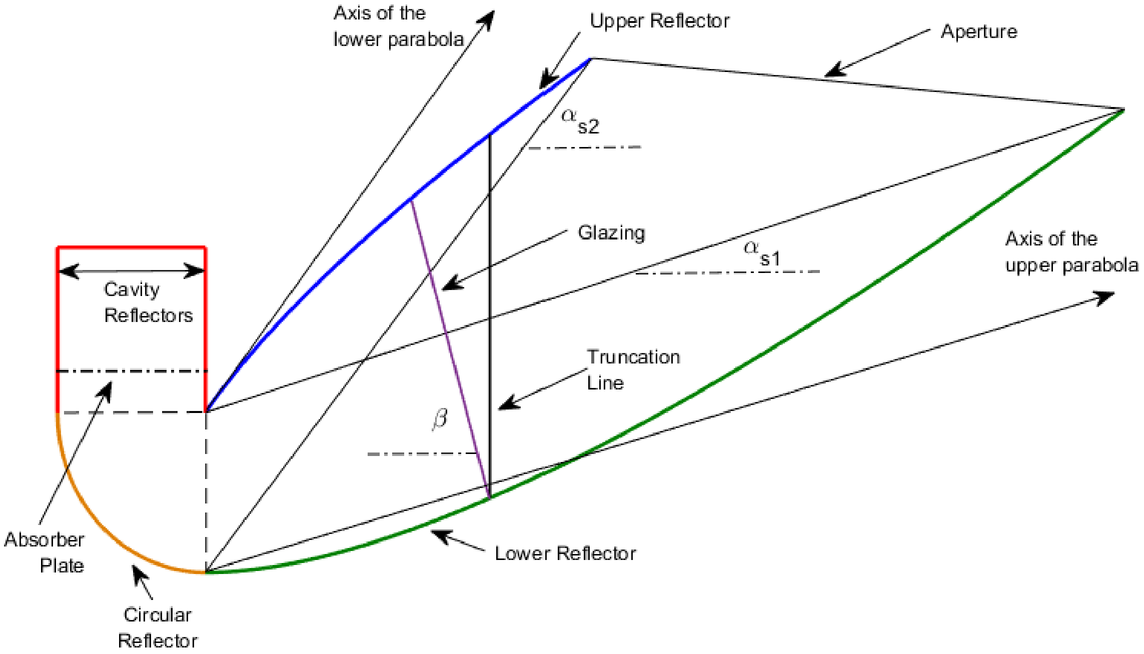


Figure 2.4.1. Solar collector's cross section sketch.

It can be divided in three sections:

- Primary section: This consists of two asymmetric parabolic reflectors that reflect solar rays coming through the aperture and concentrates them to the next section;
- Secondary section: This comprises of a circular reflector, responsible for reflecting all the incoming rays upwards;
- Tertiary section: This consists of a cavity composed of two vertically straight reflectors that receives part of the solar rays from the secondary section and directs them towards the absorber surface. This section has a function of keeping the convection supressed at the absorber due to the formation of a hot air pocket within the cavity.

[1] Non-COST Action member.

The absorber surface is inverted in order to reduce radiation loss and stabilise the thermal layers below which improves the heat transfer mechanism. Additionally, it is perforated to allow the airflow to percolate through the holes, thus enhancing the heat transfer from the absorber to the flow.

The aperture at the vertical position (at the truncation line) has been set as 330 mm (aperture width) in order to be able to hang three collectors on the wall per meter of height and therefore avoid over-shading. The glazing placed in the primary section works as a heat trap. During outdoor operation, the glazing offers protecting for the interior of the unit against the weather. Its position at a given inclination β seeks to maximise light transmittance during the operation period.

Considerations have also been given to the truncation line position – aiming to reduce the quantity of reflector material, system weight and cost – and to the angles of the axes of both parabolas (α_{s1} and α_{s2}), which influence the primary section shape. The selection of such variables must take into account the compromise between optical efficiency and concentration ratio (ratio of aperture area to absorber area) to collect more solar radiation.

Besides the variables previously mentioned, there is a minimum requirement for the collector's full operation: 8 hours a day over the summer (93 days) in Dublin (53º latitude), from 8am to 4pm. This means that all incoming direct solar rays must go towards the absorber during that period, accepting solar radiation from 17º to 60º of altitude angles.

2.4.2 Optical Modelling

To assist the optical analysis, a technique called Ray Tracing has been used. This tool consists of an algorithm implemented in Matlab® that traces the path of the solar rays in 2D that enter the collector in order to predict its optical performance and thus assist with the final design. The following assumptions were used for the algorithm development:

- All reflectors are specular, i.e., the incident angle is equal to the reflected angle in relation to the normal at the intersection point;
- The reflector reflectance (ρ) is 0.95 (95% of the ray's energy is reflected at each reflection);
- 3000 equally spaced solar rays were used, each one carrying equal amount of energy (E_i) regardless of the solar altitude;
- The absorber absorptance (α_{abs}) is 0.85 (85% of the ray's energy reaching the absorber is absorbed);
- A 4-mm thick low iron glass was considered with light transmittance (τ_g) of 0.9 at normal incidence. Transmittance at different incident angles (θ) has been calculated.

Firstly, it is important to define the optical efficiency, which is the ratio between the absorbed energy and the incoming energy. Equation (2.4.1) shows the formula to calculate this as a function of the solar altitude angle α_p and the incident angle θ:

$$\eta_B(\alpha_P) = \frac{\sum_{i=1}^{3000} \rho^{n_i} \tau_g(\theta) \alpha_{abs} E_i}{\sum_{i=1}^{3000} E_i} \quad (2.4.1)$$

where n_i is the number of reflections of the solar ray i and θ is the angle between the solar altitude and the normal line to the glazing surface. Thus, the incident angle can be calculated by Equation (2.4.2):

$$\theta = \alpha_P - (90 - \beta) \quad (2.4.2)$$

Considering the requirement for full operation in the summer, Equation (2.4.3) presents the calculation of the mean optical efficiency within the solar altitude angle range (17º – 60º):

$$\eta_{MO} = \frac{\sum_{j=17^o}^{60^o} \sum_{i=1}^{3000} \rho^{n_i} \tau_g(\theta) \alpha_{abs} E_i}{\sum_{j=17^o}^{60^o} \sum_{i=1}^{3000} E_i} \quad (2.4.3)$$

Moreover, it is important to define the global optical efficiency (η_{GO}) that corresponds to the fraction of incident solar energy measured at the site throughout all the period analysed – 8 hours a day (28800 seconds) for 93 days – whose calculation is presented by Equation (2.4.4).

$$\eta_{GO} = \frac{\sum_{m=1}^{93} \sum_{k=1}^{28800} G_{B,mk} \cos(\theta_{mk}) \rho^{n_i} \tau_g(\theta_{mk}) \alpha_{abs} + \frac{G_{D,mk}}{C} \rho^{n_i} \bar{\tau}_g \alpha_{abs}}{\sum_{m=1}^{93} \sum_{k=1}^{28800} (G_{B,mk} + G_{D,mk})} \quad (2.4.4)$$

where G_B is the beam or direct radiation, G_D is the diffuse radiation, $\bar{\tau}_g$ is the glazing transmittance for diffuse radiation and C is the concentration ratio. Two assumptions were made: i) the diffuse radiation was considered isotropic, which implies that the amount of diffuse component entering the collector is directly proportional to 1/C; and ii) the glazing transmittance was considered as a constant value. The data of G_B and G_D at each second were measured at DIT Kevin Street, Dublin in 2014.

Lastly, the total absorbed energy S_T can be estimated by Equation (2.4.5), which is the portion of the incident energy on the aperture whose units are in MJ per m^2 of absorber.

$$S_T = G_T \eta_{GO} C \quad (2.4.5)$$

where G_T is the total solar radiation measured in that period. This optical analysis did not considered the tertiary section because the position of the absorber surface in the cavity must be selected from experimental results or fluid dynamic analysis, which is beyond the scope of this study. For the collector's design, the tertiary section reflectors will have the value of the absorber width and height.

2.4.3 Results

In order to achieve the optimum design, the simulation started from the collector with the following characteristics: α_{s1} = 17º, α_{s2} = 60º, aperture width ($W_{aperture}$) of 330 mm, collector length (L) of 1250 mm and β = 90º (vertical position). From that, variations in β and α_{s2} were investigated until finding the final design. With the assistance of the software SolidWorks®, the sketch of the initial design was performed, and by this drawing, the absorber width was found with the aim of achieving the maximum concentration ratio. Hence, the absorber width (W_{abs}) is 145 mm with the concentration ratio (C) of 2.276. Figure 2.4.2 shows dimensions of the profile.

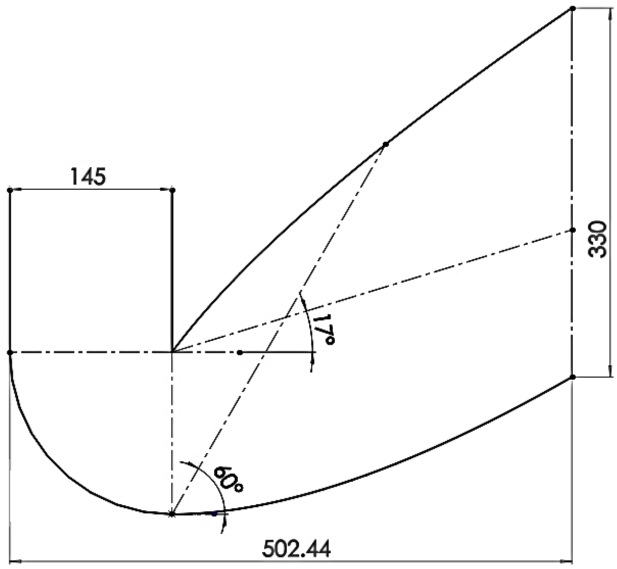


Figure 2.4.2. Drawing of the collector's initial design.

Once the concentration ratio of the collector is set, the next step was to run the Ray Tracing to find the optimal glazing inclination that maximises S_T. It is evident that, at this inclination, there is the smallest energy loss through the glass. Figure 2.4.3 shows the variation of S_T and η_{MO} as a function of β.

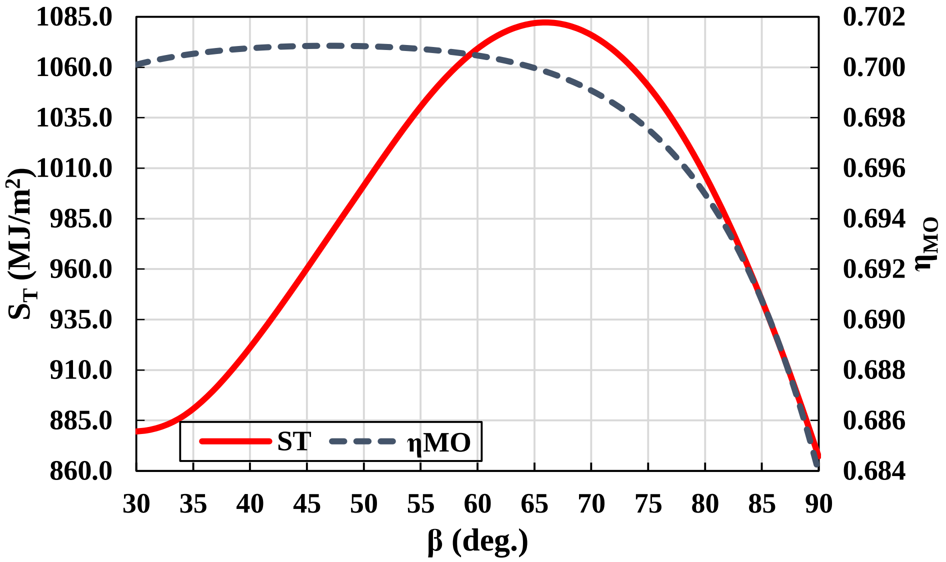


Figure 2.4.3. Graph of total absorbed energy and mean optical efficiency *versus* glazing inclination.

It can be noticed that the best inclination is 66º, leading to an η_{MO} of 0.6998 and S_T of 1082 MJ/m^2. Comparing to the initial design (β = 90º), S_T was raised by almost 25% and η_{MO} by approximately 2.3%. It was also observed that the inclinations that result in the highest values of mean optical efficiency (whose maximum is 0.7008) are close to 53º. However, the position at these inclinations does not provide the highest amount of total absorbed energy, as the energy at 66º is almost 11% higher than that at the position of maximum η_{MO}.

Sequentially, the analysis shows the influence of the angle of the lower parabola axis α_{s2}. Figure 2.4.4 shows the variation of S_T and η_{MO} as function of α_{s2}.

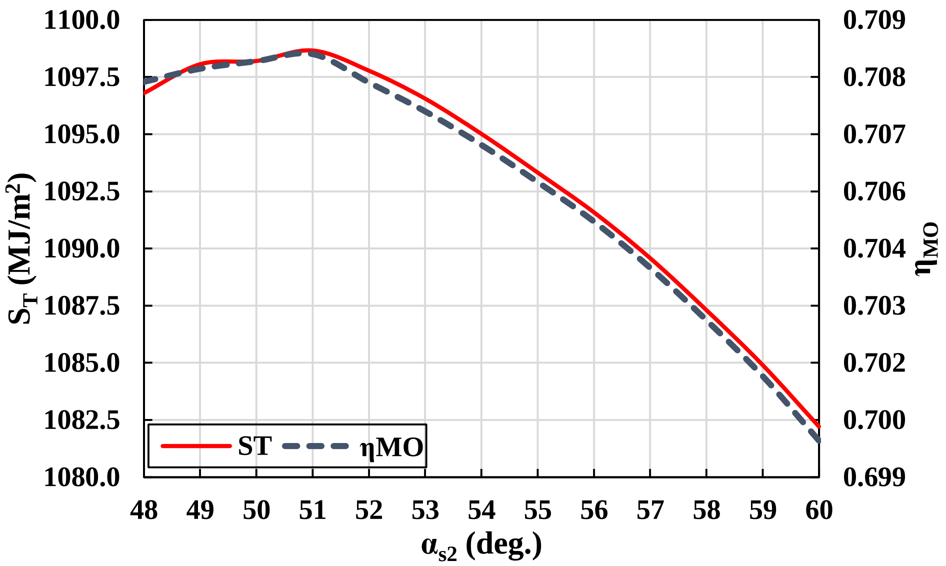


Figure 2.4.4. Graph of total absorbed energy and mean optical efficiency *versus* angle of the lower parabola axis. Glazing inclination of 66º.

From this result, it is noted that the influence of α_{s2} on S_T and η_{MO} is less significant than that of β on the same dependent variables. The highest values were achieved at α_{s2} = 51º. At this condition, S_T = 1099 MJ/m^2 and η_{MO} = 0.7086, increasing by 1.52% and 1.26% respectively, from the variables at α_{s2} = 61º. The variation of α_{s2} also influences the parabolic reflectors and, consequently, changes the size of the solar collector at the primary section. As α_{s2} decreases, the full width of the collector decreases and the optical efficiency increases as observed in Figure 2.4.4. Hence, the drop of α_{s2} to 51º is positive in terms of energy collection and material cost savings. Figure 2.4.5 shows a comparison of collectors with different values of α_{s2} regarding reflector cost and collector width. Dimensions were obtained from drawings on SolidWorks®. For the cost, the calculations was done based on the price of reflector sheet provided by the German company ALANOD, which is €50/m^2.

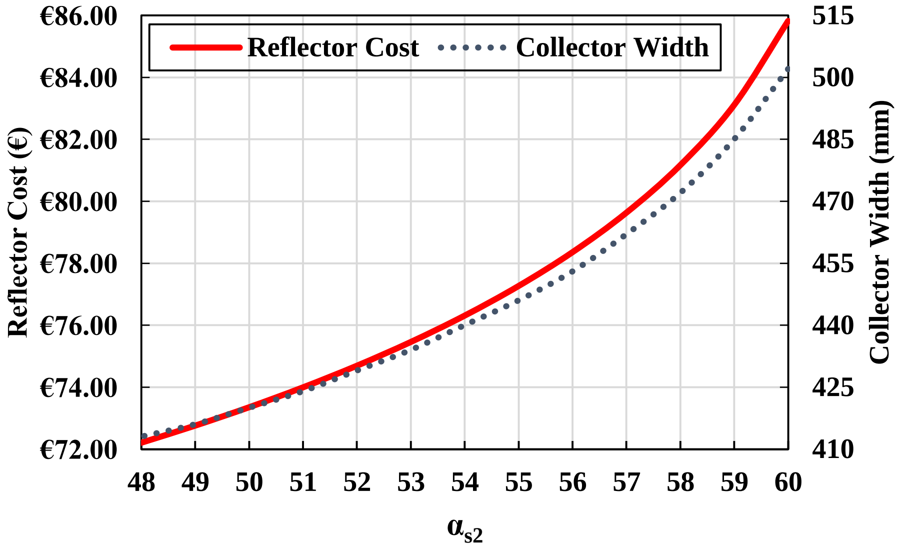


Figure 2.4.5. Graph of reflector cost and collector width *versus* angle of the lower parabola axis.

Figure 2.4.5 shows that as α_{s2} decreases, the collector becomes smaller and less expensive. This is because of the parabolic shape modifications caused by the rotation of the lower parabola axis. The reflector cost drops from nearly €86 at α_{s2} = 60º to €74 at α_{s2} = 51º, reducing by 14% of the initial cost.

With the design variables found by the optical analysis, Table 2.4.1 depicts the values of the geometry parameters and Figure 2.4.6 presents the final collector's shape and dimensions.

Table 2.4.1. Description of the geometric parameters of the final design.

Geometry Parameter	**Value**
Aperture Width	330 mm
Absorber Width	145 mm
Concentration Ratio	2.276
Glazing Width	270 mm
Glazing Inclination	66º
Collector Length	1250 mm
Collector Width	424 mm

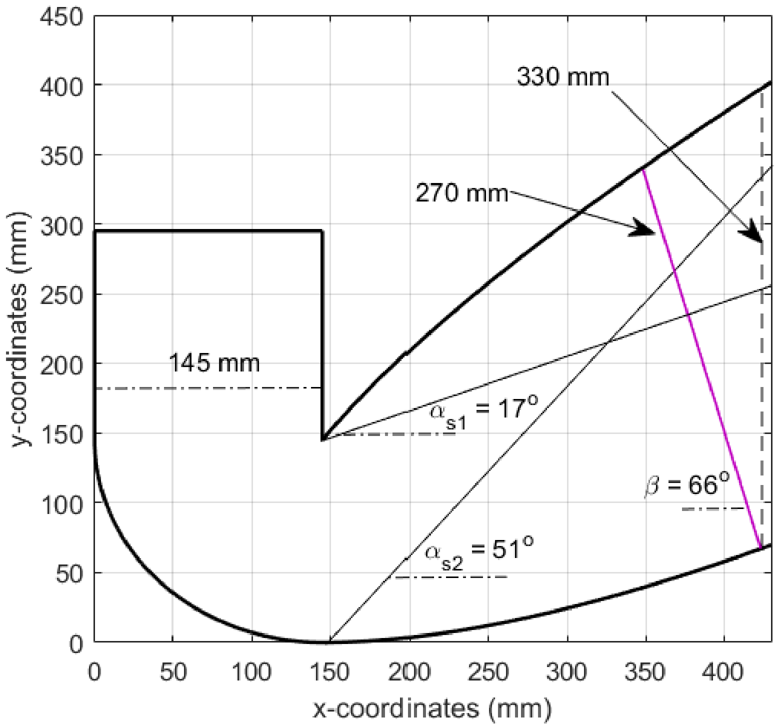


Figure 2.4.6. Cross section with dimensions of the solar collector to be fabricated.

Figure 2.4.7 shows the optical characterisation of the selected design in terms of η_B as a function of solar altitude angle, with 66º of glazing inclination. The angular acceptance is defined as the ratio between the number of solar rays reaching the absorber and the number of solar rays coming into the collector.

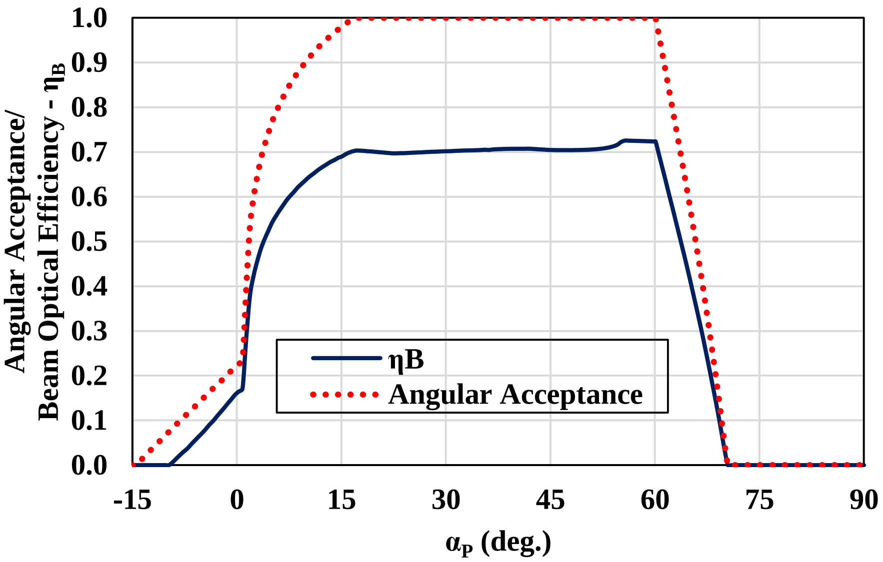


Figure 2.4.7. Graph of optical efficiency and angular acceptance *versus* solar altitude angle.

As observed, at the range of 17º – 60º of solar altitude angles, all the incoming rays reach the absorber and η_B lies between 0.6970 and 0.7255. The highest values of η_B are between 55º and 60º of α_P, which is explained by the least number of reflections at the reflector.

Figure 2.4.8 presents the graphics of Ray Tracing where it is possible to visualise the path of the incoming rays until they reach the absorber surface.

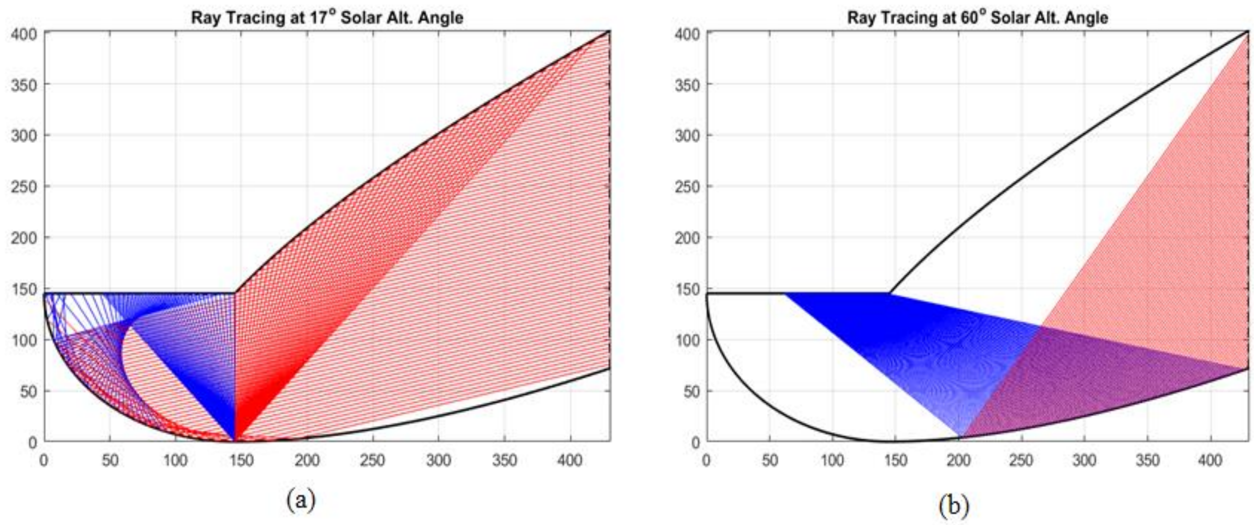


Figure 2.4.8. Graphic results of Ray Tracing for solar altitude angle of (a) 17º and (b) 60º.

In Figure 2.4.8(a) the rays enter the collector at 17º solar altitude angle which is the lower limit of the requirement and α_{s1} = 17º. This means that all the rays that hit the upper parabolic reflector converge to its focal point, at the intersection of the lower parabola and the circular reflector. In Figure 2.4.8(b) where α_P is 60º, the upper limit represents the case of least number of reflections previously mentioned.

2.5 INSTALLATION OPTIONS/STRATEGIES

Yiannis Tripanagnastopoulos

2.5.1 General concepts for building installation of solar thermal collectors

The facade and horizontal or inclined roofs of houses, hotels, athletic centers and other buildings constitute appropriate surfaces for an expanded use of solar thermal collectors and photovoltaic panels. By BISTS one refers to the Building Integrated Solar Thermal Systems and by BIPV to the Building Integrated Photovoltaics. There is also a third category, the Building Integrated Photovoltaic/Thermal systems (BIPVT), which are consisted of PV panels combined with heat extraction units, not only to cool PV cells, but to provide heat together with electricity. Building Adapted or Building Applied solar energy systems is the usual installation mode of solar thermal collectors and photovoltaics to buildings.

The architectural integration of BISTS depends on the structural, functional and aesthetical variations of the solar energy systems and the building configuration. The solar thermal collector unit, which is addressed to be used as BISTS, has to fulfill more specifications than ordinary collectors that are simply added on the building roof or façade. BISTS can be classified according to the heat extraction fluid type and its circulation mode, as liquid type (mainly water and water-glycol) and air type collectors, for natural or forced circulation (by using fans or pumps to the use or to the energy storage) correspondingly. The installation options are depended on the building type, form and energy needs, as well as on the solar energy system type and its operation requirements.

Solar energy systems are suitable for the built environment, but due to their visibility, specific architectural requirements are needed to be adapted. Several types and forms of solar energy systems comprise new and interesting materials, which can be easily integrated into buildings, creating new shapes and symbolizing the ecological concept. These systems also appear as a new material in the architect's hands, ready to be shaped to create alternative buildings. Apart from the typical forms of solar energy systems new designs have been developed to address building integration. In addition, BISTS combined with geothermal heat pumps (GHP) and biomass boilers to adapt energy demand of buildings, aim to cost effective systems.

The passive function of the building in energy demand must be combined with the design of the active system, which is integrated on building roof and facade, for hot water and electricity needs, adapting also the other forms of building energy consumption. As far as new buildings are concerned, their design must provide the possibility of passive and active energy system combination, to avoid high cost and wrong integration of systems regarding building's architecture. This integration is related with their harmonization with a building's architecture and the environment, aiming to adapt the energy needs of zero or nearly zero energy buildings.

A very important feature of architectural integration is multi-functionality. Solar thermal collectors must be integrated into buildings performing as multifunctional elements. In addition to collecting solar energy they must replace conventional building envelop materials. The solar element must be able to perform as a typical building envelop fulfilling the necessary functions of the building regarding weather protection, thermal insulation, accepted visibility level and passive solar gain. In addition, solar thermal collectors should combine effectively the opaque parts with the transparent parts and the mobile elements that are located and their compatibility in terms of material and function. Normally, solar thermal collectors have less compatibility with the transparent parts of the building mainly due to the fact that their absorbers are opaque. The insulation behind the absorber plate and the insulation of the building envelop can potentially become one single element or to complement each other; the absorber for unglazed collectors and the glazing for glazed ones can take, under a purely functional point of view. This is very interesting aspect of integration basically to reduce the use of materials and bring down cost. An interesting issue is that evacuated tubes have been used as balcony railings (Figure 2.5.1).

Figure 2.5.1 Building integration of evacuated tubes.

The solar energy systems that are suitable for building integration can be collectors of flat plate, glazed and unglazed, evacuated tubular collectors and also Compound Parabolic Concentrating (CPC) collectors. Most of the flat plate collectors are of liquid heating type and only a small percentage of them are of air heating type. The well-known Flat Plate Thermosiphonic Units (FPTU) and the less widely applied Integrated Collector Storage (ICS) systems are solar water heaters, aiming to cover domestic needs of 100–200 l of hot water per day and are suitable for locations with favourable weather conditions (Tripanagnostopoulos and Souliotis, 2004).

The unglazed (bare type) solar collectors are cheaper than typical glazed collectors, but the increased absorber thermal losses limit their effective use in low temperature applications. Solar air heating collectors are less efficient than liquid heating thermal collectors, but they are cheaper and can cover large surfaces of building facades and inclined roofs, they don’t suffer of freezing during winter (as it happens with water type solar thermal collectors) and can be used for space heating during winter and cooling by air ventilation during summer. Low or medium concentration solar energy systems can be also integrated to buildings, but they are not widely applied yet (Tripanagnostopoulos 2015).

The characteristic of the material and their surface texture used in thermal collector systems must be in harmony with the same characteristics of other elements of the building envelop. The shapes of solar collector modules have to be compatible with the building composition grid and with the various dimensions of the other façade elements. It is actually the choice of the technology that affects the basic form of the module. The development of cut-to-size module prototypes had the aim of providing modules whose size can be adapted directly on site. There should be variations in the basic form of collector module shape and size as according to the exposed available surface and type of collectors chosen.

2.5.2 Building Integration aspects

The emerging concerns for environmental protection and global energy saving have introduced new architectural design rules for buildings, aiming at buildings of reduced energy consumption with effective integration of solar energy systems with satisfactory aesthetics as well. Another aspect is the fulfilling of building roofs and façades by solar energy systems under the new consideration of architectural and economical aspects. For higher acceptance and a higher application of solar systems, architectural aspects have to be taken into consideration. Solar energy systems have to become an integral part of the building, ideally becoming standard construction elements adapted to building architecture. Higher levels of building integration require new research and development efforts, in close interaction with architects, construction companies and manufacturers of building envelopes. To achieve energy efficient buildings, several technologies in solar as well as in materials with advanced thermal and optical properties, should be combined and possible synergy effects to be used.

System integration concerns issues on how to include the solar technology into the energy supply system of the building with regard to optimization of energy gains and solar fraction. A high quality of architectural integration of solar energy systems is a key issue for a successful perception of solar energy systems by designers and larger public acceptance of both, solar thermal and electrical systems. Considering the building integration concept, the selection criteria for solar energy systems, their placement on building roof and façade should be not only to provide energy to the building, but to be also part of the architecture. This concept is a step to new building design and construction and has an influence to define the future architecture. In this way, the solar energy systems that are fabricated for building integration, should adapt size, colour and shape requirements for the building that they are going to be integrated.

For an aesthetic building integration of solar energy systems it is important to think about the form and the available surface areas on façade and roof of the building and to pay attention to their type, performance and colour. The integrated solar energy system should be of high aesthetics because they are directly visible, as they constitute a large part of the external building surface. In an extended use of solar energy, the majority of the exterior surfaces of buildings will be covered with absorbing surfaces of solar thermal collectors and photovoltaics and their form and colour should be taken under consideration, especially in the case of buildings with traditional architecture. It is important, additionally to the integration of solar energy systems, to use new heat-insulating materials and special glasses, which reduce thermal losses of buildings during the winter and energy consumption for cooling during the summer. These systems are already considered necessary structural materials for the improvement of energy behavior of buildings, giving at the same time a new visage to them. Aiming to cover the energy demand of buildings, the solar energy conversion systems are the most suitable and environmentally friendly devices.

2.5.3 Solar energy systems functionalities

The several types and forms of solar thermal collectors can constitute constructive material for buildings, which can be further developed with many advantages. The scientists are facing those new technology challenges effectively by giving encouraging results, since solar energy systems are able to provide more and more ecological, aesthetic, socioeconomic and technical benefits. BISTS can be used as construction materials to buildings, which allow innovative architectural designs and can have several interesting aesthetic figures. The colour of solar thermal absorbers can vary from dark black to other colour as blue, green, red, etc. Furthermore, they may offer different colour tone, depending on design demands. Large residential buildings, hotels, hospitals, commercial and industrial buildings with large available roof areas, offer a field of significant interest for the installation of solar collectors (Figure 2.5.2).

Figure 2.5.2 Building integrated solar thermal collectors.

The BISTS provide thermal energy to the building in the form of hot water and space heating and cooling. Additionally, other forms of renewable energy may contribute to the buildings energy balance, as from PVs, photovoltaic/thermal (PV/T) collectors and small wind turbines. Heated air or water from solar thermal or PV/T collectors can be stored or delivered directly to the use. PVs and wind turbines provide electricity for the corresponding demand. Thermal energy produced by BISTS may reduce the space heating load of a building by adding solar gains directly (e.g. by a passive window) or indirectly (e.g. by transferring heat from the collector through a storage to a heating element) into the building. The heat removal fluid may be used also to preheat fresh air needed in the building. Air is heated directly or indirectly and using forced flow or thermosiphonic flow, is used to provide space air heating and/or ventilation to the building. In some cases, an auxiliary heating system is used to augment the heat input because of comfort reasons.

Hot water demand in the building, mainly of the residential sector, is the most widespread application. In the majority of water heating BISTS, a heat exchanger or an integrated solar water heater is used to transfer the collected heat to a thermal storage and/or directly to a DHW application. In most cases, an auxiliary heating system is used to augment the heat input. Also, there are a number of methods in providing a cooling (and/or ventilation) effect to a building, shading, cooling, ventilation and reverse operation of solar collecting elements for night-time radiation cooling. The majority of BISTS are mounted on the façade or roofing structures, but a significant number can be applied in other mounting modes to the buildings.

An additional classification can be referred, considering the mode of installation, for new buildings, refurbishment or retrofit, which is often related to the form of building design or components utilized, pre-fabricated or customized. Depending on the level of integration of

BISTS the main characteristics can be enhanced by some functionalities. As first case is the use of BISTS for domestic solar water heating. The hot water is typically delivered at 50°C - 60°C. The main element for water heating is typically a flat-plate or a vacuum tube solar collector with water (or water-glycol mixture) as the heat removal fluid. In some cases however, air collectors can also be used with the hot water produced through an air-water heat exchanger. Most of solar collectors are non-concentrating collectors with a stationary mounting and heat removal fluid circulation through the collector. Except for thermosiphon (FPTU) and integrated collector storage (ICS) systems, which need no control and pumps, solar thermal collectors for domestic hot water and systems for space heating and cooling, as well as air-collectors for space heating and cooling are suitable for ventilation, are using thermal storage, differential thermostats, pumps of fans, to complete the solar thermal system.

Conventional simple flat-plate solar collectors have been developed for use in mild to warm climates, where their performance becomes less effective when conditions are unfavorable during cold, cloudy and windy days. Evacuated tube solar thermal collectors, of heat pipe type, or of fluid circulation type, operate differently than other conventional collectors and are suitable for colder climates. Flat type evacuated solar thermal collectors have been also developed recently. Most solar hot water systems have a kind of thermal storage. The storage in typical systems may contain enough water to supply for one or two days demand, which is usually of 120 to 300 or more liters, depending on the available solar thermal collector surface area and the heat removal fluid flow mode. Solar heat is transferred to the storage directly or through heat exchangers, by free (natural) or forced flow.

2.5.4 Efficiency aspects of BISTS regarding installation modes

The four main options for building integration of solar thermal systems are on tilted roofs, flat roofs, facades and shading systems. South facing sloped roofs are usually best suited for BISTS installation because of the favourable angle with the sun. One option is to mount the collectors above the roofing system. Another option is to replace conventional building materials in parts of the building envelopes, such as the roofs or facades. If the solar thermal systems are in thermal contact with the building skin, it results to an elevated temperature in the collector, due to the lower thermal losses. In this case a higher performance of the collectors is obtained.

For flat building roofs solar thermal collectors can be mechanically fixed to the roof structure, or can be suitably integrated. Depending on the latitude of the location where the building is established, the collectors should have the optimal slope, but it is more difficult for their integration as the roof slope and azimuth angles should be considered. The building's surface area to be covered by solar thermal collectors varies from case to case. In general, areas that are shaded for the majority of the day should be avoided. Regarding space heating, there is a seasonal mismatch between heating season requirement and solar potential. Space heating is needed in the winter, while the thermal energy output from the solar system is maximum in the summer. Solar space heating systems are usually connected with typical gas, oil or biomass boilers.

A more efficient mode is the combination of geothermal heat pumps (GHP) with the solar energy system, which can boost the heat that is extracted from the ground, to achieve working fluid temperatures up to 50 ^{o}C to 60 ^{o}C or more, with a satisfactory COP. If there is a BIPV system, the electricity from the photovoltaics can drive effectively the heat pumps. In case of BIPVT systems, the PV can adapt the electricity demand of a heat pump and the heat from PV/T collectors can increase the COP of it.

BISTS provide many opportunities for innovative architectural design and can be aesthetically appealing. In order to grow BISTS applications, there needs to be a greater acceptance from the construction sector and end-users and also greater willingness to integrate them to buildings. The use of passive building elements for heating applications has been extensively investigated by architects and a range of design procedures have been developed. The use of the building envelope or even the complete house as a collector-storage device is feasible. Also, ambient air may be preheated by a solar thermal system in order to reduce the building heating load. Uncovered façade collectors are an interesting option and the systems may be combined with heat recovery heat exchangers to provide the additional heat. For solar cooling, adsorption or absorption chillers or desiccant and evaporative cooling can be performed, by using the heat from solar collectors.

2.5.5 Architectural Integration aspects of BISTS

The building potential for BISTS, apart of architectural data requires an appropriate set of criteria, including the climatic situation, urban planning and characteristics of existing building technology systems. The architectural integration quality can be defined as a result of a controlled and coherent integration of the solar collectors simultaneously under all functional, constructive, and aesthetic points of view. The design of thermal collectors integration is a very complex process because of a large number of constraints, related to the building architecture and construction, building placement and surroundings, climate, characteristics of the existing heating system, together with conflicting energy, aesthetic and economic requirements. The tilt angle of thermal collectors has a significant influence on energy production and it has a great influence on the functional and aesthetic aspects of the building. Also, the quality and aesthetic characteristics of thermal collectors have a considerable effect on the building aesthetics and they have a great influence on the economics, energy performance and functional aspects. From an architectural aspect, different specifications are required for the collectors regarding their placement, application, dimensions, colour and construction possibilities. Various possibilities for fulfillment of these specifications result in a variability of building envelopes with BISTS.

The placement possibilities of BISTS depend on the climatic conditions, orientation and inclination, position on the building envelope, and shading effects. For the selection of an optimal solution for BISTS placement, system efficiency should be considered as it is strongly influenced by orientation and inclination of the solar thermal collector's absorbing surface. The effective mode is to be the collectors at a tilt equal to the latitude, with plus 15° for the winter and minus 15° in the summer. Deviation to southeast and southwest up to 30° is also acceptable. For space heating applications the solar yield is optimized for 60° to 90° inclination. Inclination may be also important in areas with high snow loads. The larger the inclination angle, the easier it is for snow to slide off flat-plate collectors. Regarding evacuated tube collectors, their shape and heat retention result to longer snow shedding time. It is not recommended to apply solar thermal panels on periodically shaded surfaces of building envelope because it results in a system of lower efficiency and may cause damages such as glass cracks.

For architects, BISTS must be part of a holistic approach for energy sustainable buildings. A high-quality of these solar systems can provide a substantial part of the building's energy needs. By the holistic approach, the integration of these systems replaces a conventional building material and adapts aesthetically the architectural figure of the building. Mounting the collectors on building external surfaces, they can be part of the watertight skin or they can be used as building component (Reijenga and Kaan, 2011). The aim of architectural and building integration of these systems is to reduce the requirement for land and the costs, in addition to aesthetics. It is evident that solar thermal collectors integrated into buildings give a more elegant look and is more efficient to integrate these systems when constructing the building, rather than mounting it afterwards. Usually there are three locations for integrating these systems into buildings. They are the roofs, facades and building components like balcony railings, sunshades and sunscreens.

Solar thermal collectors 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. In case of mounting the collectors **on** building envelope and in parallel with it, there is no savings in substituting elements as the materials underneath the solar modules are not replaced. The solar thermal collectors can be used as an architectural element, mainly for new buildings. Saving of materials is possible where the cost of the substituted elements is below that of the traditional elements. It offers a pleasant and clean appearance (Fuentes, 2007).

Integrating of these systems into the façade and roof, it is important to consider the construction characteristics of the specific technology to be integrated together with the specificities of the constructive system hosting them. This is to ensure that the new multifunctional façade elements meet all the safety façade constructive requirements. Mounting solar collectors directly to the wall without an air gap causes a fundamental modification of the vapor transfer; i.e. it flows out when the cladded solar thermal collectors are cold and it is the other way round when they are heated up (Probst and Roecker, 2011).

2.5.6 Installation practical issues

Several additional functions related to building physics and constructional requirements can be addressed by BISTS, as thermal insulation, acoustic insulation, humidity regulation, rain and wind tightness, solar protection, daylighting, structural functions, fire resistance and security protection. In case of integrated solar thermal systems that cover a small building external surface, they are of poor functionality, while the fully integrated systems on building surface affect the aesthetic potential and design options. Thermal collectors can be used to replace normal building components with their multifunctional potential as an external skin similar to that exhibited by integrated PV systems. The application of building integrated solar thermal façade collectors can avoid the need for conventional cladding materials, which will reduce system integration cost. In terms of functions, light permeability requires a new type of semi-transparent collectors or Fresnel lenses with tracking absorbers (Tripanagnostopoulos et al., 2007).

Solar thermal collectors can be integrated into the building roof in several ways. One is to be part of the external skin, the other to be glued onto insulation material. This type of warm roof construction system is very well suited to renovating large flat roofs. Using collector modules as roof covering material, it reduces the amount of building materials needed, which is very favorable for a sustainable building and can help to reduce costs. The clean finish and beautifully integrated collectors is in perfect harmony with the overall expression of the roof.

Dimensions in BISTS

The aesthetical possibilities like dimensions, form, jointing, colours, texture etc. of BISTS can be affected by the materials and constructional elements of the used collectors. In addition, the type of fluid used can affect the eventual appearance. Variations in the dimensions of glazed solar thermal collector usually are limited and the production is not flexible. Variations in the form of curved thermal collectors or non-rectangular shapes, it results to more expensive production. For unglazed collectors in conventional roof and facade claddings, various systems are available and designers have greater flexibility.

Some problems can be identified in relation to dimensions in BISTS. Most of the manufactured solar thermal collectors are modules with fixed sizes and forces to adapt standard collector size. For a wide application of BISTS, solar thermal collectors of variable size and shape are needed. As standardized products are often not available, it is required the production processes to be adapted. In addition to solar thermal collectors, dummy elements with the same appearance but with no solar collecting capability can be used for building integration.

Integration hurdles of BISTS

Due to the low flexibility of available products and their formal characteristics, the integration of solar thermal collectors has a number of hurdles. There are no variations in colours and those available are black and dark. The irregular appearance of their absorbers, the visibility of piping, their low dimensional flexibility and large size at the façade scale, and finally the lack of dummy elements are other challenges that has to be dealt with.

Solar thermal collectors available in the market are manufactured usually in larger and bulky sizes so in general even smaller buildings will have to use systems of larger sizes. In existing buildings, these systems are mounted on the roof as independent roof elements and do not go in co-relation with the tiles used. They are placed at the suitable locations on the building external surface, which is determined by solar exposure and operation requirements. In case of specific architectural needs, the remaining spaces can be covered or clad with dummy elements. Solar thermal collectors with bulkier size and fixed shapes are less flexible. This is mainly due to the need for a non-flexible hydraulic circuit fixed to the solar absorber to collect the heat. The freedom in module shape and size would require reconsidering the hydraulic system pattern each time and so is not that practical. For architectural integration, the shape and size of the solar module should be compatible with the building composition grid and with the various dimensions of the other envelop elements.

However, colour collectors can be achieved using novel colours on the glazing covering the absorbers. These result in glazing that not only hide the black colour of the absorber and its imperfections, but can also be used as facade cladding on the non-exposed areas of the building envelope, opening the way to the concept of active solar facades and offering a new level of freedom to architects (Munari Probst et al., 2010; Roecker et al., 2007).

BISTS with coloured absorbers

The integration of solar collectors in buildings should be compatible with the architectural design, and solar collectors with coloured absorbers would be aesthetically preferable

(Tripanagnostopoulos et al., 2000). The coloured absorbers are of interest for solar thermal applications, considering that they are more flexible than collectors with black absorbers for a variety of architectural integration which require aesthetic compatibility of solar collectors (Figure 2.5.3). The efficiency of solar collectors is significantly dependent on the absorptance and the emittance of the surface, where the incoming solar radiation is converted to thermal energy, the absorber. The absorber of these collectors is normally black in order to maximize the absorption of the solar spectrum. (Probst and Roecker, 2011; Tripanagnostopoulos et al., 2000). The development of several black selective coatings will certainly result in a wider use of solar collectors with selective absorbers in recent years. Although the general appearance of the selective absorbing surface is black, they appear to be slightly coloured for some angles of view because of the interferential optical properties of coatings. Selective coatings/filters reflect only a small part of the solar spectrum in the visible range while letting the rest of the radiation heat the absorber. These coloured absorbers are available at the cost of reduction in the efficiency. The range of colours may not be available as much as that of PV systems. Variations and availability in range of colours is a very important feature of integration. The efficiency of collectors with coloured absorbers (with or without glazing) can be close to that of collectors with black absorbers if colour paints of dark tone are used (Tripanagnostopoulos et al., 2000).

Figure 2.5.3. Building integrated coloured solar thermal collectors.

The colour of the BISTS collector depends primarily on the absorber colour, but also to some extent on the cover material. Flat plate solar collectors are of black appearance because of the colour of the absorber, which is employed to maximize the absorption of solar spectrum. By this way it is aimed to avoid the monotony of the black colour collectors by using absorbers of blue, red–brown, green or other colour. These collectors are of lower thermal efficiency than that of the usual black type collectors, because of the lower collector absorbance, but they are of more interest to architects for applications on traditional or modern buildings. The application of solar collectors with coloured absorbers is a new concept and regarding the total solar system, it is noticed that the increase in cost (by using larger area of collectors to overcome the lower efficiency of the coloured absorber) is balanced by the achieved aesthetic harmony with the building architecture. The difference in energy output is at an acceptable level considering the improvement in aesthetics and this implies the use of proportionate larger collector aperture areas to have the same energy output as that of typical black coloured collectors. Polymer type solar thermal collectors is another option for BISTS (Figure 2.5.4). An optimistic perspective is the use of unglazed coloured absorbers, which are suitable for large building facades, with perforated collectors an effective mode.

Figure 2.5.4. Polymeric solar thermal collectors for building integration.

Gladding aspects of BISTS

Contemporary facade cladding technology utilizes facade cladding panels placed over a load bearing substructure, where the air gap between the panel and the wall is ventilated. In these façade structures, air heated in the air gap is usually ejected and thus a significant amount of potentially useful heat is lost. A solar wall provides pre heated fresh air required in the building with a dark coloured vertical corrugated metal cladding to become solar absorber. The perforated absorbers allow outside air to flow through thousands of tiny perforations/holes on the metal surface. The air absorbs the heat and rises to the top of the wall, where it is directed into a canopy plenum and via an active fan, ducted to the internal building space (Figure 2.5.5).

Figure 2.5.5. Building integrated solar air heaters.

The fan augments the natural buoyancy effect, inducing a negative pressure in the wall cavity to draw air through the holes. Various metal panel profiles are available from deep grooved shapes which have sufficient internal air space capacity to much shallower profiles. Aluminium panels have the best properties regarding corrosion resistance. This type of solar thermal collector is easy to integrate into most building forms. They can be styled, shaped, and designed in a variety of colours. The thermal collectors can be integrated during the construction phase or after the completion of the building and provide heat, weather proofing, thermal insulation, noise attenuation, day-lighting control and shading.

Glasses of various colours combined with several diffusing finishing (acid etching, structured glass etc) are produced that are able to hide the absorber. Such glazing will allow the use of the same product both on façade areas equipped with solar absorbers (as collector external glass) and in front of the non exposed areas (as façade cladding)**,** opening the way to a broad variety of active façade designs. The active elements can then be positioned at the exposed areas, and their quantity is determined only by thermal needs. However, in reality few manufacturers offer the flexibility to choose between different absorber colours.

The absorbers of the solar thermal collectors also have variations in terms of surface texture and finish. These are available from corrugated, embossed, perforated, regular and irregular in terms of surface geometry. Evacuated tube collectors have exposed glass tubes. The surface is matt, glossy or structured finishes. The glazing above the absorbers in case of glazed collectors may shine when sunlight falls on the surface and glare could be a problem. In case of unglazed collectors, the absorber surface texture and finish is clearly visible and hence can be an option concerning possible patterns on the envelope they are laid to. Flat plate solar thermal collectors with their opaque nature can only be integrated into the opaque parts of façade and roof. Jointing between different collector modules has an important influence on the integration quality. The jointing is usually observable and hence must be similar to the jointing of other cladding material on the same surface for uniformity.

Other integration issues

The vertical position of the installed solar thermal collectors on building façade provides a good compromise between solar gains and architectural integration. In addition, dummy elements can be used to the non-exposed areas with the same black colour and texture. The collectors produce maximum energy in the winter season which is used to heat the floor of the building. During summer the system produces enough energy for the hot water needs of the building. It is also possible to integrate solar collector elements as sun screening or on balcony surfaces as they are usually oriented toward south and west. Besides the use of thermal collectors as cladding multifunctional elements in the facade, they can equally be used as balcony railings. The tubular vacuum collectors, as balcony railings, make the conventional railing unnecessary. Most important is that these tubes make solar energy visible.

The absorbers of uncovered thermal collectors are of several types as corrugated, embossed, perforated (Figure 2.5.6), etc. The surface can have a matt, glossy or structured finish. In glazed thermal collectors, a clear glazing above the absorbers reflects the sun light specularly and glare could be a problem. Surface textured glass can avoid glare and hide absorber features. Variations in the surface texture and finish beneath the glass covering may also be hidden.

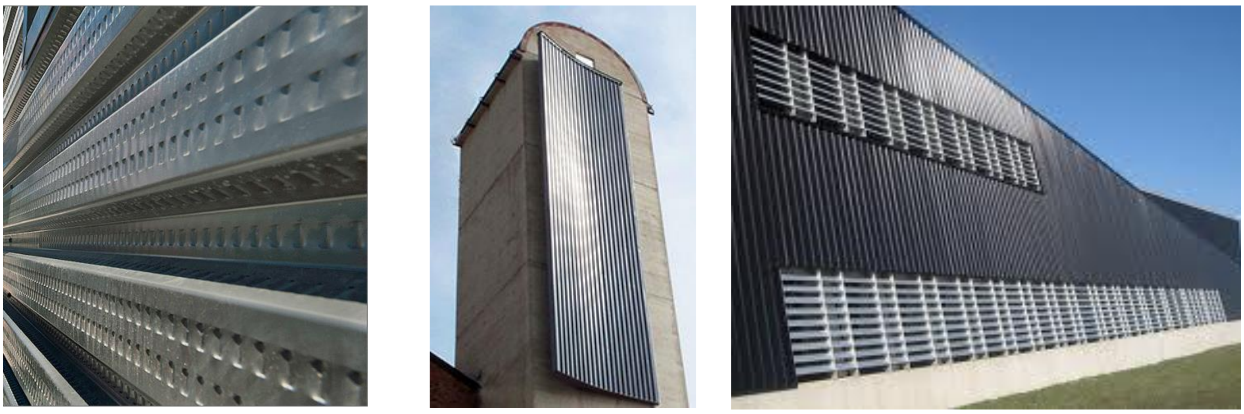


Figure 2.5.6. Building integrated perforated solar air heaters.

Clear glass collectors can be suitably integrated to complement the glass surfaces of a façade or roof. Opaque solar thermal collectors are normally integrated into opaque elements of a façade or roof, are architecturally pleasing regarding form and colour, can adapt well to overall modularity and create a satisfactory composition that will result in good integration and renders high architectural quality. The unglazed solar thermal collectors, on the other hand, are less efficient than glazed collectors, because of the high rate of thermal losses from their surface to ambient, mainly due to wind convection losses.

BISTS designed for either new and/or existing buildings as part of the wall or roof construction should undergo the same weather testing as the construction product that they replace. Any building integrated or not thermal collector should offer weather aging resistance and tested in exposed solar radiation, wind protection and air tightness of the complete construction. A comprehensive set of regulations and guides for exterior envelope design and construction should be provided, including guidelines and criteria to which particular building structure standard should be evaluated.

Thermal insulation in solar thermal collectors minimizes heat loss through the rear and the sides of the collector, improving the solar system performance. Insulation in BISTS minimizes heat loss from the collector to improve the solar system performance and the collectors are used to insulate the building. Also hygrothermic behaviour and diffusion of water vapour through the material and the construction has to be taken into account.

Transparent or translucent insulation materials have been developed. They have high thermal insulation properties and permit the transmission of solar radiation to the absorbing element of the collector. These materials have been successfully used in massive building walls, transforming them into passive solar (collector/storage) walls and for improving the performance of active solar thermal collectors when the insulating materials are used behind a glass cover. However, the materials have to be able to withstand the high temperatures of the collector achieved during stagnation (Figure 2.5.7).

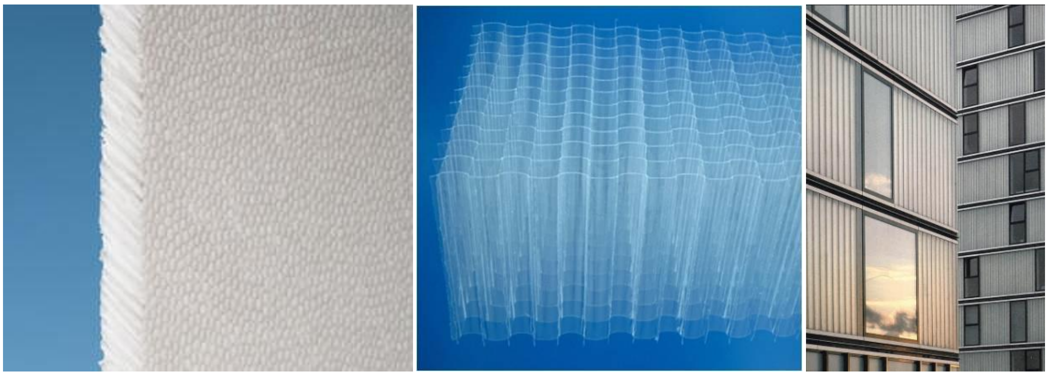


Figure 2.5.7 Samples of transparent insulating material and building integration.

2.5.7 Environmental benefits of using BISTS

The greater use of solar thermal systems, particularly in the form of BISTS, contributes to lower life-cycle costs and environmental impacts, thus contributing to the reduction of the overall life-cycle impacts of the building sector. The environmental sustainability of an installation is related to its materials and components, which can be recycled, reused or replaced. In the frame of this concept, Life Cycle Analysis (LCA) or Environmental impact techniques are useful tools for the evaluation of the environmental profile. LCA and other aspects which are important in the environmental sustainability of building integrated solar systems, include Life Cycle Analysis (LCA) and related critical factors.

2.5.8 Conclusions

The use of heat-insulating materials and effective glazing to buildings can achieve a considerable reduction of energy demand and following it, the integration of active and passive solar energy systems can adapt their energy demand. The integration of solar energy systems should be effectively harmonized with the building architecture and the environment. BISTS can cover the energy needs of the building and if it is necessary they could be combined with geothermal heat pumps, biomass boilers and small wind turbines. In this chapter concepts for building installation of solar thermal collectors are presented, including integration aspects, collector functionalities and efficiency remarks. Some parameters that affect system performance regarding installation options are analyzed and strategies for the wider application of BISTS are included.

REFERENCES

Fuentes, M. 2007. Integration of PV into the built environment. Available: http://www.brita-in-pubs.eu/bit/uk/03viewer/retrofit_measures/pdf/FINAL_12_Integration_of_PV_red_kth_rev1.pdf [Accessed 15 March, 2012].

Munari Probst, M. C., Schueler, A. & Roecker, C. 2010. Bringing colours to solar collectors: a contribution to an increased building "integrability". *Colour & Light in Architectecture.* Venice, Italy.

Probst, M. C. M. & Roecker, C. 2011. *Architectural Integration and Design of Solar Thermal Systems,* Oxford, UK, Routledge Taylor and Francis Group.

Reijenga, T. H. & Kaan, H. F. 2011. PV in Architecture. *In:* LUQUE, A. & HEDEDUS, S. (eds.) *Handbook of Photovoltaic Science and Engineering.* Second ed.: John Wiley & Sons.

Roecker, C., Munari Probst, M. C., De Chambrier, E., Schueler, A. & Scartezzini, J.-L. 2007. Facade Integration of Solar Thermal Collectors: A Breakthrough

Tripanagnostopoulos, Y., Souliotis, M. & Nousia, T. 2000. Solar collectors with coloured absorbers. *Solar Energy*, 68, pp.343-356.

Tripanagnostopoulos Y., Souliotis M., 2004, “ICS solar systems with horizontal (E–W) and vertical (N–S) cylindrical water storage tank”. *Renewable Energy* 29, pp 73–96.

Tripanagnostopoulos Y., Siabekou Ch. and Tonui J. K.. 2007. “The Fresnel lens concept for solar control of buildings”. *Solar Energy* 81, pp. 661-675.

Tripanagnostopoulos Y., 2015, “Operational and aesthetical aspects of solar energy systems for building integration” Int Conf EuroElecs 2015, COST Action TU1205 Symposium, July 2015, Guimaraes, Portugal.

2.6 TESTING

Christoph Maurer, Helen R. Wilson[2], Tilmann E. Kuhn[2]

Measurement methods to characterise BIST elements in a laboratory were presented by (Maurer et al., 2012). First the optical measurements of different layers of BIST elements are presented, before the calorimetric measurements are discussed which provide the solar thermal performance and the energy flux to the building interior with defined boundary conditions.

2.6.1 Optical measurements

Optical measurements of components for BIST are especially interesting when a new BIST element is being developed or an existing one is to be optimized. As large incidence angles of the solar radiation often occur on building envelopes, the transmittance and reflectance should be measured as a function of incidence angle. If a BIST element includes spectrally selective layers, the optical measurements should also be spectrally resolved. Furthermore, if a BIST element includes several transparent layers, polarization-dependent measurements should be performed. For a double glazed cover, the absolute error due to neglecting the polarization at an incidence angle of 60° can be at least three percentage points. If the solar transmittance of the double glazing is small, the relative error can be large. For more than two glass panes, the error is even larger.

Measurement procedures for the transmittance and the reflectance of layers in general and for (near-)normal radiation are presented by (EN 14500, 2008). The direct-direct transmittance and reflectance of thin samples can be measured for different angles of incidence with a small integrating sphere which can rotate around the sample as presented by Figure 2.6.1 (Wilson, 2007). The direct-hemispherical transmittance can be measured by a test facility as presented by Figure 2.6.2. The sample can rotate together with the large integrating sphere which measures the direct-hemispherical transmittance (Platzer, 1987). The direct-hemispherical reflectance can be measured by an irradiated rotatable sample within an integrating sphere. Light-scattering and textured components may need suitable measurement facilities as described by (Wilson et al., 2009). For materials with complex angle-dependent optical properties, photogoniometer measurements to determine the bidirectional scattering distribution function (BSDF) are recommended (Apian-Bennewitz, 2010). The hemispherical-hemispherical transmittance and reflectance can be calculated from the direct-hemispherical transmittances and reflectance at different incidence angles e.g. with the formulas provided by (EN 14500, 2008) for special cases which fulfil specified conditions of symmetry.

There are various methods to calculate the effect of multiple reflections in a stack of optical layers e.g.

- approaches for layer systems based on spectral normal-hemispherical values like (EN410, ISO9050, EN13363 or ISO15099)

[2] Non-COST Action member. Added testing experience for components for building envelopes which go beyond BISTS (like glass and conventional building envelopes), but which are very helpful to be applied for BISTS.

- detailed layer systems with angle-dependent, spectrally resolved, polarization-dependent calculation for direct and for diffuse radiation based on (Maheu et al., 1984; Maheu and Gouesbet, 1986)
- matrix methods like (Klems, 1993b, 1993a; Ward et al., 2011)
- ray-tracing methods like (Ward and Shakespeare, 1998)

When applied to opaque BIST elements, the result is typically the effective absorptance of each layer depending on the direction of incident radiation. In the case of semi-transparent BIST elements, the effective visible and solar transmittance of the BIST element depending on the direction of radiation from outside the building is typically needed and if possible also the reflectance of the BIST element from inside the building for accurate building energy simulations.

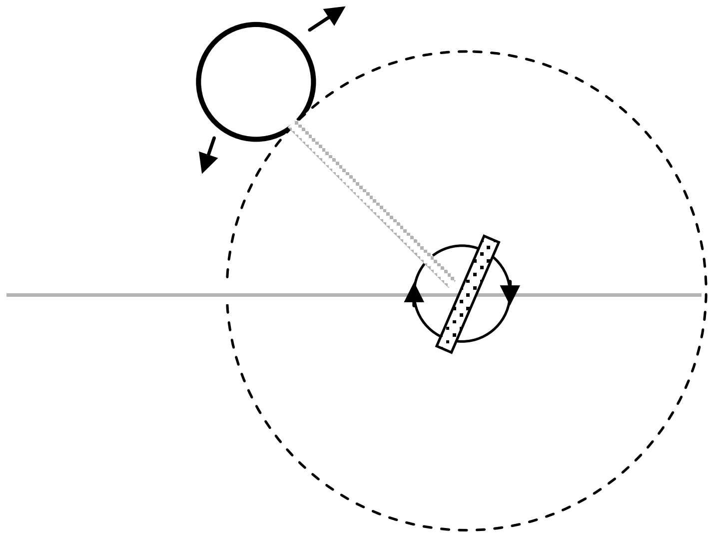


Figure 2.6.1. Schematic drawing of a centrally mounted sample which is irradiated from the left. A small integrating sphere can rotate around the sample to determine the direct-direct transmittance or reflectance for different incidence angles.

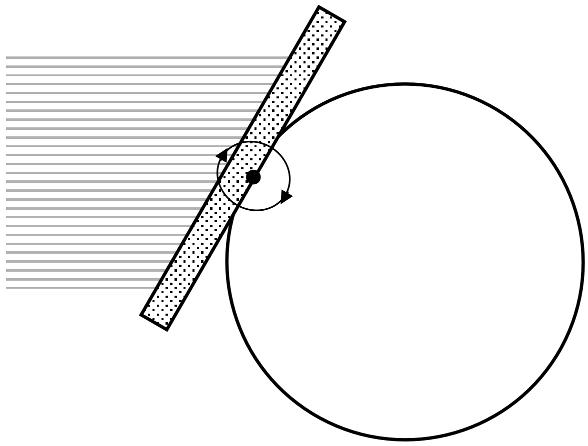


Figure 2.6.2. Schematic drawing of a test facility for the direct-hemispherical transmittance. The sample (dotted) is mounted at the opening of an integrating sphere, which can be rotated around an axis passing through the sample for different incidence angles of the radiation from the left.

2.6.2 Calorimetric measurements

Typical measurements of the solar thermal performance according to (ISO 9806, 2013) are only valid for rear-ventilated BIST installations because the same ambient temperature is assumed on all sides of the collector. If the energy flux from the BIST to the building interior cannot be neglected, a simultaneous measurement of the solar thermal performance and of the energy flux to the building interior is necessary to characterize both quantities as a function of the temperature and mass flow of the heat transfer fluid and the temperatures of the ambient air and of the interior space. A methodology to measure the energy flux of a BIST element towards the building interior is presented by (Kuhn, 2014). A measurement example for a semi-transparent facade collector to validate a BIST simulation model is presented by (Maurer, 2012). Calorimetric measurements are the most important measurements of BIST elements. Figure 2.6.3 presents a cross-section through the indoor calorimeter for building envelope elements of the TestLab Solar Facades at Fraunhofer ISE. The ambient air temperature, the irradiance and the external heat transfer coefficient can be adjusted as well as the temperature of the artificial interior and the internal heat transfer coefficient. A black absorber has the temperature of the artificial interior and absorbs nearly all radiation which is transmitted through the sample. Heat flux sensors inside the calorimeter absorber measure the energy flux to the interior. At the same time, the fluid flow and the fluid inlet temperature through the BIST element are controlled by a thermostat. The solar thermal performance can be calculated, using the measured fluid output temperature as input data.

Additional temperature sensors can be applied e.g. to investigate temperature distributions inside the BIST element. Additional edge insulation allows the measurement of centre-of-glazing values. The comparison of measurements with and without additional edge insulation is used to assess the quality of the edge design and allows BIST dimensions to be predicted for different ratios of collector area and edge perimeter.

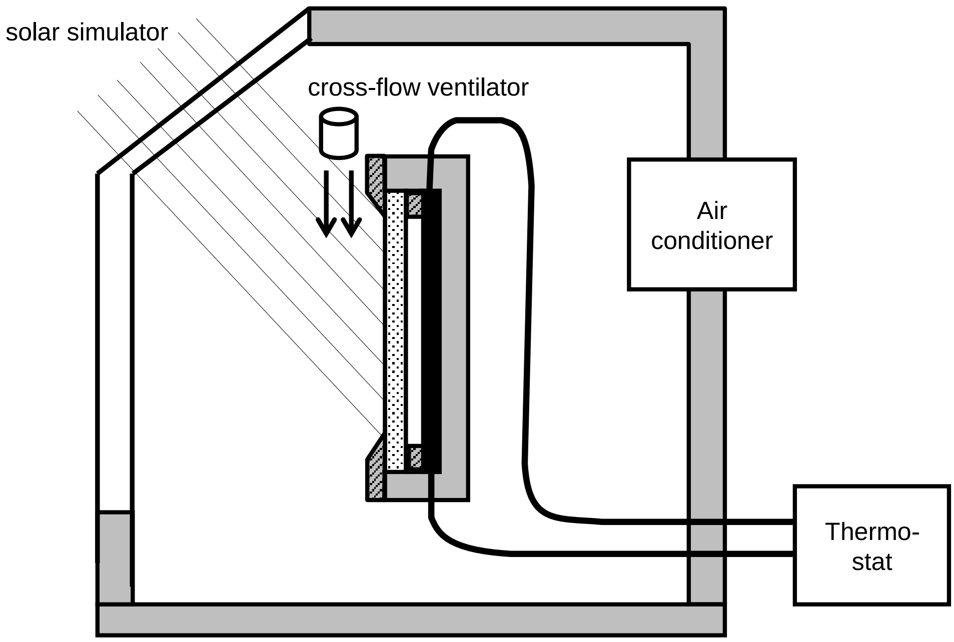


Figure 2.6.3. Cross-section through the g value calorimeter. The sample (dotted area) is irradiated by a solar simulator. The measurement chamber is air-conditioned and a thermostat controls the temperature of the black calorimeter absorber. Edge insulation (hatched area) can be applied to minimize edge effects.

In addition to the indoor calorimeter, Fraunhofer ISE has also developed an outdoor test facility for real-size building envelopes (OFREE) which also provides the energy flux to the building interior as well as the solar thermal performance. It can measure BIST elements up to 3.77 m height and 1.5 t weight and track them at defined angles with respect to the sun. OFREE can also control the temperature of the artificial interior and the heat transfer coefficient. Although the ambient temperature cannot be adjusted, the direct solar radiation has a much smaller divergence and realistic spectral properties, so it is recommended for BIST elements with strong angular or spectral dependence.

BIST installations in buildings can and should be monitored to check their real-life behaviour. However, monitoring takes a lot of time and the boundary conditions can be controlled and measured less accurately than in the laboratory. Therefore, calorimetric measurements in a test laboratory are recommended to characterize BIST elements.

REFERENCES

Apian-Bennewitz, P., 2010. New scanning gonio-photometer for extended BRTF measurements. Optics + Photonics, paper 7792-24. SPIE conference proceedings 7792.

EN 14500, 2008. Blinds and shutters - Thermal and visual comfort - Test and calculation methods. CEN 91.060.50.

ISO 9806, 2013. Solar energy - Solar thermal collectors - Test methods (DIN EN ISO 9806:2014-06). International Organization for Standardization. https://www.beuth.de/de/norm/din-en-iso-9806/205210944. Accessed 19 July 2016.

Klems, J.H., 1993a. A New Method for Predicting the Solar Heat Gain of Complex Fenestration Systems I. Overview and Derivation of the Matrix Layer Calculation. ASHRAE Transactions 100, Part 1.

Klems, J.H., 1993b. A New Method for Predicting the Solar Heat Gain of Complex Fenestration Systems II. Detailed Description of the Matrix Layer Calculation. ASHRAE Transactions 100, Part 1.

Kuhn, T.E., 2014. Calorimetric determination of the solar heat gain coefficient g with steady-state laboratory measurements. Energ. Buildings 84, 388–402.

Maheu, B., Gouesbet, G., 1986. Four-flux models to solve the scattering transfer equation in terms of Lorenz-Mie parameters. special cases. Appl. Optics 25 (7), 1122–1128.

Maheu, B., Le Toulouzan, J. N., Gouesbet, G., 1984. Four-flux models to solve the scattering transfer equation in terms of Lorenz-Mie parameters. Appl. Optics 23 (19), 3353–3362.

Maurer, C., 2012. Theoretical and experimental analysis and optimization of semi-transparent solar thermal façade collectors. Dissertation, Freiburg, 118 pp.

Maurer, C., Di Lauro, P., Hermann, M., Kuhn, T.E., 2012. Transparent solar thermal collectors – measurements and modelling. German and English version, in: Thermische Solarenergie / 22. Symposium. Ostbayerisches Technologie-Transfer-Institut e.V. (OTTI),, Regensburg.

Platzer, W.J., 1987. Solar transmission of transparent insulation material. Sol Energ Mater 16 (1-3), 275–287.

Ward, G., Mistrick, R., Lee, E.S., McNeil, A., Jonsson, J., 2011. Simulating the Daylight Performance of Complex Fenestration Systems Using Bidirectional Scattering Distribution Functions within Radiance. LEUKOS.

Ward Larson, G., Shakespeare, R.A., 1998. Rendering with radiance. The art and science of lightning visualization. Morgan Kaufmann Publishers.

Wilson, H.R., 2007. Polarisationseffekte bei winkelabhängigen Messungen von Reflexion und Transmission. Colloquium Optische Spektrometrie COSP 2007, Berlin. CD-ROM available from PerkinElmer.

Wilson, H.R., Hutchins, M.G., Kilbey, N.B., Anderson, C., 2009. Intercomparison of transmittance and reflectance measurements of light-scattering and patterned glass with spectrophotometers and integrating spheres. Final report. International Commission on Glass. http://www.icg-tc10.org/pubdetail.asp?PubID=134.

2.7 COMMISSIONING

Stefan Remke

The term commissioning describes the process by which the building integrated solar system (BISTS) or any other building system is tested in order to verify that it functions according to its design objectives or specifications.

It includes design review, installation verification, system start-ups and functional performance tests, and complete documentation of the BISTS. It is therefore the practical proof of the systems design, of the correct functioning of the system components and of the correct completion of the installation.

All steps mentioned before, are especially necessary for a proper system performance of solar thermal systems, as these are usually custom made with several components and subsystems. This circumstance can produce solar systems with installation deficiencies, which do not perform properly. Moreover, these systems can undergo stagnation conditions associated with fairly high temperatures and evaporation of the working fluid which requires a proper function of safety devices.

In case of more complex systems, operations and maintenance (O&M) staff training can form part of the process. There are commissioning service concepts with an even wider scope, accompanying all project phases form the pre-design to the post-acceptance, but again, this is a question of the complexity of the installations.

Within the course of the commissioning, all system parameters should be adjusted according to the design specifications. Records have to be kept of all tests and measurements which should be enclosed to the as-built documentation of the project. As the commissioning of the system represents the interface between the construction phase and the operation phase, the technician in charge should also pay special attention to the completeness of the documentation and a consistent labelling of pipes, ducts, instruments and components. Where monitoring, or SCADA (Supervisory Control and Data Acquisition) systems are installed, the verification of a correct data transfer and sensor and device assignment should form part of the process.

According to the country of installation and the size, particularly the nominal thermal performance of the solar thermal system, the commissioning process may be subject to technical regulations and standards, e.g. (VDI, 2010), (UNE, 2004) (ASHRAE, 2013) (ASHRAE, 2005) (ASHRAE, 2007). In any case, it is recommended to prepare a checklist prior to testing, in order to structure the commissioning procedure.

2.7.1 Preparing the Commissioning Process

Building integrated solar systems (BISTS) can vary considerably in size and complexity and so will the associated project documentation. In general, the following documents should be available prior to system start-ups, functional tests and parameter adjustment:

- Design intent document (DID) which defines the technical design criteria (e.g. use and occupancy information, system temperatures, solar fractions, energy considerations, documentation requirements, applicable codes, standards and regulations etc.)

- As-built installation* plan which reflects all changes implemented during the construction phase
- Description of the systems function.
- Manuals of components and subsystems

The study of these documents should go along with a critical design review, checking for functional as well as testing, adjusting and balancing (TAB) issues, such as:

- Balancing and adjusting devices, e.g. dampers and valves that allow to adjust parameters
- Access as needed for observing physical responses (e.g. pressure ports, temperature measuring points)
- Access for equipment maintenance and replacement

In case of large systems, the design review should be carried out by an independent commissioning technician or team. In order to limit costs of technical modifications the commissioning person or team should already be involved in the design phase of the project. However, in case of smaller systems the installer usually carries out the commissioning and thus the design review should be understood as a final document check before the systems start-up.

For each apparatus, component and device a commissioning protocol or checklist must be prepared, which includes all operating parameters. It shall indicate the quantities of every parameter as designed in the project and the quantities measured on site. The difference between both will indicate the necessary adjustment and balancing, particularly of the hydraulic circuits. It is of fundamental importance to record the project data and test data on site for the company or person who will take charge of the maintenance (IDAE, 2007). Typically, the providers of the main components (e.g. solar collectors, storage tanks, heat pumps etc.) provide generic forms for the commissioning of their systems and components. These can be used and, if needed, adapted to the situation in question.

Every commissioning procedure requires tools and measuring devices, such as:

- Regular tool box
- Measuring devices for temperature, pressure, air flow etc.
- Special equipment like circulating pumps or fans to clean and test ducts
- Gas sniffers, smoke machines and/or leak detector spray for leak detection
- Laptop with service software for data communication and SD cards, USB memory sticks to download data from SCADA devices

These should be available and, where required, calibrated.

As BISTS form part of the building envelope, a safe access to the outer parts of the system has to be provided. This could require the allocation of scaffolds or ladders and safety equipment such as harnesses.

All in-situ TAB procedures should be carried out in the presence of the responsible installer in order to facilitate interventions where necessary. In the scheduling for these procedures, time and weather conditions, for instance for solar-collector testing, have to be considered.

2.7.2 Installation verification

Since the physical conditions in air (low pressure, high flow) and liquid (high pressure, low flow) conducts respectively are greatly different, the commissioning of air and liquid circuits will be treated separately in this section.

2.7.2.1 Testing of pipeworks for liquids

All pipeworks shall be subject to leak testing. All parts of the pipework or segment under test shall be made available for viewing leaks and repairing them if necessary. Thermal insulation should not be installed before the testing has concluded. All ends of the pipe section under test must be hermetically sealed.

Prior to testing, the pipes must be cleaned of all residues from the assembly, as metal chips, oil etc. Cleaning is carried out by filling the pipework with water and emptying it repeatedly. Detergents may be added to the water in order to intensify the cleaning process.

It should be checked that equipments, devices and accessories which are included in the section of the pipework withstand the test pressure. Otherwise, such elements should be cut-off by closing valves or replacing them by plugs. The highest points of the pipework shall be equipped with purge valves in order to release air during the TAB and the operation of the system.

The pressurizing source (e.g. Pump with variable frequency drive) must have a pressure equal or greater than the test pressure. The connection should be equipped with the following accessories:

- Shut-off valve
- Water filter
- Retention valve
- Adjustable pressure reducing valve adjustable
- Pressure gauge adequately scaled and properly calibrated
- Safety valve, calibrated at the maximum pressure of the network
- Flexible hose for connection

Before filling the system, the gas pressure of the expansion vessel should be verified, and if necessary adjusted to the design value. The nominal system pressure should be around 0,5 bar higher than the gas pressure of the vessel, in order to press some working fluid into the vessel. This fluid later serves as a reservoir for the compensation of volume variations due to changing temperatures.

The filling will take place from the lowest part of the circuit. It is of fundamental importance to systematically remove all air which is displaced by water during the filling process via the purge valves. As air is a compressible fluid, the presence of air pockets in the network would impede leak testing because the pressure stability required for leak detection could not be achieved.

When the pipework is filled, preliminary leak detection is carried out under hydrostatic pressure conditions, which are determined by its heights. Special attention has to be paid at the joints. Leakage is detected by the formation of a drip or a water jet or in case of very small openings, by wet surfaces.

Subsequently the pressure test is performed by raising the pressure to the test value and closing the shut-off valve. If the pressure goes down, it should be verified first, that all valves and plugs are hermetically closed. If so, the network is checked for leaks. If leakage occurs, it shall be repaired and the test repeated until no leakage is detected. The test will last the time necessary to verify visually the tightness of each and every of the joints.

In many geographical regions, solar systems are operated with antifreeze fluids. In this case, the water has to be exchanged by the antifreeze fluid. Ready-to use fluids have a certified freezing point. In case of antifreeze-water-mixtures, it should be checked by means of a refractometer or a densimeter, whether the freezing point meets with the requirements specified in the project. If pure water is used as a work fluid, it should be filtered and its chemical should be adjusted in order to avoid corrosion and fouling on the inner surfaces of the pipework. Many manufacturers of solar collectors mark certain ranges for the chemical composition of the work fluid or even require the use of a determined product. In any case, the following limits should be met:

- Free CO_2 < 50 mg/l
- Calcium Carbonate < 200 mg/l
- Total Soluble salts < 500 mg/l
- 5 < pH > 12

After the test, the pressure will be reduced to the nominal value and equipment, devices and accessories will be reconnected.

Finally, the dilatation of the pipework and the function of the expansion tank and other safety devices are tested under stagnation conditions. Stagnation shall be induced by switching off the circulation pump, under sufficiently high solar radiation levels (H_R > 80% of the maximum design value) during at last 1 hour (ASIT, 2009).

2.7.2.2 Testing of ductworks for air ventilation

All ductworks shall be subject to leak testing. All parts of the ductwork or segment under test shall be made available for viewing leaks and repairing them if necessary. Thermal insulation should not be installed before the testing has concluded. Supply registers or return air grills are sealed using adhesive tapes, cardboard, or non-adhesive reusable seals. One register or return is left unsealed, and the calibrated fan (see below) is connected to it. Prior to testing, the ducts must be cleaned of dust and other residues from the assembly. Cleaning is carried out by means of vacuum cleaners, compressed air, or brushes. In ducts with plain surfaces, water can be applied in order to intensify the cleaning process.

The calibrated test fan which is connected to the ductwork, shall have a capacity of 2 – 3 times the nominal volume flow of the ductwork and at least the same static pressure. Additionally, a device is needed to measure fan flow and building pressure.

Pressure is monitored in one of the branches of the ductwork while the calibrated fan delivers air into the system. As air is delivered into the ductwork, pressure builds and forces air out of all of the openings in the various ductwork connections or through the seams and joints of the BISTS. The tighter the ductwork system (e.g. fewer holes), the less air is needed from the fan to create a change in the ductwork pressure.

Duct leakage can be detected auditively or visually be help of tracers, like smoke or aerosols dispersed in the test flow.

2.7.3 System start-up and functional testing

For start-up, all balancing devices of the pipe- or ductwork should be fully open. If possible, the design value of the flow should first be approximated by adjusting the speed of the pumps or fans respectively. Many pumps provide speed selectors or converter to adjust the speed.

The design flow can then be adjusted precisely by means of the balancing devices. Special attention has to be paid to the hydraulic balancing of pipe branches, e.g. the subfields in bigger collector installations.

For every heat exchanger in the pipework, design power, temperatures and flow should be known and adjusted respectively.

2.7.4 Commissioning of the control system

The controller or control system manages the functions of the system. In some cases, the programming of the controller might be custom made, in other cases predefined programs are chosen from a library and only the parameters have to be adjusted to the design values. In any case the commissioning requires a detailed manual of the controller, the program and its functions.

For testing the wiring, the controller should first be set to the manual mode and all actors, like pumps and valves should be switched on and off. When switching the actors, it should be checked weather the consequent heat flow in the pipework is coherent. This can be done by touching the tube or, in case of temperatures >60°C, by a surface temperature sensor.

Subsequently the set points of all parameters are adjusted and the system is switched back to automatic mode.

If a datalogging or monitoring system is installed, the data acquisition, transmission and storage should also be tested. These systems help a lot in fault diagnosis and in the continuous monitoring of the system behaviour in widely different conditions.

2.7.5 Documentation of the commissioning process

The documentation available and should be given at least the following:

- A specification of the system, which bases include project and criteria adopted for development.
- A reproducible copy of the final plans comprising at least schemes first of all facilities, planes engine room and floor plans where It should indicate the route of the pipeline and the status of the terminal units.
- A list of all materials and equipment used, indicating manufacturer, make, model and performance characteristics.
- The compilation of the measurements gives the results of the partial and final tests.
- A manual operation of the main equipment installation.

REFERENCES

ASHRAE. 2005. Guideline 0-2005, The Comissioning Process (in Spanish). Atlanta : American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2005.

ASHRAE. 2007. Guideline 1.1-2007, HVAC&R Technical Requirements for the Commissioning Process. Atlanta : American Society of Heating, Refrigerating and Air-Conditioning, 2007.

ASHRAE. 2013. Standard 202-2013, Commissioning Process for Buildings and Systems. Atlanta : American Society of Heating, Refrigerating and Air-Conditioning, 2013.

ASIT. 2009. *Guía ASIT de la Energía solar térmica.* Madrid : Asociación solar de la Indústria Térmica, 2009.

IDAE. 2007. *Comentarios al Reglamento de instalaciones térmicas en los edificios (RITE-2007).* Madrid : Instituto para la Diversificación y Ahorro de la Energía, 2007.

UNE. 2004. UNE 100151:2004, Air Conditioning Site Pressure Testing of Pipework. Madrid : AENOR Asociación Española sw Normalización y Certificación, 2004.

VDI. 2010. VDI 6039:2010-01 (Draft) Facility management - Managing of building commissioning - Methods and procedures for building-services installations. Düsseldorf : VDI-Verlag, 2010.

2.8 MAINTENANCE

Jayanta D. Mondol

2.8.1 Introduction

The effective performance of a building integrated solar thermal (BIST) system depends on appropriate siting, system design, and installation as well as the quality and durability of the components. Once a system is in place, it has to be properly maintained to optimise its performance and avoid breakdowns. Different systems require different types of maintenance. For large scale BIST systems, the structure should be as simple as possible to minimise the maintenance requirement. When a solar collector is to be mounted on an existing building, it is important to keep the maintenance requirements as low as possible in order for the collectors to be attractive to users. It is also crucial that the air tightness and load bearing capacity of the construction are not impaired by the integration of the collector.

For a BIST system, the services and replacement of components are difficult therefore, a guaranteed long durability of the components and materials is desirable. It is necessary to perform lifetime tests on a material and component intended for use in building-integrated systems, preferably including outdoor tests and tests of accelerated ageing, to confirm the long term durability of the system. The durability of the collector should preferably be as high as that of the rest of the building envelope. It must also withstand temperature changes and ageing. If it is necessary to replace parts of BIST system, it must be possible for this to be done easily.

Correct use and maintenance of the BIST system is essential if the benefits of enhanced energy efficiency are to be realised.

- the whole system, including components should be properly commissioned and tested, taking account of the manufacturer's recommendations to achieve optimum energy efficiency; and,

- written information should be made available for the user on the operation and maintenance of the whole system, including the recommended frequency of scheduled maintenance.

The main maintenance issues for different types of BIST systems as outlines by Zhang et al. (2015) are presented in Table 2.8.1.

2.8.2 Visual Inspection

The BIST system should be easily accessible for maintenance, and the visual aspect has to be taken into account given the strong impact of the facade on the building architecture. The visual inspections of the BIST systems involve checking the solar collectors, its components and solar circuit for visual changes. Dust, dirt and faults reduce significantly the efficiency of solar collectors. Periodic cleaning is necessary in dry, dusty climates. The optical efficiency of some collector is reduced by somewhere between 0.3% and 1 % after 8 to 16 years. For an acrylic based collector, the complete cleaning is very difficult to achieve because the dirt tends to be "burnt on" and thus affects the optical efficiency significantly. For glass based collectors, the rain cleans the surface naturally and cleaning is not recommended unless the collector is installed in an exceptionally dry polluted place which experiences high dust conditions. In some places in the glass tube moss accumulates on the underside of tubes which tends to affect the radiation transmission through the side of the tubes. Many flat plate panels collect dirt on the interior of the glass. Both glass and acrylic “age” and aging tends to diminish the optical transparency. The transmission is best preserved by non-ferrous white glass and 10% worse for acrylic coverings. The accessibility to the panels is vital for cleaning and maintenance.

Shading can affect the performance of the collector therefore visual check is required for shading of the collectors during the day on an annual basis. Vegetation growth over time or new construction may produce shading that wasn't there when the collectors were installed.

Regular inspection is required to check for cracks in the glazing of the collector and to see if seals are in good condition. The damaged glazing due to weather conditions has to be replaced. Leakage from the collectors and the attachments must be avoided. Leakage occurs most frequently at the attachments or where the roof/facade is penetrated. Fluid leaks at pipe connections should be thoroughly checked. Checking the duct connections and seals is necessary. Ducts should be sealed with a mastic compound. All wiring connections should be tight. Insulation around the piping, duct and wiring should be checked for damage or degradation. The condition for flashing and sealant around roof/facade penetrations should be checked. All fixers of the BIST components to any support structures for tightness should be checked. It is necessary to make sure the valve is not stuck open or closed. For solar air heating systems, the dampers should be opened and closed properly. The operation of the distribution pumps or blowers/fans should be checked if they start operation when the sun is shining on the collectors after mid-morning. If they don’t start operation, then either the controller has malfunctioned or the pump or blower has. The storage system should be checked for cracks, leaks, rust, or other signs of corrosion. Visual inspection is required to check that the system pressure has not dropped into red zone, the flow gauges indicate correct flow levels and all valves and pumps are working correctly.

2.8.3 Frost Protection

For BIST systems that use liquids as heat transfer fluid, need protection from freezing in cold climates. Two main options are used to protect the collector and piping from damage due to freezing temperatures. These are

- Use an antifreeze solution as the heat-transfer fluid, and
- Drain the collector(s) and piping (collector loop), either manually or automatically, when there's a chance the temperature might drop below the liquid's freezing point.

Antifreeze solutions (propylene glycol or ethylene glycol) in liquid (hydronic) solar heating collectors need to be replaced periodically. Antifreeze fluids degrade over time and normally should be changed every 3–5 years. The frost protection of antifreeze fluids is checked with a hydrometer or refractometer (Anon, 2005).

‘Draindown’ or ‘drainback’ systems typically use a controller to drain the collector loop automatically. Sensors on the collector and storage tank tell the controller when to shut off the circulation pump, to drain the collector loop, and when to start the pump again. To ensure that the collector loop drains completely, there should also be a means to prevent a vacuum from forming inside the collector loop as the liquid drains out. Usually an air vent is installed at the highest point in the collector loop. It is a good practice to insulate air vents so that they do not freeze. Also make sure that nothing blocks the airflow into the system when the drain cycle is active.

Improper placement or the use of low-quality sensors can lead to their failure to detect freezing conditions. The controller may not drain the system, and expensive freeze damage may occur. It is important to make sure that the sensor(s) have been installed according to the manufacturer's recommendations, and check the controller at least once a year to be sure that it is operating correctly.

In integral collector storage or "batch" systems, the collector is also the storage tank. Placing large amounts of insulation around the unglazed parts of the collector and covering the glazing at night or on cloudy days will help to protect the collector from cold temperatures. However, water in the collector can freeze over extended periods of very cold weather. The collector supply and return pipes are also susceptible to freezing, especially if they run through an unheated space or outside. This can happen even when the pipes are well insulated. It is best to drain the entire system before freezing temperatures occur to avoid any possible freeze damage.

2.8.4 Corrosion

Most well-designed solar systems experience minimal corrosion mainly due to galvanic corrosion. This corrosion happens when two dissimilar metals coming into contact with each other causing an electrolysing process. One metal has a stronger positive electrical charge and pulls electrons from the other, causing one of the metals to corrode. The heat-transfer fluid in some solar energy systems sometimes provides the bridge over which this exchange of electrons occurs.

Oxygen entering into an open loop hydronic solar system causes rust in any iron or steel component. Such systems should have copper, bronze, brass, stainless steel, plastic, rubber components in the plumbing loop, and plastic or glass lined storage tanks.

Checking the corrosion protection of the solar liquid is done indirectly by establishing the pH value. Test strips are suitable for this with which the pH value can be read from a colour scale. If the pH value falls below the original value to under 7, the frost protection mixture should be exchanged.

Most of the metals used in building facades such as steel, aluminum, copper, titanium, zinc and bronze are not in their pure form, but as alloys. Usually metals used in facade cladding systems content a primary metal > 90%. The most common and significant physical phenomena to take into consideration in the design phase because of the metal based cladding systems is corrosion. The corrosive process is a great problem because it needs to be renewed frequently resulting in higher maintenance costs. Some metals do not corrode, others form a regenerative anticorrosion layer which changes the appearance with the time, e.g. the copper. A third group - iron and steel - requires special treatments in order to resist environmental influences.

Table 2.8.1 Maintenance issues for different types of BIST systems (Zhang et al., 2015).

Type of BIST System	Maintenance issues
Wall based	• More costs for outdoors' cleaning and maintenance. • Risk of condensation and thermal frost within insulation. • Cold bridge and acoustic problems at a penetration hole. • Additional imposed static and wind that require additional fixed structures. • Lessen climate disturbance of original facade unit.
Window based	• Have risks in reducing life expectancy caused by water leakage, or thermal breakage and expansion under high temperature. • If placed within a cavity of glazing unit, the life expectancy can be extended.
Balcony based	• Requires high demand both quality and installation due to totally external exposure for both overall performance and safety aspect. • Additional moveable shading in clear vision area is necessary. • Additional support structure is needed. • Easy cleaning and maintenance.
Roof based	• Have risks in reducing life expectancy caused by water leakage or thermal breakage and expansion under high temperature. • Less costs for outdoors' installation, cleaning and maintenance. • Lessen climate disturbance of original roof structure.
BIPV/T air based	• Require moderate maintenance effort, • Less risks related to freezing or leaking

2.8.5 Scaling

If water with a high mineral content (i.e., hard water) is circulated in the collectors, mineral build up in the piping may need to be removed by adding a de-scaling or mild acidic solution to the water every few years. Scale build up reduces system performance in a number of ways. If the system uses water as the heat-transfer fluid, scaling can occur in the collector, distribution piping, and heat exchanger. In systems that use other types of heat transfer fluid (such as glycol, an anti-freeze), scaling can occur on the surface of the heat exchanger that transfers heat from the solar collector to the domestic water. Scaling may also cause valve and pump failures on the potable water loop. Scaling can be avoided by using water softeners or by circulating a mild acidic solution (such as vinegar) through the collector every 3–5 years, or as necessary depending on water conditions.

2.8.6 System monitoring

The performance of a BIST system needs to be constantly monitored to ensure it is performing at the desired level. A comprehensive monthly monitoring procedure is needed to track system performance and allow for changes to the system set-up to that ensure maximum performance is achieved. A comprehensive operating data monitoring system ensures that failures or faults are signalled and quickly detected. This allows the system owner to instigate measures to remedy the fault.

Currently, control units installed with forced circulation solar thermal systems usually control the system by measuring collector outlet and storage temperatures, providing some basic monitoring features. Sometimes, the flow rate in the collector circuit is measured as well for control purposes and to calculate the energy yield provided by the collector field. To further optimise the system performance, additional information is needed, i.e. pressure in the hydraulic circuits, radiation intensity, temperature stratification in the storage and the expected heat demand profile and characteristics. Advanced controllers include capabilities related to remote maintenance and metering for billing. The pressure and temperature, and the controller setting must be checked on a regular basis. If provided, within the scope of maintenance the data for system function and yield monitoring can also be recorded. Table 2.8.2 shows the stagnation control strategies for solar thermal systems.

Table 2.8.2. Stagnation control strategies for solar thermal systems (Zhang et al., 2015).

Stagnation control scheme	**Protects collectors**	**Protect system components**	**Performance of durability impact**
Drain-back or drain down	No	Yes	Collector loop open to atmosphere may increase corrosion or fouling
Control based (e.g. night heat rejection, recirculation etc)	Yes	Yes	May result in available energy being dumped at night
Steam back	Not always	Not always	Potential thermal shock/scalding on restart
Collector venting	Yes (if carefully designed)	Yes (if carefully designed)	May experience small performance penalty if not carefully implemented
Heat waster on collector loop	Yes	Yes	If powered may require auxiliary generators
Heat pipe control (Evacuated tube collector)	No	Yes	System may be incorporable for remainder of day

2.8.7 Safety

Regardless of the location of the BIST system, always consider appropriate safety measures. Maintenance, repairs, or inspections of the BIST system require that a safety plan be developed. During the installations process, safety regulation must be followed to provide a safe situation for the workers, especially during roof work. There are large differences between individual countries regarding the safety regulations to be followed during the installation of solar thermal systems.

REFERENCES

Anon 2005 Planning and Installing Solar Thermal Systems, a guide for installers, architects and engineers (2005), James and James Ltd, London, UK

Zhang X, Shen J, Tang L, Yang T, Xia L, et al. (2015) Building Integrated Solar Thermal (BIST) Technologies and Their Applications: A Review of Structural Design and Architectural Integration. J Fundam Renewable Energy Appl 5: 182. doi:10.4172/20904541.1000182

2.9 LIFE CYCLE ASSESSMENT (LCA) AND ENVIRONMENTAL ISSUES ABOUT BUILDING-INTEGRATED SOLAR THERMAL SYSTEMS

Chrysovalantou Lamnatou, Daniel Chemisana

2.9.1 Introduction

Building-integrated (BI) solar systems are important for the building sector (for example, towards zero or nearly zero buildings) and they offer multiple advantages (higher aesthetic value, etc.) in comparison to building-added (BA) solar systems (Kalogirou, 2013). One of the main characteristics of the BI systems is that they replace a building component (e.g. façade) and they are not added on the building as the traditional BA configurations. The above mentioned feature of building integration (which reveals the replacement of certain building components and materials) along with the fact that there are different BIST (building-integrated solar thermal) systems (for production of thermal energy (only); for production of thermal and electrical energy: BIPVT (building-integrated photovoltaic/thermal); for production of thermal and electrical energy by adopting sunlight concentration: BICPVT (building-integrated concentrating photovoltaic/thermal); passive solar walls (e.g. Trombe walls); passive solar façades; etc.) demonstrate that BI solar systems show interest also from environmental point of view (Lamnatou et al., 2015a; Chemisana, 2011; Lamnatou et al., 2015b). In the literature there are some studies which present LCA (life cycle assessment) or, in general, environmental issues about different types of BIST installations. In the following paragraphs certain of these investigations are presented.

With respect to BIST systems which produce thermal energy for the building, the environmental profile of a gutter-integrated BIST system has been investigated by Lamnatou et al. (2014; 2015c; 2015d). Different configurations were examined (collectors connected in series and tubes (cold-water tube and hot-water tube) at different levels, etc.) for different scenarios (with/without recycling; France´s vs. Spain´s electricity mix), based on embodied energy and embodied carbon (Lamnatou et al., 2014). The system with parallel connection (and tubes at different levels), by adopting recycling showed an EPBT (energy payback time) of 0.5 years. The profile of the above mentioned system was also examined by means of EI99 (Eco-indicator 99) and IMPACT 2002+ (Lamnatou et al., 2015c; Lamnatou et al., 2015d).

In terms of façade-integrated configurations, Lenz et al. (2012) presented a work about a transparent solar thermal collector for façade integration, based on CML 2007 and primary energy. On the other hand, Pomponi et al. (2015) conducted a comparative LCA between double-skin-façade refurbishments and an up-to-standard single-skin alternative configuration. Energy and carbon (operational and embodied) were examined. It was demonstrated that double-skin façades are more energy-efficient than single-skin in 98% of the cases, and more carbon-efficient in 85% of the cases.

Concerning BIPVT, Agrawal and Tiwari (2015) studied several issues, including EPBT and CO_2 emissions of glazed PVT/air systems which can be used for building integration or for integration into a dryer. The EPBT was calculated to be 1.8 years. Crawford et al. (2006) investigated BIPV (building-integrated photovoltaic) panels with heat recovery (BIPVT) and without heat recovery (and other scenarios) and it was noted that heat recovery in combination with a BIPV system (BIPVT) reduces the EPBT of a typical BIPV system.

Kamthania and Tiwari (2014) presented a work about semi-transparent hybrid PVT double pass façade (several issues were studied, including EPBT and CO_2 mitigation). Furthermore, Battisti and Corrado (2005) investigated PV and PVT systems (roof-integrated; for space heating or domestic hot water) and it was mentioned that all the studied configurations presented environmental PBTs considerably lower than their expected lifespan (3-4 years vs. 15-30 years).

Taking into account that BIST are a recent tendency in the building sector (Lamnatou et al., 2015a; 2015b), as it was mentioned in the review study of Lamnatou et al. (2015e) about BIST LCA, there is a potential for more LCA studies about these systems, especially based on multiple LCIA (life cycle impact assessment) methods (midpoint, endpoint approaches, etc.) since most of the studies available in the literature examine CO_2 emissions and embodied energy.

In the frame of this concept, the present chapter presents an overview of LCA studies and investigations which include environmental issues about BIST systems, highlighting critical aspects which influence their profile from environmental point of view.

2.9.2 General issues about LCA

Given the fact that the environmental awareness increases, businesses and the sector of industry are assessing how their activities influence the environment. The society has become concerned in terms of environmental degradation and natural resource depletion. In this way, many businesses offer «greener» products and adopt «greener» processes. In the frame of this concept, the performance (from environmental point of view) of the products and the processes has become a critical issue, which is why certain companies examine options to reduce their environmental impact (SAIC, 2006).

The concepts of LCA and life-cycle thinking are scientific approaches related to business decision supports and modern environmental policies, in the frame of sustainable consumption and production (ILCD Handbook, 2010).

The term «life cycle» includes the major activities during the lifespan of a product from manufacturing, use and maintenance, to the final disposal (the raw material acquisition needed for the manufacturing of the product is included) (SAIC, 2006).

LCA is a comprehensive and structured method for quantifying material- and energy-flows as well as their emissions during the life-cycle of a product (Fthenakis et al., 2011). In an LCA study, the resources consumed and the emissions (for a certain product) are compiled and documented in an LCI (life cycle inventory). An impact assessment is then conducted, by taking into account, the natural environment, the human health and issues associated with the use of natural resources (ILCD Handbook, 2010).

The impacts which are considered in the frame of an LCIA include multiple impact categories (climate change, ozone depletion, eutrophication, acidification, human toxicity, etc.). It should be noted that the resources and the emissions are assigned to each of these impact categories. Moreover, they are then converted into indicators by utilizing impact assessment models. In this way, different emissions and resources consumed, and different options of a product, can then be cross-compared with respect to the impact indicators (ILCD Handbook, 2010).

The ISO 14040/44 standards offer the indispensable framework for conducting an LCA study. LCA is an internationally standardised method and management tool (according to ISO 14040 and 14044, 2006) for quantifying the resources consumed, the emissions and the environmental/health impacts that are related to goods/services/products (ILCD Handbook, 2010).

An LCA consists of four phases (ISO 14040 and 14044, 2006):

1) Goal and scope definition: during this phase the aim of the LCA is clearly defined (consistent with the application).
2) LCI: it includes data collection and calculations in order to evaluate the major inputs/outputs of a product system.
3) LCIA: the aim of this phase is the evaluation of the significance of potential environmental impacts.
4) Interpretation: during this phase, the outcome is interpreted in accordance with the aim defined in the goal and scope of the study.

More information can be found in (ISO 14040 and 14044, 2006).

2.9.3 LCIA methods and environmental indicators

In the following paragraphs, information about different LCIA methods and environmental indicators is presented, with emphasis on these methods/indicators which are related with the references cited in the following section (section 2.9.4).

For an LCA investigation in an energy context, it is critical the evaluation of the primary-energy inputs in order to produce a given product. In this way, the least energy-intensive industrial option (among alternative options/configurations) can be determined. Thereby, the concept of «embodied energy» arises presenting the quantity of energy needed to process (and supply to the construction site) a material. In order to evaluate the magnitude of this embodied energy, an accounting methodology should be adopted for summing the energy inputs over the greatest part of the material supply chain or life-cycle. In the same concept with embodied energy, the emissions of energy-related pollutants (for example CO_2 emissions which are related to global warming and climate change) may be studied over the life-cycle (e.g. of a product). Thus, the notion of «embodied carbon» arises (Hammond and Jones, 2008).

It should be noted that the primary energy includes primary energy from renewable and from non-renewable resources. Given the fact that primary energy from non-renewable resources has a higher impact on the nature, this indicator has broad application (it is known as embodied energy or grey energy). Non-renewable primary energy comes from fossil and nuclear energy sources while renewable primary energy refers to energy generated e.g. by the wind and by solar radiation (Hildebrand, 2014). In the frame of this concept, CED (cumulative energy demand) method presents characterization factors for the energy resources divided into 5 impact categories: non-renewable, fossil; non-renewable, nuclear; renewable, biomass; renewable, wind, solar, geothermal; renewable, water (PRé, 2014).

By knowing the primary energy demand over the life-cycle of a system, the energy metric EPBT can be evaluated. EPBT is the time needed for a renewable energy system to produce the same amount of energy (primary energy equivalent) that was utilized to produce the system itself (Fthenakis et al., 2011). Based on the equation of EPBT which is used for PV systems (Fthenakis et al., 2011), an equation that has been used for BIST systems (Lamnatou et al., 2014) is following presented:

$$EPBT = \frac{E_{in}}{E_{out.a} - E_{O\&M.a}} = \frac{E_{mat} + E_{inst} + E_{disp} + E_{transp}}{E_{out.a} - E_{O\&M.a}} \quad (2.9.1)$$

where,

E_{in} presents the total inputs (primary energy) for the manufacturing of the materials/components of the system, system installation, disposal and transportation.

$E_{out.a}$ is the annual output of the solar thermal system (converted into primary energy).

$E_{O\&M.a}$ refers to the annual inputs (primary energy) during the use phase of the system.

E_{mat} presents the total inputs (primary energy) for the phase of manufacturing (materials of the collectors and system additional components; manufacturing of the collectors).

E_{inst} includes the inputs (primary energy) that are needed for the installation of the system.

E_{disp} refers to the inputs (primary energy) which are related to the disposal of the materials/components at the end of their life.

E_{trans} are the inputs (primary energy) regarding the transportation of the materials/components from the factory gate to the building and from the building to the disposal site.

Based on the concept of EPBT, the GPBT (greenhouse-gas payback time) (Chow and Ji, 2012) can be also evaluated, by taking into account the $CO_{2.eq}$ emissions over system life-cycle (instead of the primary energy quantities which are presented in Eq. 2.9.1). For example, in the study of Lamnatou et al. (2016) about BIST LCA, for the calculation of the GPBT, the following equation has been adopted:

$$GPBT = \frac{life-cycle\ CO_{2.eq}\ emissions}{annual\ \ avoided\ \ CO_{2.eq}\ \ emissions} \quad (2.9.2)$$

More specifically in the above mentioned reference (Lamnatou et al., 2016), the GPBT was calculated by adopting three different ways. According to these three options of Eq. (2.9.2), the life-cycle $CO_{2.eq}$ emissions include: 1) material manufacturing (only for the collectors), 2) life-cycle emissions[3] except the inputs for pumping and auxiliary heating, 3) life-cycle emissions including the inputs for pumping and auxiliary heating. For all these cases, the annual avoided $CO_{2.eq}$ emissions are evaluated based on the annual output of each system and based on the gas oil emissions as reference (DEFRA, 2012).

[3] The following phases are taken into account: material/collector manufacturing, manufacturing of the materials for the additional components, installation, use phase (general maintenance; replacement of some components), transportation and disposal.

Based on EPBT, another energy metric which is known as EROI (energy return on investment) can be calculated. EROI shows how easy (regarding energy terms) is to exploit the available primary energy sources by investing a certain amount of energy which one has at one's disposal (Raugei et al., 2012). The evaluation of EROI can be based on the following equation (Raugei et al., 2012):

$$EROI = \frac{system\ lifetime}{EPBT} \qquad (2.9.3)$$

With respect to the energy performance of a system, the overall energy performance e.g. of a BIPVT system can be evaluated by comparing the total energy input with the total energy output. In the work of Kamthania and Tiwari (2014), the ratio of these two quantities is presented as EPF (electricity production factor). Another concept related with the energy production of a system is the LCCE (life cycle conversion efficiency) which, in the study of Kamthania and Tiwari (2014), is defined as the net energy productivity of a system with respect to the solar input radiation over the lifespan of the system.

Regarding EI99 method, it is the successor of Eco-indicator 95 and both methods adopt 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 consideration. For the damage assessment, the damages of the impact categories result in 3 types of damages (human health, ecosystem quality, resources) (PRé, 2014).

In terms of IMPACT 2002+ method, it is acronym of IMPact Assessment of Chemical Toxics and it proposes a feasible implementation of a combined midpoint/damage approach, connecting 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) (PRé, 2014).

Concerning CML method, in 2001, a group of scientists under the lead of CML (Center of Environmental Science of Leiden University) presented a set of impact categories and characterization methods for the impact assessment. The impact assessment method implemented as CML-IA methodology and it refers to midpoint approach (PRé, 2014).

Another method is EPS 2000 (Environmental Priority Strategies in product design) and it is a damage oriented method.

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

Moreover, Ecological footprint presents the biologically productive land and water a population needs in order to produce the resources it consumes and to absorb a 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 utilisation and to CO_2 emissions from fossil energy utilisation (PRé, 2014).

On the other hand, there are some studies which are based on LCCA (life cycle cost analysis). There are several costs related with acquiring, operating, maintaining and disposing of a system. In the frame of an LCCA, all the relevant present and future costs related to a system are taken into account. The goal is the estimation of the overall cost of project alternatives and to choose the design/option which ensures that the facility will offer the lowest overall cost (Agrawal and Tiwari, 2010).

Moreover, a newly-developed LCIA method (which is not included in the studies which are presented in section 4) is ReCiPe (successor of EI99 and CML-IA). ReCiPe presents the integration of the problem-oriented approach (CML-IA) and the damage-oriented approach (EI99). The problem-oriented approach refers to impact categories at midpoint level. ReCiPe includes 2 sets of impact categories (with the associated sets of characterization factors). At the midpoint level, 18 impact categories are included (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, freshwater eutrophication, freshwater ecotoxicity, fossil fuel depletion, minerals depletion and freshwater depletion). At the endpoint level most of the midpoint impact categories are multiplied by damage factors and they are aggregated into 3 endpoint categories (human health, ecosystems and resource surplus costs). The three endpoint categories are normalized, weighted and they are aggregated into a single-score (PRé, 2014). Based on ReCiPe endpoint score, another type of PBT (ReCiPe PBT) can be evaluated (Lamnatou and Chemisana, 2015).

For the case of BI solar systems, the PBTs can be also calculated with an alternative way, by taking into account that there is material replacement (since BI systems replace a building component, e.g. a wall). For example, Chow and Ji (2012) presented EPBT and GPBT for a BIPVT by considering material replacement.

Finally, in Table 2.9.1 a brief presentation of the above mentioned methods is provided.

2.9.4 LCA and environmental issues about the BIST: A review

2.9.4.1 Passive solar systems/solar walls

Bojić et al. (2014) presented a work about the energy and the performance (from environmental point of view) of buildings with and without Trombe walls. For the evaluation of the performance (from environmental point of view) the total amount of primary operating energy (for winter heating) and the annualized embodied energy consumed by adopting the Trombe walls, were taken into account. Two Trombe walls were adopted at the south side of a «Mozart» house in Lyon, France (the house was according to the French thermal regulation). Several constructions of Trombe walls were evaluated. The annual life-cycle energy use by the houses with Trombe walls may be lower for the case when the core material has lower embodied energy and lower density. For heating by means of electricity there are much higher values with respect to the optimum thickness of the core layer and that of the primary energy consumption than that for heating by adopting natural gas. For the case of the building with Trombe walls, the annual (final) energy savings for heating were found to be about 20%. For the utilisation of electrical heating and optimum core thickness, the energy ratio was calculated to be around 6 and the EPBT was found to be approximately 8 years. For the use of natural gas heating these values were calculated to be about 3 and 18 years, respectively.

Table 2.9.1. Brief presentation of certain methods (based on (Pré, 2014) classification) related (most of them) with section 4.

Methods	Explanations
Single issue	
CED	CED includes characterization factors for the energy resources divided into non-renewable and renewable impact categories
Greenhouse gas protocol	It is an accounting standard for GHG emissions
IPCC 2013	IPCC 2013 offers information about GWP (global warming potential) in a timeframe of 20, 100 and 500 years
USEtox	Characterization of human and eco-toxicological impacts
Ecological footprint	Regarding characterization, in the frame of LCA, the ecological footprint is the sum of time integrated direct and indirect land occupation, related to nuclear energy use and to CO_2 emissions from fossil energy use
European	
CML-IA	Midpoint approach
EPS 2000	Damage-oriented approach
IMPACT 2002+	Combination midpoint/damage approach
ReCiPe	Combination of the problem-oriented (midpoint) with the damage-oriented (endpoint) approach
Superseded	
EI99	Damage-oriented approach

Nowzari and Atikol (2009) investigated the temperature behavior of a hypothetical two-story building with a vented Trombe wall (Larnaca, Cyprus). The study included LCCA and the results showed that constructing a 15 m^2 thermal storage wall in Cyprus is economically feasible in comparison to installing a 3 kW gas heater.

Stazi et al. (2012) presented a work about a Trombe wall in a solar residential building prototype in Ancona (central Italy). An integrated approach for the optimization of the energy performance and the performance from environmental point of view of complex building envelopes that combines LCA, energy simulation and optimization analysis with factorial plan technique was proposed. The performance from environmental point of view was evaluated with respect to energy demand and CO_2 emissions for the production phase and the operational phase. The methodology was applied to a case study with solar wall systems. The optimization analysis showed that it is possible to reduce CO_2 emissions as well as CED of the solar walls (for the production and for the use phase) up to -55% comparing to a traditional design. It was noted that the proposed methodology can be generally applied in the frame of sustainability analysis, design and optimization of efficient façade configurations.

In addition, Peuportier (1998) conducted a study about the life-cycle simulation method EQUER applied to building components. EQUER is linked to a thermal simulation tool and to a data base which includes several processes (fabrication, waste management, etc.). Renewal and recycling of products is considered and the findings (e.g. in terms of GWP and acidification potential) are presented by means of spider charts. It was noted that the proposed tool can be adopted for example for the comparison of different architectural designs. A possible use for the configuration of a Trombe wall with transparent insulation materials was presented.

Pomponi et al. (2015) presented a life-cycle energy and carbon assessment of double-skin façades for office refurbishments. A multi-skin façade consists of different layers and between these layers air can move (Lamnatou et al., 2015b). The façades are physical barriers between outdoors and indoors and double-skin façades offer a solution for low-carbon refurbishment because of their ability to reduce the consumption of energy (as well as the related carbon emissions) of the building they are applied to (Pomponi et al., 2015). Even if there are research studies on maximising the operational energy savings of double-skin façades, there are no many studies about their life-cycle performance. In the frame of this concept, Pomponi et al. (2015) presented a comparative LCA between double-skin façade refurbishments and an up-to-standard single-skin alternative configuration. A parametric approach was used (including the analysis of 128 double-skin façade configurations through primary data). Energy and carbon, operational and embodied, were taken into account. The findings revealed that double-skin façades are more efficient from energetic point of view than single-skin in 98% of the cases, and more efficient from carbon point of view in 85% of the cases.

Kim (2011) presented a comparative LCA of a TCFS (transparent composite façade system) and a GCWS (glass curtain wall system). The proposed TCFS is a sustainable alternative to a high-performance glass wall in which the biofiber composite core plays the role of a shading device and the airspace between the polymer skins offers insulation. The comparison of the two configurations was based on the life-cycle energy consumption and CO_2 emissions. The findings demonstrated that the total life-cycle energy for the case of the TCFS was found to be 93% of that of the uncoated GCWS. With respect to the total $CO_{2.eq}$ emissions, for the TCFS were calculated to be 89% of the uncoated GCWS.

In Table 2.9.2, literature studies about LCA and environmental issues of passive solar systems are presented. From Table 2.9.2 it can be seen that: 1) in general, there are few studies, 2) most of the cases are about Trombe walls (for Mediterranean countries) and 3) the major part of the investigations focuses on embodied energy and CO_2 emissions.

2.9.4.2 BI solar systems which produce thermal energy

An LCA study about energy-generating components for façade-integration into high-rise buildings has been presented (Lenz et al., 2012). For the LCA the phases of production, use (operation, maintenance) and end-of-life were taken into account. CML 2007 method was adopted. Different environmental impact categories were analysed (acidification potential, eutrophication potential, GWP, etc.). Moreover, primary energy issues were also examined. Preliminary results for a transparent solar thermal collector in two different façade layouts, which can be found in the frame of non-residential high-rise buildings, were presented. The major environmental impact was found for the production phase due to the use of energy-intensive materials (e.g. metals, glazing). The adoption of recycling for the metals reduced the overall life-cycle impact up to 30%. The maintenance phase had almost no influence on the overall life-cycle impact. It was noted that the transparent solar thermal collector in different layouts and different façade integrations seems to offer advantages from environmental point of view if the component is applied on the south façade. In addition, for the case where the heat produced by the solar system substitutes the conventional heat production (for example, a condensing gas boiler) while the building is in operation, remarkable energy savings (in terms of non-renewable primary energy) can be achieved (Lenz et al., 2012).

Table 2.9.2. Literature studies about LCA and environmental issues of passive solar systems.

Study	Type of system	Location	Studied issues/methods	Results
Bojić et al. (2014)	Trombe wall	Lyon, France	Primary energy, EPBT, etc.	For the building with Trombe walls, the annual final energy savings (for heating) were about 20%.
Nowzari and Atikol (2009)	Trombe wall	Larnaca, Cyprus	LCCA, etc.	Constructing a 15 m^2 thermal storage wall in Cyprus is economically feasible (in comparison to installing a 3 kW gas heater).
Stazi et al. (2012)	Trombe wall	Ancona, Italy	CO_2 emissions, CED, etc.	It is possible to reduce CO_2 emissions and CED of solar walls (for production and use phase) up to -55% (in comparison to a traditional design).
Peuportier (1998)	Trombe wall		GWP, primary energy, acidification potential, etc.	In comparison to the reference case, the passive houses with Trombe wall show higher impact during construction (due to the additional components) and lower impact during use phase (due to the energy gains).
Pomponi et al. (2015)	Double-skin façade	London, UK	Life-cycle energy and carbon assessment, etc.	Double-skin façades are more energy-efficient than single-skin (in 98% of the cases) and more carbon-efficient (in 85% of the cases).
Kim (2011)	TCFS and GCWS	Detroit, MI, USA	Primary energy consumption, $CO_{2.eq}$ emissions, etc.	Total life-cycle energy: for the TCFS is 93% of that of the uncoated GCWS; total $CO_{2.eq}$ emissions: for the TCFS are 89% of the uncoated GCWS.

The profile (from environmental point of view) of a patented (Cristofari, 2006) BIST system based on the concept of integration into the gutters of a building (Motte et al., 2013) has been investigated by Lamnatou et al. (2014; 2015c). Three configurations were examined: 1) reference system (collectors connected in series and tubes (cold-water tube and hot-water tube) at different levels), 2) collectors of parallel connection and tubes at different levels, 3) collectors of series connection and tubes at the same level. The results (Lamnatou et al., 2014) revealed that the EPBT of the reference system decreases to less than 2 years by adopting parallel connection while it is about 0.5 years if recycling is also considered. The embodied carbon of the configurations was found to be around 0.16 t $CO_{2.eq}/m^2$ without recycling and about 0.02–0.03 t $CO_{2.eq}/m^2$ with recycling. Moreover, it was demonstrated that $CO_{2.eq}$ emissions are strongly associated with the electricity mix considered (Lamnatou et al., 2014).

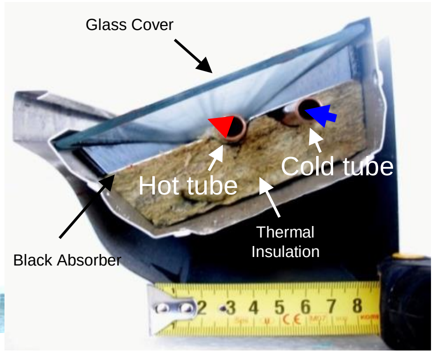
In addition, the profile of the above mentioned three gutter-integrated BIST configurations was also examined by means of EI99 and IMPACT 2002+, verifying that the configuration with the collectors in parallel connection can considerably improve the performance (from environmental point of view) of the reference system (Lamnatou et al., 2015c). By taking into account only the phase of material manufacturing of the collectors (per m^2 of absorber surface), the category «respiratory inorganics» presented the highest impact due to the copper tubes and the aluminium casing/gutter. By considering only, the materials of system additional components, it was demonstrated that copper (tubes: exterior/interior primary circuit) is the material with the highest impact (especially for the damage category «human health»). The above mentioned findings were verified by means of EI99 and IMPACT 2002+. Furthermore, the results of Lamnatou et al. (2015c) showed: a) good agreement with results from the literature about small-scale, solar thermal domestic hot water systems, b) that the proposed BIST system presents better profile (from environmental point of view) than conventional heating sources.

Additional results about the performance (from environmental point of view) of the above mentioned gutter-integrated BIST configurations have been presented (Lamnatou et al., 2015d). These additional results include life-cycle EI99 Pts/kWh, life-cycle IMPACT 2002+ Pts/kWh, EPBT and GPBT, based on different scenarios. Comparisons with the literature (with solar thermal systems and with conventional systems (coal-based, electrical, etc.)) were also presented and critically discussed. In general, the results according to all the selected LCIA methods and environmental indicators (Lamnatou et al., 2014; 2015c; 2015d) showed that the reference system (collectors of series connection; tubes at different levels) with small modifications such as parallel connection of the collectors (collectors of parallel connection; tubes at different levels) has remarkably improved efficiency and thereby, considerably improved profile from environmental point of view. Moreover, a further reduction of the impact is achieved by adopting recycling.

In addition, Lamnatou et al. (2016) conducted a study about BIST systems based on vacuum-tube collectors. The study included two parts. In the first part, a literature review was presented, including references about vacuum-tube technology (vacuum-tube/BIST systems, the profile (from environmental point of view) of vacuum-tube collectors, etc.). Critical issues (for example about the integration of vacuum-tube collectors into the building) were also highlighted. The literature review revealed that most of the vacuum-tube/BIST configurations are about façade-integration and there are few studies about the performance (from environmental point of view) of vacuum-tube collectors. As a continuity of the issues presented in the first part of the article of Lamnatou et al. (2016), the second part included a case study about the comparison (from environmental point of view) of a vacuum-tube/BIST with a flat-plate/BIST system, based on LCA. The studied systems were the previously mentioned flat-plate gutter-integrated configuration (2)[4] (Lamnatou et al., 2014; 2015c; 2015d) and another gutter-integrated configuration based on vacuum-tube collectors, both patented (Cristofari, 2006) and developed/tested at the University of Corsica, in France. Different LCIA methods, environmental indicators, scenarios and databases were adopted.

With respect to the BIST systems studied (from environmental point of view) by Lamnatou et al. (2016), in Figure 2.9.1(a) (left) the solar gutter based on System I (flat-plate/BIST) is illustrated. In Figure 2.9.1(a) (right) the components of one unit of System I are presented and it can be seen that System I is based on flat-plate collectors consisting of a highly-selective absorber, a glass cover, one tube for the flow of the cold water (lower insulated tube), one tube for the flow of the hot water (in thermal contact with the absorber), thermal insulation, external casing and gutter. In Figure 2.9.1(b), System II (vacuum-tube/BIST) is illustrated and it can be observed that each of the main tubes consists of two concentric copper tubes (the vacuum tubes are interconnected by means of the copper tubes; the heat transfer fluid enters from the larger copper tube and comes out from the smaller copper tube). It should be mentioned that there are 8 rows of 2 tubes inside the gutter (16 m total length). Furthermore, System I and System II have the same length (16 m) as common reference.

a)

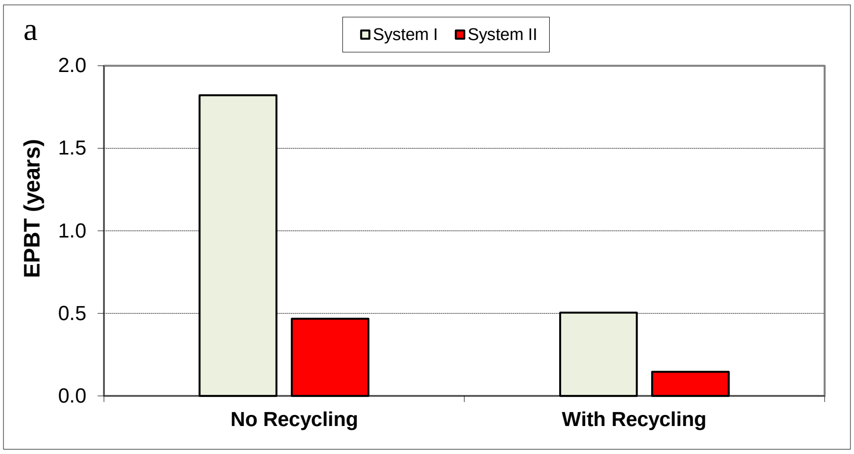



b)


Figure 2.9.1. a) The solar gutter based on System I (left) and details about the flat-plate collectors of System I (right), b) the solar gutter based on System II (left) and the vacuum-tube technology of System II (right) (Lamnatou et al., 2015c; Lamnatou et al., 2016).

[4] In the study of Lamnatou et al. (2016) and in Figure 1(a), configuration (2) is presented as System I.

Regarding the results about the profile (from environmental point of view) of System I and System II, the EPBT was found to be 1.8 and 0.5 years, for the flat-plate/BIST and the vacuum-tube/BIST, respectively. By adopting recycling these EPBT values were calculated to be 0.5 and 0.1 years, respectively (Figure 2.9.2a). Remarkable differences between System I and System II can be also observed by focusing on GPBTs (Figure 2.9.2b). For the scenario without recycling, System I shows GPBTs from 1.4 to 13.7 years (according to the three options of Eq. 2.9.2) while for System II these GPBT values range from 0.5 to 4.1 years. On the other hand, Figure 2.9.2(b) reveals that by using recycling there is a reduction of 0.4-1.8 years in terms of the GPBT values (Lamnatou et al., 2016).



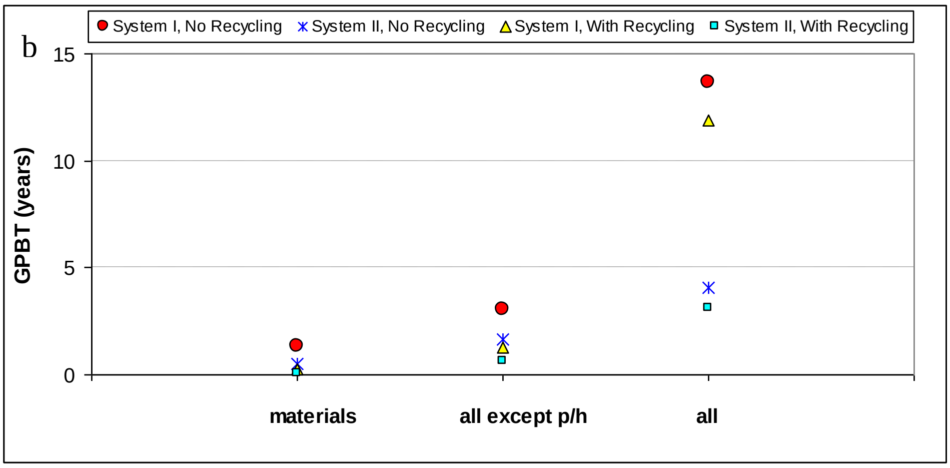


Figure 2.9.2. a) EPBT (years), b) GPBT (years): the GPBT has been calculated based on the three options of Eq. (2)[5]. System I vs. System II. Scenarios with and without recycling. Average values between ICE (Hammond and Jones, ICE, 2011) and ALCORN (Alcorn, 2003) databases (Lamnatou et al., 2016).

In the study presented by Lamnatou et al. (2016) were also included: 1) EROI (it has been calculated based on Eq. 2.9.3), 2) the avoided impact during use phase (by means of USEtox, ecological footprint and France´s electricity mix as well as with reference the $CO_{2.eq}$ emissions of a domestic gas boiler). The results were compared with the literature and good

[5] By considering as life-cycle $CO_{2.eq}$ emissions: 1) materials (= only material manufacturing for the collectors), 2) all except p/h (= all the phases except of pumping/auxiliary heating (p/h)), 3) all (= all the phases (including p/h)).

agreement was observed. In general, the findings of the study of Lamnatou et al. (2016) verified that remarkably higher impact can be avoided by utilizing the vacuum-tube/BIST (System II) instead of the flat-plate/BIST (System I).

In Table 2.9.3, literature studies about LCA and environmental issues of BI solar systems which produce thermal energy are presented. From Table 2.9.3 it can be observed that: 1) in general, there are few studies, 2) different environmental issues have been studied (based on embodied energy and embodied carbon, EI99, IMPACT 2002+, CML 2007, USEtox, etc.), 3) the systems refer to façade-integration and gutter-integration (most of the studies are about gutter-integrated configurations).

Table 2.9.3. Literature studies about LCA and environmental issues of BI solar systems which produce thermal energy.

Study	Type of system	Location	Studied issues/methods	Results
Lenz et al. (2012)	Façade-integrated solar thermal collectors	Europe	CML 2007, primary energy, etc.	If the produced heat substitutes e.g. a condensing gas boiler (building operation), considerable energy savings can be achieved.
Lamnatou et al. (2014)	Gutter-integrated solar thermal collectors: flat-plate	Ajaccio, France	Embodied energy, embodied carbon, etc.	Reference system EPBT: less than 2 years by parallel connection; around 0.5 years if recycling is also considered.
Lamnatou et al. (2015c)	Gutter-integrated solar thermal collectors: flat-plate	Ajaccio, France	EI99, IMPACT 2002+, embodied energy, embodied carbon, etc.	Material manufacturing of the collectors: «respiratory inorganics» show the highest impact due to the copper tubes and aluminium casing/gutter.
Lamnatou et al. (2015d)	Gutter-integrated solar thermal collectors: flat-plate	Ajaccio, France	EPBT, GPBT, EI99, IMPACT 2002+, etc.	The reference system (collectors of series connection; tubes at different levels) with parallel connection of the collectors (tubes at different levels) shows remarkably improved profile (from environmental point of view).
Lamnatou et al. (2016)	Gutter-integrated solar thermal collectors: flat-plate vs. vacuum-tube	Ajaccio, France	USEtox, Ecological footprint, EPBT, EROI, GPBT, etc.	EPBTs: 1.8 and 0.5 years, for the flat-plate and the vacuum-tube, respectively (with recycling: 0.5 and 0.1 years, respectively).

2.9.4.3 BI systems which produce thermal and electrical energy

In Table 2.9.4, studies about BI solar systems which generate both, thermal and electrical energy (BIPVT) are presented. It can be seen that different types of PV cells have been adopted, by using air as working fluid. Most of the applications are façade-integrated and roof-integrated, for variable climatic conditions (Australia, India, etc.). In addition, from

Table 2.9.4 it can be observed that most of these references present EPBT, CO_2 emissions, economic issues and they refer to BIPVT systems without sunlight concentration.

With respect to the EPBT values, the results (Table 2.9.4) show EPBTs ranging from around 1 to 14 years, depending on the system. In terms of the heat recovery, Crawford et al. (2006) noted that the utilisation of heat recovery in combination with a BIPV system (BIPVT) reduces the EPBT of a typical BIPV system. Moreover, Battisti and Corrado (2005) mentioned that the performances of the PVs (from energetic and from environmental point of view) are more interesting when the module is utilized as dual-output and when the design of the system is more integrated with the whole building design (in the work that they presented, the use of heat recovery for domestic hot water production reduced the environmental PBT more than 50%).

Regarding the type of the PV cells, Kamthania and Tiwari (2014) adopted different PV cells (silicon and non-silicon based) and HIT (heterojunction with intrinsic thin layer)-type PV module was recommended for the proposed system because of its low EPBT, high EPF and LCCE. Furthermore, Agrawal and Tiwari (2010) noted that although the mono-crystalline BIPVT system is more appropriate for the case of residential consumers based on its energy and exergy efficiencies, the amorphous silicon BIPVT is more economical.

In the literature there are also some investigations which study both BA PVT and BIPVT configurations (Table 2.9.5). Most of these works give emphasis on EPBT and CO_2 emissions and they are about air-based systems (for the climatic conditions of India and Hong Kong). The findings of these studies show that for some cases the BA systems present better performance (from environmental point of view) in comparison to the BI configurations. For example, the BA PVT and BIPVT systems which were investigated by Chow and Ji (2012), showed EPBTs 2.9 and 3.8 years, respectively. In terms of the GPBT, for the BA PVT it was found to be 3.2 years while for the BIPVT it was calculated to be 4 years (Chow and Ji, 2012). With respect to the production of thermal energy (parallel with the production of electrical energy), Tiwari et al. (2009) noted that the EPBT shows remarkable reduction by considering the increase in the annual energy availability of the thermal energy in addition to the electrical energy. Finally, it should be mentioned that the heat energy captured by the PV panels can be ducted into the HVAC system of the building where it can be utilized to displace the conventional heating load (Source: SolarWall).

Table 2.9.4. Literature studies about LCA and environmental issues of BIPVT systems.

Study	**PV cells**	**Fluid**	**System**	**Location**	**Studied issues/ methods**	**Results**
Agrawal and Tiwari (2015)		Air	Glazed PVT: integration into building or dryer.	New Delhi, India	EPBT, CO_2 emissions, technoeconomic analysis, etc.	EPBT: 1.8 years
Crawford et al. (2006)	Crystalline silicon; amorphous silicon	Air	BIPVs with heat recovery (BIPVT) and without; other scenarios	Sydney, Australia	EPBT, embodied energy, etc.	BIPVs with heat recovery (BIPVT) EPBTs (years): 4-9 amorphous, 6-14 crystalline.

Kamthania and Tiwari (2014)	Silicon and non-silicon based (CdTe; CIS; HIT; CIGS, etc.)	Air	Hybrid PVT double pass façade.	Srinagar, India	EPBT, CO_2 mitigation, etc.	CO_2 mitigation, carbon credits earned: maximum for HIT and minimum for CIGS.
Battisti and Corrado (2005)	Multi-crystalline silicon	Air Water	PV and PVT (roof-integrated; space heating or domestic hot water).	Rome, Italy; Sydney, Australia	EPBT, $CO_{2.eq}$ PBT, etc.	For all the studied systems: PBTs lower than their lifespan (3-4 y vs. 15-30 y).
Agrawal and Tiwari (2010)	Mono-crystalline silicon; poly-crystalline silicon; ribbon crystalline silicon; amorphous silicon; CdTe; CIGS	Air	BIPVTs fitted as rooftop: electrical energy and thermal energy for space heating.	New Delhi, India	Life-cycle cost, etc.	Cost of unit power generation by the amorphous silicon BIPVTs: US $ 0.1009 per kWh (quite close to the cost of power generation by the conven-tional grid).
Rajoria et al. (2013)		Air	PVT modules (case 1); PVT tiles (case 2)	India: Delhi, Jodhpur, Bangalore, Srinagar	CO_2 mitigation, enviro-economic study, etc.	CO_2 mitigation (based on thermal energy gain) for Bangalore for case1 and case 2: 90.85 and 99.81 t CO_2/annum, respectively.
Rajoria et al. (2016)		Air	Opaque (case A); solar cell tiles (silicon) (case B); semi-transparent (case C).	New Delhi, India	EPBT, carbon credit, LCCA, etc.	For case C the minimum EPBT in terms of energy and exergy (0.70 and 1.84 years, respectively).
Menoufi et al. (2013)	Mono-crystalline	Water	BICPVT	Lleida, Spain	EI99, EPS 2000, etc.	The phase of material manufacturing was studied; considerable environmental impact reduction is achieved by replacing the conventional BIPV with BICPV.

2.9.5 Issues related with BIST profile from environmental point of view

2.9.5.1 Recycling

Each material has a resource footprint and a pollution footprint (especially for the phase of production) and much of this can be avoided by using recycling products (rather than manufacturing from new raw material). A product which can be easily recycled will normally be preferable in a comparison to a product that is initially quite «green» but it cannot be recycled. Within the building industry, many products/materials have poor durability and low recycling potential. On the other hand, there are others that can be recycled several times (Berge, 2009).

Material recycling includes melting or crushing the component and separating it (into its original constituent materials, which then re-enter the process of manufacturing as a raw material). Especially for the case of the metals, this is an efficient solution. Furthermore, the potential for material recycling is highly dependent upon the purity of the item, given the fact that the separation of different constituents maybe difficult, and thereby, costly or near impossible (Berge, 2009).

Table 2.9.5. Literature studies about LCA and environmental issues of both BA PVT and BIPVT systems.

Study	**PV cells**	**Fluid**	**System**	**Location**	**Studied issues/ methods**	**Results**
Tiwari et al. (2009)	Mono-crystalline	Air	PVT with and without BOS: BA and BI (roof or wall).	New Delhi, India	EPBT, etc.	EPBT (outdoor without BOS): 3.00-3.96 years.
Agrawal and Tiwari (2013)	Mono-crystalline silicon	Air	Unglazed and glazed PVT tiles vs. conventional PVT air collectors.	Srinagar, India	CO_2 emissions, thermal energy gain, etc.	CO_2 emissions reduction per annum (based on thermal energy gain), unglazed and glazed PVT tiles, higher by 62.3% and 27.7% compared to the conventional PVT.
SolarWall		Air	BA PVT and BIPVT systems.		CO_2 emissions, etc.	BIPVT: considerable reduction in CO_2 emissions.
Chow and Ji (2012)	Single-crystalline silicon	Water	BIPVT (vertically mounted) and BA PVT (free standing).	Hong Kong	EPBT, GPBT, cost PBT, etc.	EPBTs: 2.9 years for the BA PVT at the best angle of tilt and 3.8 years for the BIPVT.

Regarding BIST recycling, in the studies of Lamnatou et al. (2014; 2015c; 2015d; 2016) about gutter-integrated BIST systems (presented in subsection 2.9.4.2), scenarios with material recycling for glass, aluminium and copper have been examined. For all the cases which were evaluated, the adoption of recycling resulted in a remarkable reduction of the impact. For example, in the study of Lamnatou et al. (2015d), the life-cycle impact of System 2 (collectors of parallel connection; tubes at different levels) according to IMPACT 2002+ was found to be 0.000118 and 0.000111 Pts/kWh for «No Recycling» and «Recycling», respectively. Moreover, based on EI99, System 2 presented a life-cycle impact of 0.0085 and 0.0072 Pts/kWh (for «No Recycling» and «Recycling», respectively). In terms of GPBT values, by using recycling there was a reduction of 1.4-2.6 years (Lamnatou et al., 2015d).

2.9.5.2 Materials for storage

Except of the classic heat storage e.g. with water tank, in the literature there are some studies which propose the utilization of PCM (phase change material) as heat storage for BIST systems. PCMs are materials whose latent heat at the solid-liquid phase transition point is utilized in applications such as energy storage. Due to the fact that PCMs present high storage density, they allow the construction of compact energy storage (Source: Life Cycle Inventory of Sodium Acetate and Expanded Graphite, 2008).

Regarding PCM for BIST, Hengstberger et al. (2016) proposed high-temperature PCM for the overheating protection of façade-integrated solar thermal collectors. Moreover, Lin et al. (2016) conducted a study about the thermal performance and optimization of buildings with integrated PCM and PVT collectors. In addition, Lachheb et al. (2015) developed an integrated component for passive-solar-wall applications which can offer high thermal energy storage potential in building materials. The proposed by Lachheb et al. (2015) component was made by conditioning paraffin inside 24 copper tubes (that were regularly inserted and aligned in a gypsum matrix). On the other hand, Liu and Li (2015) presented an experimental study about the thermal performance of a solar chimney without and with PCM.

Certainly, the materials utilized for storage influence the BIST profile (from environmental point of view). The degree of this influence depends on the environmental impact of these materials. For example, in the report Life Cycle Inventory of Sodium Acetate and Expanded Graphite (2008) it was noted that the total GHG (greenhouse gas) emissions for the case of PCM with sodium acetate are approximately 5 kg/kg.

2.9.5.3 PV cell material

For the case of BIPVT systems (and in general for PVT and PV systems), their performance (from environmental point of view) is considerably influenced by the type of the PV cells. Thereby, it is necessary to present some general information about certain PV cell materials.

General issues about PV cells

PV cells utilize semiconductor materials in order to produce electricity from solar energy. The most commonly adopted semiconductor element is silicon (Si) and solar cell is an electronic device which converts solar energy directly into electrical energy (by means of the photovoltaic effect). Multi-crystalline Si PVs have the major part of the market share, followed by mono-crystalline Si, followed by CdTe (cadmium telluride) thin-film. Even if CdTe thin-film has the lowest module production cost, multi-crystalline Si offers higher efficiency, reducing the cost for the mounting structure and for the installation (since those are proportional to the area necessary for installation). During the life-cycle of silicon PVs (when the typical Siemens process is adopted), the solar grade silicon production is the most energy-intensive stage (Source: Fthenakis, siteresources.worldbank.org).

It should be noted that except of the above mentioned PV cells, there are also other types of PV cells such as amorphous and nanocrystalline Si, CIGS (copper indium gallium diselenide) and organic PV cells (which are based on different materials and manufacturing processes) (Source: Fthenakis, siteresources.worldbank.org).

With respect to some examples about EPBT values for rooftop mounted PV systems (for U.S- and European- production and installation under average U.S. irradiation of 1800 kWh/m^2/year and 0.75 performance ratio), in the literature EPBTs (including BOS, frame and module) of about 1.6 years (for mono-Si and multi-Si) and 0.7 years (for CdTe) have been presented (Source: Fthenakis, siteresources.worldbank.org).

Hazardous materials related to PV cell production

The production process of crystalline Si wafers starts with the mining of silica (SiO_2) that is found in the environment as sand or quartz. Then, silica is refined at high temperatures in order to remove the O_2 and produce metallurgical grade silicon. For achieving very high purities there is a chemical process that exposes metallurgical grade silicon to hydrochloric acid and copper. Regarding, the production of crystals of mono-crystalline or multi-crystalline silicon, the high temperature necessary for crystalline-Si production makes it an extremely energy intensive and expensive process, and there is production of large amounts of waste (80% of the initial metallurgical grade silicon is lost during the process). In general, there are several chemicals which are used during the production of crystalline silicon (for example, corrosive chemicals) and these need special handling and disposal (Source: SVTC, 2009).

In addition, CdTe thin-film PVs use layers of CdTe and cadmium sulfide (CdS). The major hazards (in terms of health and safety) due to the manufacture of CdTe cells are related with the use of cadmium, cadmium sulfide, cadmium chloride and thiourea. Cadmium is carcinogen and extremely toxic (Source: SVTC, 2009).

Concerning CIS (copper indium diselenide) and CIGS, numerous chemicals are used during the production of these PV cells and many of them are very toxic (e.g. hydrogen selenide (or selenium hydride)) (Source: SVTC, 2009).

Example of a BIPVT system with different types of PV cells

Kamthania and Tiwari (2014) investigated the performance of semi-transparent hybrid PVT double pass façade for the weather conditions of Srinagar, India. Different configurations were evaluated, including various silicon and non-silicon PV technologies: ribbon-, mono-, amorphous-, poly-, crystalline-, silicon; CdTe; CIS; HIT; CIGS. The results demonstrated that:

1) The net annual electrical energy (including, overall annual thermal energy and overall annual exergy output) of the HIT PV panel was the maximum (because of the high efficiency of this module amongst the other PV modules) while it was the minimum for the amorphous-silicon PV panel (because of the lowest module efficiency).
2) EPF and LCCE were found to be maximum for the HIT PV module and minimum for the CIGS.

3) CO_2 mitigation and carbon credits earned were maximum for the HIT PV and minimum for the CIGS.

Kamthania and Tiwari (2014) concluded that the HIT PV panel is recommended for the proposed system because of its low EPBT, high EPF and LCCE.

2.9.5.4 Heat transfer fluid

Certainly, the heat transfer fluid influences the performance (from environmental point of view) of a system. For example, for the case of PVT, Tripanagnostopoulos et al. (2005) studied several PVT configurations and it was mentioned that natural or forced air circulation is low-cost and simple solution to remove the heat from the PV modules; nevertheless, it is less effective at low latitudes. Moreover, Tripanagnostopoulos et al. (2006) presented results on PVT/air vs. PVT/water applications. It was noted that the most interesting case for domestic applications (even if there is an increase in terms of the materials needed for the heat exchanger) is the combination of air and water heat recovery, which reduced the environmental PBTs for all the studied configurations. By comparing the findings about PVT/air systems (Tripanagnostopoulos et al., 2006) with those from their previous work about PVT/water systems (Tripanagnostopoulos et al., 2005) and based on similar system operating temperature (25^{o}C), it was found that the cost PBTs, EPBTs and CO_2 PBTs were higher for the PVT/air because of the lower thermal efficiency of the air heat extraction in the PVT/air configurations.

At this point it should be noted that except of the above mentioned concepts of PV/water and PV/air, there are also bi-fluid PVT systems. Assoa et al. (2007) presented a PVT system which combines preheating of the air and production of hot water (in addition to the electrical function of the PV cells). It was found that the thermal efficiencies are able to reach around 80%. Thus, the adoption of a bi-fluid PVT configuration is expected to influence the profile (from environmental point of view) of a PVT system.

2.9.5.5 The concentration of the sunlight

The PVs can be combined with concentrators (devices which concentrate solar radiation). These systems are known as CPV (concentrating photovoltaic). In CPVs, sunlight is focused onto the PV cell by means of e.g. reflective or refractive optical devices. CPVs are characterized by their CR (concentration ratio) (Tripanagnostopoulos, 2007). CR is the ratio between the aperture area of the primary concentrator and the active cell area and for BICPV (building-integrated concentrating photovoltaic) applications CRs less than 10× (one-axis tracking is sufficient for their operation) show interesting characteristics (Chemisana, 2011).

There are several critical issues which influence the environmental performance of CPVT (and BICPVT) systems:

- CPVs present higher efficiency than the PVs without concentration. Nevertheless, this can be achieved in an effective way by keeping the PV temperature as low as possible (Tripanagnostopoulos, 2007). Higher PV output over the life-cycle of a CPVT or BICPVT system is favourable for certain environmental indicators which include the lifetime energy production of the system.

- In the frame of PV applications, the use of solar radiation concentration devices means replacement of the expensive PV cells with a cheaper solar radiation concentrating device (Tripanagnostopoulos, 2007). The utilisation of less material for the PV cells can be also considered as an advantage from environmental point of view (Chemisana, 2011).

- The distribution of the solar radiation on the surface of the absorber (PV module) and its temperature rise are two issues which affect the electrical output. The uniform distribution of the concentrated solar radiation on the surface of the PV and the appropriate cooling are critical parameters which are associated with the effective operation of the system and the high electrical output (Tripanagnostopoulos, 2007).
- CR influences the profile (from environmental point of view) of a BICPVT (or BICPV) device. A sensitivity analysis of an LCA study (based on EI99 method) for a BICPVT and for different CRs showed that increasing the CR results in reducing CPV system environmental impact. Nevertheless, it was highlighted that this requires further analysis and confirmation, considering the PV efficiency and the optical efficiency under different CRs (during operational phase). Furthermore, it was noted that the increase of the CR is also associated with higher optical losses (Menoufi et al., 2013).

2.9.5.6 Other parameters

Durability and lifespan

The durability of the components and the materials of a BIST system is a critical factor because it is associated with their ability to resist wear and tear on the building during the use phase. Certainly, the durability is also related with the profile (from environmental point of view) of the system. This is because more durable components with longer lifetime need fewer replacements (or no replacement) over the use/operational phase of the system, e.g. of a BIST system (Lamnatou et al., 2014; Lamnatou et al., 2015c). The durability of certain building materials can reach 50 years and it should be noted that for some cases the durability of the materials is influenced by the climate (Berge, 2009).

Type of materials and components

Traditionally solar thermal systems have been dominated by metal and glass components. However, in the literature there are works which present polymeric materials for solar thermal applications (IEA (2015), SHC Position paper, Task 39) as well as for PVT applications (Cristofari et al., 2009).

The position paper of Task 39 of IEA (IEA (2015), SHC Position paper, Task 39) presented polymeric materials for solar thermal systems. These materials offer advantages such as good energy performance for medium- and low-temperature applications, reduction of the cost, environmental benefits, multi-functional design of polymeric collectors (e.g. replacement of conventional roofs and façades). Nevertheless, there are some barriers. For example, the investment for suitable production units, e.g. extruders or injecting molding systems is relatively high and only viable for the case of high production rates; thereby, there is a need for a corresponding big market. On the other hand, polymer technology suffers from the image of not being durable, e.g. for certain collector designs overheating protection is necessary (IEA (2015), SHC Position paper, Task 39).

In the investigation of Cristofari et al. (2009) about the thermal behaviour of a copolymer PVT, it was mentioned that polymeric materials for solar collectors show advantages (cost reduction, reduction of the weight of the system, no corrosion, etc.) and disadvantages (large thermal expansion, low thermal conductivity, limits in terms of the service temperature, etc.).

The use of additional components/materials can influence the performance of a solar system from energetic as well as from environmental point of view. For example, the results of the LCA study of Tripanagnostopoulos et al. (2005) showed that the use of reflector for PVT/water systems for buildings (glazed and unglazed configurations; case for replacing electricity only) resulted in a reduction of 0.1-0.5 years in EPBTs and CO_2 PBTs, depending on the scenario.

The type of integration into the building and the type of application

For some cases, building integration of a solar system (apart from the multiple advantages that offers) may reduce the energy output of the system. In this way, the performance (from environmental point of view) of the BI solar system is affected (Lamnatou et al., 2014; Lamnatou et al., 2015c).

The application of a solar system (building sector vs. industry, small-scale vs. large-scale, low-temperature vs. medium temperature heating, hot air vs. hot water heating, etc.) is an additional issue which may be related with the profile (from environmental point of view) of a solar system. For example, Kalogirou and Tripanagnostopoulos (2007) proposed PVT systems for industrial applications. Furthermore, Kroiß et al. (2014) presented low-cost PVT systems which combine a polypropylene thermal absorber with a commercial PV for desalination. The works of Kalogirou and Tripanagnostopoulos (2007) and Kroiß et al. (2014) are for BA systems but these types of applications could be also examined for BI configurations. For example, Pak (2014) presented a BI solar desalination system. On the other hand, Tiwari et al. (2016) proposed another type of application based on a PVT integrated into a greenhouse solar dryer.

2.9.6 Conclusions

The present study presents an overview about studies based on LCA and studies which include environmental issues about BIST systems (including passive solar configurations; systems which produce thermal energy; systems which produce both thermal and electrical energy (BIPVT)). Representative references from the literature are presented and they are cited according to certain criteria (for example, related to the specific characteristics of each system).

Concerning the investigations about passive solar systems, the review reveals that most of these works are about Trombe walls. In addition, the greatest part of these investigations is based on embodied energy and CO_2 emissions.

With respect to BI solar systems which produce thermal energy, the review shows that: 1) different environmental issues have been studied (based on embodied energy and embodied carbon, EI99, IMPACT 2002+, CML 2007, USEtox, etc.) and 2) the systems refer to façade-integration and gutter-integration (most of the studies are about gutter-integrated configurations).

Regarding BIPVT systems, the review reveals that: 1) different types of PV cells have been adopted, by using air as working fluid, 2) the applications are façade-integrated and roof-integrated and 3) most of the references present EPBT, CO_2 emissions, economic issues about BIPVT systems without sunlight concentration. In addition, some studies show that by adopting a PVT (instead of a PV only) configuration, the system shows better performance from energetic and from environmental point of view. In the literature there are also some investigations which evaluate both BA PVT and BIPVT systems, revealing that for some cases the BA systems show better performance (from environmental point of view) in comparison to the BI configurations.

General issues about LCA, LCIA methods, environmental indicators and parameters related with BIST profile from environmental point of view (PV cell material and heat transfer fluid for the BIPVT, concentration of the sunlight, type of building-integration, etc.) are also presented in separate sections.

Conclusively, given the fact that there are few BIST LCA investigations, as a future prospect, there is a need for more LCA studies (and, in general, for studies which include environmental issues about BIST). In the frame of this goal, investigations based on embodied energy, EPBT, CO_2 emissions, GPBT, in combination with LCIA methods such as ReCiPe (which combines midpoint with endpoint approach) can provide useful information. Regarding the types of the systems, more studies are needed for passive BIST, for active BIST (which produce thermal energy or both thermal/electrical energy) and for some specific types of BIST e.g. with sunlight concentration.

In addition, given the fact that a BIST replaces the materials of a building component (for example, the materials of a wall), the concept of «material replacement» and the evaluation of different scenarios in terms of the materials that are replaced, can also provide useful information about BIST profile from environmental point of view.

LIST OF SYMBOLS AND ABBREVIATIONS

ALCORN	ALCORN database
BA	Building added
BI	Building integrated
BICPV	Building integrated concentrating photovoltaic
BICPVT	Building integrated concentrating photovoltaic/thermal
BIPV	Building integrated photovoltaic
BIPVT	Building integrated photovoltaic/thermal
BOS	Balance of system
CdS	Cadmium sulfide
CdTe	Cadmium telluride
CED	Cumulative energy demand
CIGS	Copper indium gallium diselenide
CIS	Copper indium diselenide
CML 2007	CML 2007 method
CML-IA	CML-IA method
$CO_{2.eq}$	$CO_{2.equivalent}$
CPV	Concentrating photovoltaic

CR	Concentration ratio
Eco-indicator 95	Eco-indicator 95 method
Ecological footprint	Ecological footprint method
EI99	Eco-indicator 99 method
EPBT	Energy payback time
EPF	Electricity production factor
EQUER	EQUER LCA tool
EROI	Energy return on investment
GCWS	Glass curtain wall system
GHG	Greenhouse gas
GPBT	Greenhouse-gas payback time
GWP	Global warming potential
HIT	Heterojunction with intrinsic thin layer
HVAC	Heating, ventilation and air-conditioning
ICE	ICE database
IMPACT 2002+	IMPACT 2002+ method
IPCC	Intergovernmental panel on climate change
LCA	Life cycle assessment
LCCA	Life cycle cost analysis
LCCE	Life cycle conversion efficiency
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
PBT	Payback time
PCM	Phase change material
Pts	Points
PV	Photovoltaic
PVT	Photovoltaic/thermal
PVT/air	Photovoltaic/thermal with air as working fluid
PVT/water	Photovoltaic/thermal with water as working fluid
ReCiPe PBT	ReCiPe payback time
ReCiPe	ReCiPe method
Si	Silicon
SiO_2	Silica
TCFS	Transparent composite façade system
USEtox	USEtox method

REFERENCES

Agrawal B., Tiwari G.N., Life cycle cost assessment of building integrated photovoltaic thermal (BIPVT) systems, Energy and Buildings, 2010;42:1472-1481.

Agrawal S., Tiwari G.N., Overall energy, exergy and carbon credit analysis by different type of hybrid photovoltaic thermal air collectors, Energy Conversion and Management, 2013;65:628-636.

Agrawal S., Tiwari G.N., Performance analysis in terms of carbon credit earned on annualized uniform cost of glazed hybrid photovoltaic thermal air collector, Solar Energy, 2015;115:329-340.

Alcorn A., Embodied Energy and CO_2 Coefficients for NZ Building Materials, Research and publication by the Centre for Building Performance Research, Victoria University of Wellington, Prepared with support from Building Research Association of New Zealand, Wellington, 2003.

Assoa Y.B., Menezo C., Fraisse G., Yezou R., Brau J., Study of a new concept of photovoltaic–thermal hybrid collector, Solar Energy, 2007;81:1132-1143.

Battisti R., Corrado A., Evaluation of technical improvements of photovoltaic systems through life cycle assessment methodology, Energy 2005;30:952-967.

Berge B., The ecology of building materials, second edition, translated by C. Butters and F. Henley, Elsevier, Architectural Press; 2009.

Bojić M., Johannes K., Kuznik F., Optimizing energy and environmental performance of passive Trombe wall, Energy and Buildings 2014;70:279–286.

Chemisana D., Building Integrated Concentrating Photovoltaics: A review, Renewable and Sustainable Energy Reviews, 2011;15:603-611.

Chow T.T., Ji J., Environmental Life-Cycle Analysis of Hybrid Solar Photovoltaic/Thermal Systems for Use in Hong Kong, Hindawi Publishing Corporation, International Journal of Photoenergy, Volume 2012, Article ID 101968, 9 pages, doi:10.1155/2012/101968

Crawford R.H., Treloar G.J., Fuller R.J., Bazilian M., Life-cycle energy analysis of building integrated photovoltaic systems (BiPVs) with heat recovery unit, Renewable and Sustainable Energy Reviews, 2006;10:559–575.

Cristofari C., Device for collecting rainwater and solar energy originating from light radiation. Patent no. WO 2006/100395 A1: 28/09/2006, 2006.

Cristofari C., Notton G., Canaletti J.L., Thermal behaviour of a copolymer PV/Th solar system in low flow rate conditions, Solar Energy, 2009;83:1123-1138.

DEFRA (2012), 2012 Guidelines to Defra / DECC's GHG Conversion Factors for Company Reporting: Methodology Paper for Emission Factors, July 2012, PB 13792, Published by the Department for Environment, Food and Rural Affairs, UK.

Fthenakis V., Photovoltaics: Present Status and Future Prospects, Center for Life Cycle Analysis, Columbia University, New York, Report from World Bank (Source: siteresources.worldbank.org).

Fthenakis V., Frischknecht R., Raugei M., Kim H.C., Alsema E., Held M., de Wild-Scholten M. (2011), Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity, 2nd edition, IEA PVPS Task 12, International Energy Agency, Photovoltaic Power systems Programme.

Hammond G.P., Jones C.I., Embodied energy and carbon in construction materials, Proceedings of the Institution of Civil Engineers – Energy, 2008;161(2):87-98.

Hammond G., Jones C., Inventory of Carbon and Energy (ICE), Department of Mechanical Engineering, University of Bath, UK, 2011.

Hengstberger F., Zauner C., Resch K., Holper S., Grobbauer M., High temperature phase change materials for the overheating protection of facade integrated solar thermal collectors, Energy and Buildings, 2016;124:1–6.

Hildebrand L., Strategic investment of embodied energy during the architectural planning process, Architecture and the Built Environment, 2014, abe.tudelft.nl

IEA (2015), SHC Position paper, Task 39, Polymeric Materials for Solar Thermal Applications, Solar Heating & Cooling Programme, International Energy Agency, June 2015

ILCD Handbook, International Reference Life Cycle Data System (2010), Analysis of existing Environmental Impact Assessment methodologies for use in Life Cycle Assessment, European Commission, Joint Research Centre, Institute for Environment and Sustainability.

ISO 14040:2006. Environmental management – Life cycle assessment – Principles and framework.

ISO 14044:2006. Environmental management – Life cycle assessment – Requirements and guidelines.

Kalogirou S.A., Building integration of solar renewable energy systems towards zero or nearly zero energy buildings. International Journal of Low-Carbon Technologies, 2013;0:1-7.

Kalogirou S.A., Tripanagnostopoulos Y., Industrial application of PV/T solar energy systems, Applied Thermal Engineering, 2007;27:1259-1270.

Kamthania D., Tiwari G.N., Energy metrics analysis of semi-transparent hybrid PVT double pass I considering various silicon and non-silicon based PV module Hyphen is accepted, Solar Energy 2014;100:124-140.

Kim K.-H., A comparative life cycle assessment of a transparent composite façade system and a glass curtain wall system, Energy and Buildings, 2011;43:3436–3445.

Kroiß A., Präbst A., Hamberger S., Spinnler M., Tripanagnostopoulos Y., Sattelmayer T., Development of a seawater-proof hybrid photovoltaic/thermal (PV/T) solar collector, Energy Procedia, 2014;52:93-103.

Lachheb M., Karkri M., Nasrallah S.B., Development and thermal characterization of an innovative gypsum-based composite incorporating phase change material as building energy storage system, Energy and Buildings, 2015;107:93–102.

Lamnatou Chr., Chemisana D., Evaluation of photovoltaic-green and other roofing systems by means of ReCiPe and multiple life cycle-based environmental indicators, Building and Environment 2015;93:376-384.

Lamnatou Chr., Chemisana D., Mateus R., Almeida M.G., Silva S.M., Review and perspectives on Life Cycle Analysis of solar technologies with emphasis on building-integrated solar thermal systems, Renewable Energy, 2015e;75:833-846.

Lamnatou Chr., Mondol J.D., Chemisana D., Maurer C., Modelling and simulation of Building-Integrated solar thermal systems: Behaviour of the system, Renewable and Sustainable Energy Reviews, 2015a;45:36-51.

Lamnatou Chr., Mondol J.D., Chemisana D., Maurer C., Modelling and simulation of Building-Integrated solar thermal systems: Behaviour of the coupled building/system configuration, Renewable and Sustainable Energy Reviews, 2015b;48:178-191.

Lamnatou Chr., Notton G., Chemisana D., Cristofari C. (2015d), Evaluation of the environmental profile of a building-integrated solar thermal collector, based on multiple life-cycle impact assessment methodologies, Conference EURO ELECS 2015, 21-23 July, Guimarães, Portugal.

Lamnatou Chr., Notton G., Chemisana D., Cristofari C., Life cycle analysis of a building-integrated solar thermal collector, based on embodied energy and embodied carbon methodologies. Energy and Buildings, 2014;84:378-387.

Lamnatou Chr., Notton G., Chemisana D., Cristofari C., The environmental performance of a building-integrated solar thermal collector, based on multiple approaches and life-cycle impact assessment methodologies, Building and Environment, 2015c;87:45-58.

Lamnatou Chr., Cristofari C., Chemisana D., Canaletti J.L., Building-integrated solar thermal systems based on vacuum-tube technology: Critical factors focusing on life-cycle environmental profile, Renewable and Sustainable Energy Reviews, 2016;65:1199–1215.

Lenz K., Wittstock B., Jäger M., Schneider S., Sedlbauer K., LCA of energy generating components for facade integration in existing high-rise buildings, International Journal of Sustainable Building Technology and Urban Development, 2012;3(3):168-176.

Life Cycle Inventory of Sodium Acetate and Expanded Graphite, Short Report, Provider: Dr. Niels Jungbluth, ESU-services Ltd. Customer: Benoit Nguyen, HEIG-VD / LESBAT, Uster, 15. January 2008.

Lin W., Ma Z., Cooper P., Sohel M.I., Yang L., Thermal performance investigation and optimization of buildings with integrated phase change materials and solar photovoltaic thermal collectors, Energy and Buildings, 2016;116:562–573.

Liu S., Li Y., An experimental study on the thermal performance of a solar chimney without and with PCM, Renewable Energy, 2015;81:338-346.

Menoufi K., Chemisana D., Rosell J.I., Life Cycle Assessment of a Building Integrated Concentrated Photovoltaic scheme, Applied Energy, 2013;111:505-514.

Motte F., Notton G., Cristofari C., Canaletti J.L., Design and modelling of a new patented thermal solar collector with high building integration, Applied Energy, 2013;102:631–639.

Nowzari R., Atikol U., Transient Performance Analysis of a Model Building Integrated with a

Trombe-Wall, Proceeding of the 7th IASME / WSEAS International Conference on heat transfer, thermal engineering and environment (I'09), 20-22 August 2009, Moscow, Russia.

Pak H., Building Integrated Solar Desalination (BIDSAL): preliminary works with multiple effect solar still, Energy Procedia, 2014;62:639–646.

Peuportier B., The life cycle simulation method EQUER applied to building components, Proceedings CIB World Building Congress, Gavle, Sweden, 7-12 June, 1998.

Pomponi F., Piroozfar P.A.E., Southall R., Ashton P., Farr E.R.P., Life cycle energy and carbon assessment of double skin façades for office refurbishments, Energy and Buildings, 2015;109:143–156.

PRé, various authors, SimaPro Database Manual, Methods Library, Report version 2.7, May 2014.

Raugei M., Fullana-i-Palmer P., Fthenakis V., The energy return on energy investment (EROI) of photovoltaics: Methodology and comparisons with fossil fuel life cycles, Energy Policy, 2012;45:576-582.

Rajoria C.S., Agrawal S., Dash A.K., Tiwari G.N., Sodha M.S., A newer approach on cash flow diagram to investigate the effect of energy payback time and earned carbon credits on life cycle cost of different photovoltaic thermal array systems, Solar Energy, 2016;124:254-267.

Rajoria C.S., Agrawal S., Tiwari G.N., Exergetic and enviroeconomic analysis of novel hybrid PVT array, Solar Energy 2013;88:110-119.

SAIC (2006), Life cycle assessment: principles and practice, by Scientific Applications International Corporation (SAIC), Contract No. 68-C02-067, Work Assignment 3-15, EPA/600/R-06/060, May 2006.

SolarWall, Source: http://solarwall.com/en/products/pvthermal.php

Stazi F., Mastrucci A., Munafò P., Life cycle assessment approach for the optimization of sustainable building envelopes: An application on solar wall systems, Building and Environment 2012;58:278-288.

SVTC (2009), Toward a Just and Sustainable Solar Energy Industry, A Silicon Valley Toxics Coalition, White Paper, January 14, 2009.

Tiwari A., Barnwal P., Sandhu G.S., Sodha M.S., Energy metrics analysis of hybrid – photovoltaic (PV) modules, Applied Energy, 2009;86:2615-2625.

Tiwari S., Tiwari G.N., Al-Helal I.M., Performance analysis of photovoltaic–thermal (PVT) mixed mode greenhouse solar dryer, Solar Energy, 2016;133:421–428.

Tripanagnostopoulos Y., Aspects and improvements of hybrid photovoltaic/thermal solar energy systems, Solar Energy, 2007;81:1117-1131.

Tripanagnostopoulos Y., Souliotis M., Battisti R., Corrado A., Energy, Cost and LCA Results of PV and Hybrid PV/T Solar Systems, Progress in Photovoltaics: Research and Applications, 2005;13:235-250.

Tripanagnostopoulos Y., Souliotis M., Battisti R., Corrado A., Performance, Cost and Life-cycle Assessment Study of Hybrid PVT/AIR Solar Systems, Progress in Photovoltaics: Research and Applications, 2006;14:65-76.

2.10 ENVIRONMENTAL LIFE-CYCLE ANALYSIS OF SOLAR SYSTEMS

Ricardo Mateus, Sandra M. Silva and Manuela G. Almeida

2.10.1 Introduction

The reduction of energy consumption and the use of energy from renewable sources in the buildings sector are important measures needed to reduce European Union (EU) energy dependency and carbon emissions. The potential of emissions mitigation in this sector is relevant as much as 80% of the operational costs of standard new buildings can be saved through integrated design principles, often at no (or little) extra cost over the lifetime of the measure (Boermans et al., 2015).

Buildings require energy both in the form of heat (e.g. for the domestic hot water preparation, space heating and even space cooling) and electricity (e.g. for lighting, electric appliances, heating and cooling). Therefore, solar thermal (STC), photovoltaic (PV) and hybrid photovoltaic-thermal (PVT) systems are necessary technologies for building applications since they can be used to replace non-renewable energy systems in proving renewable heat, electricity and cooling energy sources.

In the feasibility studies regarding the benefits of using solar systems, it is also necessary to consider the potential environmental impacts related to their manufacture, transportation and maintenance and the environmental benefits related to the energy savings (Lamnatou et al., 2015a).

The challenge is thus to develop and select cost-effective strategies for increased efficiency and deployment of renewable energy to achieve the best building performance (e.g. less energy use, fewer carbon emissions and higher co-benefits related with indoor environmental quality) at the lowest possible effort (e.g. initial costs, life cycle costs and occupant's disturbance in the case of building renovation).

The assessment of the life-cycle performance of a new building or of an energy renovation scenario can be based on several indicators, such as cost, operational energy consumption or environmental impacts of building materials and energy consumption. Whatever the indicators used the generic pattern of its time evolution and payback time can be schematised as shown in Figure 2.10.1.

Nevertheless, recent studies (e.g. (Mateus & Bragança, 2011; Lamnatou, et al., 2015a)) concluded that most assessments are not based on a comprehensive LCA methodology, since they are only focused on a small number of environmental indicators. The reasoning for this is the simplification of the LCA method for practical use, considering only the indicators that express the commitment of the building design with the EU energy targets. Two popular indicators generally used to assess and compare the environmental life-cycle performance both at buildings and energy systems level are the energy payback time (EPBT) and carbon emissions payback time (GPBT). Other studies state that there is a lack of findings based on the use of comprehensive life-cycle analysis methods to assess the benefits of using solar systems (e.g. (Tiago Filho et al., 2016)).

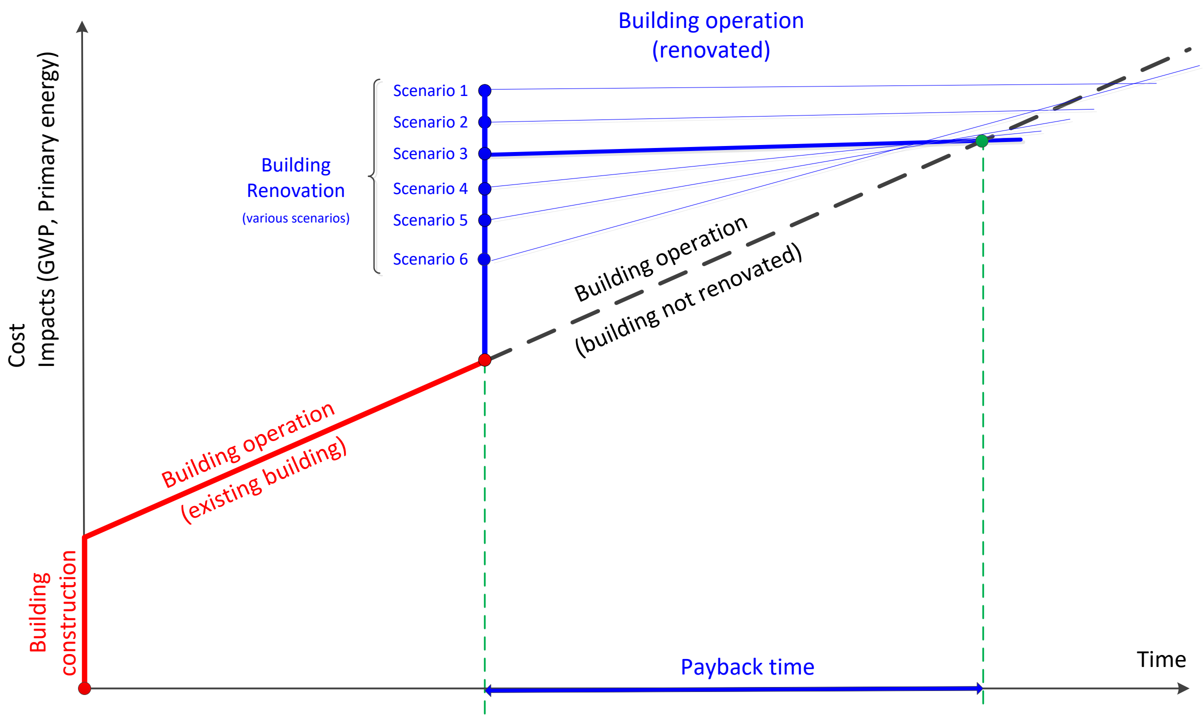


Figure 2.10.1. Schematic representation of the payback time of renovation operations (Ott et al., 2014).

Based on this context, the main goals of this section are: to define sustainable construction and to present the new standards in the context; to discuss the importance of the Life Cycle Assessment (LCA) method in the assessment of the environmental benefits resulting from the use of solar systems; to present the method to perform a life-cycle analysis to a building integrated or added Solar Thermal System for domestic hot water preparation; and to present the indicators used in the assessment of the environmental performance. At the end, a case study of an energy renovation project is presented in order to show the practical application of the LCA method in the assessment of the environmental benefits of using a Solar Thermal Collector (STC). In order to present the differences and discuss the results of using generic or specific Life-cycle Inventory (LCI) data in the early design stage, two renovation scenarios are presented.

2.10.2 The concept of sustainable building

Sustainable building is aimed at promoting the design, construction, renovation and operation of buildings that are more balanced at environmental, social and economic aspects.

As presented in Figure 2.10.2, sustainable building is the shift from the old paradigm where buildings were designed to meet only three aspects of competiveness (time, cost and quality) to a new paradigm where the human satisfaction, the minimal potential environmental impacts and the reduction of raw-material and energy’s consumption are in the centre of the design options.

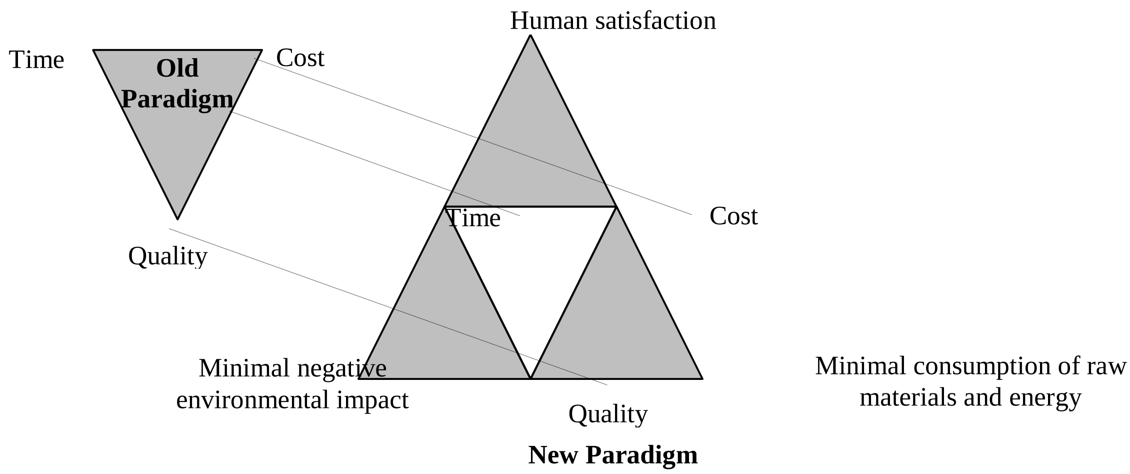


Figure 2.10.2. Holistic approach to building sustainability analysis.

Optimizing building sustainability involves various relations between built, natural and social systems. Therefore, it comprises hundreds of parameters, most of them interrelated and partly contradictory. This way, this process is only possible through a systematic approach.

Sustainability assessment tools are useful to gather and report information for decision-making during different phases of construction, design and use of a building (holistic approach).

In order to standardize and promote the interpretation and comparison of results from different assessment methods developed in Europe, the European Committee for Standardization (CEN) created the Technical Committee 350 (CEN/TC 350). The CEN/TC 350 is divided in five Working Groups (WG) (Figure 2.10.3): WG1 – Environmental Performance of Buildings; WG2 – Building Life-cycle Description; WG3: Products Level; WG4: Economical Performance of Buildings; and WG5 – Social Performance of Buildings.

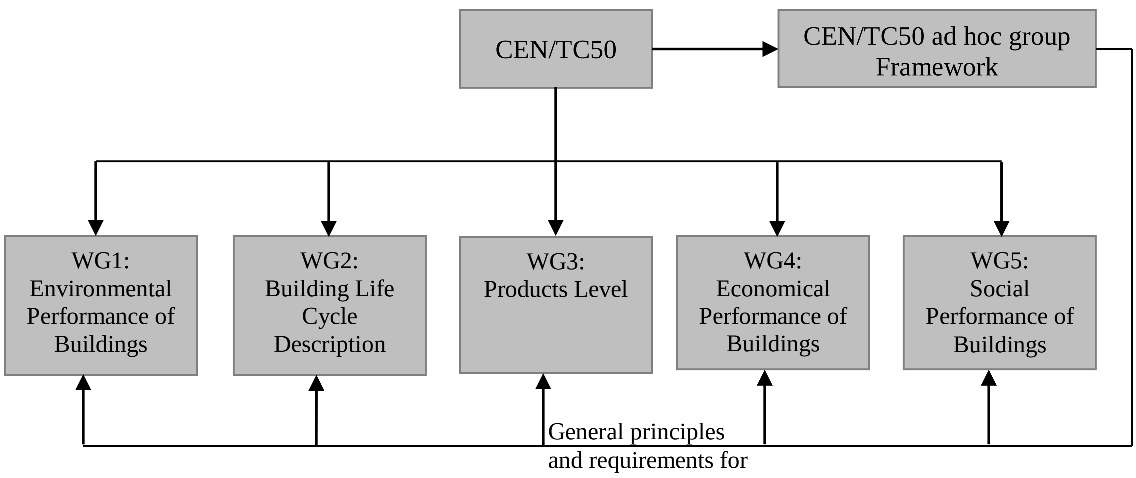


Figure 2.10.3. Organization of CEN Technical Committee 350.

This technical committee is providing the rules to assess the sustainability of the construction works, including buildings, to be applied in the different life-cycle stages of a building (Figure 2.10.4): pre-operation phase, operation phase and end-of-life phase. It also allows the quantification of the environmental benefits beyond the system boundaries, that result, for instance, from the recycling of materials to be used in a new life-cycle.

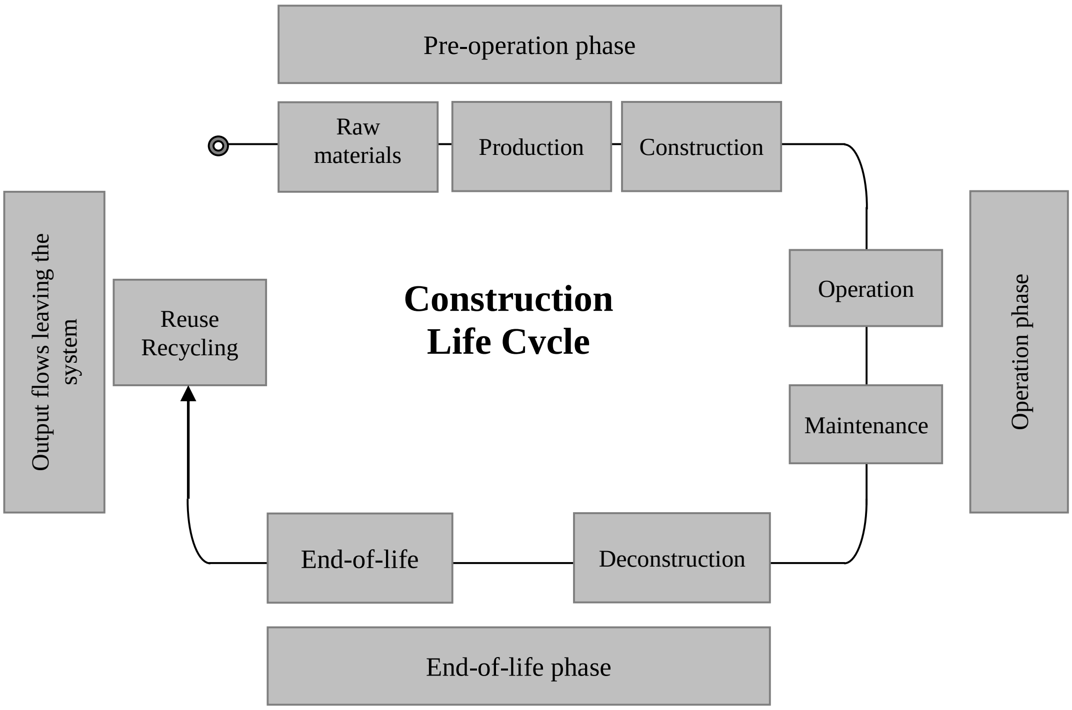


Figure 2.10.4. Life-cycle phases of a construction.

As a result of the work carried out to date the following main standards have been produced to support the evaluation of the environmental, social and economic performance of a building (CEN, 2010; CEN, 2011a,b; CEN, 2011a,b; CEN, 2014; CEN, 2015):

- EN 15643-1:2010, Sustainability of construction works - Sustainability assessment of buildings - Part 1: General framework;

- EN 15643-2:2011, Sustainability of construction works - Assessment of buildings - Part 2: Framework for the assessment of environmental performance;

  EN 15643-3:2012, Sustainability of Construction Works - Assessment of Buildings - Part 3: Framework for the assessment of social performance;

- EN 15643-4:2012, Sustainability of Construction Works - Assessment of Buildings - Part 4: Framework for the assessment of economic performance;

- EN 15978:2011, Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method;

- EN 16309:2014, Sustainability of construction works - Assessment of the social performance of buildings - Calculation method;

- EN 16627:2015, Sustainability of construction works - Assessment of the economic performance of buildings - Calculation method;

As discussed by several authors, the use of STC can have positive impacts in the different dimensions of sustainable development, mainly at environment and economic levels. In a study developed for the Portuguese context (Monteiro da Silva et al., 2016), authors concluded that the Greenhouse Gas Payback Time (GPBT) is under 19 months and the Economic Payback Time (EPBT) under 16 months. In other location, Kalogirou (2010) investigated a domestic, thermosiphon solar water heater (for the climate conditions of Nicosia, Cyprus) and concluded that the energy spent for manufacture/installation was recouped in approximately 13 months. At the level of PVs, for example, Lu and Yang (2010) studied the sustainability of a roof-mounted 22 kW building integrated PV system in Hong Kong and concluded a GPBT ranging from 3.6 to 5.3 years (depending on the considered energy mix) and an EPBT of 7.3 years.

2.10.3 Methodology to quantify the environmental benefits of using solar thermal systems in buildings

2.10.3.1 Steps of LCA at the building scale

Life-cycle analysis (LCA) is an analytical methodology that is aimed to assess the resources content and the environmental impacts associated with the life-cycle of a manufactured product. The LCA method is standardized by the International Organisation for Standardisation (ISO 14040:2006) (ISO, 2006). It has several applications, including: i) analysis of the contribution of the various life-cycle stages to the global environmental impact; ii) comparison between products; and iii) internal and external communication. Currently there are two specific rules for defining the framework and requirements of an LCA: ISO/FDIS 14040:2006 (ISO, 2006a), Environmental Management – Life Cycle Assessment – Principles and framework; and the ISO/FDIS 14044:2006 (ISO, 2006b), Environmental Management – Life Cycle Assessment – Requirements and guidelines.

According to ISO 14040:2006 (ISO, 2006a) and ISO 14044:2006 (ISO, 2006b), and as shown in Figure 2.10.5, the implementation of an LCA analysis is essentially an iterative process that is accomplished in four phases (ISO, 2006a; ISO, 2006b):

- Definition of Goals and Scope;
- Life-Cycle Inventory;
- Life-Cycle Impact Assessment;
- Interpretation.

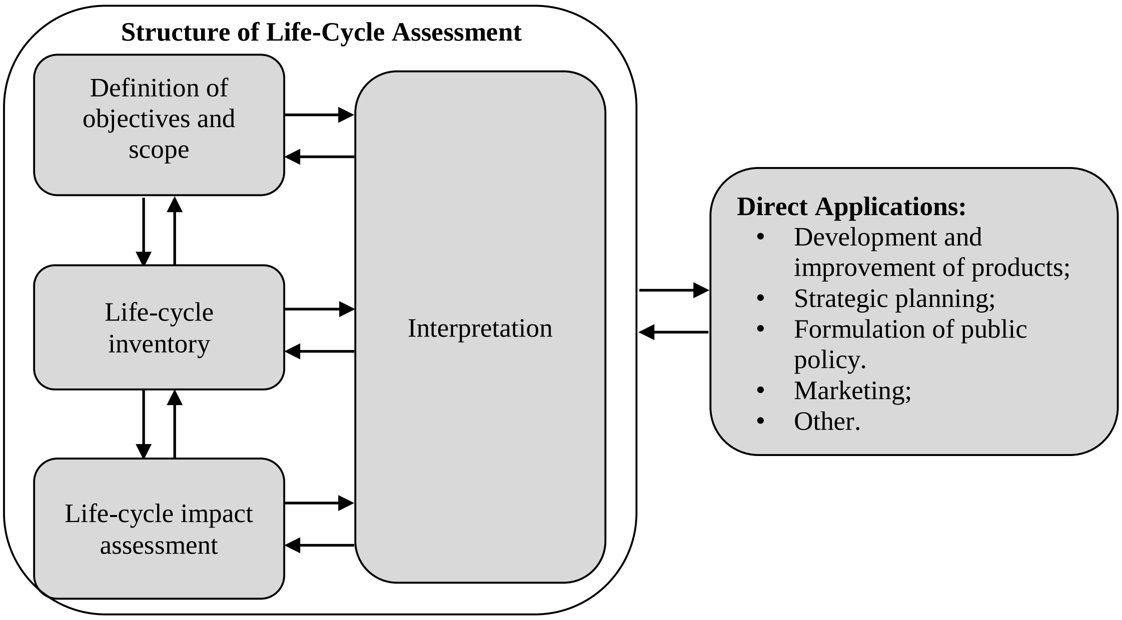


Figure 2.10.5. Stages of LCA (according to standard ISO 14040:2006).

As presented in Figure 2.10.6, according to EN 15978:2011 (CEN, 2011b) a typical life cycle of a building can be separated into four distinct stages (product, construction, use and end-of-life) each consisting of one or several life cycle modules. The product stage refers to the collection of raw materials through resource extraction, the transportation of raw materials and the manufacture of these raw materials into products. The construction stage includes the transportation of the building materials to the construction site and the construction-installation processes. The use stage refers to heating, cooling and electricity requirements, water services and other services including maintenance, repair, material replacement and refurbishment. The last stage, end-of-life, includes the decommissioning, deconstruction and demolition of the building, the waste processing of building products and assemblies, intermediate transportation steps and the disposal of demolition waste. The building assessment information also includes supplementary information beyond building life cycle. This includes the benefits and loads beyond the system boundary resulting from reuse/recovery/recycling potential and from in-situ production of energy that it is exported outside the system boundary. In the next subsections, each phase of the LCA method is briefly introduced.

i) Goal and scope

In this phase the objectives of the study are formulated and specified according to the intended application and the following aspects are identified: the objectives; the target audience of the evaluation; the various stages that compose the building life-cycle and its relevance to the purpose of the study; the functional unit that will be assessed; the boundary conditions; and the methodology for the allocation of impacts and consumption of raw materials in the various processes. In defining the Goals and Scope, the object of study is described in the form of functional unit. When comparing, for example, two different solar systems the functional unit may be "one solar system to heat the hot water of a three occupant’s dwelling".

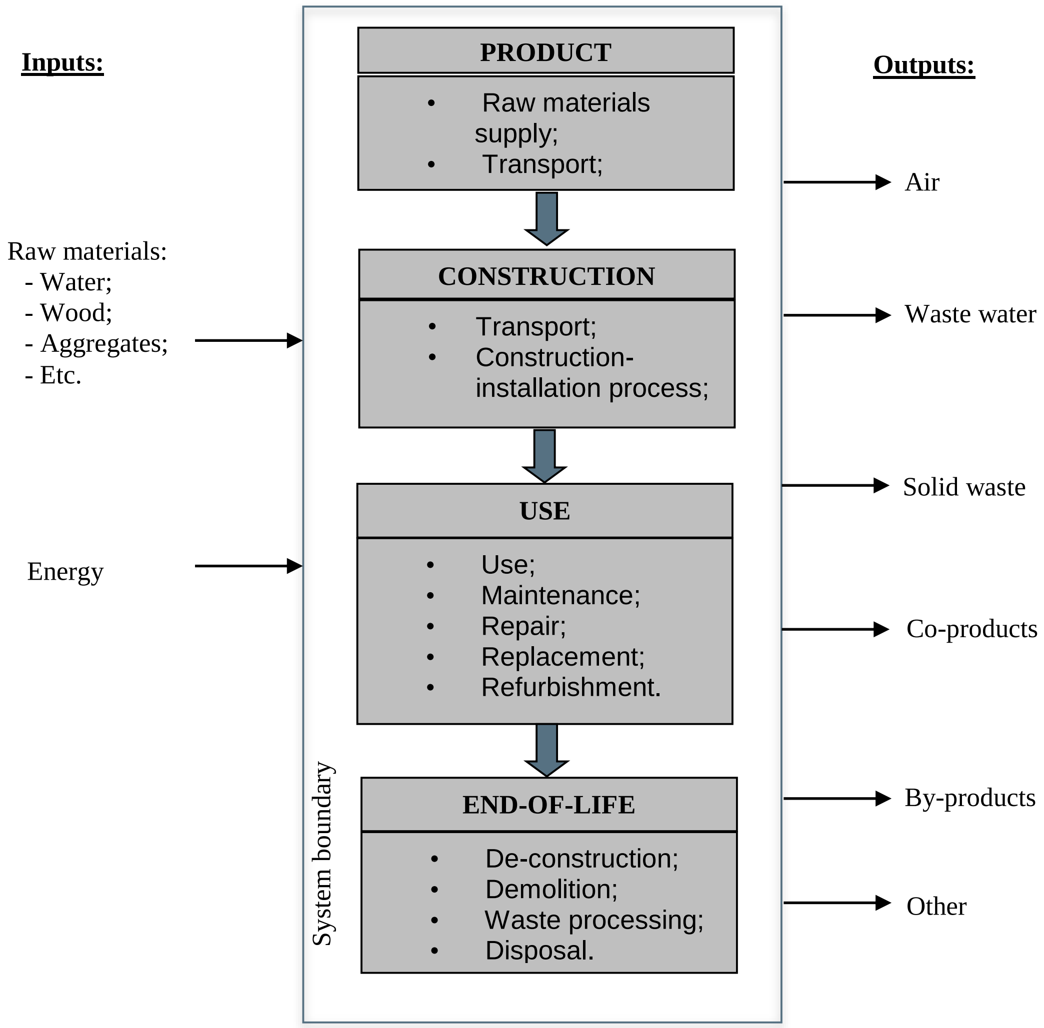


Figure 2.10.6. Schematic representation of building life cycle breakdown into elementary stages (CEN, 2011b).

ii) Inventory assessment

The life-cycle inventory entails the quantification of the flows for and from a product system. In traditional life-cycle environmental analysis, the inventory flows include inputs of water, energy and raw materials, and releases to air, land and water (Figure 2.10.7).

This phase is very time consuming, since it is often necessary to collect, from the companies, data associated with the production system. However, approximately 80% of the data that is needed for a common LCA analysis is already published (Pré-consultants, 2008).

One of the sources of information more accepted by the experts in LCA is the Ecoinvent database (Weidema et al., 2013). The latest version available of Ecoinvent (v3.1) contains life-cycle inventory data for over 4000 industrial processes, including energy supply, resource extraction, materials supply, chemicals, metals, waste management systems and transport services. Gabi datasets (Gabi, 2015) are another important source of average LCI data that is used in LCIA, namely at the European scale.

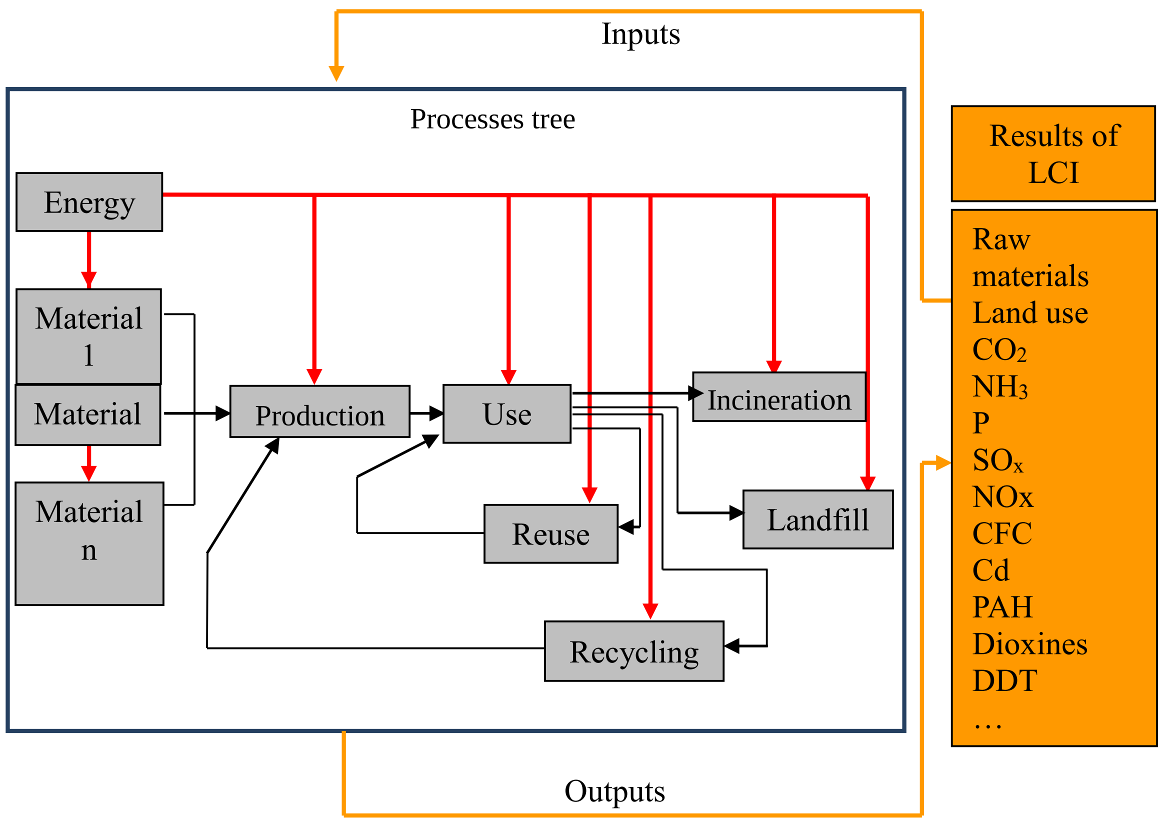


Figure 2.10.7. Schematic representation of the inventory stage of a LCA.

Besides the common building products, Ecoinvent datasets include average LCI data about solar thermal collectors and PVs, namely at the level of building-added systems and components. At this level, this database covers building-added solar thermal systems plus both building-added and building-integrated photovoltaic systems, but there is no data related to hybrid photovoltaic/thermal systems.

An analysis regarding the available LCI data related with solar systems can be found in the publication of Lamnatou et al. (2015a).

The Ecoinvent 3.1 database includes, for the several types of solar thermal collectors and systems (Figure 2.10.8): LCI data for system components; LCI data for complete systems and LCI data for delivered heat. The LCI data includes the production (i.e. materials, heat exchange fluid, copper pipes used in the installation of the system, water and energy used during production), delivery of the system parts with a van, mounting processes in the roof and disposal, but excludes auxiliary heating. The presented values are not from a specific installation or from a specific building-added STCs producer, but are based on the average LCI of the collectors and complete systems sold in Switzerland during a year and therefore they intended to represent the average technology that is currently available on the market. Although the context of the LCI data is Switzerland, since there are only slightly differences between the technologies used within the European countries it is possible to assume that these figures are valid at the European scale.

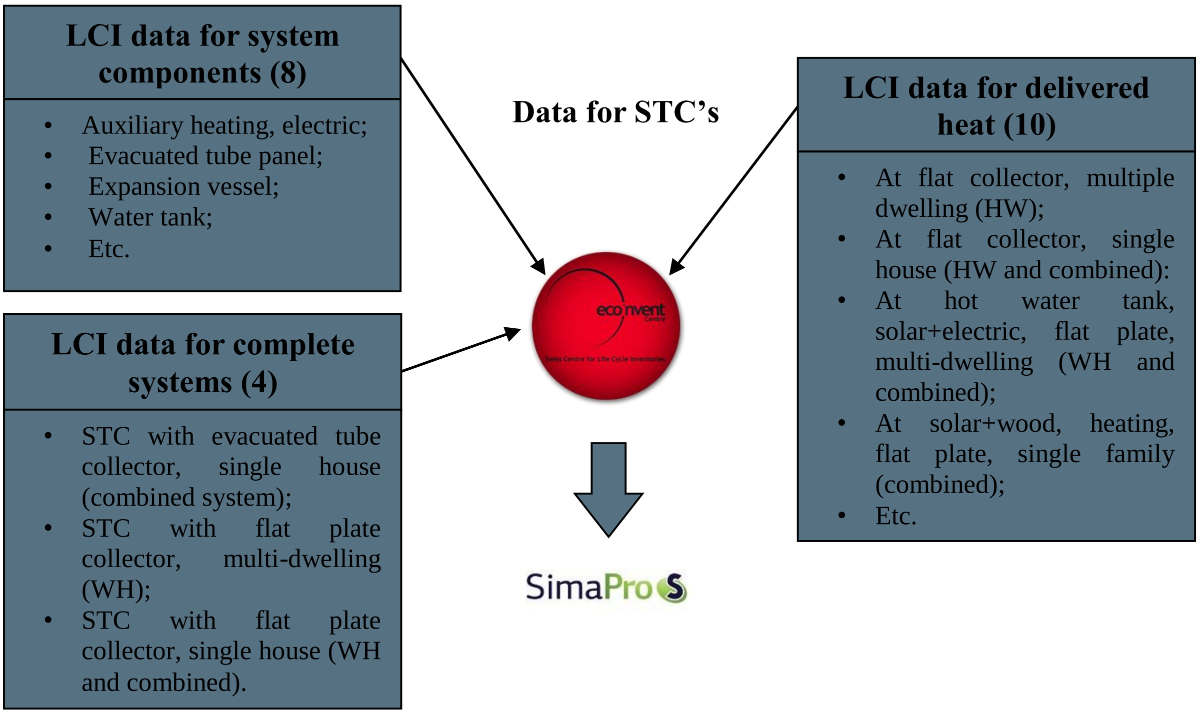


Figure 2.10.8. Schematic representation of the inventory stage of a LCA.

Regarding the inventory data related with the consumed energy, Ecoinvent also presents, for each energy vector, the inventory for each Mega Joule (MJ) of consumed energy.

iii) Life-cycle impact assessment

The Environmental Impact Assessment Methods (EIAM) comprise the analysis of the input and output of materials, of energy consumption and of emissions to the environment of a product over its life cycle and therefore are based on the life-cycle inventory. According to EN15978:2011 (CEN, 2011b) the results are expressed as indicators that represent the quantified environmental impacts and aspects caused by the building during its whole life cycle. This standard states that the assessment of the environmental performance of a building is based in 22 indicators, subdivided in the following four types (Table 2.10.1): i) indicators describing environmental impacts (7 indicators); ii) indicators describing resource use (8); iii) indicators describing waste categories (3); and iv) indicators describing the output flows leaving the system (4).

Analysing the current state-of-art in the field of life-cycle analysis of design alternatives at the scale of buildings (e.g. (Mateus & Bragança, 2011; Abd Rashid & Yusoff, 2015)), building components (e.g. (Pargana, 2014; Mateus et al., 2013)) or building technical systems (e.g. (Lamnatou, et al., 2015a; Lamnatou, et al., 2015b; Belussi et al. 2015)) it is possible to verify that for practicality most studies consider a limited set of indicators in the analysis rather than considering the complete list of the EN 15804:2012 (CEN, 2012c) environmental indicators.

Table 2.10.1. Indicators to be considered in the assessment of the environmental performance according to EN 15978:2011 (CEN, 2011b).

Type of indicators	**Indicator**	**Unit**
Indicators describing environmental impacts	Global warming potential, GWP	kg CO_2 equiv
	Depletion potential of the stratospheric ozone layer, ODP	kg CFC 11 equiv
	Acidification potential of land and water; AP	kg SO_2^- equiv
	Eutrophication potential, EP	kg $(PO_4)^{3-}$ equiv
	Formation potential of tropospheric ozone photochemical oxidants, POCP	kg Ethene equiv
	Abiotic Resource Depletion Potential for elements; ADP_elements	kg Sb equiv
	Abiotic Resource Depletion Potential of fossil fuels ADP_fossil fuels	MJ, net calorific value
Indicators describing resource use	Use of renewable primary energy excluding energy resources used as raw material	MJ, net calorific value
	Use of renewable primary energy resources used as raw material	MJ, net calorific value
	Use of non-renewable primary energy excluding primary energy resources used as raw material	MJ, net calorific value
	Use of non-renewable primary energy resources used as raw material	MJ, net calorific value
	Use of secondary material	kg
	Use of renewable secondary fuels	MJ
	Use of non-renewable secondary fuels	MJ
	Net use of fresh water	m^3
Indicators describing waste categories	Hazardous waste disposed	kg
	Non-hazardous waste disposed	kg
	Radioactive waste disposed	kg
Indicators describing the output flows leaving the system	Components for re-use	kg
	Materials for recycling	kg
	Materials for energy recovery (not being waste incineration)	kg
	Exported energy	MJ for each energy carrier

As already concluded by other authors (e.g. (Ortiz et al., 2009; Khasreen, 2009)) commonly used environmental impact categories in this type of studies are global warming potential, acidification, ozone depletion and eutrophication. Therefore, in the comparative analysis of the potential environmental impacts resulting from the implementation of STC, it is recommending that only type 1 group of indicators of this standard are considered. According to the EN 15978:2011 (CEN, 2011b), the impact assessment should involve seven midpoint environmental impact categories, i.e. global warming, ozone depletion, acidification of soil and water, eutrophication, photochemical ozone creation and depletion of abiotic resources (elements and fossil, separately). These environmental impact categories are assessed using the characterization factors of the CML-IA life-cycle impact assessment method (developed in the Netherlands by the Institute of Environmental Sciences (CML) of Leiden University).

In addition to these indicators, two additional environmental categories are normally considered (Table 2.10.2). These categories are calculated based on a single issue method, the Cumulative Energy Demand (CED) (Frischknecht et al., 2007). This method expresses the depletion of energy resources based on the higher heating value and, in fact this provides the calculation of six environmental categories (Monteiro & Freire, 2012) (non-renewable, fossil; non-renewable, nuclear; non-renewable, biomass; renewable, biomass; renewable, wind, solar, geothermal; renewable, water) which were grouped and presented in a simplified form in only two categories with the same unit (mega Joule—MJ): Non-renewable Cumulative Energy Demand (CEDNRE) and Total Cumulative Energy Demand (CEDTOT). According to several authors (e.g. (Ferreira et al., 2014)) these two indicators that describe the life-cycle energy consumption are of most importance in the comparison between different energy targets in building renovation.

Table 2.10.2. LCA method and declared unit that was used to quantify the environmental indicators.

Indicators	**Units**	**Methods**
Global warming potential (GWP)	[Kg CO2 $_{equiv.}$]	CML-IA baseline (v3.02)
Depletion of the stratospheric ozone layer (ODP)	[KgCFC-11 $_{equiv.}$]	CML-IA baseline (v3.02)
Acidification potential (AP)	[Kg SO2 $_{equiv.}$]	CML-IA baseline (v3.02)
Eutrophication potential (EP)	[Kg PO4 $_{equiv.}$]	CML-IA baseline (v3.02)
Formation potential of tropospheric ozone (POCP)		
Abiotic deplet. potential of fossil resources (ADP_{FF})	[Kg C2H4 $_{equiv.}$]	CML-IA baseline (v3.02)
Deplet. of abiotic resources-elements ($ADP_{elements}$)	[MJ $_{equiv.}$]	CML-IA baseline (v3.02)
Cumulative Energy Demand – non renewable (CED_{NRE})	[kg.SB $_{equiv.}$]	CML-IA baseline (v3.02)
Cumulative Energy Demand – total (CED_{TOTAL})	[MJ $_{equiv.}$]	Cumulative Energy Demand (v1.09)
	[MJ $_{equiv.}$]	Cumulative Energy Demand (v1.09)

To facilitate the quantification of the environmental impacts, a life cycle analysis software (e.g. SimaPro or Gabi) is used to modulate the life cycle of the analysed renovation scenarios and to assess the abovementioned life cycle impact categories.

As an example, Table 2.10.3 presents the life-cycle impact assessment of building-added solar thermal collectors. Figures presented in this Table are not from a specific installation or building-added STCs producer. The values are based in the average LCI of the collectors and complete systems sold in the Switzerland during a year and therefore they intended to represent the average technology that is currently available on the market. Although the context of the LCI data is Switzerland, since there are only slightly differences between the technologies used within the European countries it is possible to assume that these figures are valid at the European scale. The functional unit of the values presented in Table 2.10.3 is 1 m^2 for the collectors and one piece for the solar thermal systems and they represent the typical system technology available in the Swiss market. A combined system is the one that is used at the same time for domestic hot water and for indoor spaces heating.

Table 2.10.3. Life-cycle impact assessment of Building-Added solar thermal collectors (Infrastructure) (source: Lamnatou, et al., 2015a).

Solar thermal collectors (Infrastru-cture)	**Life-cycle impact category**						**Embodied energy**	
	ADP	**GWP**	**ODP**	**AP**	**POCP**	**EP**	**ADP_FF**	**ERE**
Evacuated tube collector	6.74 E-01	9.03 E+01	8.42 E-06	7.81 E-01	3.26 E-02	6.55 E-01	1.48 E+03	1.38 E+02
Flat plate collector	6.81 E-01	1.02 E+02	9.69 E-06	9.76 E-01	5.00 E-02	6.65 E-01	1.52 E+03	2.56 E+02
Solar system, flat plate collector, multiple dwelling, hot water	7.00 E+01	1.02 E+04	1.47 E-03	8.44 E+01	5.21 E+00	6.24 E+01	1.60 E+05	1.85 E+04
Solar system, flat plate collector, one-family house, hot water	9.83 E+00	1.33 E+03	1.35 E-04	8.77 E+00	6.24 E-01	5.93 E+00	2.13 E+04	2.65 E+03
Solar system, flat plate collector, one-family house, combined system	1.95 E+01	2.84 E+03	3.52 E-04	1.98 E+01	1.34 E+00	1.39 E+01	4.35 E+04	5.29 E+03
Solar system with evacuated tube collector, one-family house, combined system	1.77 E+01	2.35 E+03	3.06 E-04	1.58 E+01	1.03 E+00	1.25 E+01	3.90 E+04	3.68 E+03

2.10.3.2 Modelling the life-cycle of buildings with added or integrated solar thermal collectors

Modelling the life-cycle of a solar thermal collector is a process that is normally integrated in the whole life-cycle assessment of a building. The whole life-cycle analysis is based in the quantification of the materials and energy flows and the physical boundary includes, as presented in Figure 2.10.9 (Lamnatou, et al., 2015a):

- Construction element: It includes the materials used for the external (roof, windows, etc.) and the internal (internal wall, etc.) building fabrics. A construction element is made of one or more materials. Each material corresponds to a material layer. Examples of a construction element: roof, external wall, window, internal partition.

- Building Integrated (BI) solar thermal systems: BI solar thermal systems are made of different systems, such as the heating or the ventilation systems. Each system is made of components (boiler, pump, etc.) and each component is made of materials and may consume energy. Solar thermal collectors and also PV systems are included in this context.

- Other building systems: It includes, besides the BI solar thermal system, the installed technical equipment to support the operation of a building, as defined in EN 15978:2011 (CEN, 2011b) (e.g. artificial lighting, elevators, etc.).

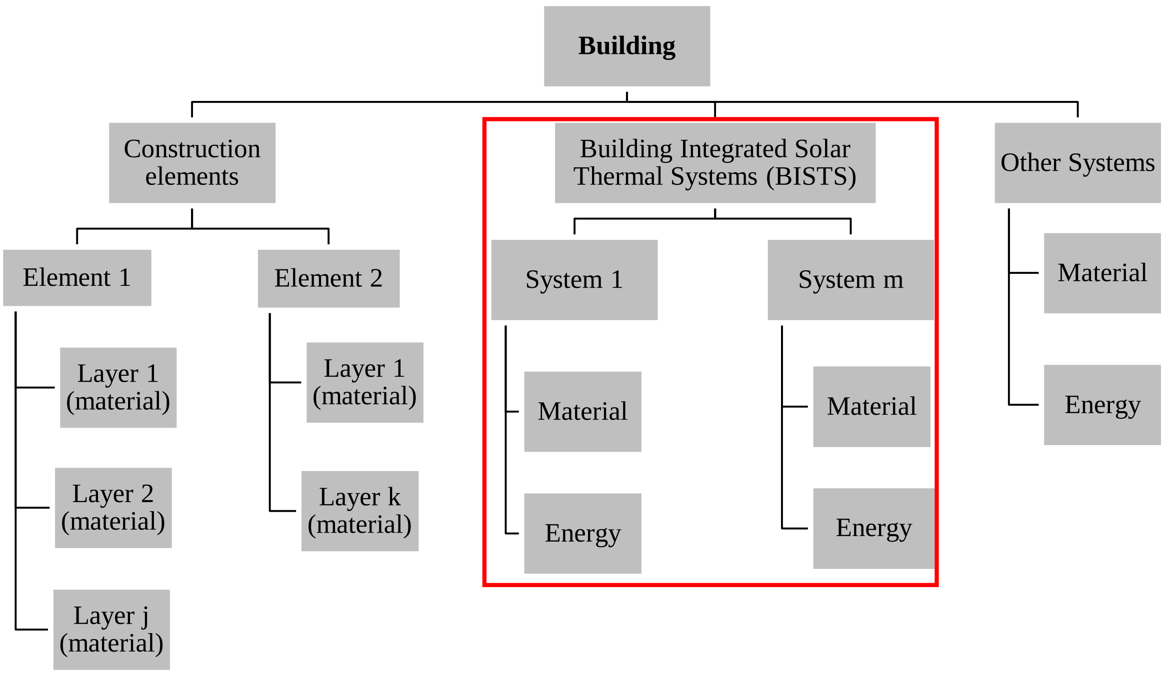


Figure 2.10.9. Structure of the building model used for LCIA.

In order to assess the whole life-cycle environmental impacts and the contribution of the BI solar thermal system to the environmental impacts and benefits, the following processes must be included in the LCIA (Lamnatou, et al., 2015a):

- Materials used for construction elements and BI solar thermal system components. It should include the materials added (or replaced) during the construction or renovation of a building. The stages corresponding to the manufacturing, maintenance replacement and elimination of these materials must be included in the calculation. It also includes materials added for energy generation or harvesting (e. g. solar collectors, PVs, heat pump). The LCIA is influenced by the service life of the construction materials and the BI solar thermal component and therefore it should be defined. A longer service life can compensate a higher environmental impact;

- Energy consumed by BI solar thermal system: This includes the energy used by the BI solar thermal system to fulfill its requirements (heating, cooling, domestic hot water production, etc.) during building operation stage;

- The energy delivered inside and outside the building system and produced at the building scale by the BI solar thermal system: necessary to calculate the benefits and loadings both at and beyond the system boundary. The benefits and loadings beyond the system boundary are calculated when the building integrates a system for in-situ energy production that produces energy that it is exported outside the system boundary.

As presented in Figure 2.10.10, a typical LCA study about BI solar thermal system includes the following stages: extraction of raw materials, production of the components, system assembling, system operation (including energy delivery inside and outside the building boundary) and maintenance, system disposal and all transportations that take place in the different life-cycle stages.

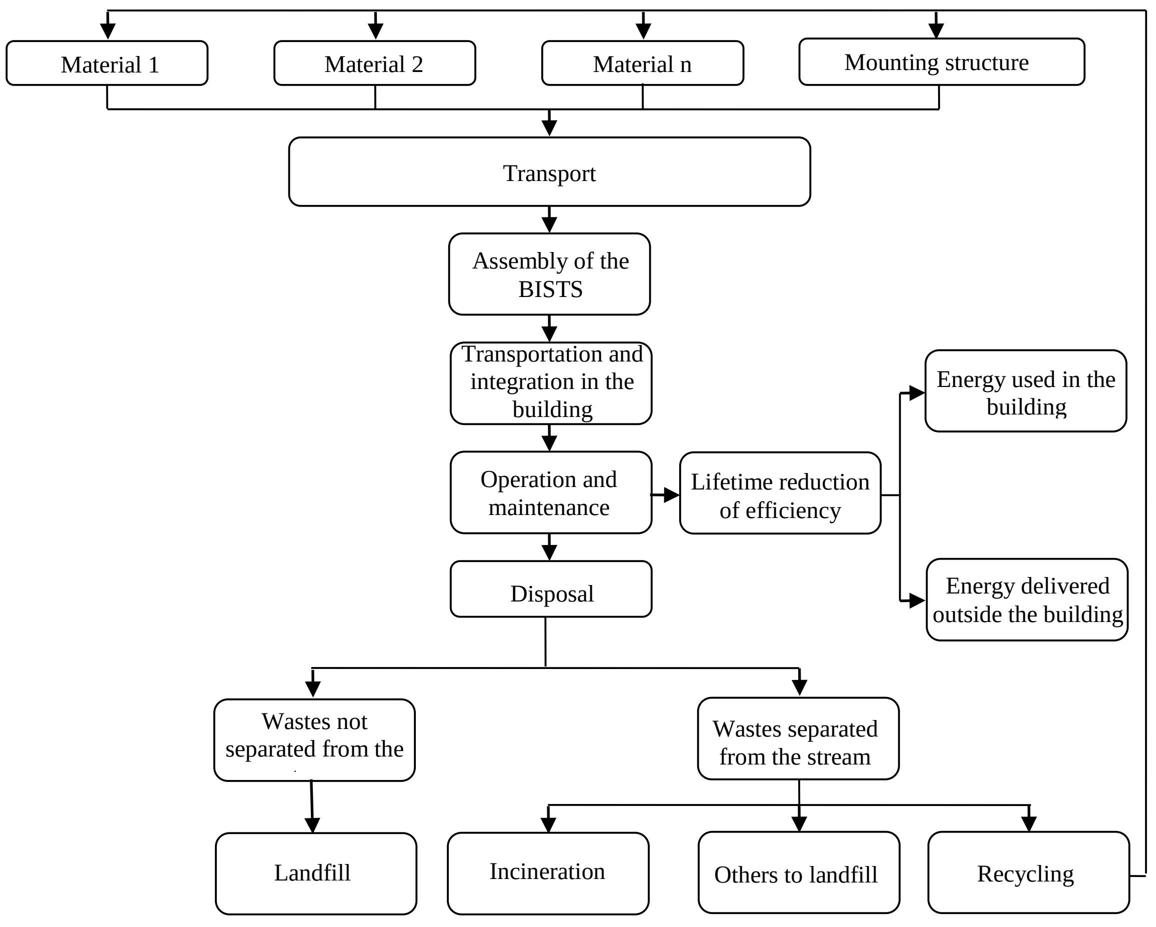


Figure 2.10.10. Structure of the building model used for LCIA.

2.10.4 Case study

2.10.4.1 Goal and scope

In order to present the environmental benefits resulting from the implementation of a Solar Thermal Collector (STC) in an energy renovation of a dwelling, two renovation scenarios will be presented. This study is also aimed to present the differences in the results from using data for the average European STC technology and for a tailored (specific) STC. This study is intended at assessing the contribution of the STC in the energy balance to produce the Domestic Hot Water (DHW) and therefore the effect of other active and passive energy renovation principles will not be considered.

The lifetime considered for the renovation project is 40 years and therefore the cumulative environmental impacts for this operation period will be considered together with the embodied impacts of the used equipment. Following the recommendations from other studies (e.g. (Monteiro da Silva et al., 2016)), a lifetime of 20 years is considered for the equipment used (STC, heat pump and light oil boiler).

2.10.4.2 Methodology

i) Life–cycle impact assessment

The methodology used in this study uses it is according to the EN 15978:2011 (CEN. 2011b). Nevertheless, rather than considering all indicators presented in this standard, this is focused in the three main environmental indicators are considered in this study: Total Cumulative Energy Demand (CED_{TOT}), non-Renewable Cumulative Energy Demand (CED_{nRE}) and Global Warming Potential (GWP). Table 2.10.4 presents the LCA method and the declared unit that was used to quantify the environmental indicators.

Table 2.10.4. LCA method and declared unit that was used to quantify the environmental indicators.

Indicators	Units	Methods
Global warming potential (GWP)	[Kg $CO_{2\ equiv.}$]	CML-IA baseline (v3.02)
Cumulative Energy Demand – non-ren. (CED_{NRE})	[$MJ_{equiv.}$]	Cumulative Energy Demand (v1.09)
Cumulative Energy Demand – total (CED_{TOTAL})	[$MJ_{equiv.}$]	Cumulative Energy Demand (v1.09)

The impacts resulting from the end-of-life stage are simulated using a scenario were: i) materials resulting from the dismantling of the systems are transported for an average distance of 50km; ii) 95% of the aluminium and glass are recycled and the remaining materials are placed in a landfill; iii) and the glycol is incinerated. In order to facilitate the life-cycle assessment process, a life-cycle analysis software (SimaPro 8.0.5) was used to modulate the life-cycle of the analysed renovation scenarios and to assess the abovementioned life-cycle impact categories.

ii) Quantification of the energy needs for DHW

The calculations of the energy needs followed the methodology of the Portuguese regulation for the thermal performance of residential buildings (Portugal, 2013) which is based on the quasi-steady state method presented in ISO 13790:2008 (ISO, 2008). The Portuguese thermal regulation provides the values of the degree-days and uses the envelope heat balance method for the calculation of heating needs. With regard to cooling needs, it uses the average difference between indoor-outdoor temperature and the envelope heat balance during the cooling period. The energy used for Domestic Hot Water (DHW) preparation is calculated according to the reference DHW consumption: 40 litres per person and per day, heated at 60ºC.

The primary energy was calculated considering the conversion factors of 2.6 kWhPE/kWh for electricity and 1 kWhPE/kWh for natural gas, biomass and thermal energy from solar systems. For the calculation of the non-renewable primary energy, the contribution of the on-site renewable energy systems (solar thermal) is deducted from the total amount of primary energy use, which is according to Portuguese regulation.

2.10.4.3 Description of the building and energy renovation scenarios

i) Existing scenario

The building is a four-bedroom single-family dwelling located in the city of Porto, North of Portugal (Figure 2.10.11). According to the Köppen classification, this building is located in a Warm-summer Mediterranean climate (Csb). In this city, the average annual sum of the horizontal solar irradiation is around 1600 kWh/m^2 (Figure 2.10.12). The dwelling does not have any obstacles nearby to obstruct the access of the sun, which highlights the location's high potential to harvest solar radiation.

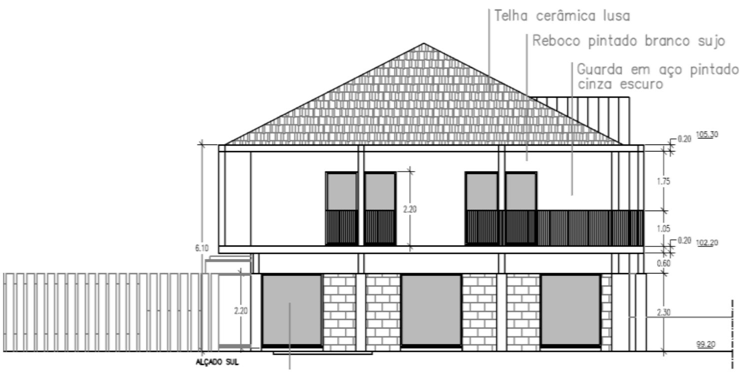


Figure 2.10.11. Main facade of the case study (facing south).

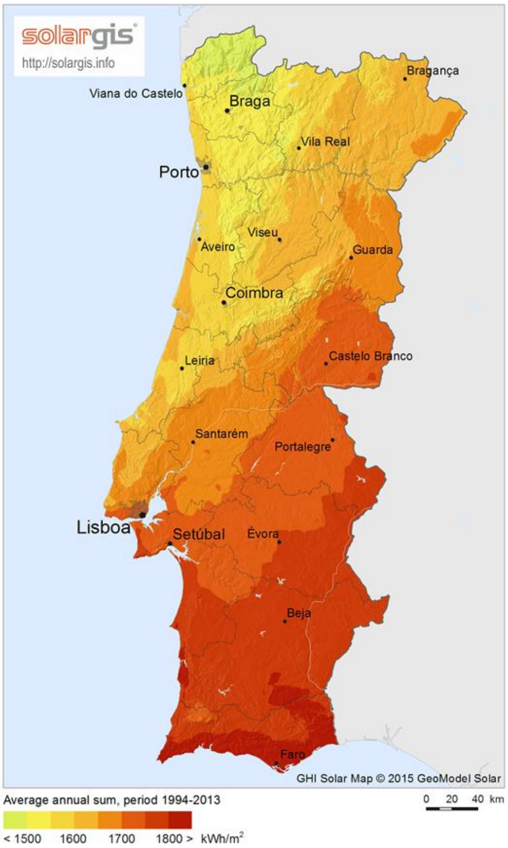


Figure 2.10.12. Global Horizontal Irradiation (GHI) in Portugal (source: solargis.com).

Before the renovation, the building used a non-modulating and non-condensating light oil boiler with an efficiency of 94% as a DHW heating system. The delivered energy to heat the hot water is 1912 kWh/m^2.

ii) Implementation of a conventional STC – Scenario 1

In this scenario, the light oil boiler is replaced by a conventional solar thermo-symphonic flat plate collector, assisted by an auxiliary heat pump. Conventional means that the used STC is built up with the average technology used across Europe. Therefore, the inventory data for a system like this was extracted from the Ecoinvent 3.1 database.

According to the Portuguese thermal code for residential buildings (Portugal, 2013), the STCs to be considered in new buildings or major energy renovations must produce the same energy as a conventional/reference flat solar thermal system with an area equal to the number of bedrooms plus 1 m^2. Therefore, 5 m^2 of solar thermal collectors is considered in this study and the system is designed to provide 65% of the DHW's energy needs. The remaining energy is provided by an air-water heat pump with a Coefficient of Performance (COP) of 3. The flat plat collectors are connected to a water tank that has a capacity of 300 litres.

iii) Implementation of a specific STC – Scenario 2

In this scenario, it is considered that the DHW is produced by a new type of solar thermal collectors that are being designed and the auxiliary heat by an air-water heat pump with a COP of 3. The solar thermal installation has 5 m² of flat plate collectors and yearly covers

80% of the energy needs. The heat pump provides the rest of the necessary energy. In this scenario the flat plat collectors are connected to a 300 litres water tank placed inside the house that is connected to a recirculation pump.

2.10.5 Results

2.10.5.1 Life-cycle inventory

The systems in the existing and scenario 1 are considered to be conventional. Therefore, the life-cycle inventory regarding the embodied materials (type and amount of materials) and embodied energy used to manufacture both systems were based in the EcoInvent 3.1 database. In the considered lifetime, systems are replaced once, on year 20. Regarding the transportation, mounting on the building and maintenance impacts, those were considered to be the average ones defined in the used life-cycle inventory database.

Regarding the operation stage,

Table 2.10.5 presents the amount of delivered energy used for the hot water preparation and the energy vector used in the existing scenario. Table 2.10.6 presents the data considered for scenario 1.

Table 2.10.5. Amount of delivered energy used for the hot water preparation and the energy vector used in the existing scenario.

Consumer	Delivered energy (kWh/year)	Vector	Covers (%)	Efficiency (%)
Domestic hot water	1912	Light fuel oil	100	94

Table 2.10.6. Amount of delivered energy used for the hot water preparation and the energy vector used in scenario 1.

Consumer	Delivered energy (kWh/year)	Vector	Covers (%)	Efficiency (%)
Domestic hot water	1912	Electricity	35	3
		Solar thermal	65	-

In scenario 2, since it uses a new type of STC, a specific inventory related to the type and amount of materials used to manufacture the STC was carried out. The inventory of materials used to manufacture the flat plate collectors and the water tank are presented in Table 2.10.7.

Table 2.10.7. Materials used to manufacture the solar collector and the water tank implemented in scenario 2.

	Material	**Quantity (kg)**
Solar collector	Aluminium sheet (primary aluminium)	15.40
	Flat glass	14.20
	Copper tube	5.10
	Mineral wool	2.31
	Polyester	0.17
Water tank	Chromium steel	28.00
	Mineral wool	8.20
	Copper tube	11.30
	Tube insulation (elastomer)	3.60
	Propylene glycol	2.90

Regarding the inventory related with the assembly of materials to manufacture the new STC system, since this system is still in an early stage of development, it is not possible to use specific data related to the manufacture process. Therefore, a scenario considering these impacts equivalent to 30% of those related with the used materials was considered. This figure is similar to the one set by the EcoInvent 3.1 database for conventional STC systems and was used by other authors in similar studies (e.g. (Lamnatou, et al., 2015b)).

For the transportation stage, from the factory to the construction site, a scenario considering that the system is transported in an average distance of 50 km using a light van was used. Regarding the impacts resulting from the mounting processes in the construction site, a scenario considering it equivalent to the ones resulting from the consumption of 1 kWh of electricity was used. As an example other studies, consider these impacts equivalent to 3% of the material's embodied impacts (e.g. (Lamnatou, et al., 2015b)). Due to the lack of data, the maintenance impacts were not considered in this scenario.

Table 2.10.8. Amount of delivered energy used for the hot water preparation and the energy vector used in scenario 2.

Consumer	**Delivered energy (kWh/year)**	**Vector**	**Covers (%)**	**Efficiency (%)**
Domestic hot water	1912	Electricity	20	3
		Solar thermal	80	-

2.10.5.2 Life-cycle impact assessment

Table 2.10.9 presents for each considered scenario the results from the quantification of the environmental indicators. Figure 2.10.13 and Figure 2.10.14 present, respectively, the life-cycle cumulative energy demand and global warming potential of each renovation scenario.

Table 2.10.9. Results from the quantification of the environmental indicators.

Scenario	**CED_Tot (MJ)**	**CED_nRE (MJ)**	**GWP (Kg.eq. CO_2)**
Before renovation	404 517.50	400 800.50	26 800.00
Scenario 1	175 780.50	164 500.50	12 200.00
Scenario 2	174 982.50	146 508.60	12 600.00

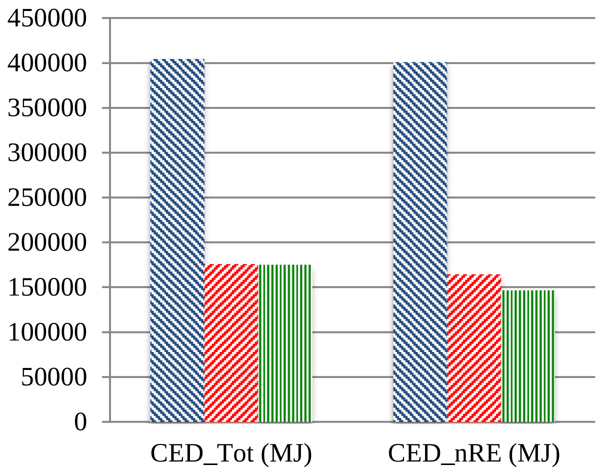


Figure 2.10.13. Life-cycle cumulative energy demand (Total – CED_Tot and non-Renewable – CED_nRE) of each scenario.

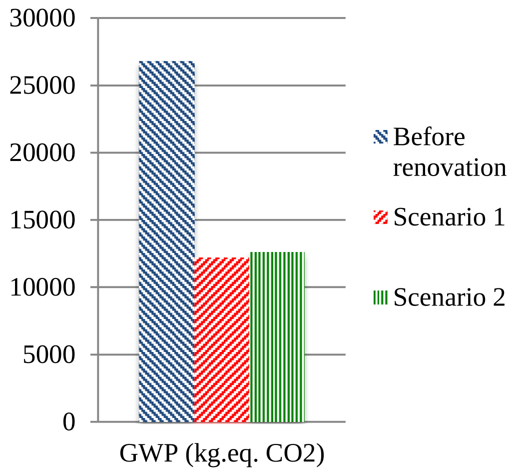


Figure 2.10.14. Life-cycle global warming potential (GWP) of each scenario.

2.10.5.3 Discussion of results

From the analysis of results obtained in section 2.10.5.2 it is possible to conclude that in the city of Porto, Portugal, the implementation of solar thermal collectors in the replacement of conventional hot water production systems is a very good option to reduce the potential life-cycle environmental impacts of a residential building. For a four-bedroom residential building, a solar system that covers around 65% of the energy needs to heat the water and that uses a heat pump as an auxiliary heating source, will have a potential to reduce both the life-cycle cumulative energy demand and CO_2 emissions in around 55%.

Results also show a very small difference from the life-cycle impact assessment results obtained from the use of generic inventory data or specific inventory of materials used in a STC system. This allows the conclusion that in an early design stage of both a new building or energy renovation scenario, it is suitable to use generic (average) European life-cycle inventory data to assess the embodied impacts of solar systems and to support decision making towards the choice of the most energy efficient solution.

REFERENCES

Abd Rashid A.F., Yusoff S., A review of life cycle assessment method for building industry, Renew. Sustain. Energy Rev., 2015;45:244–248.

Belussi L., Mariotto M., Meroni I., Zevi C., Svaldi S.D., LCA study and testing of a photovoltaic ceramic tile prototype, Renew. Energy., 2015;74:263–270.

Boermans T., Hermelink A., Schimschar S., Grözinger J., Offermann M., Thomsen K.E., et al., Principles for Nearly Zero-Energy Buildings - Paving the way to effective implementation of policy requirements, 2011. (available at: http://www.bpie.eu/documents/BPIE/ publications/LR_nZEB study.pdf, accessed: October, 2016).

CEN, EN 15643-1:2010, Sustainability of construction works - Sustainability assessment of buildings - Part 1: General framework, Brussels: CEN; 2010.

CEN, EN 15643-2:2011, Sustainability of construction works - Assessment of buildings - Part 2: Framework for the assessment of environmental performance, Brussels: CEN; 2011a.

CEN, EN 15643-3:2012, Sustainability of Construction Works - Assessment of Buildings - Part 3: Framework for the assessment of social performance, Brussels: CEN; 2012a.

CEN, EN 15643-4:2012, Sustainability of Construction Works - Assessment of Buildings - Part 4: Framework for the assessment of economic performance, Brussels: CEN; 2012b.

CEN. EN 15804. Sustainability of construction works - environmental product declarations - core rules for the product category of construction products. Brussels: CEN; 2012c.

CEN, EN 15978:2011, Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method, Brussels: CEN; 2011b.

CEN, EN 16309:2014, Sustainability of construction works - Assessment of the social performance of buildings - Calculation method, Brussels: CEN; 2014.

CEN, EN 16627:2015, Sustainability of construction works - Assessment of the economic performance of buildings - Calculation method, Brussels: CEN; 2015.

Ferreira M., Almeida M., Rodrigues A., Silva S.M., Comparing cost-optimal and net-zero energy targets in building retrofit, Build. Res. Inf., 2014; 1–14.

Frischknecht R., Jungbluth N., Althaus H.-J., Bauer C., Doka G., Dones R., et al., Swiss Centre for Life Cycle Inventories Implementation of Life Cycle Impact Assessment Methods, 2007.

Gabi, Gabi LCA Databases. http://www.gabi-software.com/databases/gabi-databases/. 2015.

ISO, ISO 14040:2006, Environmental management - Life cycle assessment - Principles and framework, Geneva: ISO; 2006.

ISO, ISO 14044:2006, Environmental management - life cycle assessment - requirements and guidelines. Geneva: ISO; 2006.

ISO, ISO 13790:2008 - Energy performance of buildings - Calculation of energy use for space heating and cooling, Geneva, 2008.

Kalogirou S., Thermal performance, economic and environmental life cycle analysis of thermosiphon solar water heaters, Sol. Energy, 2009;83:39–48. doi:10.1016/j.solener. 2008.06.005.

Khasreen M.M., Banfill P.F.G., Menzies G.F., Life-Cycle Assessment and the Environmental Impact of Buildings: A Review, Sustainability., 2009;1:674–701.

Lamnatou C., Chemisana D., Mateus R., Almeida M.G., Silva S.M., Review and perspectives on Life Cycle Analysis of solar technologies with emphasis on building-integrated solar thermal systems, Renew. Energy, 2015;75: 833–846.

Lamnatou C., Notton G., Chemisana D., Cristofari C., The environmental performance of a building-integrated solar thermal collector, based on multiple approaches and life-cycle impact assessment methodologies, Build. Environ., 2015b; 87:45–58.

Lu L., Yang H.X., Environmental payback time analysis of a roof-mounted building-integrated photovoltaic (BIPV) system in Hong Kong, Appl. Energy, 2010;87:3625–3631.

Mateus R., Bragança L., Sustainability assessment and rating of buildings: Developing the methodology SBToolPT–H, Build. Environ., 2011;46:1962–1971.

Mateus R., Neiva S., Bragança L., Mendonça P., Macieira M., Sustainability assessment of an innovative lightweight building technology for partition walls – Comparison with conventional technologies, Build. Environ., 2013; 67:147–159.

Monteiro H., Freire F., Life-cycle assessment of a house with alternative exterior walls: Comparison of three impact assessment methods, Energy Build., 2012;47:572–583.

Monteiro da Silva S., Mateus R., Marques L., Ramos M., Almeida M. G., Contribution of the solar systems to the nZEB and ZEB design concept in Portugal – Energy, Economics and Environmental Life-cycle Analysis, Solar Energy Materials and Solar Cells, 2016;156: 59–74.

Ortiz O., Castells F., Sonnemann G., Sustainability in the construction industry: A review of recent developments based on LCA, Constr. Build. Mater., 2009;23:28–39.

Ott W., Bolliger R., Ritter V., Citherlet S., Favre D., Perriset B., et al., Methodology for Cost-Effective Energy and Carbon Emissions Optimization in Building Renovation (Annex 56), Guimarães, 2014. (available at: http://www.iea-annex56.org/Groups/GroupItemID6/STA_methods_impacts_report.pdf, accessed October, 2016).

Pargana N., Pinheiro M.D., Silvestre J.D., Brito J. de, Comparative environmental life cycle assessment of thermal insulation materials of buildings, Energy Build., 2014;82:466–481.

Portugal, Regulamento de Desempenho Energético dos Edifícios de Habitação [Portuguese Thermal Regulation]. Decreto-Lei no. 118/2013 de 20 de Agosto, Portugal, 2013.

Pré-consultants, SimaPro Database Manual – Methods Library, Product Ecology Consultants, Amersfoort, 2008.

Tiago Filho G.L., Rosa C.A., Barros R.M., Dos Santos I.F.S., Silva F. das G.B. da, Study of the energy balance and environmental liabilities associated with the manufacture of crystalline Si photovoltaic modules and deployment in different regions, Sol. Energy Mater. Sol. Cells, 2016;144:383–394.

Weidema B.P., Bauer C., Hischier R., Mutel C., Nemecek T., Reinhard J., et al., Overview and methodology. Data quality guideline for the ecoinvent database version 3, St. Gallen, 2013. http://www.ecoinvent.org/files/dataqualityguideline_ecoinvent_3_20130506.pdf.

2.11 ECONOMICS

Christoph Maurer, Mervyn Smyth

2.11.1 Introduction to BISTS economics

The economic benefit of BISTS (like BIPV) can be identified based on the direct economic impact, indirect economic impact, and qualitative value as outlined below.

- **Direct Economic Impact**

Any integrated building solar system is generally procured through a construction budget. Any thermal energy offset by the BISTS generates a saving that can reduce the building's operational cost. The BIST system also reduces the overall construction material costs (opposed to separate elements) and may offer additional revenue in the form of financial incentives and tax credits. In the in case of Hybrid PVT building integrated systems there is also a reduction in electricity costs, perhaps improving power yield (due to lower module temperatures) and reliability.

- **Indirect Economic Impact**

Many businesses and organisations may have a 'worth' attributed to company goals or interests, being sustainable or 'green' is one obvious example. Offsetting fossil fuel usage through a BISTS may equate to environmental emission reductions, which if they can be quantified, valued or perhaps even traded will accrue additional economic benefits. A further indirect cost may be achieved through the BIST system's contribution to a building's thermal performance. Through improved envelope structures reduced heat loss or heat gain can have a positive impact on auxiliary thermal or air conditioning loads. Likewise, BISTS that offer a shading function (without reducing daylight penetration) can have further cost benefits.

- **Qualitative Value**

Some BISTS benefits are subjective. For some building operators, a considerable value of a BISTS may be associated with a positive image, public awareness and perception or impact on the built environment (LCA or embodied energy) when the technology is installed. It is very difficult to assign a true cost value to these subjective considerations, but they do influence the value of the BIST system installed and how the building operator views them.

Given the many variables and economic impacts, to physically quantify the value of any BIST system is a complex task. The following section sets out a general methodology, followed by a discussion of the challenges faced when applying the method.

2.11.2 General methodology

To determine to actual cost of a BISTS, a number of initial cost estimates must be considered; investment cost and economic savings.

- **Investment Cost**

The BISTS investment cost is estimated per square meter from the additional costs associated by the solar thermal element added to the building envelope (c_{idsenv}). This can be calculated as the difference between the overall investment cost per square meter of the BISTS building envelope (c_{isenv}) and the investment cost per square meter related to a conventional element of the building envelope (c_{irenv}) as the reference:

$$c_{idsenv} = c_{isenv} - c_{irenv} \tag{2.11.1}$$

The first challenge is to define the reference building envelope as there are many reference possibilities available, although just one needs to be derived for the first approximation. The same approximation process needs to be conducted for the building services element and their respective interconnection. The investment cost for the building services includes the solar thermal function per square meter of BISTS area (c_{idbs})

$$c_{idbs} = (c_{isbs} - c_{irbs}) / A_{BISTS} \tag{2.11.2}$$

Where (c_{isbs}) is the investment cost for the building services in a BISTS configuration and (c_{irbs}) is the investment cost for the building services based on the reference case (c_{irbs}) and (A_{BISTS}) is the effective surface area covered by the BISTS.

If the value of a building including BISTS can be estimated reasonably well without the financial savings by the BISTS and reflecting only the image of the BISTS building, then the difference between the value of a BIST building $c_{iBISTbuild}$ and its reference building $c_{irbuild}$ can also be considered.

$$c_{idBISTbuild} = (c_{iBISTbuild} - c_{irbuild}) / A_{BISTS} \tag{2.11.3}$$

The total investment cost (c_{dBISTS}) for the solar thermal element of the building envelope, including the necessary building services is calculated by:

$$c_{idBISTS} = c_{idsenv} + c_{idbs} - c_{idBISTbuild} \tag{2.11.4}$$

In addition, the annual operating costs per square meter for the BISTS, maintenance (c_a), the discount rate (r) and the service life of the system (T), must be estimated.

- **Potential Economic Savings**

In order to determine the potential economic savings, the performance of the BISTS needs to be estimated. The calculation methods used in the economic assessment of conventional solar thermal collectors may be used (in general terms) if the building integration element is neglected. Otherwise, a better approximation may be arrived at by using a simple model for BISTS (Maurer et al., 2015) or a detailed physical model if it is available (Lamnatou et al., 2015b, 2015a). The solar thermal performance of the BISTS can only be applied to a specific climate at a specific physical mounting and orientation and needs to be calculated to include the building and building services load for both with and without the BISTS installed. The result of such a simplified approach yields the typical annual non-renewable primary energy demand for the BISTS (Q_{BISTS}) and the typical annual non-renewable primary energy demand for the reference case (Q_r), both in terms of kWh/a.

These values can then be used to determine the non-renewable primary energy saving *(Q_{dBISTS})* by the BISTS in one year for the specific location dependant applications and per square meter of BISTS area (q_{dBISTS}):

$$q_{dBISTS} = (Q_r - Q_{BISTS}) / A_{BISTS} \tag{2.11.5}$$

The cost of saved non-renewable primary energy energy (c_{sh}) is calculated by:

$$c_{sh} = \frac{c_{idBISTS} + \sum_{n=1}^{T} c_a (1+r)^{-n}}{\sum_{n=1}^{T} q_{dBISTS} (1+r)^{-n}} \tag{2.11.6}$$

This is the sum of the total cost of ownership per square meter of BISTS divided by the total savings of non-renewable primary energy both at present time. In a European context this can be regarded as the Levelized Cost of Heat (LCoH) in €/kWh, with the caveat that it includes not only the contribution of renewable heat of the solar thermal element but also includes the influence of the BISTS on the building heating and cooling demand. A negative cost value represents a profit.

The cost of saved non-renewable primary energy (c_{sav}) can be compared with the LCoH of non-renewable heat sources. Together with an average CO_2 emission per kWh of non-renewable primary energy (*e*), the cost of saved CO_2 emissions (c_{sc}) can be calculated:

$$c_{sc} = \frac{c_{sh}}{e} \tag{2.11.7}$$

2.11.3 Challenges in BISTS application

There are numerous challenges that exist for any renewable and non-renewable investments; however, the challenges are exceptionally large for new and emerging areas in building integrated solar with particular issues for innovative BIST systems. Many stakeholders do not have significant experience of BISTS and minimal information is available surrounding BISTS (when contrasted to BIPV) and virtually nothing relating to the detailed economic performance of BISTS.

2.11.3.1 The challenge of influence

It is difficult to quantify the value of a BISTS solution in general, because the performance of a BISTS is very dependent upon the location, orientation, building configuration and its respective building services infrastructure. Specific cases can be analysed and optimised, but if only one parameter is changed, the performance and associated economics of the whole system can be significantly altered. To address this issue, ‘reference installations’ are analysed in detail to identify which parameters (or range of parameters) can be used as indicators in benchmarking performance.

2.11.3.2 The challenge of detail

At the outset of any building construction exercise, important detailed design consideration is minimal. These design decisions are crucial to the effective simulation of BISTS performance and yet often the time and effort required through detailed modelling and simulation of the BIST envelope cannot be justified. Generating a large (open access) database relating to BISTS characteristics and features, together with performance calculations and measurements and associated economic and cost values could help prospective BISTS stakeholders to make initial (ball-park) estimations for their specific BISTS projects.

2.11.3.3 The challenge of quantifying

The value of a building depends on many factors one of which is thermal performance. Whilst information relating to building performance through a building envelope thermal resistance or the time since the last building envelope refurbishment is important, there are many subjective parameters that are just as important in how a building is valued. The aesthetics of a building are very important and the inclusion of a BISTS could have a significant impact of the appearance of the building envelope. Aesthetics and other opinion based factors, unlike a thermal characteristic, are very hard to quantify. Stakeholders can estimate the particular benefits and drawbacks based on their experience and/or on feedback from targeted surveys in which they can ask opinions on differing building envelope configurations. Information relating to wide scale statistical surveys on such parameters on existing buildings with or without BISTS would be beneficial to potential stakeholders.

2.11.3.4 The challenge of differences

When deciding upon a perfect reference BISTS envelope, it is obvious that no one function can be considered in isolation and therefore selecting a system based on solar contribution alone without considering a different appearance or mounting configuration, for example is difficult. One factor will always influence another and this difference in like-for-like comparison will always influence the consumer’s choice of system. BISTS envelopes compete with many other building envelope possibilities and often consideration of investment cost, ecological or architectural/aesthetic factors may often be more important that the inclusion of a renewable energy system in the building fabric. The wide variety of options is in its own a significant barrier to choice and may only be addressed by analysing a select few of the most promising examples. Similarly, changes to the BISTS envelope can have a negligible or significant impact upon the demand on building services systems, adding a further additional challenge. One BISTS configuration may reduce the cooling load passively (reducing AC loads) whilst another system provides a (renewable) heat supply to the building but uses additional electricity. These differences make the energy cost and associated CO_2 emissions more difficult to compare than in a case where just one variable changes. Such issues can be analysed in detail, but often need specific expertise to be accurately assessed.

2.11.3.5 The challenge of the future

No one knows exactly how the BISTS technologies of today and associated economics will evolve in the future, which in turn implies that a lot of assumptions regarding energy prices and discount rates, for example, will be necessary. Likewise, for new and untried products, the required maintenance or service life can be estimated, but some uncertainty will always remain. To quantify the uncertainty in BISTS, the following procedure is recommended which is based on the Monte-Carlo method. Firstly, the important output values and the most uncertain parameters are defined and the uncertainty of these parameters is estimated. Then a large number of random parameter groups are generated based on the uncertainty of the individual parameters. Finally, the output values are calculated for each parameter set and are presented in histograms. By analysing these histograms, the risk of deviations within a certain range can be quantified.

2.11.4 Conclusions

This section outlines forms of economic impact and value associated with BISTS and presents a generalised methodology for calculating BISTS economic investment potential. Several important challenges have been recognised, highlighting the difficulties that may arise in using such a generalised approach. Finally, appropriate solutions have been suggested that address the limitations and knowledge gaps that currently exist in resolving the future challenges identified. For the first time, a simple framework has been created that forms the basis for an applied economic analysis of existing and new BISTS.

REFERENCES

Lamnatou, C., Mondol, J.D., Chemisana, D., Maurer, C., 2015a. Modelling and simulation of Building-Integrated solar thermal systems: behaviour of the coupled building/system configuration. Renewable and Sustainable Energy Reviews 48, 178–191.

Lamnatou, C., Mondol, J.D., Chemisana, D., Maurer, C., 2015b. Modelling and simulation of Building-Integrated solar thermal systems: Behaviour of the system. Renewable and Sustainable Energy Reviews 45, 36–51.

Maurer, C., Cappel, C., Kuhn, T.E., 2015. Simple models for building-integrated solar thermal systems. Energy and Buildings 103, 118–123.

2.12 LEGAL ISSUES

Christian Cristofari, Rosita Norvaišienė, Gilles Notton

2.12.1 Introduction

The European Union (EU27) possesses some 25 thousand million square metres of buildings for a population of 512 million inhabitants, an area equivalent to about three times that of Corsica or Cyprus (8.6 and 9.2 km²). The mean annual growth of the residential construction sector in Europe is 1%.

In area, the European building stock is 25% "non-residential" part (tertiary sector, hospitals, schools, administration, etc.) and 75% "residential" (dwellings). Inthe residential area, 64% is made up of individual housing, and 36% communal housing.

In the residential buildings sector, 39% were built before 1960, 43% in the interval 1961–1990 and 17% in the interval 1991–2010. More than half of European dwellings are therefore not insulated.

In central and eastern Europe [BG, CZ, EE, HU, LT, LV, PL, RO, SI, and SK] where urban heating systems are widespread, coal is the most often used fuel in the residential sector.

Oil is the most common fuel in northern and western Europe [AT, BE, CH, DE, DK, FI, FR, IE, LU, NL, NO, SE, and UK].

Gas is used as a heating fuel in all regions, and is the one most frequently used in buildings in the EU; renewable energies make up 21%, 12% and 9% of end-user consumption in central and eastern Europe, southern regions [CY, GR, ES, IT, MT, PT] and northern and western regions, respectively.

Buildings account for 40% of total energy consumption in the EU, and 36% of greenhouse gas emissions (European Commission, 2013). This sector, which consumes more energy than either industry or transport, is therefore of major importance for mitigating the EU's energy dependency and carbon emissions.

Based on a European residential building stock of 300 million housing units, and an annual new construction rate equal to 1% of existing stock, we will examine (i) the different European directives relevant to the renovation of these buildings, and (ii) how the various European countries apply these directives, and what their respective levels of requirement are. We will go on to benchmark heating regulations for new buildings.

Finally, we will address the question of how much weight energy policy in European countries gives to the use of renewable energy sources, in particular solar heating systems.

2.12.2 European directives concerning the energy performance of buildings

European Union policy and strategy recognise the importance of tight energy regulation for the heating of both new constructions and the renovation of existing buildings. Such regulation is crucial to reaching long-term energy and climate objectives, and to achieving a positive economic impact.

The construction sector is accordingly taken into account in all the EU strategies for energy conservation, managing climate change and making efficient use of resources planned for 2050.

- To reach its long-term decarbonisation targets, The EU's roadmap provides for a reduction in carbon emissions in the residential and service sector of 88–91% by 2050 relative to the levels of 1990 (COM, 2011a).

- To meet its objectives for 2050 and achieve future energy sustainability, the EU stresses the importance of controlling energy consumption in both new and existing buildings; the large energy savings thus made will help significantly to reduce energy demand, ensure a more secure energy supply, and improve competitiveness (Energy Roadmap 2050 - COM, 2011 b).

- The EU has also legislated on improving the energy performance of buildings through the integration of renewable energy sources. The Renewable Energy Directive (2009/28/EC) requires Member States to introduce measures to increase the share of renewables in the construction sector through building regulations and codes of practice. This requirement covers new buildings and existing ones undergoing substantial renovation.

Given the tardiness of the European Union Member States in reaching the objectives set for 2020[6] in energy efficiency improvement, new legislation was introduced: the Energy Efficiency Directive (EED 2012/27/EU), issued in November 2012. This Directive supersedes the Cogeneration Directive (2004/8/EC) and the Energy Service Directive (2006/32/EC). It also introduces a large number of requirements for Member States, including in the domain of energy efficiency in buildings.

This directive is meant to improve the energy performance of buildings in the EU, taking into account the different climate conditions and local features. It sets minimum requirements and common methods. It covers the energy used for space heating, production of hot water, cooling, ventilation and lighting.

The Member States must set cost-optimal minimum energy performance requirements and review them at least every five years.

New buildings must meet the minimal standards and be equipped with high-efficiency replacement energy systems. Occupied buildings owned by public authorities must undergo conversion so that energy consumption is nearly zero[7] by 31 December 2018 (two years later for other new buildings).

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[6]One of the '20/20/20' objectives in the EU's climate and energy programme for 2020: 20% reduction in greenhouse gas emissions in the EU relative to 1990 levels, 20% increase in the share of the EU's energy consumption from renewable sources, and 20% greater energy efficiency in the EU. http://ec.europa.eu/clima/policies/package/index_en.htm. Stimulating building renovation: a brief overview of good practice

[7] Nearly-zero energy buildings have very high energy performance. The nearly-zero or very low energy required must largely come from renewable sources, especially sources on site or located nearby.

Existing buildings undergoing major renovation work must improve their energy performance to meet EU requirements.

The Member States will put in force a diagnostic system for energy performance. This system will give potential buyers or tenants information on a building's energy performance together with recommendations to improve it. This information must appear in all commercial support material for the sale or rent of buildings.

On 1 January 2017, the Commission will examine the progress made towards meeting the energy performance objectives and will make new proposals if necessary.

2.12.3 Uneven application of directives by EU Member States

2.12.3.1 Renovation of existing buildings

The BPIE (Buildings Performance Institute Europe) has made an accurate analysis of the strategies and objectives set by the different Member States. It found differences among Member States in both strategies and objectives. (BPIE_A, 2013).

France, with the Grenelle Environment Forum, stands among the most ambitious Member States. Its declared objective is to reduce the energy consumption of the existing building stock by 38% between now and 2020 (Grenelle I), with 400 000 renovations in the years 2013–2017 (Grenelle II) (NEEAP_FR, 2011). The BPIE report considers these objectives difficult to meet in view of current trends.

Germany, with its national Energiewende policy, has set clear objectives: double the pace of energy modernisation in buildings from 1% to 2% per year; reduce energy demand for heating by 20% between now and 2020, and reduce primary energy needs in the construction sector by 80% between now and 2050.

Some Member States are relying on collaboration rather than incentives or standards. The Netherlands have set no compulsory requirement for energy renovation of buildings, but the Ministry of Housing has signed a convention with building societies to improve the energy performance of new houses. Austria has likewise set no national requirements for building renovation.

It is also important to underline that the ways decision-making powers are delegated also influence the policies implemented in the different Member States, in particular in Italy and Belgium, where regional authorities can decide on energy policy and how it is applied. France offers another example: Corsica, alone among French regions, has a 3 thousand-million-euro multi-annual energy programme, with the renovation of 25 000 dwellings planned over 8 years (SRCAE, 2013).

Some Member States have prioritised cost-optimisation of energy renovation. In Denmark, the amortisation period must be less than 75% of the installation's lifespan, failing which the conditions of the renovation work must be reviewed. Exceptions are made for work deemed essential, such as replacing floors, outside walls, doors, windows or roof structures.

In the United Kingdom, energy performance requirements apply provided they can be met "technically, functionally and economically". The amortisation period must be less than 15 years.

Scope for individual initiative ranges widely among Member States. In Finland, there are minimal requirements for energy efficiency in renovation work, but "the owner decides when and what repairs are done, and what the best methods are for improving energy efficiency within the regulatory framework".

Conversely, the standards imposed on individuals may sometimes be very restrictive. In Denmark, the renovation of some buildings must include the installation of a solar energy heating system.

However, energy performance standards have been introduced throughout the EU. They fall into two categories: (i) those concerning the overall performance of renovated buildings, and (ii) those concerning parts of the construction and specific equipment.

These two approaches are mostly combined in the EU. Standards concerning specific items are very often added onto the overall objectives. Almost all the EU countries have set in place requirements for newly installed roofs, windows and boilers.

Table 2.12.1 shows that most EU Member States have introduced specific conformity requirements for various parts of building exteriors and technical systems. These itemised requirements are easier to meet than those for the overall energy performance of the renovated building. Only some Member States have introduced overall energy performance regulations for the whole of a renovated building; very few have energy performance requirements that focus only on the renovated area. In some Member States, the requirements for the whole building or part of it are combined with requirements for individual items (BPIE, 2011).

Table 2.12.1. Overview of building requirements for major renovations and ambitious renovation policies and regulations (BPIE_B, 2013).

Austria Specific maximum heating energy demand targets for major renovation of residential and non-residential buildings. Values for renovated buildings are around 25-38% higher than new build requirements. Heat recovery must be added to ventilation systems when renewed. Maximum permitted U values for different elements in case of single measure or major renovations

Prescriptive requirements to limit summer over-heating.

Requirements related to the maximum heating energy demand of renovated buildings. North Austria: Additional requirements regarding the maximum externally induced cooling demand. Since 2012, major renovations should achieve at least the B rating (≤50kWh). Expected to change to A+ rating (≤10kWh) before 2020.

Belgium There are specific component requirements (i.e. maximum U-values) as well as additional prescriptive requirements such as for ventilation, summer comfort etc. [Brussels]:

Minimum energy performance threshold for rented homes. From 2015, major renovations should achieve a very low energy standard (NEEAP-BCR, 2011)

[Flanders]: When extension or renovation, “protected volume” > 800 m³: same requirements as for new buildings (U/R-value, K-level, E-level, ventilation and for residential buildings also summer overheating). When renovation, “protected volume” ≤ 800 m³: only U/R-values for new and renovated parts of the building + ventilation.

[Brussels region]: Since 2010, major renovation of public buildings should achieve low energy standards. From 2015, all buildings that undergo major renovations should comply with the very low energy standard.

[Flanders]: 1. For renovation of residential buildings (with extension) ≤800m³:

- When a building permit is required -> energy performance requirements exist for parts of building envelope being replaced or with extension:

  -maximum R-values or minimum U-values

  -certain requirements for ventilation

- Control and compliance through EPB-system (EPC-declaration done by an independent energy expert)

2. When expansion or renovation of a ‘protected volume’ ≥ 800m³ -> same requirements as for a new building. New standard for roof insulation from 2015: if a dwelling has a roof that does not meet the minimum required standard, it will receive a penalty point during the evaluation of the building. From 2020 and on, it will be illegal to rent out buildings with inadequate roof insulation.

Bulgaria Regulations requiring performance-based standards of existing housing and other buildings after renovation. Requirements for new and renovated buildings are the same.

Switzerland Renovated buildings are required to use no more than 125% of the space heating demand of an equivalent new building. A single element approach may also be applicable for renovations.

Cyprus Minimum energy performance requirements (class A or B) for new buildings and for buildings over 1 000 m^2 undergoing major renovation.

Czech Republic Performance-based requirements when a building over 1 000 m^2 is renovated. Requirements for new and renovated buildings are the same. Individual parts of the building envelope and systems in the buildings have to fulfil minimum requirements. If it is not possible to achieve the minimum performance criteria, this has to be proven by means of an energy audit.

There are also minimum requirements in case of major renovation of individual building elements such as for U-values, internal temperature at the internal leaf of envelope structures (which has to be higher than dew point temperature), thermal bridging limits to avoid condensation, thermal stability of the room in summer and in winter, minimum efficiency of boilers, etc. Furthermore, buildings shall achieve a healthy indoor climate.

Germany Both energy performance and specific component-based requirements. For renovations of single components or systems, there are specific requirements for these components/systems. Alternatively, the building owner can choose to prove that the primary energy demand requirements for retrofitted buildings are met (140% of the demand for a comparable new building).

Building surface components and building system components must not be changed in a way that decreases the energy performance of the building. There are additional cost-effective obligations that need to be fulfilled by the building owners within a specific time-frame for: insulation of hot water pipes and top floor ceilings, retrofit of HVAC systems and replacement of electrical heat storage systems.

Target: 2050- climate neutral building stock.

Component-specific minimum efficiency requirements which have to be fulfilled when changing or modernising a building component. However, where no renovation takes place there is no requirement to fulfil any performance standard at all.

OR

Holistic assessment analogous to the calculations for new buildings. All retrofitting obligations are also subject to the precondition of cost-effectiveness.

Denmark Component level requirements when existing buildings are refurbished for change of use of the building and for complete or partial renovation of building elements or technical systems, regardless of the building size. Individual parts of the building envelope and systems in the buildings have to fulfil certain minimum requirements in the renovated building. Thus there is no overall performance requirement for the renovated building, but only for the individual components and systems. Minimum U-values and linear losses requirements.

The partial renovation measures must be cost-effective (i.e. payback time shorter than 75% of the measure’s lifetime). If the implementation of the full requirement is not profitable to the owner, a lower level of renovation or indeed none at all, has to be implemented. In case of replacement of floors, external walls, doors, windows or roof structure, requirements apply regardless of cost-effectiveness. Thermal bridging should be avoided in external construction elements including windows and doors due to the risk of condensation. There are special energy requirements (less strict) when renovating windows with small transparent fields due to preservation of architectural values. In the case of renewal of an installation in existing buildings, the same requirements of an installation in new buildings apply.

Minimum energy requirements for building components in case of a) change of use of building, b) complete renewal of elements, c) partial renewal of elements. However, all energy upgrading measures must be economically feasible (payback time ≤75% of expected lifetime of the measure).

In the case of a replacement of floors, external walls, doors, windows or roof structure, the minimum energy performance requirements apply regardless of cost-effectiveness. In the case of renewal of an installation in an existing building, the requirements are the same as for the installations in new buildings. From the beginning of 2013, the installation of oil-fired and natural gas heating units in new buildings will no longer be allowed.

Estonia Performance-based requirements for all building types when buildings undergo major renovations. Values for renovated buildings are around 25-38% higher than new build requirements.

Spain Existing buildings over 1000 m^2 must comply with the same minimum performance requirements as new buildings if more than 25% of the envelope is renovated. There are additional energy efficiency requirements for building elements, heating and lighting systems, minimum solar-thermal contribution and in certain cases also for minimum solar photovoltaic contribution.

Finland Shift from requirements concerning the heat loss of individual components to one indicator (the E index) describing the total calculated energy use of the building. New regulations came into effect on 1 June 2013 introducing minimum energy performance requirements for energy efficiency concerning renovations. There are three ways to achieve these requirements: a) improving the heat retaining capacity of building parts that need reparation or renewal, b) improving the energy efficiency of the building by examining the whole building’s energy consumption in relation to its surface area, c) reducing the building‘s E-number, by reducing the total energy consumption of the buildings. Technical systems (like heating and ventilation) have their own requirements and should be checked when insulation is added to the building, when air-tightness is improved, or when systems are renewed.

Minimum requirements for energy efficiency concerning renovations that are subject to a license, a change in use or the renewal of technical systems. The decision to start renovation work remains voluntary, according to the regulations. The property owner decides when and to what extent he or she will make the repairs, and what are the best methods to improve energy efficiency within the regulatory framework.

There are three alternatives to improve energy efficiency:

> *1. Improving the heat retaining capacity of the building parts that need repairing or renewing so they conform to the required standards*

2. Improving the energy efficiency of the building according to the level defined for that type of building

3. Calculating the building's E-number

France Performance-based requirements for buildings undergoing renovation apply for residential buildings and values depend on the climate and type of heating (fossil fuel/electricity). Requirements for components also apply during building renovation. New renovation requirements for all buildings are expected to come in 2013.

For major renovations (>1000 m^2): the overall energy performance target for renovated buildings built after 1948 is in the range 80-165 kWh/m^2/year since 2010.

For renovations <1000 m^2: element-based requirements for replacement or renovation of elements (for heating, insulation, hot-water production, cooling and ventilation equipment).

For large renovations, a minimum summer comfort level is required in order to avoid the use of cooling systems. Smart systems should be installed every time there is major renovation work on a building.

Targets:

- *Renovate 400,000 housing units per year starting in 2013.*

- *Renovate the 800,000 most energy-consuming social housing units by 2020.*

- *Undertake work on energy efficiency in public and private tertiary sector buildings between 2012 and 2020.*

- *Start the energy renovation of State and public buildings before 2013.*

For major renovation of buildings > 1000 m^2: global energy performance target for renovated buildings, built after 1948 (dwellings: 80-165 kWh/m^2/year from 2010 onwards.

Non-residential buildings: the savings should be 30%)

For major renovation of buildings < 1000 m^2, or buildings > 1000 m^2 undergoing minor renovation: a minimum performance level for elements replaced or installed (for insulation, heating, hot-water production, cooling and ventilation equipment)

Greece Individual parts of the building envelope and systems in the buildings have to fulfil certain minimum requirements in the renovated building.

Minimum thermal resistances defined for different types of building components and also different efficiency of systems. Thermal bridges are also considered.

Hungary Performance-based requirements (in terms of primary energy) apply for residential buildings, offices and educational buildings. Requirements for new and renovated buildings are the same.

The specific primary energy consumption in kWh/m^2 must comply with the requirement, either for the renovated zone or for the whole building - option that can be selected by the designer. The requirement cannot be met if the components are of low quality.

Italy Energy performance requirements are based on single components, with the same requirements as new buildings.

There are also minimum energy efficiency requirements for boilers.

Energy performance requirements regarding major renovations.

Additional requirements for the installation of RES systems for heating and PV.

[Bolzano County]: By the end of 2019, owners of buildings will be allowed to expand the surface of their dwelling by up to 20% or up to $200m^3$, only if the building achieves heating consumption below $70kWh/m^2/yr$.

[Region of Valle D'Aosta]: in case of expansion by 20% of buildings with a floor area higher than $2000m^2$ or in case of new dwellings, the energy performance of the building must comply with the local energy class B level ($\leq 50kWh/m^2/yr$ for heating).

[Trento Province]: the minimum requirement is energy class B+, while for an expansion of the building up to 30%, the minimum energy performance requirements are more restrictive.

[Torino city]: Energy and environmental requirements for the improvement of the façade and the roof thermal insulation when undertaking major renovation activities. Criteria based on ITACA protocol. Voluntary scheme assessing the energy performance of the building based on these criteria. Based on the points collected through the ranking criteria, buildings are eligible for different public financing incentives.

Lithuania Building meets requirements of A++ energy efficiency class (nearly zero-energy building) if ratio between renewable and non-renewable energy in the building is more than one. Up to 50–70 % energy share from renewable sources in district heating is to be achieved until 2020. However, there are no specific provisions for solar heat.The energy performance class of buildings after major renovation must be not less C. The energy performance class of new buildings must be not less than B. Buildings over 1.000 m^2 undergoing major renovation must achieve the energy performance standard of a Class D building where D corresponds to 110 kWh/m^2yr for buildings > 3 000 m^2; 130 $kWh/m^2/yr$ for buildings from 501 to 3000 m^2; 145 kWh/m^2 a for buildings up to 500 m^2.

Individual parts of the building envelope and systems in the buildings have to fulfil certain minimum requirements depending on renovation.

Latvia Requirements on different elements are applicable.

Malta U-value requirements for building renovation.

Netherlands The Energy Performance Standard (EPN) sets requirements for the energy performance of major renovations of existing buildings (expressed as an energy performance coefficient).

For renovations, the same EPN requirements as for new buildings apply. Stricter efficiency requirements for heating, hot water, cooling and ventilation systems in existing homes and large residential buildings (offices, schools, shops, hospitals, etc) are expected to be applied from July 2013. All materials and products used for renovation must have an approved label.

For new skylight windows, or renovation of existing ones, new insulation requirements apply.

Norway Building regulation requirements as for new buildings only apply when the purpose or use of the building is changed at renovation or in case of major renovations. The requirements are either for the renovated zone or for the whole building (an option of the designer).

Poland For major renovations or system component replacement there are the same requirements as for new buildings.

Portugal Special requirements for buildings over 1000 m^2 and over a specified energy cost threshold. A mandatory energy efficiency plan must be prepared and all energy efficiency improvement measures with a payback of less than 8 years must be implemented (compulsory by law). The threshold is based upon 40% of the worst performing buildings by typology.

Minimum requirements for thermal resistances defined for different types of building components and for energy efficiency of buildings systems. These values are based on moisture and mould prevention. Furthermore, buildings shall achieve a healthy indoor climate.

Thermal bridging should be avoided in external construction elements including window and doors because of the risk of condensation. There are minimum energy requirements for the building as a whole as well as minimum insulation levels for the building envelope and minimum requirements for shading of windows.

Romania The actual energy performance of a building is compared with a "reference building" which is a virtual building having the same geometry as the actual building but the energy performance of a new one - concerning individual parts of the building envelope and systems (indirectly, after renovations, the building have to fulfil certain minimum requirements for the individual components and systems as well as an overall performance requirement).

Slovenia Minimum requirements apply to major renovations (i.e. if at least 25 % of the envelope is renovated). The requirements apply to all buildings, irrespective of floor area. There are also minimum requirements for heating systems.

Sweeden Depending on the size of the renovation, the renovated zone has to fulfil the energy requirements for new buildings. In case of heritage buildings or when renovation may negatively influence other features of the building, then the energy requirements may be lowered. In case of major renovation, the minimum energy efficiency requirements may be extended also to other parts of the building.

Slovakia When major renovation is foreseen, there are requirements to improve the thermal performance by at least 20%.

There are minimum requirements in terms of energy use and energy performance (delivered energy), U-value for building structures as well as, walls, roofs, windows, insulation of heat and hot water systems, thermal comfort and indoor air quality.

United Kingdom Specific energy efficiency requirements for residential buildings when replacing “controlled elements” such as windows, boilers and thermal elements. Moreover, there are energy performance requirements for buildings over 1000 m^2 undergoing major renovation in so far as they are “technically, functionally and economically feasible”.

For the repairing/ renewal of a building element (thermal element), like the wall, floor, roof etc., the performance of the whole element should be improved to achieve specific

U-value standards. These improvements should also be technically, functionally and economically feasible (i.e. payback time ≤15 years). More specifically, for roof renovation and repair, requirements apply in case of 50% or more of the roof refurbishment.

In Scotland, homes must meet the “Tolerable Standard”, which comprises of a variety of criteria, including satisfactory thermal insulation.

When a thermal element (i.e. a wall, floor, roof etc.) is subject to a renovation and its U-value is below a required threshold, the performance of the whole element should be improved to achieve specific U-values, provided the area to be renovated is greater than

50% of the surface of the individual element or 25% of the total building envelope.

However, the upgrading of a thermal element should also be technically, functionally and economically feasible. Moreover, when 50% or more of the roof area is being refurbished, the whole of that roof must be brought up to the thermal efficiency demanded by the current regulations. Furthermore, from April 2018, private rented properties must be brought up to a minimum energy efficiency rating of 'E'. This provision will make it unlawful to rent out a residential or business premise that does not reach this minimum standard.

[Scotland]: Homes must meet a tolerable standard, which includes certain energy performance requirements.

2.12.3.2 New buildings

After the oil crises of the 1970s, various European countries developed policies for energy conservation, one result of which was a formalisation over the years of different regulations for habitat heating. The example of France, with six successive sets of regulations for heating, is representative of how regulations have evolved in Europe. In 1974, the first heating regulations in response to the first oil crisis required a thin layer of insulation and a regulated heating system. It concerned only new dwellings. The second heating regulations of 1982 added a maximum heating restriction. The third heating regulation of 1988 required minimal performance for equipment and systems (e.g. heating yield). The fourth heating regulation of 2000 was a turning point in that residential buildings were now included. An overall performance target was added, together with a new summer comfort factor. The fifth heating regulation of 2005 followed on from the previous ones, but was more demanding, and the latest regulations of 2012 took a major leap forward, requiring a three-fold reduction in primary energy (PE) consumption, measured in kWh PE/m²/year, in new buildings (Figure 2.12.1).

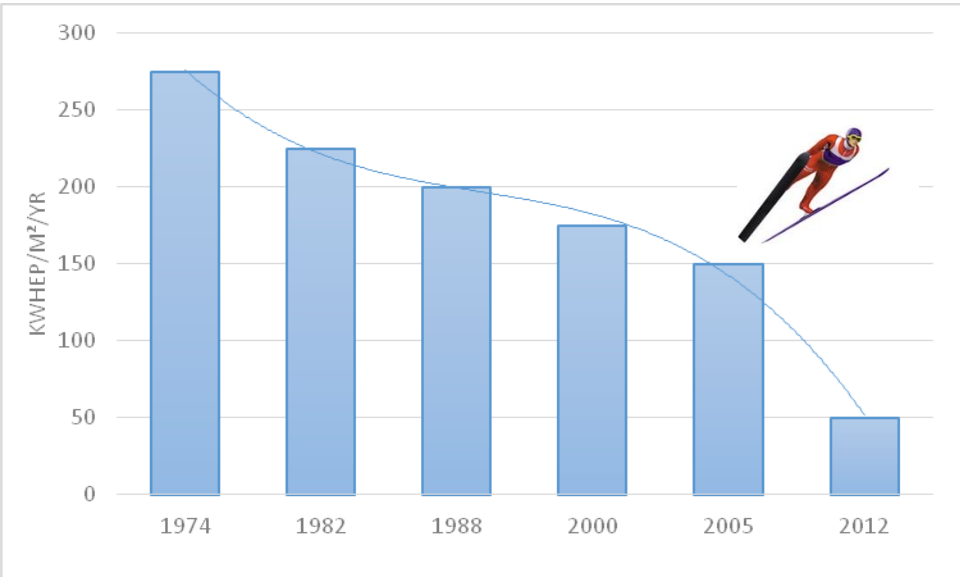

Figure 2.12.1. Trend in energy consumption requirements for new buildings in France.

To meet the objectives set in the European Directives, EU Member States have drawn up **results-based requirements** based on general indicators of overall habitat performance (overall heating regulations), and **means-based requirements** based on different items or systems composing the building or involved in its running (itemised heating regulations).

For countries with heating regulations integrating results-based requirements, we find:

- An indicator related to heating need, where a limiting value is set: France has changed this indicator to take into account the bioclimatic need of the habitat, which now integrates building orientation,

- An indicator for maximal energy consumption, where a limiting value is set: this is found in the energy label,

- An indicator for summer comfort in some southern European countries, where a reference temperature ceiling is set.

For countries with heating regulations integrating means-based requirements, we find:

- Requirements concerning heat insulation, especially of outside walls, roofs and low floors (Table 2.12.2 which gives examples of limit values in different countries), which in some countries may be integrated into overall regulations,

- Requirements for airtightness of the building envelope (on average 0.6 $m^3/h/m^2$ [envelope surfaces not including low floors]),

- Requirements for natural light entry (minimal surface area of bay windows – X% of living space area) and coefficients of heat loss through bay windows (which in some countries may be integrated into an overall regulation – U Table 2.12.3),

- Requirements for the development of renewable energy sources (integration of a minimum X kWh PE/m^2/year),

- Requirements for summer comfort (protection from sun, classification of zones [noise]),

- Requirements for proper use of buildings (measurements of energy consumption).

Table 2.12.2. Limit values of U (W/m^2K) for construction items in different countries.

***U* (W/m^2K)**	**Germany**	**United Kingdom**	**Belgium**	**Denmark**	**Spain**	**France**	**Italy**	**Switzerland**
Outside walls	0.24	0.28	0.32	0.20	0.74	0.36	0.33	0.20
Roof	0.24	0.17	0.27	0.15	0.46	0.20	0.29	0.20
Low floors	0.24	0.22	0.35	0.12	0.62	0.27	0.32	0.20

Table 2.12.3 Limit values of Uw (W/m²K) for bay windows in different countries.

U_w (W/m²K)	Germany	United Kingdom	Belgium	Denmark	Spain	France	Italy	Switzerland
Bay windows	1.30	1.60	2.20	1.65	3.10	1.80	2.00	0.70

In a sample of eight countries studied we observe three countries, FR, DE and SW, that use both types of requirement, i.e. means-based (itemised regulations) and results-based (overall regulations), three countries, BE, DK and ES, that use only means-based requirements (itemised regulations), and two countries, UK and IT, that use only results-based requirements (overall regulations). The most and least demanding values of heat loss were respectively Switzerland and Spain.

The heating regulations of these countries came into force at different dates (Figure 2.12.2). We note that only three countries, ES, FR, IT adjust the regulations according to the climate zone.

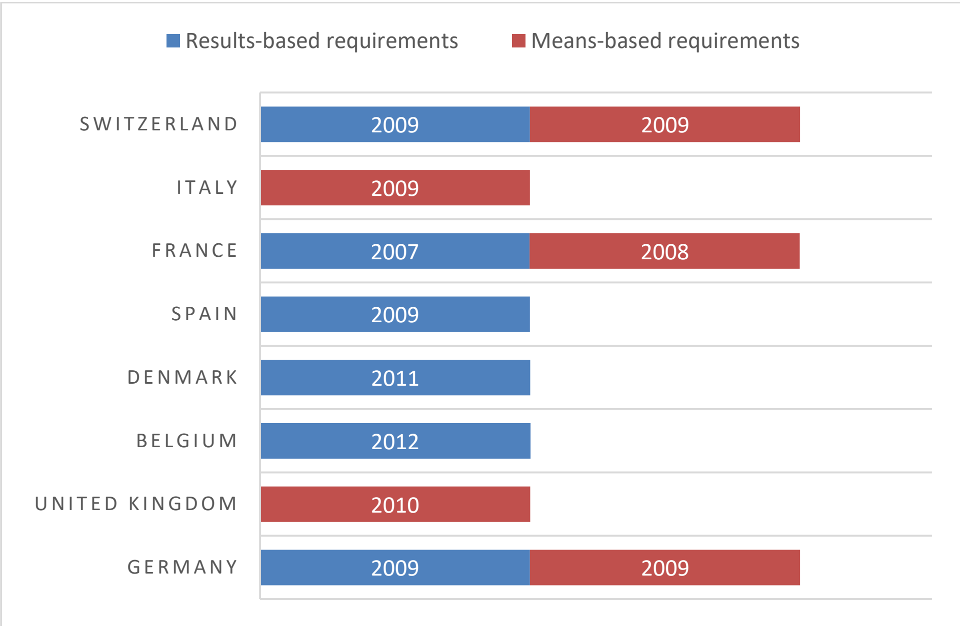

Figure 2.12.2. Dates heating regulations came into force by country.

The Directive 2009/28/EC positively encourages the use of obligations as a means of increasing the share of renewables as an energy source in buildings. According to 13.4: *"Member States shall introduce in their building regulations and codes appropriate measures in order to increase the share of all kinds of energy from renewable sources in the building sectors".*

2.12.3.3 Solar heating

The first regulations concerning solar heating were introduced in Israel in 1980, in response to concerns about the security of energy supplies after the second oil crisis. Despite its success, two decades passed before the next instance of such regulation came into force in Barcelona. In the 1980s and 1990s, renewable energy sources were not a priority, because energy prices had fallen, and the research carried out by the IPCC on climate change had not yet prompted the relevant public policy decisions.

All new buildings and those that are to undergo major renovation should be covered by solar regulations. In these cases, the advantages are obvious, and the extra cost due to the regulations would be minimised. Various obstacles – administrative (use of roofs in protected areas and buildings), economic (cost of solar heating systems) and social (aesthetic acceptability) – hinder the political decision-making needed to impel the implementation of drastic regulations for solar heating.

Even so, the EU must make its energy transition: in the medium term 100% of the energy needs of buildings should be covered by renewables. Buildings are central to any overall energy conservation strategy. If the EU covered 50% of its hot water consumption with solar energy, it would save some 12 Mt PE per year, or 1% of end-user energy consumption in the EU. This figure is the equivalent of the total consumption of about 10 million households (ESTIF, 2007).

The integration of solar heating systems in buildings may offer a solution for speeding up and massifying their adoption.

2.12.4 Legislation that partially favours building aesthetics – the example of France

From the outset, installations harnessing solar energy have been tarnished by a reputation for creating an eyesore, which has turned many potential users away. On the aesthetics front, photovoltaic systems already offer households and designer large room for manoeuvre, as the cells are small and modular and the electrical cabling is far more flexible to work with than regular pipework, which substantially increases their potential integratability (Hagemann I.B., 2002; Reijenga T, 2000).

Outside of the sociological dimension—which remains a complex focus of study—there are legislative roadblocks based on heritage asset conservation policy, typically:

- Heritage protection perimeters surrounding a historic-interest monument;
- Conservation-area districts;
- ZPPAUP—conservation areas for ‘Protected Urban, Architectural and Landscape Heritage’. Article 28 of French act No. 2010-788 dated 12 July 2010 was reformed to replace ZPPAUP with AVAP—Areas of Heritage Value;
- Listed or scheduled heritage sites.

An AVAP project is purposed with the development and enhancement of built-environment heritage and historic spaces, as an extension of committed sustainable development policy. Any construction or development project inside these areas must first apply for planning permission from the STAP—the local-region buildings, monuments and heritage assets authority. An ABF—Architecte des Bâtiments de France, the appointed advisor charged with supervising that any new build or development work bordering onto protected monuments will not create an eyesore—then issues their local authority with a straight consent, development consent needed or full consent procedure (MDD, 2012). Unfortunately, solar power facilities do not qualify as "showcasing heritage value".

Furthermore, the ABF also have an influence that stretches beyond AVAPs, as their scope of authority extends to:

- The surroundings in the vicinity of historic monuments and listed heritage sites: a protected-area perimeter spanning the 500-metre radius around any historic monument (French Laws 1913 -1930). This authority was enacted by the French Planning Act of 1943, which stipulates that "any home located in line of sight of a historic monument may not be extended, demolished, cleared of trees or altered in any way that might affect its character" (French Laws 1913);

- Scheduled sites: sites governed by the French Ministry for Sustainable Development, which missions the ABF out to the ground (French Laws 1930);

- Conservation-area districts: the ABF supervises that any first-fix (building envelope) or second-fix (structural interior) remodelling is compliant with the preservation and rehabilitation area map (Malraux Act of 1962 safeguarding historic-interest town centres);

- AVAPs: the ABF coordinates the study then checks the projects are code-and-regulations-compliant.

Taken together, these areas add up to represent huge potential for working thermal solar energy. As of 31 December 2012, France counted 43,180 monuments, i.e. 14,367 'listed' and 28,813 'scheduled', registered as holding historic interest (MFC, 2010), and the list is getting longer every year, plus the hundred-odd conservation-area districts that cover an average surface area of 6,600 ha each (MFC, 2010).

That said, there are signs the legislature is loosening up:

- Under round 1 of the multi-party 'Grenelle Environment' reform, the French Senate and National Assembly, initially divided on the bill, finally agreed to a measure voted in Thursday 23 July 2009, passed by a special joint government–senate committee. Under this measure, ABFs saw their powers clipped back, as the duty to secure 'permitted development' consent was replaced by a straightforward 'consultative' ruling in the vast majority of cases. Today, the decision taken essentially follows local zoning code, called PLU—Plan Local d'Urbanisme. In practice, to determine the impact of this kind of measure, it would be necessary to pore through every single 'PLU' zoning map of France, as each one is defined at local council level (or, in rare cases, at cross-local-council level);

- The French Act No. 2010-788 dated 12 July 2010, dubbed 'Grenelle Environment Round 2', amended the French Urban Planning Code by ushering in article L.111-6-2, under which paragraph 1 reads: "despite any town planning provisions to the

> contrary, planning permission may no longer oppose the installation of equipment that produces renewable energy to cover the household energy needs of the occupants of all or part of the building”.

Table 2.12.4 pools and recaps the various administrative procedures governing project sites according to area location.

This short analysis highlights how the stiff French homes and housing legislation privileges aesthetics over energy performance. Although there are signs the legislation is softening up, the conditions imposed are still strict and, in tandem with the financial grants and incentive schemes available, tend to support a policy of maximal integration of energy supply components. Indeed, government directives further anchor this policy priority given to building-integrated solar technologies to foster more landscape/architecture-conscious aesthetics and to position home solar trades and industries on a higher-value-added subsector (MEETL, 2012). Solar energy is coming to town and shaking up the old building function and design codes. Under this new paradigm, solar power facilities are now energy-producing features of the building envelope.

Table 2.12.4. Recap of the procedures applicable to residential build projects according to area location (Pref HR).

In heritage protection perimeter surrounding a historic-interest monument	In a conservation-area district	ZPPAUP*/AVAP**	In a scheduled heritage site	In a listed heritage site
-Straight consent when the building is in line of sight of a historic monument (1) -Development consent needed in line of sight of a historic monument	Development consent needed	Full consent procedure	-Straight consent -Development consent needed for permission to demolish	-Straight consent with consultative input from the local-region Nature, Sites and Landscapes Commission

*ZPPAUP—Conservation Areas for Protected Urban, Architectural and Landscape Heritage

**AVAP—Areas of Heritage Value

2.12.5 Conclusion

The European Union has legislated on improving the energy performance of buildings through the integration of renewable energy sources. The Renewable Energy Directive (2009/28/EC) requires Member States to introduce measures to increase the share of renewables in the construction sector through building regulations and codes of practice. This requirement covers new buildings and existing ones undergoing substantial renovation.

The BPIE (Buildings Performance Institute Europe) has made an accurate analysis of the strategies and objectives set by the different Member States. It found differences among Member States in both strategies and objectives. Some Member States are relying on collaboration or incentives or standards. Most EU Member States have introduced specific conformity requirements for various parts of building exteriors and technical systems.

For new building, in order to meet the objectives, set in the European Directives, EU Member States have drawn up **results-based requirements** based on general indicators of overall habitat performance (overall heating regulations), and **means-based requirements** based on different items or systems composing the building or involved in its running (itemised heating regulations).

Only two regulations concerning solar heating were introduced: in Israel in 1980 and two decades passed in Barcelona (Spain). But, all new buildings and those that are to undergo major renovation should be covered by solar regulations. In these cases, the advantages are obvious, and the extra cost due to the regulations would be minimised. Various obstacles – administrative (use of roofs in protected areas and buildings), economic (cost of solar heating systems) and social (aesthetic acceptability) – hinder the political decision-making needed to impel the implementation of drastic regulations for solar heating.

We are convinced that integration of solar heating systems in buildings may offer a solution for speeding up and massifying their adoption.

REFERENCES

COM, 2011a. European Commission 112 final. "A Roadmap for moving to a competitive low carbon economy in 2050". Available at:

http://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:52011DC0112:EN:NOT

COM, 2011b. European Commission 885 final. "Energy Roadmap 2050". Available at: http://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:52011DC0885:EN:NOT

ENERGY PERFORMANCE OF BUILDINGS DIRECTIVE- EPBD, 2002. Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings. Available at:

http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2003:001:0065:0065

ENERGY EFFICIENCY DIRECTIVE, 2012. Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC Text with EEA relevance. Available at:

http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:315:0001:0056

ENERGY END-USE EFFICIENCY AND ENERGY SERVICES DIRECTIVE, 2006. Directive 2006/32/EC of the European Parliament and of the Council of 5 April 2006 on energy end-use efficiency and energy services and repealing Council Directive 93/76/EEC. Available at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32006L0032

ENERGY END-USE EFFICIENCY AND ENERGY SERVICES DIRECTIVE, 2004. Directive 2004/8/EC of the European Parliament and of the Council of 11 February 2004 on the promotion of cogeneration based on a useful heat demand in the internal energy market and amending Directive 92/42/EEC. Available at ;

http://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX:32004L0008

ENERGY PERFORMANCE OF BUILDINGS DIRECTIVE –EPBD (recast), 2010. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast). Available at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:153:0013:0035

REGLEMENT DELEGUE (UE) no 244/2012 de la Commission du 16 janvier 2012 complétant la directive 2010/31/UE du Parlement européen et du Conseil sur la performance énergétique des bâtiments en établissant un cadre méthodologique comparatif de calcul des niveaux optimaux en fonction des coûts des exigences minimales en matière de performance énergétique des bâtiments et éléments de bâtiment (JO L 81 du 21.3.2012, p. 10-36)

RAPPORT de la Commission au Parlement européen et au Conseil «Soutien financier en faveur de l'efficacité énergétique dans les bâtiments» [COM (2013) 225 final du 18 avril 2013] Available at:

http://www.europarl.europa.eu/RegData/docs_autres_institutions/commission_europeenne/com/2013/0225/COM_COM(2013)0225_FR.pdf

RAPPORT de la Commission au Parlement européen et au Conseil «Progrès réalisés par les États membres vers des bâtiments dont la consommation d'énergie est quasi nulle» [COM (2013) 483 final/2 du 28 juin 2013]

Available at: http://eur-lex.europa.eu/legal-content/FR/TXT/?uri=URISERV:en0021

BPIE_A, 2013. A guide to developing strategies for building energy renovation. Available at: http://www.bpie.eu/documents/BPIE/Developing_Building_Renovation_Strategies.pdf

BPIE_B, 2013. Boosting building renovation. An overview of good practices Renovation requirements, long-term plans and support programmes in the EU and other selected regions

Available at: http://www.scpclearinghouse.org/upload/publication_and_tool/file/386.pdf

NEEAP_FR, 2011. “France’s Second National Energy Efficiency Action Plan (NEEAP-2).”

SRCAE, 2013 “Schéma Régional Climat, Air, Energie”, Available at:

http://www.corse.developpement-durable.gouv.fr/schema-regional-climat-air-energie-a352.html

DIRECTIVE 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC, Available at: http://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX:32009L0028

EUROPEAN SOLAR THERMAL INDUSTRY FEDERATION (ESTIF) Best practice regulations for solar thermal Project “Key issues for Renewable Heat in Europe” (K4RES-H), EIE/04/240/S07.38607 23/08/2007

Hagemann I.B. Gebäudeintegrierte Photovoltaik. 2002.

Reijenga T., What do architects need?, Switzerland, IEA-PVPS 7-03:2000, 2000.

MDD-2012. Ministère du Développement durable. http://www.developpement durable.gouv.fr/.

French Law 1913 - Loi du 31 Décembre 1913, loi sur les monuments historiques.

French Law 1930 - Loi du 2 mai 1930, Règlementation parcs et jardins, espaces naturels, terroirs marqués par l’homme.

MFC 2010. Ministère Français de la Culture, 04-patrimoine-architecture-2010.pdf (Objet application/pdf), 2010. http://www2.culture.gouv.fr/culture/deps/chiffres-cles2010/04-patrimoine-architecture-2010.pdf.

Pref HR -Préfecture du Haut-Rhin, Guide pour l'installation de panneaux solaires thermiques ou photovoltaïques dans le Haut-Rhin. Préfet du Haut-Rhin.

MEETL, 2012 - Ministère de l'écologie, de l'environnement, du transport et du logement, Politique énergétique - Ministère du Développement durable, 2012. http://www.developpement-durable.gouv.fr/Politique-energetique.html.