COST Action TU1205 (BISTS)

Building Integration of Solar Thermal Systems

State of the art on Building Integrated Solar Thermal Systems

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1 Introduction

The Renewable Energy Framework Directive sets a target of 20% for renewables by 2020. Buildings account for 40% of the total primary energy requirements in the EU and are responsible for 30% of greenhouse gas emissions. Therefore, developing effective energy alternatives for buildings is imperative. Energy in buildings is used primarily for heating and cooling and for the provision of hot water. One way to reduce the dependence on fossil fuels is by the use of renewable energy sources and systems. The benefits of solar thermal systems are well known but one area of concern has been their integration. Most solar collecting components are mounted on building roofs with no attempt to incorporate them into the building envelope. In many instances they are actually seen as a foreign element of the building. Many architects, irrespective of the potential benefits, object to this use of renewable energy systems (RES) due to this fact alone. It is therefore necessary to develop techniques that better integrate solar collectors within the building envelope and/or structures which should be done in a way that blends into the aesthetic appearance and form of the building architecture in the most cost effective way.

The Energy Performance of Buildings Directive (EPBD) requires that RES are actively promoted in offsetting conventional fossil fuel use in buildings. A better appreciation of solar thermal system (STS) integration will directly support this objective, leading to an increased uptake in the application of renewables in buildings. This uptake of RES in buildings is expected to rise dramatically in the next few years. This is further augmented by a recast of the Directive which specifies that the buildings in the EU should be nearly zero energy consumption (residential and commercial buildings by the year 2020 and public buildings by 2018, respectively). Meeting building thermal loads will be primarily achieved through an extensive use of renewables, following standard building energy saving measures, such as good insulation or advanced glazing systems. Solar thermal systems are expected to take a leading role in providing the thermal energy needs, as they can contribute directly to the building heating, cooling and domestic hot water requirements.

A solar thermal system (STS) is considered to be building integrated, if a component (in most cases the collector) is a prerequisite for the integrity of the building's functionality. If the building integrated STS is dismounted, dismounting includes or affects the adjacent building component which will have to be replaced partly or totally by a conventional/appropriate building component. This applies mostly to the case of structurally bonded modules but applies as well to other cases, such as replacing with BISTS one of the walls in a double wall façade.

The scope of this document is to present a review of current STS state of the art technological developments published in the area and the most suitable options for building integration RES applications. The aim of the document is to determine the work carried out in the area of building integration of STS. This will allow us to understand how this integration is applied so far, which will help to identify new ways that this integration will be investigated subsequently. For architects, the application of PV and STC (solar thermal collector) systems in buildings must form part of a holistic approach. A high-quality solar system can provide a substantial part of the building's energy needs if the building has been designed in the right way. Through a holistic approach, integrating these systems does not only mean replacing a conventional building material, but also aesthetically integrating it into the design, which is called architectural integration. The integration then takes over other functions of the building's skin. Mounted on a sloped roof for instance, profile systems mean that PV or STC modules can be part of the watertight skin. A distinction can be made between literal integration of these systems in the building skin as cladding elements or integrated into the roof or as building components like awnings, shading devices etc. (Reijenga, Kaan 2011). The aim of architectural and building integration of these systems into buildings is to reduce the requirement for land and the costs, in addition to aesthetics that is generated by the process. This could be the cost of a support structure and the cost of building elements, such as tiles and cladding elements. It is evident that PV and STC systems integrated into buildings give a more elegant look, and it is more efficient to integrate these systems when constructing the building, rather than mounting them afterwards. For example they may provide a high degree of solar shading for the building itself; this is particularly relevant in warm climates. Usually there are three zones for integrating the systems into buildings. These are the roofs, façades and building components like balcony railings, sunshades and sunscreens (Reijenga, Kaan 2011).

Both PV and STC systems can be incorporated into buildings by either superimposition - where the system is attached over the existing building envelope, or integration - where the system forms a part of the building envelope (Fuentes 2007).

1.1 Abbreviations and Nomenclature:

RES	Renewable energy systems
STC	Solar Thermal Collector
STS	Solar Thermal Systems
PV	Photovoltaic
PVT	Photovoltaic –thermal
BIPV	Building Integrated Photovoltaic
Active solar systems	Solar thermal systems with heat transport via a fluid transport (e.g. air, water) driven by forced convection (pump) (Duffie, Beckman 2008)
Passive solar system	Solar thermal system with heat transport without mechanical energy (e.g. by conduction through wall or be radiation or fluid transport by natural convection) (Duffie, Beckman 2008)
Indirect STS	Solar gains are transferred via an heat exchanger from a primary to a secondary medium (e.g. in many STS a water-glycol fluid is heated by STC, and the heat is transferred via an heat exchanger to potable water for hot water use in taps, showers)
Direct STS	Solar gains from the collector are directly transferred to the medium to be heated (e.g. in solar swimming pool collectors)
BISTS	Building integrated solar thermal system: We consider STS as building integrated, when some components (mainly the solar thermal collector) is an

integral part of the building functionality, not just an added element. This integration may be functional (i.e. thermal insulation, shading, construction stability etc. will be compromised) and/or relates to the appearance (aesthetics, dimensions, shape, colour etc. of the building). Thus building integration considers architectural integration in form and function.

BISTC	Building integrated solar thermal collector
LCI	Life-Cycle Inventory
LCA	Life-Cycle Assessment
EPD	Environmental Product Declaration
FPC	Flat-plate collector
ETC	Evacuated tube collector
LCCA	Life-Cycle Cost Analysis

2 BISTS Classification and Taxonomy

2.1 Classification

Building Integrated Solar Thermal Systems (BISTS) have been classified across a range of operating characteristics and system features and mounting configurations. The main classification criteria of all solar thermal systems (STS) are based on the method of transferring collected solar energy to the application (active or passive), the energy carrier (air, water, water-glycol, oil, electricity etc.) and the final application for the energy collected (hot water and/or space heating, cooling, process heat or mixed applications). Additionally for BISTS the architectural integration quality based on structural, functional and aesthetical variations have to be classified. The collector as a central element of integration has to fulfil in some cases many more specifications than ordinary, add-on collectors. Figure 2.1 illustrates a simple BISTS classification.

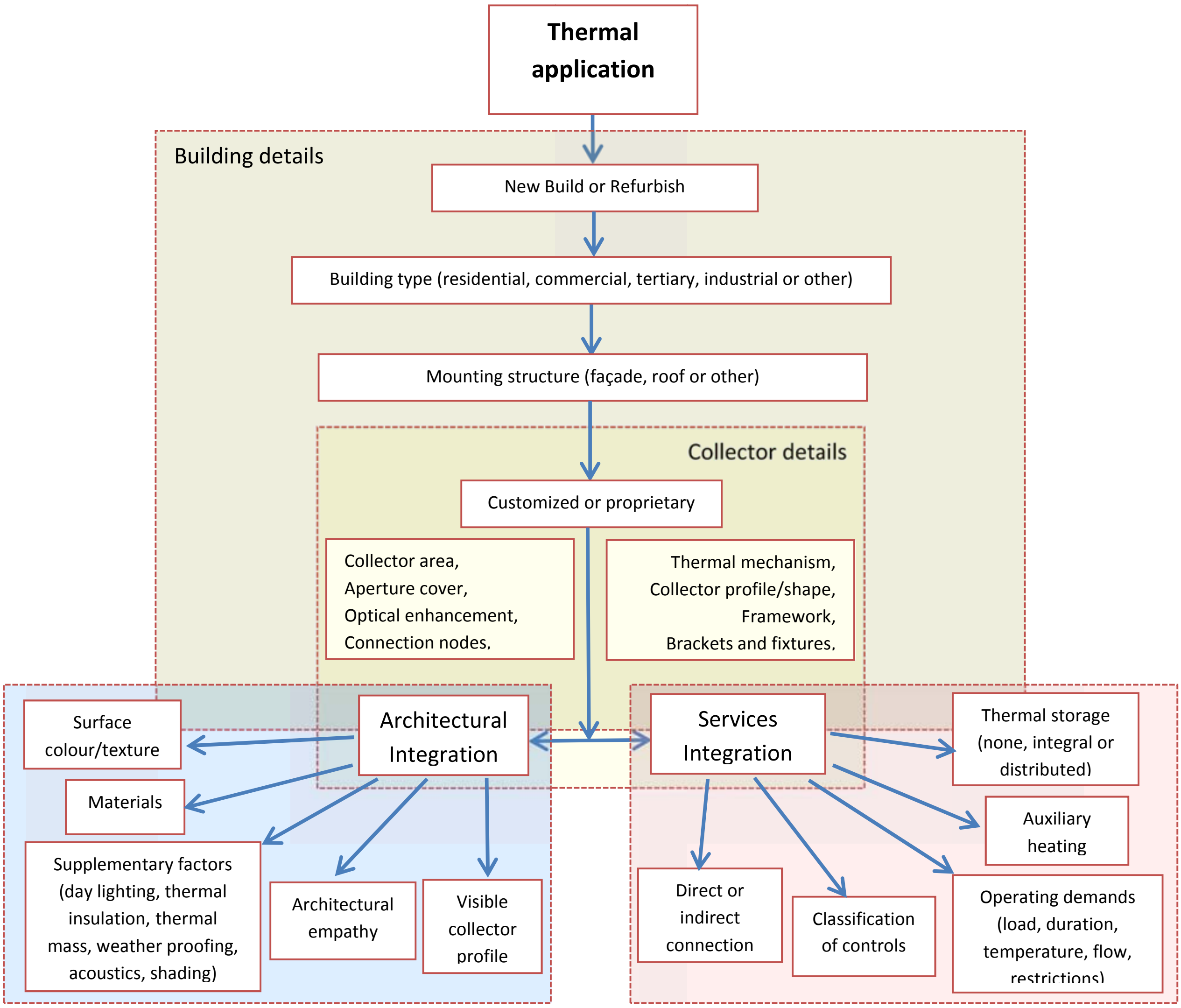


Figure 2.1. BISTS classification

The majority of BISTS can be classified as being either passive or active, e.g. in the first case using thermal buoyancy for fluid transport (natural convection or circulation) or no transport at all, and in the second case utilizing pumps or fans to circulate the thermal transfer fluid to a point of demand or storage (forced convection or circulation). A number of systems are however hybrids, operating in part through a combination of natural and forced transport methods. Many façade solar air heaters use thermal buoyancy to induce an air flow through the vertical cavities that can be further augmented with in-line fans (and heating) if necessary.

2.2 BISTS applications

The BISTS delivers thermal energy to the building but additionally other forms of energy may contribute to the buildings energy balance. For instance daylight comes through a transparent window or façade collector, or PVT systems will also deliver electrical power which may be used directly by any auxiliary electrical services. Heated air or water can be stored or delivered directly to the point of use. Although the range of applications for thermal energy is extensive, all of the evaluated studies demonstrate that the energy is used to provide one or a combination of the following;

2.2.1 Space heating

Thermal energy produced by a 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 via a storage to a heating element) into the building. An example is shown in Figure 2.2.

2.2.2 Air heating & ventilation

Thermal heat may be used also to preheat fresh air needed in the building. Air is heated directly or indirectly (in a secondary circuit) and using forced flow or thermosiphonic action is used to provide space air heating and/or ventilation to the building as shown in Figure 2.3 In some instances, an auxiliary heating system is used to augment the heat input because of comfort reasons.

2.2.3 Water heating

Hot water demand in the building is the most popular application. In the majority of water heating BISTS, a customized heat exchanger or integrated proprietary solar water is used to transfer collected heat to a (forced) heat transfer fluid circuit and on to an intermediate thermal store and/or directly to a DHW application. In most instances, an auxiliary heating system is used to augment the heat input. An example is shown in Figure 2.4.

2.2.4 Cooling & ventilation

In cooling dominated climates buildings most of the time have an excess of thermal energy, and therefore BISTS can also be a technology to extract heat from a building. There are a number of methods described in providing a cooling (and/or ventilation) effect to a building; shading vital building elements, desiccant linings, supplying heat directly to 'sorption' equipment, induced ventilation through a stack effect and reverse operation of solar collecting elements for night-time radiation cooling as illustrated in Figure 2.5.

Figure 2.2. An indirect solar-comb construction BISTS, Dieselweg project, Graz

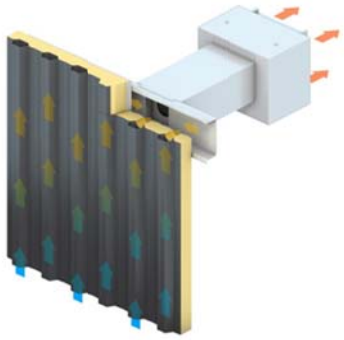


Figure 2.3. Solar air heating façade BISTS with auxiliary heating system

Figure 2.4. Roof integrated flat plate BISTS

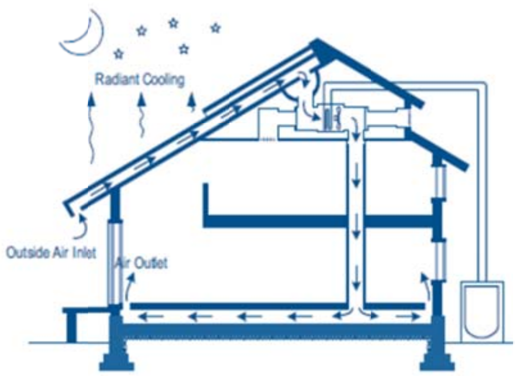


Figure 2.5. Radiant cooling via a reversed BISTS (OM Solar 2014)

The majority of BISTS documented are mounted on the façade or roofing structures, but a significant number can be classified as being 'other'. This embraces a multitude of mounting options, from shading devices to balcony balustrades such as that shown in Figure 2.6.


Figure 2.6. BISTS balustrade/railing feature

2.3 Taxonomy

An additional classification can relate to the mode of installation; new build, refurbishment or retrofit which is often related to the form of the design or components utilized be they proprietary/pre-fabricated or customized. Further sub-section classification can be related to features such as optical enhancements or indirect benefits associated with the BISTS, such as weatherproofing, acoustic attenuation or thermal insulation. A pictorial taxonomy of the wider BISTS family is shown in Figure 2.7.

In this report we restrict ourselves to housing. Industrial process heat systems are not considered.

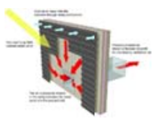
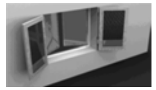
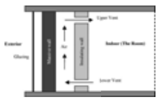
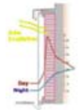
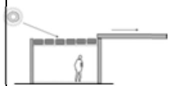
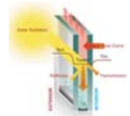
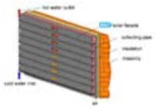
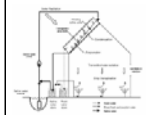
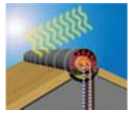
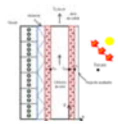
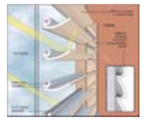
				Installed element					
				Façade		Roof		Other	
				New	Retrofit	New	Retrofit	New	Retrofit
OUTPUT	AIR	Air heating & ventilation	Active						
			Passive						
		Space heating	Active						
			Passive						
	AIR / WATER	Combined air and water heating	Active						
			Passive						
	WATER	Water heating	Active						
			Passive						
		Cooling & ventilation	Active						
			Passive						
	ELECTRICITY	PVT	Active						
			Passive						

Figure 2.7. BISTS Taxonomy

Examples of the range of designs from the taxonomy are outlined in Table A1 with a brief explanation and sources.

3 Solar thermal systems for building applications

In this section the main opportunities for STS will be briefly described with respect to the different applications potentially available in a building. Depending on the level of integration of BISTS these main characteristics can be enhanced by other functionalities and also new possibilities and combinations can be developed.

3.1 Water heating

An important application of BISTS is solar water heating for domestic purposes. The hot water is typically delivered at 50-60°C. The key element for water heating is typically a flat-plate or a vacuum tube collector with water (or water-glycol mixture) as the heat transfer medium (HTF). In some cases however, air collectors can also be used with the hot water produced through an air-water exchanger.

3.1.1 Fluid collectors

The collectors considered in this document are non-concentrating collectors with a stationary mounting. Usually the heat transfer fluid is circulated through the collector. The main components are absorber, transparent cover and possibly opaque insulation.

Flat Plate collectors

The typical construction of a flat plate collector is shown in Figure 3-1consisting of the main elements: absorber plate, fluid manifold (header plus risers), transparent cover, back insulation and casing. These types of collector are stationary, non-concentrating collectors with various absorber profiles and geometries as shown in Figure 3-2. (Kalogirou 2004)

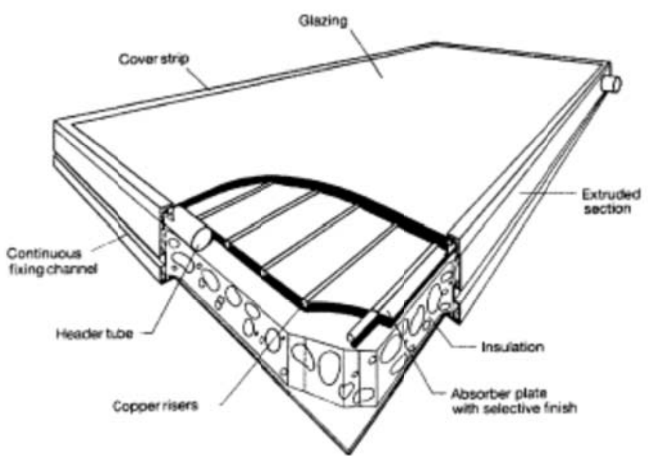


Figure 3-1: Typical Flat Plate collector (Kalogirou 2004)

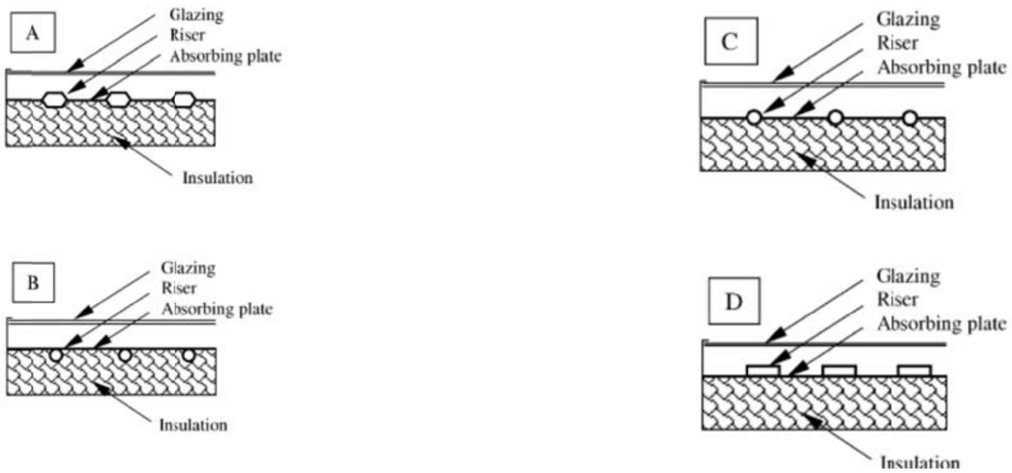


Figure 3-2 : Flat Plate collector absorber profiles and geometries (Kalogirou 2004)

Vacuum tube collectors

Conventional simple flat-plate solar collectors were developed for use in sunny and warm climates. Their benefits however are greatly reduced when conditions become unfavourable during cold, cloudy and windy days. Evacuated heat pipe solar collectors operate differently than other conventional collectors. There are two principle versions: in the first type a heat pipe is the absorber tube inside a sealed glass tube. In the second version there is a direct flow (Figure 3-3) of the HTF through pipes which have to be in good contact to the absorbing surface. The heat pipe collectorshave only one (solid) connection whereas the direct flow variants have inlet and outlet pipes which need to be connected to a header system. Very cheap vacuum tube collectors are based on the all glass Dewar container principle, and the inner glass tube with the absorber coating on the outer surface (in vacuum) is internally filled with water. No pipes are connected to the vacuum tube, but the heated water rises by natural convection and is replaced by colder water, a simple thermosyphon action.

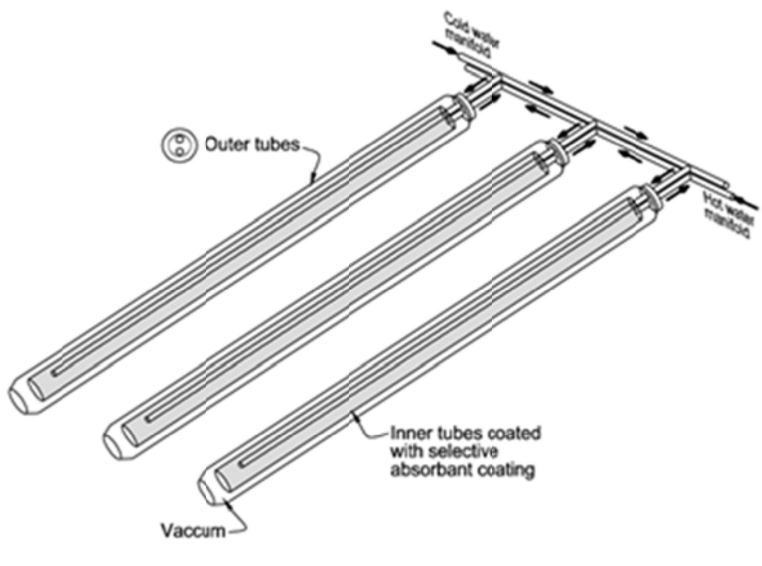


Figure 3-3 : Metal/glass water pipe evacuated tube solar collector

3.1.2 Storage

Most solar hot water systems (SHWS) have some form of thermal storage. The storage in typical systems may contain enough water to supply a 1 to 2 day demand of a household or building. Single-family systems have storage sizes of 150 to 400 litres. There are two main options, either the storage itself contains potable water and therefore should be steel tanks coated with enamel or stainless steel tanks in order to guarantee drinking water quality. Corrosion in ordinary steel tanks or the diffusion of polymer constituents of plastic tanks into potable water would deteriorate the water quality. A second possibility is however to use a simpler and cheaper storage for non-potable water (buffer storage, combi storage), where the heat from the storage is transferred via heat exchanger or contact (tank in tank solution) into the potable water circuit. Solar heat is transferred to the storage or from the storage to a potable water circuit byinternal or external heat exchangers.

3.1.3 System types

The main part of a SWH is the solar collector array that absorbs and converts solar radiation into heat. This heat is then absorbed by a heat transfer fluid (water, non-freezing liquid, or air) that passes through the collector. This heat can then be stored or used directly. Portions of the solar energy system are exposed to the weather conditions, so they must be protected from precipitation and wind, freezing and overheating caused by high insolation levels during periods of low energy demand. In solar water heating systems, potable water can either be heated directly in the collector (direct systems) or indirectly by a heat transfer fluid that is heated in the collector, passes through a heat exchanger to transfer its heat to the domestic or service water (indirect systems). The heat transfer fluid is transported either naturally (passive systems) or by forced circulation (active systems). Natural circulation occurs by natural convection (thermosiphoning), whereas for the forced circulation systems pumps or fans are used. Except for thermosiphon and integrated collector storage (ICS) systems, which need no control, solar domestic and service hot water systems are controlled using differential thermostats. Five types of solar energy systems can be used to heat domestic and service hot water: thermosiphon, ICS, direct circulation, indirect, and air. The first two are termed passive systems as no pumps are employed, whereas the remaining types are termed active systems as pump(s) or fan(s) are employed to circulate the fluid.

Natural circulation systems (Thermosiphon systems)

A natural circulation or thermosiphon system is schematically shown in Figure 3-4. Hot water rises naturally to deliver energy to the top of the high level water storage tank and returns from the bottom of the tank to the solar collector as a cooler inlet fluid.

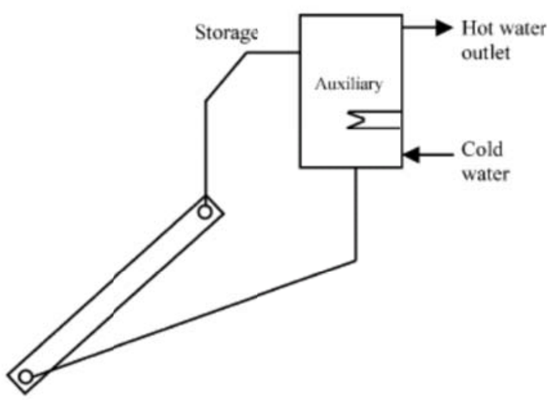


Figure 3-4 : Simple schematic of the thermosiphon system

Integrated Collector Storage systems

In an integrated collector storage system (ICS) ideally a cylindrical storage container (or a mechanically reinforced storage vessel of rectangular shape) is directly coated with an absorbing surface. The storage per collector aperture of 50-100 litres/m^2 is incorporated into the collector which may be optimized for façade or roof integration. Water is directly heated without the need for a pump and control system. As water may not achieve the set temperature, an auxillary heating system (a fast and powerful electrical or gas heater) may be connected to the outlet. When hot water is needed, the storage water has to be instantaneously heated up to service temperature then. Cold water from mains replaces the preheated water in the collector storage vessel. ICS units should be designed to optimise collection during collection periods and reduce unwanted heat loss during non-collection periods. The use of selective coatings, insulation and thermal diodes has been investigated. Transparent insulation materials have also been investigated (Goetzberger, Rommel 1987; Rommel, Wagner 1992)Special attention must also be given to issues related to freezing and negative energy balances

Forced circulations systems

In forced circulation systems a pump controlled by a control device transports the HTF through the collector circuit, whenever the solar resource is good enough to achieve a positive energy balance in the collector.

- Open circulation (Drain-Back)

One variant of the forced circulation system is the open circulation or drain back system ,shown in Figure 3-5. When the system is not operating (e.g. at night time) the fluid flows back into a collection vessel, thereby draining the collectors of the HTF. This allows the use of water as a HTF without freezing protection in cold climate operation. Attention has to be given to corrosion prevention as oxygen may enter the system when the collector field is drained.

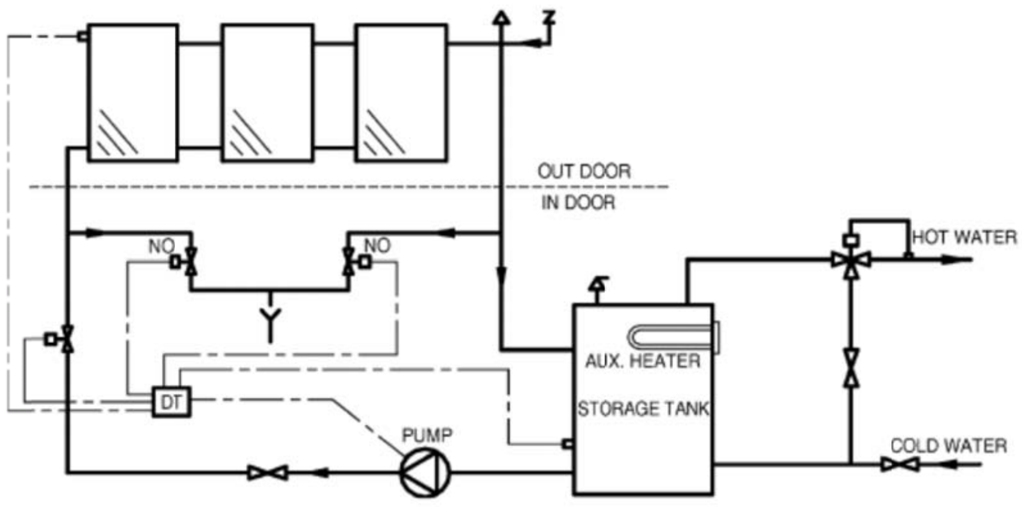


Figure 3-5 : Drain-back system (Kalogirou 2004)

- Closed circulation (Pressurized)

In a closed system the collector circuit is pressurized and therefore the boiling temperature of the fluid is raised. A schematic of the system is shown in Figure 3-6. This allows higher operational temperatures. Oxygen intrusion and corrosion in the closed circuit is much easier to control than in an open circuit. As a consequence the fluid is even in winter and night times in the collector field, and therefore in most cases freeze protection is necessary. For SHWS the consequence is that the system is indirectly heating the potable water via an heat exchanger. The freeze risk depends on the climate where the system is used. Freezing may even be prevalent in locations with a dominating cooling demand , especially in dry climates or high altitude locations.

One option is the use of water-glycol mixtures as fluid, which have a lower freezing point, depending on the glycol concentration (passive freezing protection). Another option is active freezing protection, where circulating water in the collector field is heated by an auxiliary heating or by hot water from the storage in winter time (active freezing protection). The energy balance is critical in such a system and it is therefore predominantly used in combination with vacuum tube collectors with low heat loss. A third option is the drain-down as discussed previously.

A further important issue to be considered is the legionellae problem. These bacteria develop very rapidly in water with temperatures around 30-35°C. Legionellae formation has to be avoided in potable water as occupants may be affected (even when taking a shower) resulting in serious health problems. Regular heating of the stored water for a short period of time (30 mins) above a critical temperature (55-60°C for legionellae) prevents excessive bacteria population growth.

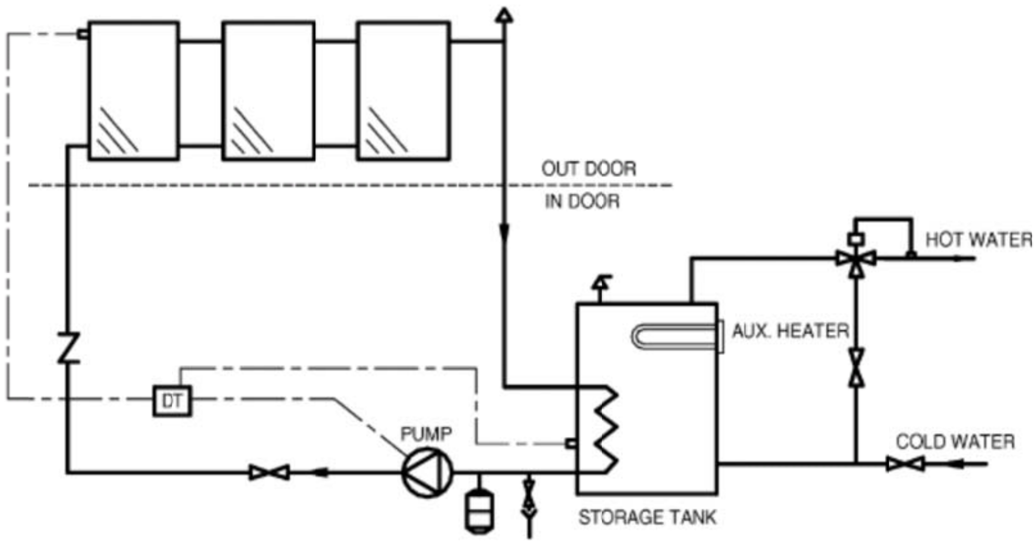


Figure 3-6 : Closed pressurized system (Kalogirou 2004)

3.2 Space Heating

Space heating has a wider range of STS possibilities than SWH. STS for space heating may be active solar systems using water or air as HTF, or they may be passive solar systems like solar collector-storage walls, direct-gain windows, sunspaces (Duffie, Beckman 2008) where solar gains are captured directly by the building structure. The latter variants cannot be switched off as active systems but with the use of solar protection devices, the solar gains can be controlled nevertheless. The problem for STS and space heating applications is the seasonal mismatch between heating season requirement and the maximum output from the solar system. Usually the system output is low during the heating season and therefore seasonal storage may be an option, improving seasonal supply and leading to higher solar fractions (Schmidt et al. 2004).

3.2.1 Solar combi systems

The solar combi system combines hot-water production and space heating in one unit. It is currently one of the most popular concepts in Europe. The collector field is than that needed for hot water production alone. Thermal storage can be provided through the use of a combi-storage unit where a small store for potable water is incorporated in a large tank (tank-in-tank system) or where an internal heat exchanger is used to heat the potable water. Alternatively a separate buffer storage vessel (for non-potable water) with an external heat-exchanger can be used. (Andersen, Furbo 2009).

3.2.2 Air collector systems

Air can be used as a working fluid to transfer collected solar thermal energy . The heated air can be directly utilised for space heating. In pre-heat operation, the outlet air from the solar collectors can be supplemented by auxiliary (heating) air handling units. Alternatively, the collector outlet air can be used to provide heat to other traditional building heating systems (e.g. heat pump, etc.), thereby increasing their operational energy efficiency. Warm air delivered from the solar collectors can be stored directly via a range of by appropriate techniques (greenhouses using thermal storage materials, phase change media, thermal mass in the form of rock storage or building envelope, etc.). Several prototypes have been implemented while many dynamic energy performance simulations (TRNSYS, EnergyPlus, in-house codes, etc.) were carried out for different system configurations. (Alkilani M. et al. 2011).

3.2.3 Solar heating with seasonal storage systems

Although individual building systems are in principle feasible with large internal thermal (water) stores, most seasonal storage systems use a collective centralised approach, as demonstrated in district heating schemes with one large central store. Depending on the local soil and geological conditions, different storage concepts have been employed , from simple concrete water tanks to rock caverns to bore hole thermal energy storage (Schmidt et al. 2004). The solar collectors can be combined in a single large collector field or integrated in smaller arrays onto individual buildings. Sweden, Denmark and Germany have completed a larger number of large demonstration projects, but only in Denmark at the moment the systems seem to be economically viable (Fisch et al. 1998; Lundh, Dalenbäck 2008; Nielsen 2012).

3.2.4 Passive solar systems

The use of passive building elements for heating applications has been extensively investigated in principle by architects and a range of design procedures have been developed (J. Douglas Balcomb 1983; Ochoa, Capeluto 2008; Duffie, Beckman 2008). The use of the building envelope or even the complete house as a collector-storage device is feasible. Passive systems may not be controlled by switching on and off of a pump, i.e. changing the operation mode. However, using shading systems the level of solar gains may be influenced.

Direct gain systems

The most cost effective and widely deployed passive system is the direct-gain window. Solar radiation enters a room and is converted to useful heat by being absorbed by the building structure. Most traditional buildings use windows, however the main motivation is not solar gain but daylight and visual contact with the external environment. These solar gains are therefore normally neglected in statistics relating to renewable energy contributions. Window technology made large improvements in the 21st century, using low-e glazing tailored to the needs of different building types. High-performance framing solutions reduce heat losses over traditional window frames (Platzer 1994b). Larger sizes are possible and in commercial buildings, glazed façades can often replace individual windows. In these situations, direct-gain components (transparent elements) and indirect gain components (opaque and absorbing elements) can be mixed easily.

Solar wall heating

Collector-storage walls have been discussed previously using a single glazing layer as an external cover for many decades (Duffie, Beckman 2008). However the efficiency of the solar wall was limited by the high thermal losses using only single glazing. The search for an improved heat balance led to the development of transparent insulation materials (TIMs) in the 1980's. (Goetzberger 1987; Braun et al. 1992). With a transparent insulation element covering the outside of a massive wall this portion of the building can be converted to a large solar wall heating area. Solar energy is converted to heat at the absorber and conducted with a time delay of some hours - depending on thickness and building material - through the massive wall into the interior. This is the reason why windows and solar wall heating with transparent insulation fit very well together: the direct solar gains can be of use immediately whilst the indirect gains from the solar wall reaches the heated space a number of hours later, thereby extending the passive solar heating period considerably. Suitable wall materials have a high density which is correlated with good conductivity and high thermal capacity. Examples are concrete, limestone and low porosity bricks. Gaseous concrete, high porosity bricks or wooden constructions with a density below 1000 kg/m^3 are not suitable, as the wall cannot store enough heat to be of benefit and is a poor conductor of heat to the interior, resulting in low efficiency, and worse, in high absorber temperatures (above 100°C) leading to thermal stress and eventually deterioration of the transparent insulation materials.

The two principle variants of transparent insulation systems are shown in Figure 3-7. The first is a highly transparent exterior cover (type T for "transparent") where most of the solar radiation is absorbed by the surface of the massive wall behind. The wall should be coated with a dark colour (black, blue, green, dark red). The choice of paint thus influences the performance of the system. The second opaque system (type O for "opaque") utilises an integrated absorber, located at the rear side of the product, similarly in construction to a solar thermal collector. Solar gains are transferred over an air gap (necessary because of building tolerances, to the wall by radiation and convection. The absorber colour cannot be selected freely by the customer for this type (Platzer 1994a; Platzer 2000).

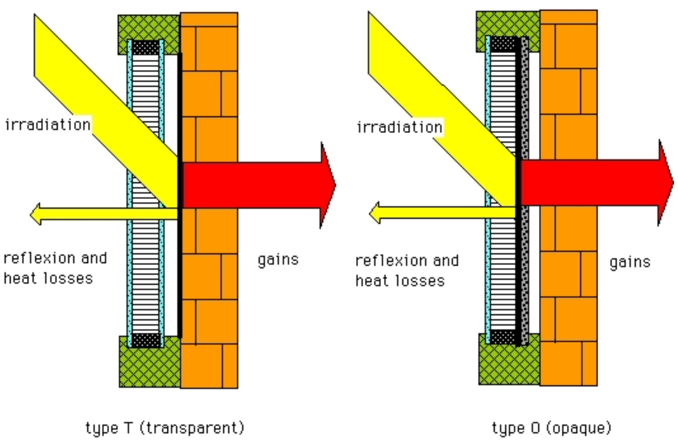


Figure 3-7 : Principle types T and O for solar wall heating with transparent insulation (type O can be vented in summer for effective overheating protection)(Platzer 2000)

Solar insulation

Non-transparent materials such as cardboard structures or mineral wool can be used in wall construction for collecting solar gains, when covered with glazing instead of an opaque element as shown in Figure 3-8. The efficiency of these systems is certainly rather low but the intention is not to convert the wall into a solar collector but rather to use the solar gains to reduce building heat losses towards attaining a zero energy balance over the heating season. The absorbed solar energy is used primarily to raise the average temperature of the outer shell to a value closer to the interior temperature level thus lowering the average temperature gradient over the heating season to nearly zero. There will be no solar heating, but the insulation level will be increased without using excessive material thickness. (gap solution 2014).

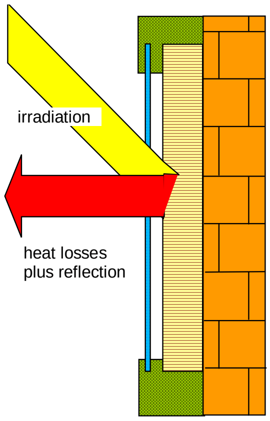


Figure 3-8 : Principle of solar insulation - solar gains and heat losses balance each other over heating season

3.3 Ventilation and cooling

Buildings need a ventilation system in order to provide fresh air for the occupants. It is one of the most important factors for maintaining acceptable indoor air quality in buildings. Indoor air quality is necessary to obtain indoor environmental quality. Indoor air parameters including oxygen, carbon dioxide or moisture content depends on ventilation. Ventilation besides exchanging air to the outside also is associated with air circulation in the building. In many climates it is necessary to heat this ventilating air prior to its supply into the building. This 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 many examples especially for commercial and industrial buildings exist. The systems may be combined with heat recovery heat exchangers to provide additional heat to the fresh air supply stream from the building exhaust air stream. A controlled ventilation system with balanced mass flows in and out is required. There are also system called Solar Wall®, perforated wall is used as an solar absorber. Air flowing through wall is heated while sun operation and can be used in ventilation system. The same system operating at night can be used for cooling.

Conversely, in cooling dominated climates the incoming air must be cooled down in order to achieve comfortable supply conditions. Air conditioning ensures maintenance of constant air parameters as temperature and humidity which defines indoor air quality in buildings. Produced cooled air have to be distributed to an occupied space. Solar thermal cooling using adsorption or absorption chillers in a closed circuit may cool down the incoming air via an air-fluid heat-exchanger (Henning, Döll 2012; Balaras et al. 2007). Flat plate, evacuated tube or concentrating solar collectors may supply driving heat for absorption or adsorption chillers. Absorption chillers require heat supplied with a high temperature (higher than 80°C), in such conditions refrigerator will work with reasonable COP.

Different solar collectors can supply heat with different temperature, for absorption system evacuated tube and concentrating solar collectors are preferred. With temperature higher than 100°C it is possible to use double effect absorption chillers, COP it this case can be higher than 1. Advantage of adsorption chillers is lower required driving heat temperature, that allows to use flat plate solar collectors. Lower temperature influences COP of a refrigerator. Typically COP of adsorption chiller with heat supplied from flat plate solar collector is around 0,5-0,6 (Cameron A., 2006.). An alternative method uses desiccant (and evaporative) cooling (DEC) where incoming air is conditioned (via moisture and temperature control) and solar thermal input is used to provide regeneration of the sorption components (Henning et al. 2001). Disadvantage of DEC systems is water consumption that occurs in system. Required heat temperature in such systems is low and can be easily supplied by flat plate solar collectors.

3.4 Combined thermal-electricity generation - PVT

For Zero Energy Buildings, cost-effective renewable energy systems as well as their energy generating capacities are important concepts. The advantages of PV systems integration in building envelopes are numerous resulting in wider adoption of these technologies in building design and construction, from offsetting building electrical demands, to providing complimentary exterior building material and components solutions. When considering solar thermal systems, the competition for suitable roof or façade area with PV is an issue of much discussion. Therefore PVThermal (PVT) collector solutions can offer an alternative option as they deliver solar thermal heat similar to conventional solar thermal collectors and generate electricity similar to standard PV modules. Careful design is necessary as thermal applications often require higher operational temperatures, whereas the PV module efficiency drops with increasing temperature. Uncovered PVT collectors are therefore particularly interesting in combination with heat pumps, whereas direct production of hot water requires glazed PVT collectors with a somewhat lower efficiency in PV compared to the simple PV modules. Good examples of optimized collector solutions are in development (Dupeyrat et al. 2011a; Dupeyrat et al. 2011b). Figure 3-9 outlines the range and scope of BIPVT parameters of concern for buildings

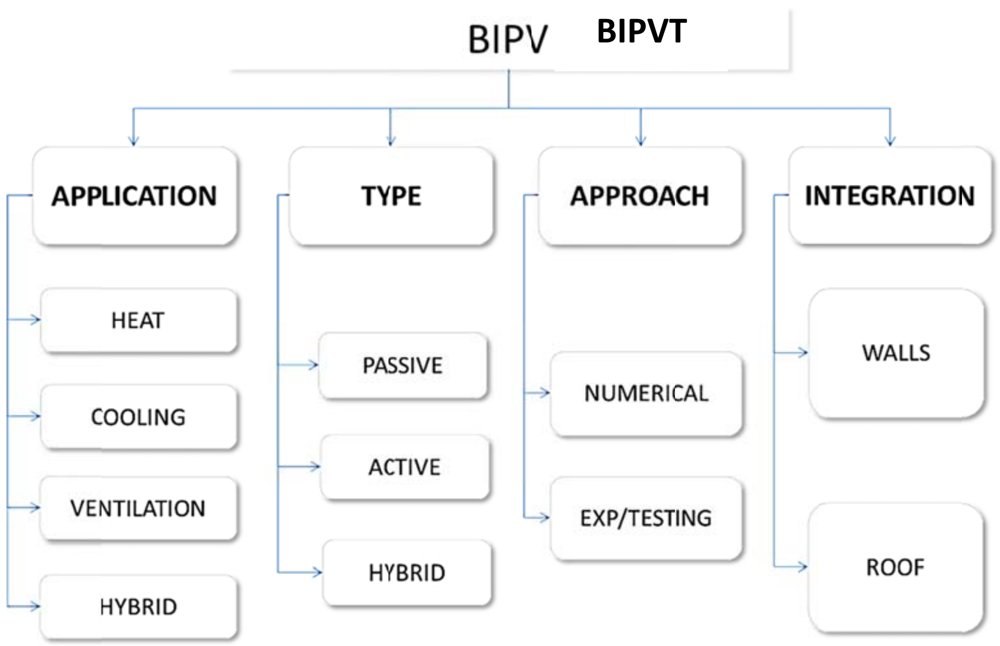


Figure 3-9 : BIPVT – Integration parameter classification

3.4.1 Integration element

Building Integrated Photovoltaic Thermal (BIPVT) systems are designed to displace traditional building components totally or partially, assuring a cross-functional role. For example, a BIPVT skylight is considered to be part of the building envelope, a solar generator of electricity, and a daylighting element. According to a study by NREL (NREL 2001), façade applications typically include vertical curtain walls, inclined curtain walls, and stepped curtain walls whereas roof applications normally include inclined roofs and skylight monitors. A publication by IEA Task 41 (Wall et al. 2012) gives a complex approach about integration solutions of PV(T) as a different building envelope component (tilted roof, flat roof, skylight, façade cladding, façade glazing, external device). The same publication report on two different approaches and definition of PV integration: BAPV(T)-Building Added Photovoltaic (Thermal) systems where photovoltaic modules are most commonly considered just as technical devices added to the building and BIPV(T)-Building Integrated Photovoltaic Thermal, where solar collectors with photovoltaic functionality are integrated into the building envelope as constructive system.

3.4.2 Type

Different types of integration and their respective functions have been studied according to their final application. Approximately 16% of the solar energy incident on a PV panel is converted to electricity, the remaining being absorbed and transformed into heat (Bouzoukas A. 2008)]. This leads to potential overheating problems for BIPVT (Krauter et al. 1999). Common approaches to BIPVT temperature mitigation and thereby useful heat extraction fall into two categories: natural ventilation and active heat recovery (Corbin, Zhai 2010) or forced/mechanical ventilation. Experimental and numerical studies have shown that passive strategies can lower cell temperatures, provide buoyancy driven natural ventilation (Brinkworth et al. 2000; Moshfegh, Sandberg 1998)or serve as solar air collectors for preheating HVAC supply air (Corbin, Zhai 2010). In their study, Corbin and Zhai explore, experimentally and numerically, the effect of active heat recovery by a liquid cooled heat absorber on the performance of a BIPVT collector, and correlations between PV performance and heat recovery. (Krauter et al. 1999)developed a study, where different types of BIPV (passively and actively cooled) have been considered. However, sometimes natural ventilation can be limited by the low rates of heat removal based on the need for low resistance for a buoyancy-driven flow and can suffer a reduced rate of heat transfer from the PV. Forced air ventilation is therefore more efficient owing to better convective and conductive heat transfer, but the required fan power can reduce the net electrical gain (Chow et al. 2008).

3.4.3 Application

The application of BIPVT systems can vary according with the building demands (space heating, DHW heating) or/and with strategies for enhanced module efficiency (cooling, ventilation). Other important issues relate to the choice of circulating fluid under a PV module usually water or air. The choice depends upon the mounting location and its application. The most commonly used fluid is air which can directly cool the modules in a cavity behind the PV which through heat recovery mechanisms can be used for space heating. (Chow et al. 2008) carried out an experimental study of a hybrid BIPV -solar system applied to buildings, using a centralised photovoltaic and solar (hot water) collector wall system. Athienitis et al. (2011) proposed a highly efficient open-loop Unglazed Transpired Collector (UTC) which made use of dark porous cladding through which outdoor air was drawn and heated by absorbed solar radiation. The BIPVT concept was applied to a full scale office building demonstration project in Montreal, Canada, and the ratio of photovoltaic area coverage of the UTC could be selected based on the fresh air heating needs of the building, the amount of the electricity generated and the available building surfaces.

3.4.4 Approach

Experimental and numerical approaches have been used to explore BIPVT integration, design and performances. Sopian et al. (1996) developed a thermal model for a single and double pass hybrid PVT air collector. Garg, Adhikari (1997)modelled hybrid solar air collectors and Hegazy (2000) studied four configurations of hybrid PVT systems and compared their performance. Natural convection inside the air gap of a BIPVT device is however a complex task. Depending on the level of detail and parameters studied, the heat transfer across these systems can be modelled using a simple thermal network model (Chen et al. 2010; Aelenei, Periera 2013; Aelenei et al. 2014) or a more complex CFD model. Moshfegh and Sandberg (1996)have carried out CFD simulations of naturally ventilated PV façades. Yang et al. (1996) developed a numerical model for a naturally ventilated PV roof and façade systems. Brinkworth et al. (2000) conducted research for a naturally ventilated PV units in a roof and included a comparison with experimental results. A model of a PVT air façade was developed in TRNSYS and presented by Bosanac et al. (2003). Kim (2012) also used TRNSYS for modelling air-type building-integrated photovoltaic-thermal systems and TRNSYS was also used by Kalogirou (2001) to model a hybrid PV-thermal solar system. Thevenar (2005) used ESP-r which proved very useful in estimating the electrical and thermal impact of building-integrated photovoltaics. Experimental studies have been associated with almost all the work conducted and published in BIPVT. These studies vary from small scale indoor studies (Agrawal, Tiwari 2010; Athienitis et al. 2005; Jie et al. 2007; Koyunbabaa et al. 2013) to large scale application studies (Athienitis et al. 2011; Gonçalves et al. 2012; Infield et al. 2004).

There are many case study examples of BIPVT systems applied in actual building operation. Eicker and Dalibard (2011) present a PVT system in a Home+ zero energy building in Stuttgart, Germany. The highly insulated passive building uses PCM thermal mass with the PVT collectors to provide heating and cooling for the building. Shahsavar et al. (2011) present the performance of a BIPVT system used for ventilation and electricity production in Kerman, Iran. The BIPVT system is roof integrated and operates in two different modes depending on the season. In summer the ambient air temperature is higher than the indoor temperature and the air exhausted from the ventilation system goes outside through the air channels below the PV panels, thus cooling them down. This results in an increase of the electricity production by 10.1%. In the winter the incoming ventilation air temperature which is lower than indoor temperature, flows in the air channels of the BIPVT system to be preheated before it enters the building. As in the summer, the BIPVT modules are cooled down which increases electrical performance by 7.2%. In addition the BIPVT panels provide 10.2% of the ventilation air heating load.

Eicker et al. (2009) reports on a BIPVT and BIST for ventilation/ cooling / heating and electricity production of the “Pompeu Fabra” Library in Mataro (Spain). TheBIPVT was integrated into the main building façade with building cooling accomplished using adsorption open cycle cooling technology. The cooling process is driven by heat from the solar thermal systems but the regeneration temperatures are not constant. In winter, cold air is preheated in the BIPVT and from BISTS before it goes to the building ventilation system. Heat from the building integrated solar systems covers 93% of the cooling demand. The average coefficient of performance (COP) is 0.5. During winter the net thermal gains are between 68 and 86 kWh/m^2.

Fong et al. (2010) simulated a PVT solar air-conditioning and cooling system for use in an office in subtropical Hong Kong. The simulated system considered the use of a solar desiccant (adsorption) air-conditioning and cooling system. The reported solar fraction of the solar driven chiller was 0.46, and the coefficient of performance for the chiller was 3.57.

An innovative Solar Window concept using a multifunctional wall element has been developed in Lund University, Sweden. The PVT component is on the inside of an anti-reflective (insulated) window with concentrating mobile reflector screens. The Solar Window provides PV electricity and heated water, besides passive space heating and daylighting. Simultaneously, the reflector screens act as sunshades and added internal insulation for the window.

3.5 Linked auxiliary systems

Due to the variable, intermittent nature of solar energy, a significant proportion of BISTS are designed to operate in tandem with some form of auxiliary system. For the most part these are heat generating, but not exclusively as BISTS have been used to augment cooling systems, albeit by the supply of heat. The auxiliary energy component must be capable of supplying 100% of the heat without any assistance from the BISTS to provide heat when the solar energy gain is not sufficient to meet the required energy delivered to the load. In addition, BISTS that have been designed to operate in a passive mode are quite often classified as a hybrid as linking with an auxiliary system generally implies an active mode of supply. The addition of an auxiliary heating (or cooling) provides a level of reliability and flexibility. Whilst the BISTS on occasions can be used to provide 100% of the building space heating or DWH load, more commonly, sometimes in operation with a thermal store, the BISTS is providing a pre-heating role. Auxiliary heating systems are generally fitted downstream of any solar (pre-heat) storage in order to control the variable temperature of the pre-heated fluid from the BISTS. Although BISTS installed with GSHPs have the option of supplying heat directly to ground for seasonal storage. The auxiliary system can then meet the shortfall in energy supply and can increase the supply temperatures if necessary.

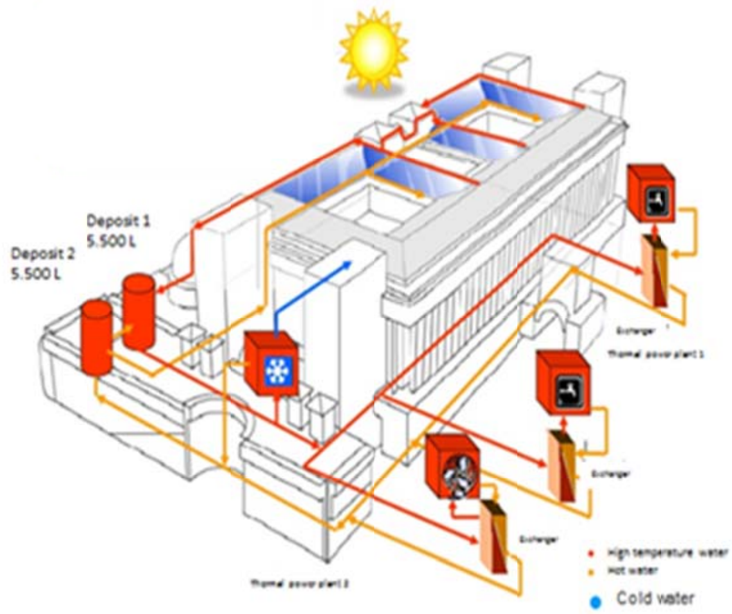


Figure 3-10 : A BISTS for hot water production with centralized storage and heating and cooling (via absorption chiller) (URBAN SOL PLUS 2008)

Figure 3-10 shows a BISTS system for hot water production with a centralized storage and heating and cooling (via absorption chiller) system.

The physical interconnection of the BISTS with any auxiliary system is generally similar to other solar thermal systems. Although given the building envelope and fabric constraints, fittings and fixture maintenance and corresponding access may be slightly more difficult, unless pre-designed to avoid these particular issues. Differences in pipework/ductwork and service components may arise based on proximity, with particular significance to air heating systems. Auxiliary plant or associated plant spaces should therefore be located close to the BISTS to minimize transfer losses (heat and resistance), with care given to the pipe/duct routes. This is a bigger issue for retro-fit BISTS installations, as these placements may already be predetermined or the existing building infrastructure may make it difficult. Another issue for retro-fit BISTS interlinking with an existing heating system may be the system performance at part-load operation. Excluding thermal storage elements, BISTS are connected to a wide range of auxiliary heating systems. In a few examples, a self-contained auxiliary system is provided as part of the supplied BISTS. Figure 3-11 illustrates Kingspan's Sol-Air Collector complete with auxiliary heating system and Figure 3-12 schematically represents an integrated solar heat-pump system with a roof integrated evaporator collector. Most BISTS with an auxiliary system however are connected to stand-alone heating system. Indirect gaseous/liquid fossil fuel combustion burner/boiler configurations (condensing, high efficiency, combination, etc.) and heat pumps are the most common (Figure 3-13) Although biomass burner/boilers have also been used. In some instances, heat supplied from the BISTS has been used to augment a district heating system (Figure 3-14).

Figure 3-11 : Kingspan's Integrated Sol-Air Collector (ISAC) supplied complete with auxiliary heating system) (Kingspan 2014)

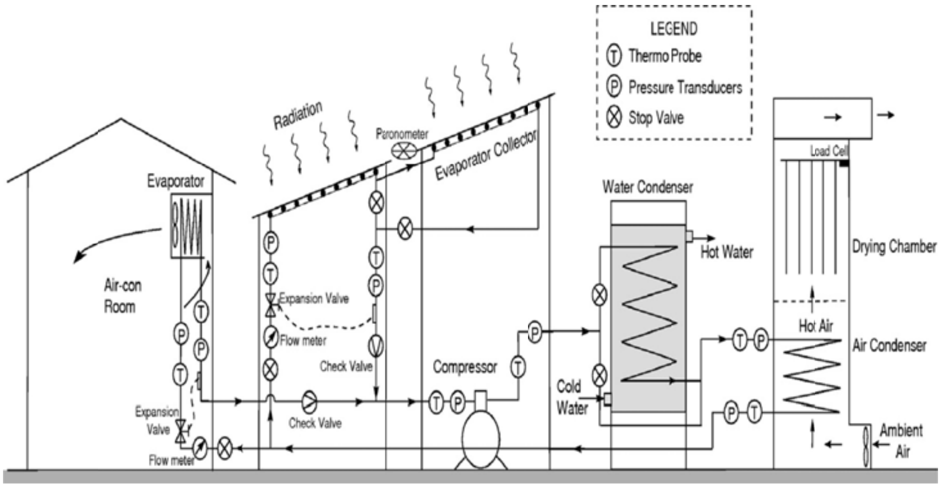


Figure 3-12 : Schematic diagram of a roof integrated (integral) solar heat-pump system (Zakaria, Hawlader 2013)

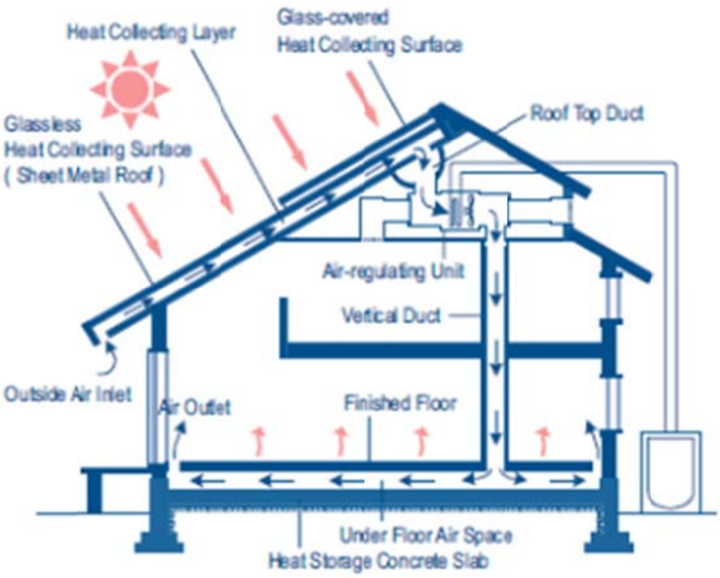


Figure 3-13 : The OM building concept in Japan with BISTS roof and warm air auxiliary heating system (Om Solar 2014)

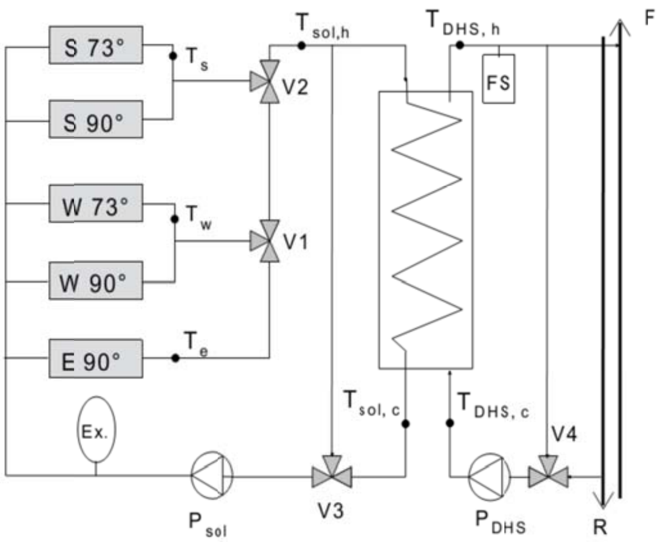


Figure 3-14 : Schematic diagram of the heat exchange interconnection of a multi-surface BISTS supplying a district heating scheme (Gajbert et al. 2005)

In domestic water heating applications, electric auxiliary heating solutions are used quite often and several possible placements for this component are common; the auxiliary heating element is located inside the solar heated tank (a one tank system) or a separate auxiliary-heated tank from the solar-heated tank (two tank arrangement with the auxiliary tank in series or in parallel). Early work conducted by (Gutierrez et al. 1974) on a forced circulation solar water heater investigated three different schemes for supplying auxiliary energy; heater in series, parallel, and in the storage tank. Their study found that the method of supplying auxiliary energy is not a significant variable when the temperature of the hot water delivered to the load is low. At 65°C the auxiliary energy requirements are reduced by 16% by changing the auxiliary heater connection from parallel to series. They concluded that for high temperature operation, the method of adding auxiliary heat should be carefully examined.

4 Architectural integration

4.1 Introduction

The building sector, which accounts for ca. 40% of total final energy consumption in Europe, provides good opportunities for energy savings (Bloem, Atanasiu 2006).The combination of energy efficiency measures and the use of renewable energy sources reduces the consumption of fuels and electricity and thereby reduces emissions of CO_2 and other pollutants.

The optimal use of the solar resource in buildings shows its influence on architectural design and building concepts. New building envelope structures and components are in development. The complex architectural integration of solar components into the building envelope is of critical importance to the appearance, form, aesthetics, investment and operating cost as well as the whole environmental impact within the life cycle of the buildings. From an architectural perspective, different specifications for components may be required such as mounting position, appearance, dimensions, geometrical shape, physical functions, light permeability, colour and construction details. Building integrated solar thermal systems (BISTS) can be used in the construction of new buildings or the refurbishment of existing buildings in order to enhance energy performance. However it is essential that additional functions are fulfilled, uppermost being the proper thermal performance which is strongly influenced by materials, constructional integration and detailing. Once users are informed that BISTS may also improve their quality of life (e.g. thermal comfort, daylight use) and that economically sound projects are possible, there will be no limit to their wide scale adoption (Cristiansen, 2006). The increasing implementation of BISTS may also instigate a transition of the building product industry towards a more open attitude with respect to different building designs, new functionalities and competitiveness of conventional building claddings. The influence of BISTS on the appearance of single buildings and building groups can be significant. However, the correct application of BISTS is not without its challenges for architects and engineers and the wider. It certainly provides a new challenge and focus for the building industry.

4.2 Architectural Integration of Solar Thermal Systems

There are many different aspects and levels of BISTS architectural integration concerning function and form - and the quality of integration differs from case to case. The first level of solar thermal system integration assesses the possibilities of BISTS integration in the given building. A building integration capability called ‘Building Potential’ can be established as a measure to assess the buildings feasibility for solar thermal integration (Krstic-Furundzic et al. 2012b; Golic et al. 2011) The ‘Building Potential’ is defined by an appropriate set of criteria including:

i. The climatic and urban planning criteria.
ii. The characteristics of existing building technology systems and
iii. Architectural criteria

Table 4.1 presents the evaluation system for the ‘building potential’ for integration of solar thermal collectors into the envelope of a dormitory building including clear and precise modelling of criteria (Krstic-Furundzic et al. 2012b)

The criteria groups	The criteria functions	Evaluation system		
		Unfavorable	Medium	Favorable
A. The climatic and urban planning criteria	1. The global solar irradiance on the building location (kWh/m²)	Low – Gh < 1200 kWh/m²	Medium – 1200 ≤ Gh ≥ 1500 kWh/m²	High – Gh > 1500 kWh/m²
	2. The number of favorable (south, south-west or south-east) oriented roof sides	Unfavorable – no roof sides with favorable orientations	Moderately favorable – one roof side has favorable orientation	Favorable – at least 2 roof sides have favorable orientations
	3. The number of favorable (south, south-west or south-east) oriented facade walls	Unfavorable – none facade wall has favorable orientations	Moderately favorable – one facade wall has favorable orientation	Favorable – at least 2 facade walls have favorable orientations
	4. The shading effect on the roof caused by the surroundings	Unfavorable – more than 50% of the favorable oriented roof sides surfaces are shaded	Moderately favorable – less than 50% of the favorable oriented roof sides surfaces are shaded	Favorable – the roof sides favorable oriented are without or almost without shading
	5. The shading effect on the facade walls caused by the surroundings	Unfavorable – all facade walls favorable oriented are shaded	Moderately favorable – the facade walls favorable oriented is less than 50% shaded	Favorable – the facade walls favorable orientated are without or almost without shading effects
B. The characteristics of existing water heating system	6. The average daily hot water consumption (l/day)	≤10,000 l/day	10,000–35,000 l/day	≥35,000 l/day
	7. The utilization of the building during summer time	Irregular utilization	Partially regular utilization	Regular utilization
	8. The fuel type used for existing water heating system	Natural gas	Fuel oil	Electrical energy
	9. The type of existing water heating system	Individual system		Centralized system
	10. The state of the existing water heating system	Good	Medium	Bad
	11. The type of the existing space heating system	Centralized system – city heating station		Separate system – fuel oil based system
C. The architectural criteria	12. The spatial and architectural organization of the dormitory (dispositions and distances of the existing heating system facilities and spaces requiring hot water)	Unfavorable	Moderately favorable	Favorable
	13. The applicability of STCs on the roofs surfaces and ratio between daily hot water consumption and favorable roof surfaces for STCs integration, C_R ratio (l/m²)	Unfavorable – C_R ≤ 30 l/m²	Moderately favorable – 30 l/m² ≤ C_R ≤ 70 l/m²	Favorable – C_R ≥ 70 l/m²
	14. The applicability of STCs on the facade walls surfaces and ratio between daily hot water consumption and favorable area of facades walls for STCs integration, C_F ratio (l/m²)	Unfavorable – C_F ≤ 30 l/m²	Moderately favorable – 30 l/m² ≤ C_R ≤ 70 l/m²	Favorable – C_R ≥ 70 l/m²
	15. The easiness of STCs mounting on the roof construction	Unfavorable	Moderately favorable	Favorable
	16. The easiness of STSs mounting on the facade walls	Unfavorable –special finishing, or a special architectural style not adequate for STCs integration	Moderately favorable – only specially designed solutions can be integrated	Favorable – no constraints
	Estimation of building potential	Unfavorable building potential		Favorable building potential

Table 4.1. Criteria for evaluation of building potential for STC integration (Krstic-Furundzic et al. 2012b)

Note: The given values of the global solar irradiance are defined on the basis of Global irradiation (Gh) in Europe.

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 formal (aesthetic) points of view (Probst et al. 2007).

Vitruvius, architect, engineer and writer at the time of Emperor Augustus (1th century BC), gives in his treaties “De Architectura” (the sole ancient treatise on architecture surviving from classical antiquity) the first known definition of architecture that is still relevant today. Architecture is defined as a coherent whole fulfilling at once functional, constructive and formal requirements (Utilitas, Firmitas, Venustas); If one of these aspects is missing, or is not considered enough, the global architectural quality of the building will be affected (Probst, 2008). Although the functional and constructive requirements for the integration of solar thermal collectors (STC) into façades has already been discussed previously, the formal requirements, fundamental for their acceptability, have not yet been duly explored and remain largely underestimated (Probst et al. 2007).

The design of STC 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). For example, the tilt angle (from 0° to 90°) of STCs has a significant influence on energy production and it has a great influence on the functional and aesthetic aspects of the building as well. Also, 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.

4.2.1 Placement possibilities

From the architectural aspect the placement possibilities of BISTS relate to: climatic conditions, orientation and inclination, position on the building envelope, and shading effects. According to this for the selection of an optimal solution for BISTS placement, the set of criteria, as shown in Table 4.1. have to be considered in the decision-making process (Golic et al. 2011).

Orientation and inclination

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, Konkle D. 2007).

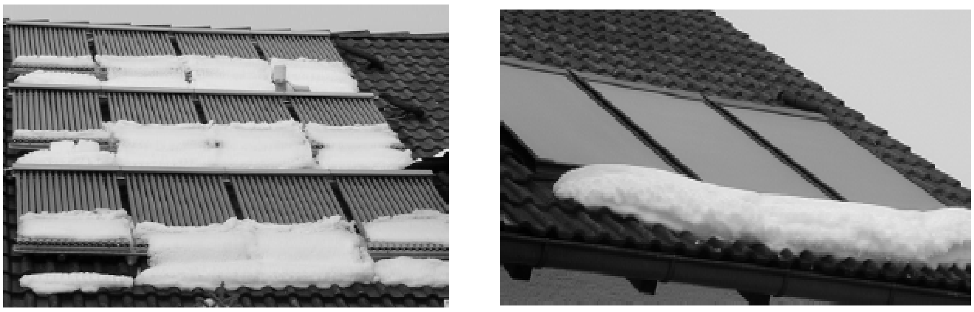


Figure 4.1. Snow shedding of flat plate collectors and the evacuated tubes.

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 neighbourhood 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 4.2. for individual residences in an Ann Arbor settlement, Michigan, USA (Appleyard, Konkle 2007).

Figure 4.2. 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)

Position on the building envelope

The addition of building integrated solar thermal devices 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. In the later case they are independent devices applied on roof or façade structure. In the former, building-integrated solar thermal systems are building components which can be substituted for conventional roof or façade cover materials (Krstic-Furundzic 2007). Development of technologies, materials, support systems and coatings is continuous, giving freedom to architectural design.

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

i. façades – vertical walls, sawtooth wall (vertical or horizontal direction), sloping wall,

ii. roofs – skylights, sawtooth roof, sloping roof,

iii. façade and roof shading devices – horizontal, vertical, tilted,

iv. overhangs – horizontal and sloped,

v. balcony railings – vertical and tilted,

vi. curved/flexible façade and roof surfaces.

BISTS position and geometry (Figure 4.3.) exert influence on integration design and construction solutions and can be applied onto transparent and/or opaque façade 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.

Solar thermal systems can be integrated in single and double skin façades. For single skin façades, they are integrated into a parapet or wall structure as a specific building component, whilst a ventilated double skin façade in itself is already a solar thermal collector (Figure. 4.4.). Design and functional variability of both façade types, as challenges to and obligation of contemporary architectural design, could be achieved by transparent and non-transparent solar thermal collector structures.

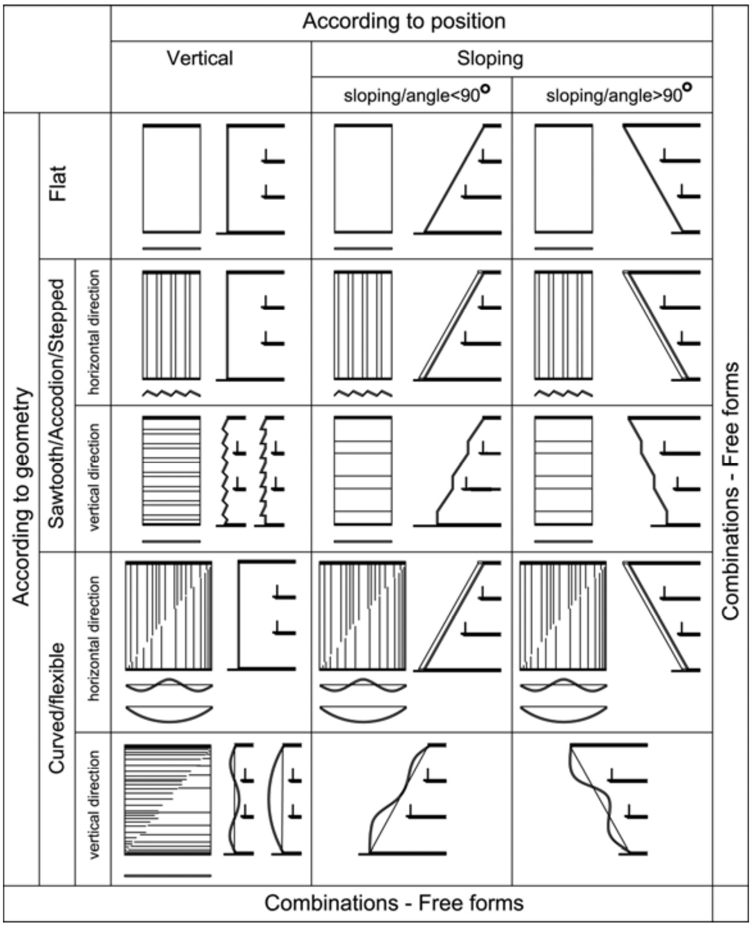


Figure 4.3. Form types of glass façades according to position and geometry of glazing surface (Krstic-Furundzic et al. 2012a).

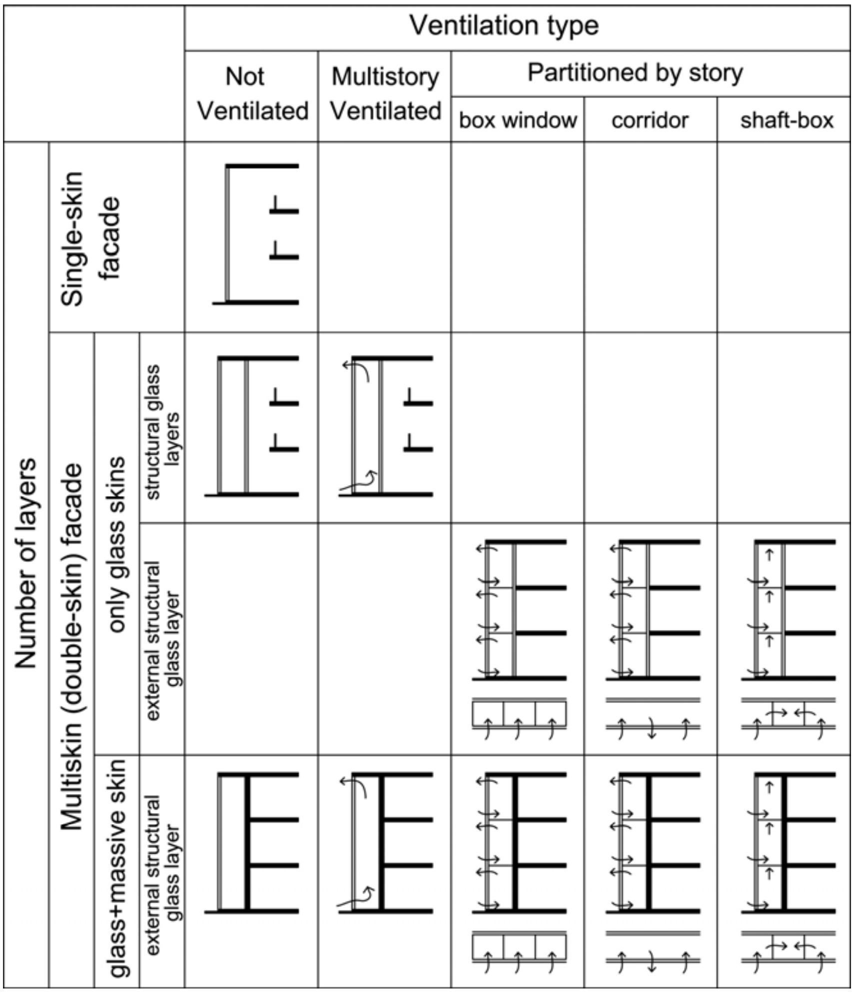


Figure 4.4. Assembly types of glass façades according to number of layers and ventilation type (Krstic-Furundzic et al. 2012a).

The area of building integrated STC depends on building utilization, thermal energy demands and available area of façade 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 4.5.

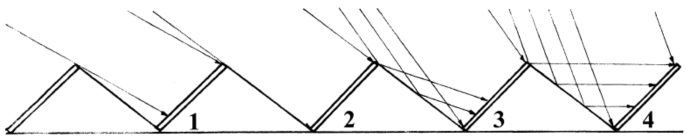


Figure 4.5. Effect of booster reflectors to collectors regarding the direction of solar rays (Tripanagnostopoulos et al. 2000)

4.2.2 Function possibilities

The main function of BISTS is to produce thermal energy. In the case of hybrid systems BIPVT 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
- Ventilation

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).

Clearly the multi-functionality of the collector makes it applicable to integration and can provide the advantage for the designer to use fewer building elements, as the collector fulfils several functions. For example application of building integrated solar thermal façade collectors may remove the need for conventional cladding materials which will be reflected in investment costs. In terms of functions, light permeability 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 4.6).

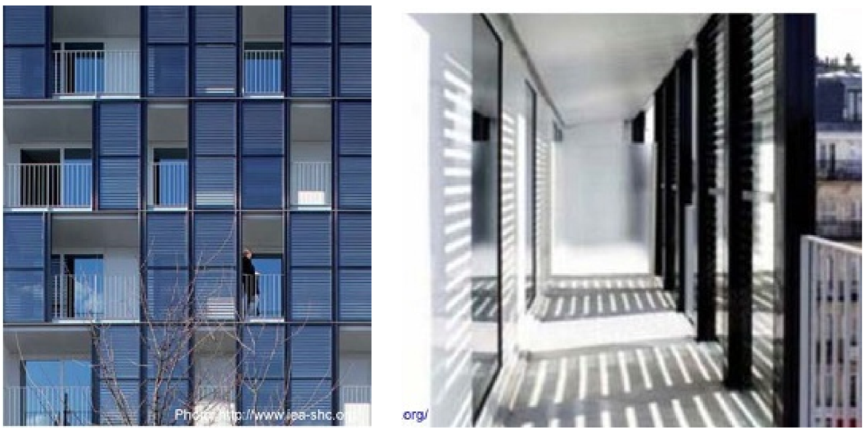


Figure 4.6. Semi-transparent collector encapsulated into a double skin façade, Social housing, Paris, France.

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 4.2).

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)

Table 4.2. Connection between functional and aesthetic aspects (Krstic-Furundzic et al. 2012b)

4.2.3 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).

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, Roecker 2007). For uncovered STC in conventional roof and façade 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.

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 a 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, 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. Advanced plastic material such as polycarbonate sustains itself at high temperatures and retains excellent properties under humid conditions. The twin wall absorber sheet contains a large number of channels filled with ceramic particles. Its thickness is 10cm. The function of the ceramic particles is to 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 water is raised to the top of the collector by means of pump power, while the drain-back to the storage is provided by gravity. A safety mechanism is built-in preventing damages, due to boiling and freezing. 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 4.7).

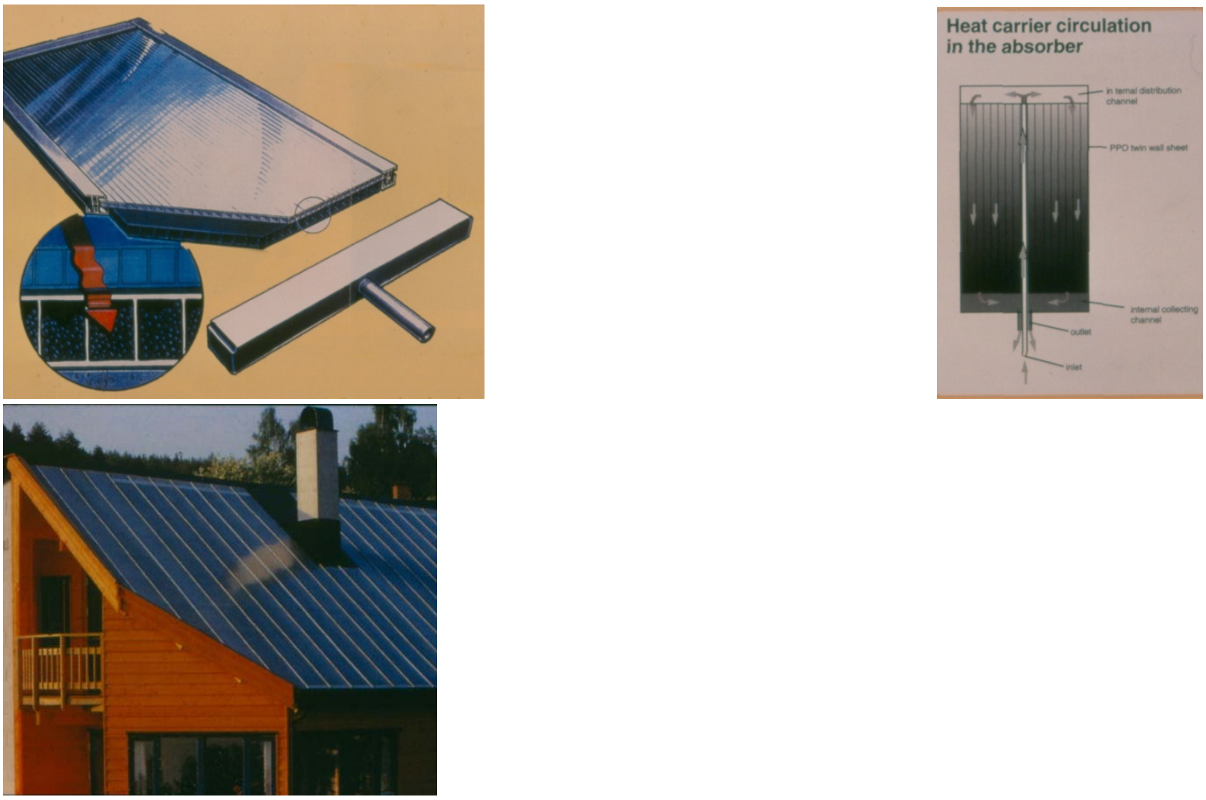


Figure 4.7. Building integrated STC made of polycarbonate twin wall absorber sheet filled with ceramic particles.

Form

Flat collector formats represent the most common form of due to the availability of flat glazing products, but concave and convex shapes are also available and can be necessary as this 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

ii. Curved collectors

iii. Evacuated (vacuum) tubes

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 becomes relevant on the non-solar exposed surfaces of the façade or roof according to the design (Probst et al. 2007). Authors of the paper note: ”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.

Colour and surface texture

The colour of the BISTS collector depends primarily on the absorber colour, but also to some extent on the cover material.

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 (α = 0.85), the coloured collectors give satisfactory results regarding the drop of the amount of collected energy for the three locations (about 7–18%), compared to collectors with black absorbers (α = 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.

Probst (2008) notes that despite an Austrian survey showing that 85% of architects would like to make use of coloured collectors, even with a slightly reduced efficiency, the integrated black collectors are still in the majority. 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).

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, Roecker 2011). In glazed STC systems, a clear glazing above the absorbers can reflect light specularly 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, Guariento 2009).

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 façade 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 façades using flat plate technologies still exists (Probst 2008). Only one manufacturer offers an alternative to the standard rubber jointing mechanisum which uses a continuous, wide, aluminium frame. For evacuated tubes the situation is different since the manufacturer supplying façade modules provides a level of jointing flexibility compatible with the façade application(Probst 2008).

4.2.4 Constructional mounting options

Different construction options are available for integrated STC. There are three mounting options for integrating STC into buildings; roofs, façades and extruding building components (such as balcony railings, sunshades, sunscreens and awnings) (Reijenga, Kaan 2011). Solar collectors should be designed with reference to the normal constraction 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 façade and roof cover (unglazed flat STC)

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.

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). Façade integrated systems include vertical and tilted positions of glazed ST collectors-modules (Figure 4.8). Glazed solar thermal integrated façades are a type of curtain wall. ST collectors-modules can be integrated into most of the contemporary suspended façade systems. Suspended façades (curtain walls) are light structures which are leaned against the building structure and are suspended in front of it (Krstic-Furundzic 2007).


Figure 4.8. Glazed solar thermal integrated façades, appearance of suspended façade (curtain wall).

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 4.9 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. 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 façade designs. Joints can also be hidden, providing a frameless appearance (Krstic-Furundzic 2007).

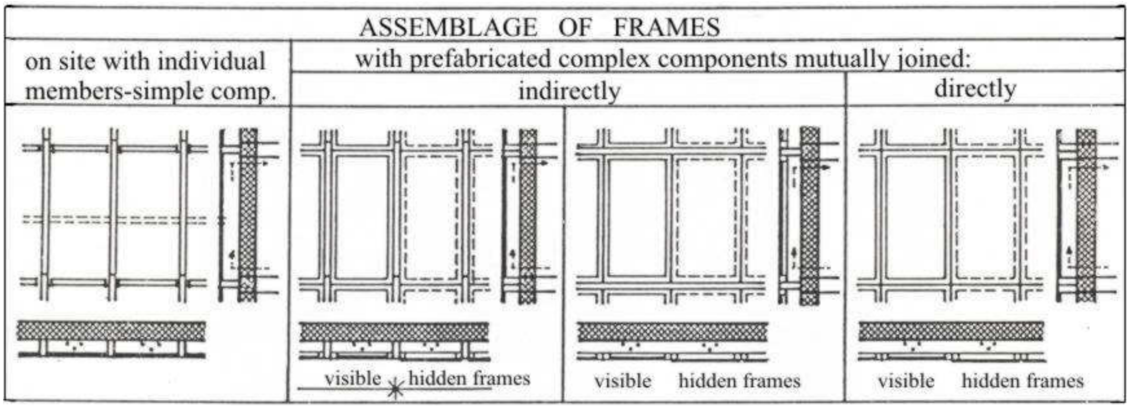


Figure 4.9. Suspended façade assemblage possibilities (Krstic-Furundzic 2007)

Hybrid PVT solar façades 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. Assemblage of multifunctional modules (M-modules) by using curtain wall technologies is acceptable as shown in Figure 4.10.

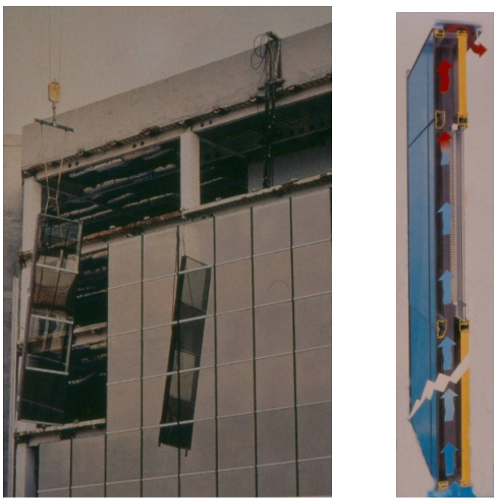


Figure 4.10. Hybrid Photovoltaic/Thermal façade constructed of prefabricated glass modules.

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 case of solid, not transparent, roof concept. Prefabricated solar thermal collectors are preferable for application on roof surfaces (Figure 4.11.). Mounting is easier and less time is needed. Unique in quality of the collector can be achieved in production at the factory.

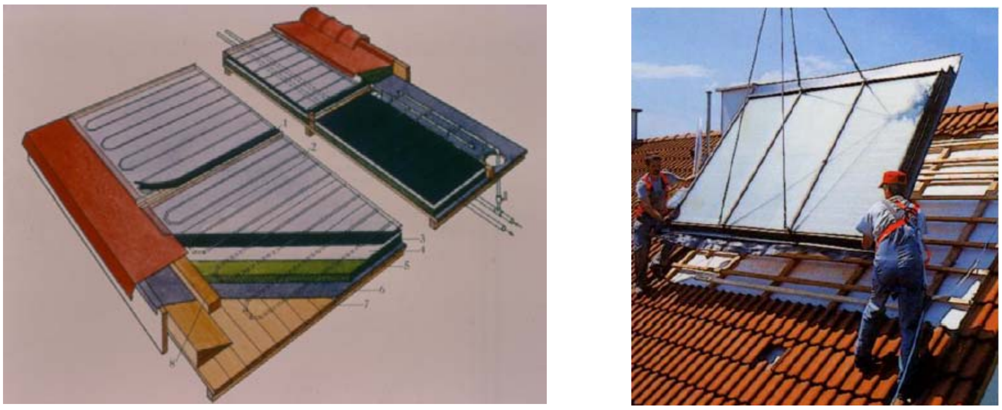


Figure 4.11. Roof integrated solar thermal collectors.

Conventional façade cover (unglazed flat STC)

Contemporary façade cladding technology utilizes façade 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 4.12). 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.

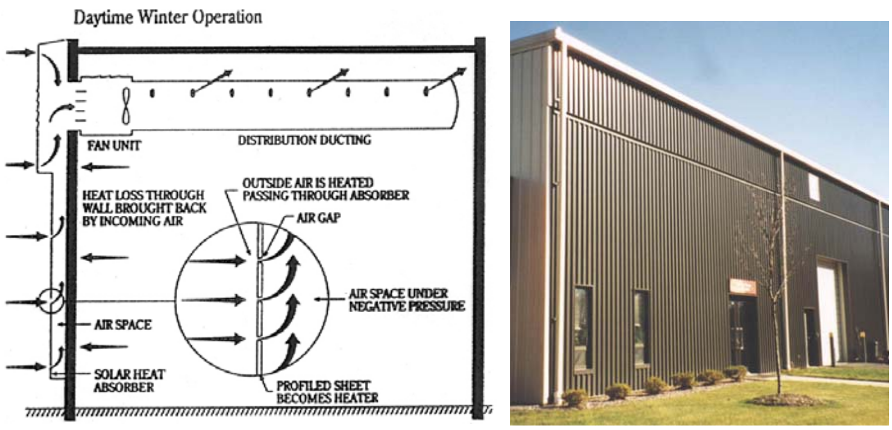


Figure 4.12. Construction as conventional façade cover, (SolarWall 2014)

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 4.13). Preheated fresh air is provided for the building. Usually dark colored roofer becomes the solar absorber. Air picks up heat and rises to the top of the roof by the stack effect, where it is ducted to the nearest fan and distributed into the building. In summer period gap layer is ventilated, the air is exhausted into outer space preventing the roof to be overheated.

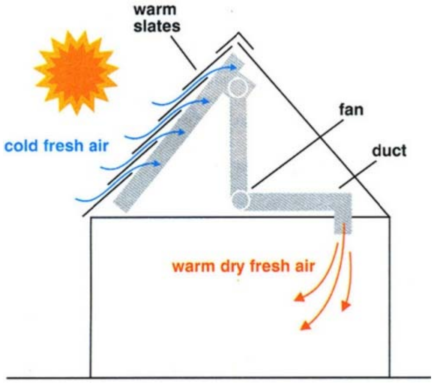


Figure 4.13. Construction as conventional roof cover – unglazed flat STC, Berwickshire, Scotland.

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 4.14):

- 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.

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

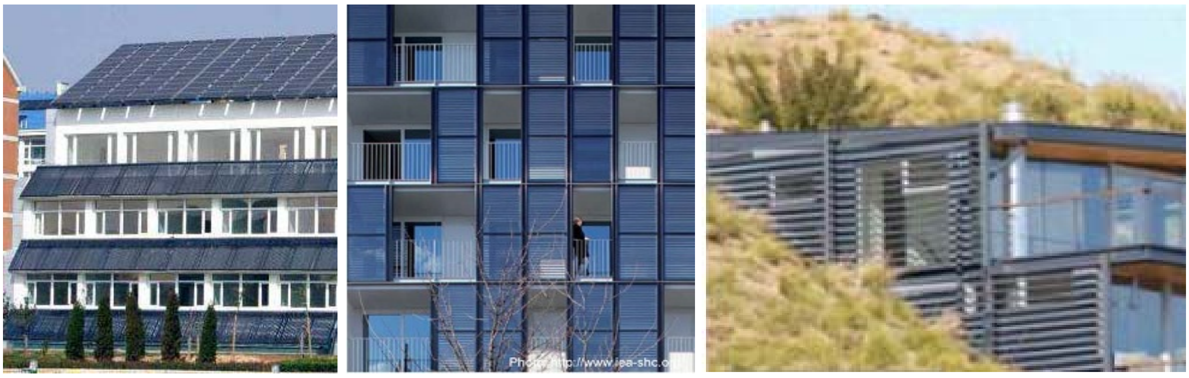


Figure 4.14. Solar thermal collector as shading device

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 15).

Figure 4.15. Solar thermal overhang and balcony railing

5 Building Physics

The building physics of a building envelope is strongly influenced by the type of Building Integrated solar thermal systems (BISTS) selected especially if the STC integration is considered part of the building structure and thereby replacing conventional building components. The STC can be integrated during the construction phase or after the completion of the building. BISTS should generally serve at least one additional function to the building envelope besides providing heat, such as weather proofing, thermal insulation, noise attenuation, daylighting control and shading

5.1 Weather Proofing

BISTS designed for either new and/or existing buildings (where they are a functional part of the wall or roof construction) should undergo the same weather testing as the construction product that they replace. Any STC, whether building integrated or not, should offer weather aging resistance and be tested for exposure to solar radiation, wind and precipitation. Two of the most common threats to the structural integrity and performance of the building enclosure are uncontrolled rainwater penetration and moisture ingress. Wind protection and adequate air tightness of the complete construction must be guaranteed. The resistance of the complete structure including the STC, other building layers, load-bearing structures and profiles should be tested for mechanical strength under wind and snow loads. Every nation, depending on the specific weather, has developed a comprehensive set of regulations and guides for exterior envelope design and construction of buildings as discussed in the literature (Canada Mortgage and Housing Corporation 2014; Dow Corning 2014; Steel Construction Info Acoustics 2014; Buonomano et al. 2013).The building codes give guidelines and criteria to which particular building structure standard can be evaluated. They may either be prescriptive or dictate required specifications. Common standards related to building practices are created through consensus processes by recognized bodies. The International Standards Organization supports the governance of standards and certifications and develops worldwide standards that frequently form the basis of laws, codes or industry regulations worldwide. Each manufacturer produces products that after testing conform to standards, usually offering guidelines in the form of manuals to describe the product in detail and its appropraiate installation and operation (Dow Corning 2014; SolarWall 2014)

5.2 Thermal insulation

Thermal insulation in solar thermal collectors minimises heat loss through the rear and the sides of the collector, improving the solar system performance. Applications of the insulation is shown in Figure 5.1. It is important that insulation remains stable at high temperatures (up to 220°C) and does not produce any emissions of organic compounds that could visibly accumulate on thermal solar collector glazing. Insulation in BISTC is likewise used to minimise heat loss from the collector to improve the solar system performance, whilst simultaneously, the collector may also be used to insulate the building area to which it is adhered or embedded in. Several insulating materials may be used, however the specifications with respect to collector insulation is different than for wall or roof insulation. Thermal and mechanical loads are often different. Also hygrothermic behaviour and diffusion of water vapour through the material and the construction has to be taken into account.

This means that certain insulation materials (e.g. polystyrene foam) cannot be used for BISTC whereas for others (e.g. mineral wool) products being used will be slightly different from the variants used for building insulation only.

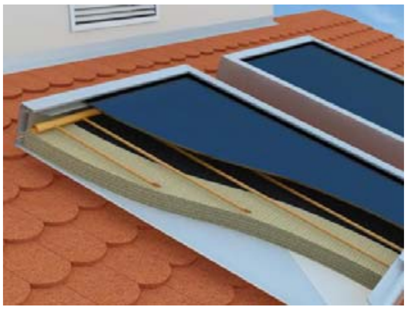


Figure 5.1. Solar panel thermal insulation (Canada Mortgage and Housing Corporation 2014)

5.2.1 Mineral wool

Mineral wool is easy to handle and widely used, open diffusion, incombustible and resistant to rotting and bugs. However for use in solar collectors on has to make sure that the correct product specifications are used. Organic binders are being used in standard products which are working well for building applications where only low temperatures below 60-80°C occur. Solar collectors however may reach much higher stagnation temperatures. Therefore some of these materials have been proved to be unsatisfactory in practice. This becomes noticeable due to condensation of organic material on the inside of the collector cover due to decomposition of the binder.

Alternative materials to mineral wool are Sheep's wool, flax, hemp or similar natural materials which are used in some collector models. These alternative insulations must be subject to very close testing for chemical long-time stability at high temperatures.

5.2.2 Rigid polyurethane foam (PUR/PIR)

Rigid polyurethane foam is generated by a chemical reaction of liquid elements with an additional low-boiling foaming agent like hydrocarbon or CO_2. The source materials (crude oil, but also renewable resources like sugar beets, corn or potatoes) react directly with blending to form a new chemical bond, polyurethane. Without any kind of facing, rigid polyurethane foam is offers long-term heat resistant up to 90°C and short-term heat resistant up to 250°C. Rigid polyurethane foam is non-aging and incombustible. It is resistant to rotting and bugs.

5.2.3 Transparent/Translucent Insulation

Transparent or translucent insulation materials have a long history in scientific development (Platzer 1994a; Stahl et al. 1984; Hollands 1965). They have thermal insulation properties similar to that of mineral wool but permit that 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 (Rommel, Wittwer 1988; Rommel, Wagner 1992) or stagnation prevention devices have to be used to limit the collector temperature- Examples for stagnation prevention are thermotropic layers which turn from transparent to reflective white above a critical temperature, a heat-pipe approach where water is evaporated at the absorber and condensed in a naturally ventilated cooler or a controlled natural ventilation of the absorber.. This is similar as for polymer collectors.

Several principles have been used in order to develop transparent (or translucent) building elements which combine high thermal resistance with solar energy transmission. Figure 5-1 depicts the principles of transparent/translucent insulation materials according to Platzer (Platzer 1994a, 1988).

Transparent insulation parallel to the absorber have been very successful in the development of heat insulation glazing with selective transparent coatings and noble gas fillings is used mainly for fenestration. Transparent/translucent insulation perpendicular to the absorber, such as honeycomb and capillary structures made from plastic (or glass) is produced by various techniques from extrusion to film weaving. The structures reduce infrared and convection heat transport depending on the aspect ratio cell length to cell width. To reduce convection even further closed cells may be used (as in the cavity design), however, reflection losses reduce the solar gains compared with the open absorber-perpendicular structures. Nearly perfect materials can be quasi-homogeneous materials like aerogels with structures smaller than the wavelength of visible light. The structures are invisible, only some remaining scattering reduces solar gains, which can be minimized by further development. These small structures also have the advantage that gas heat conduction losses can also be reduced. The equivalent conductivities including thermal radiation can reach a few Milliwatts per m, well below the conductivity of air. Due to constraints such as mechanical stability, practical applicability and cost, the most commonly used transparent insulation in any real sense are plastic honeycomb and capillary structures products.

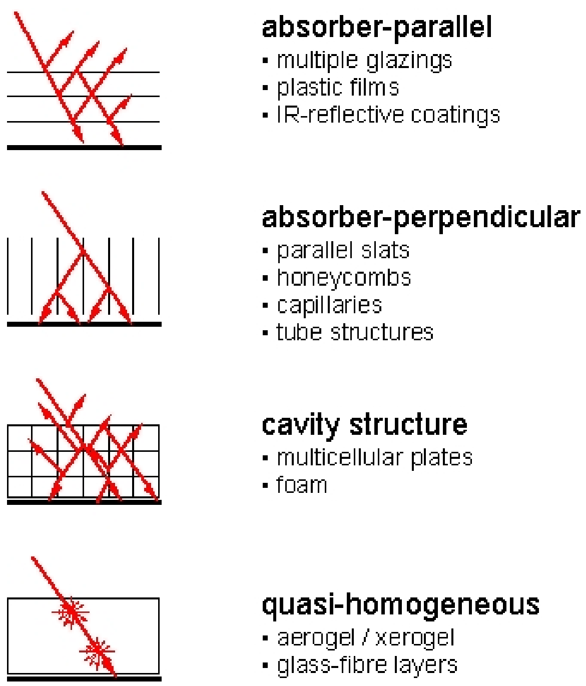


Figure 5-1. Classification of Translucent Insulation Materials (Platzer 1988)

Honeycomb materials are light-guiding and very good convection suppression devices (Charters, Peterson 1972; Hollands et al. 1992). However they need to be at least 30-100mm thick in order to reach reasonable thermal resistance. Aerogel is one of the most fascinating materials because it combines in principle, due to its nanoporous structure, clear vision through the material with thermal conductivity values down to about 40% of mineral wool. This permits to production of extra slim collectors with very low heat losses. Nanoporous opaque powder insulation can also be used in the form of opaque back/side insulation with even lower thermal conductivity values.Honeycomb materials are used as collector thermal insulation by Tigi Ltd. (Tigi Ltd. 2014). Aerogel for use as collector pipe insulation has been developed by Solar Century (Nansulate 2014).

5.2.4 Insulation Thickness

When a solar collector is being built, there is a delicate balance between the thickness of layers, the collector weight and the thermal properties. The goal is to keep all layers effective, but as light and thin as possible. Solar manufacturers must find the balance between performance, constructive restraints and cost. The thickness of the back wall insulation is, in most cases between 40mm and 70mm (Peuser et al. 2013). This alone is not sufficient for thermal insulation in walls of buildings in Northern and Central Europe, but perhaps it may be sufficient in Southern Europe. Apart from increasing the thickness of the insulation with a decreasing effect on the overall U-value, thermal bridging and edge insulation must be considered. A thermally insulating broken edge can prevent a thermal bridge within the façade or roof construction.

5.3 Vapour transport

Glazing acts as external vapour barrier. As long as a sealed collector is installed on a standard wall construction, vapour transmission is no different to that of a regular façade. In general, vapour exits through the wall to the cooler environment of the building. Outer layers are selected that are more open to diffusion in order to avoid destructive interstitial condensation within the wall construction. In the case of absorbers and glazing integrated into the façade system, the direction of vapour transfer can change due to the fact that the outer layer reaches higher temperatures and therefore the temperature gradient is reversed. In this case vapour should be able to exit the wall to the interior of the building. This is why inner layers should be more open to diffusion for integrated systems (Bergmann, Weiss 2002). Other wall constructions with weak vapour barriers were also calculated. For new façade systems, simulations (with Wufi+) are necessary. The results for several fully integrated systems are shown in Figure 5.4. Humidity introduced into the wall during the construction is often neglected in simulations, but drying of the construction has to be assured. The measurements of Bergmann and Weiss (2002) on a wooden and a concrete test façade did not reveal any critical condensation in any layer behind the glazing or the absorber.

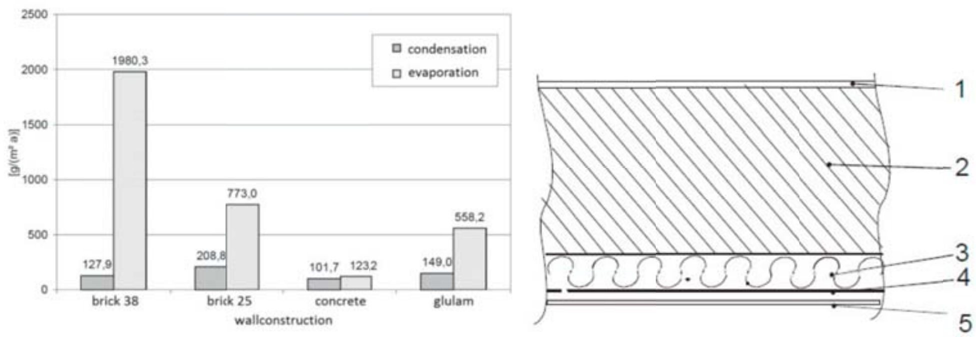


Figure 5-2. (left) Annual condensation and evaporation potential for different wall constructions, (Bergmann, Weiss 2002). (right) Wall constructions: (1): interior plaster, (2): brick 38cm / brick 25cm / concrete, (3): insulation, (4): absorber, (5): glazing (Similar configuration for "glulam" with more wooden layers) source (Bergmann, Weiss 2002).

5.4 Noise attenuation

When BISTS replace building elements they should offer at least the same noise attenuation as the elements they replace. Two important characteristics of sound which humans can detect are the level or loudness and the pitch or frequency. The construction details of the roof, floor, walls and their junctions affect greatly the acoustic performance of a building. Typical sound levels and insulating values are presented in Figure 5.5.

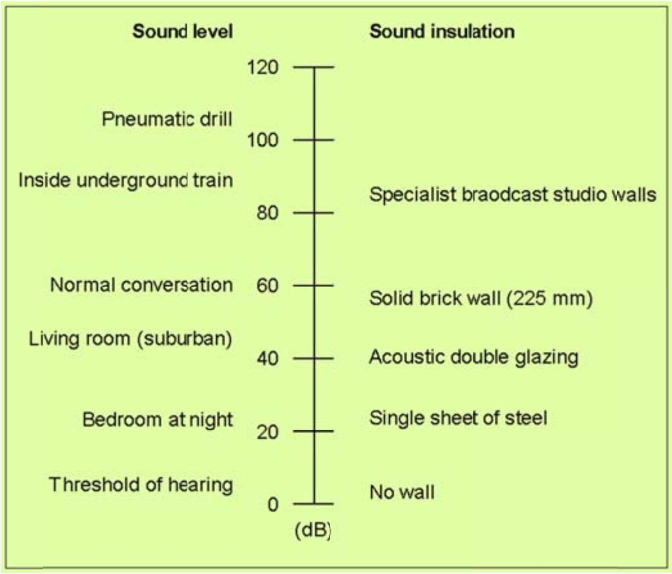


Figure 5.5. Typical sound levels and insulation values (Steel Construction Info Acoustics 2014)

Depending on the method of integration, a number of categories of acoustic performance should be considered as indicated in Figure 5.6.

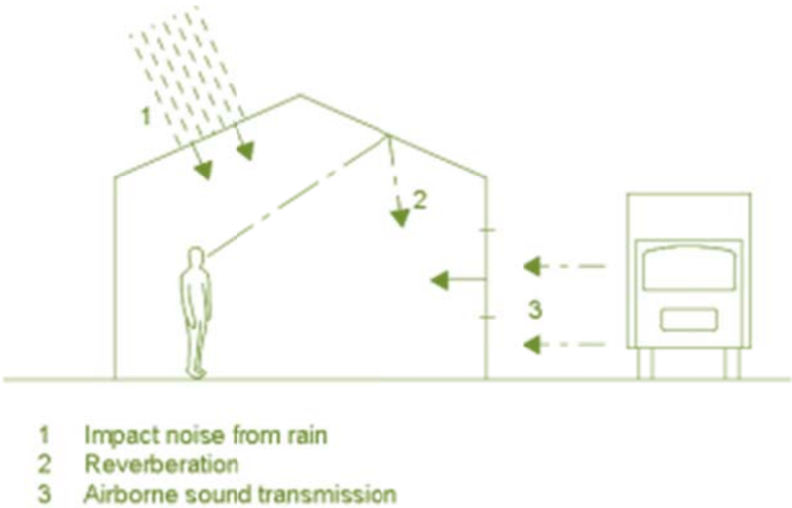


Figure.5.6. Categories of acoustic performance (Steel Construction Info Acoustics 2014)

The noise created by the impact of rain or hail on the roof element may create a nuisance for the occupants. This can be reduced by the use of flexible insulation to act as a damper. Any STC including components (e.g. glazing, absorber, etc) could be optimised by choosing glass thickness and gas filling with respect to noise.

Reverberation may be caused by sound waves reflecting off hard internal surfaces, including elements of the building envelope. This is especially important in double façade constructions where noise can be transmitted from one room to the other. Typically, the internal finishes of the building should be used to limit reverberation, with the use of sound absorbing liners.

Where there is a need to limit the passage of sound through the building envelope, sound reduction through claddings and STC are needed. The acoustic performance of a particular cladding system will depend upon the thermal insulating material, the weather sheet and liner sheet profiles and the method of assembly. Consideration should also be given to attenuating noise originating from services equipment and machinery. Reduction of noise from services is particularly important in industrial buildings where the noise is high.

Sound insulation is controlled by the total mass per unit area of the separating construction the isolation of different layers within the construction and the sealing of gaps particularly at the interfaces and junctions. Detailed standards with regulations and requirements are set for the building envelope in each country which must also be followed by BISTS. These standards differ according to the particular building usage, which may be residential, educational, healthcare, etc. and its intended placement. For England and Wales, acoustic performance requirements are covered under Part E of the Building Regulations 2000 and a means of meeting these requirements is given in(Approved Document E). For general regulations and standards for some EU countries see (European Parliament 7/18/2002; ISO 140-3:1995; Rasmussen 2006, 2010, 2013; Amundsen et al. 2011; Bradley, Birta 2001; Olafsen, Strand 2009).

5.5 Daylighting and solar protection

In general, building integrated solar thermal systems are considered as an obstruction to daylighting, thus serving as potential solar shading devices. This is due to the opaque nature of the absorber element in tubular or flat plate collectors, which require an absorptive opaque surface to function properly. Hence they have always been perceived as a hindrance to the transmission of daylighting into buildings. This is particularly important in the case with buildings that have a user-intensive activity close to the glazed façades, such as school buildings or offices, where daylighting levels may influence the task quality. However it is feasible to design a solar thermal façade with daylighting in many ways, even reducing glare or solar gains inside the buildings. One such method is to combine the absorbing and transparent component parts in a way that when solar radiation is directly incident upon the structure, glare reduction and solar protection can be provided by the opaque absorber whereas diffuse light may be transmitted into the building.

6 Environmental performance and sustainability

6.1 Environmental benefits of using BISTS

Energy use in the European domestic and tertiary sectors represents about 40% of the annual EU total energy use and about a third of greenhouse gas emissions(Koroneos, Nanaki 2012). Among these, about two thirds are related to the residential sector and the remaining part to commercial buildings. The largest proportion of this energy is used for water and space heating. Nowadays and in the context of EU policies (e.g. 2010/31/EU – Nearly Zero-Energy Buildings), the integration of solar systems both in the construction of new buildings and in building refurbishment, is considered a priority in the development of a more sustainable built environment. The greater use of solar thermal systems, particularily 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 (Ardente et al. 2005).

6.2 Environmental sustainability

The environmental sustainability of an installation is related to its materials and components. Certainly, it is desirable that with the adoption of sustainable materials that they can be recycled, reused or replaced in a green manner. In the frame of this concept, Life Cycle Analysis (LCA) or Environmental impact techniques are useful tools for the evaluation of the environmental profile e.g. of a solar installation. LCA and other aspects which are important in the environmental sustainability of Building Integrated (BI) solar systems include Life Cycle Analysis (LCA) and related critical factors. (Bojíc et al. 2014; Battisti, Corrado 2005;Burch, Salasovich 2005; Jang et al. 2008).

6.2.1 Life-cycle inventory and life-cycle impact assessment

The inventory analysis entails the quantification of the material and energy flows for and from a product system. The objective of Life-Cycle Inventory (LCI) is to support the selection of appropriate and accurate datasets for a given Life Cycle Assessment (LCA) case study. Life-cycle inventory information for BISTS is still difficult to find, since most producers do not make this information open to public. Therefore, most LCA studies use generic data and state-of-art shows that one of the sources of information more accepted by the experts in LCA is the Ecoinvent database (Koroneos, Nanaki 2012). The Ecoinvent database includes average data related with the production (i.e. materials, water and energy used during production) and disposal of the several types of solar collectors and other solar systems but excludes auxiliary heating. This database also includes LCI data related with the delivery of heat with a solar system. Although the context of the LCI data for BISTS is Switzerland, it is accepted the use of this data at the European scale. Reasoning for this is that the technological level of the BISTS used all over Europe is identical.

With the work undertaken by CEN/TC 350, the Environmental Products Declarations (EPDs) become an important source of information for the application of LCA methodologies and sustainability assessment of construction works. Therefore, it is expected that in a near future BISTS manufactures make the specific environmental data related with their products public.

6.2.2 Critical issues related with the LCA of the solar thermal systems

From the studies which were previously presented, critical issues related with the life-cycle of solar thermal systems arise: Embodied energy and embodied carbon: Embodied energy is the quantity of energy required to process, and supply to the construction site, a material. In the same concept, the emission of energy-related pollutants (like CO_2), which is a concern in the context of global warming and climate change, may be viewed over their life-cycle. In this way, arises the notion of 'embodied carbon' (Hammond, Jones 2008). Embodied energy and CO_2 emissions are of great interest and most of the studies which were previously presented are based on these issues.

Ecopoints: According to some Life Cycle Impact Assessment (LCIA) methodologies such as EPS 2000, EI99, IMPACT 2002+, the impact of a product is evaluated based on ecopoints. For example the total ecopoints per produced kWh for a solar and a conventional system can be compared by adopting several scenarios e.g. in terms of solar system output under various climatic conditions (Lamnatou, Chemisana 2014). The number of system components is crucial since more complicated systems are expected to have higher initial impact (during manufacturing phase). Thus, new concepts such as nanofluid collectors which eliminate the need for a copper back plate/tubing are proposed from some authors (Otanicar, Golden 2009) as an alternative solution for the reduction of system embodied energy. Usually solar systems have higher initial impact in comparison with conventional systems but on a long-term reference frame (during use/operational phase) this additional impact can be compensated. By comparing the EPBT of a solar with a conventional system after a certain point (during system use phase) the solar system shows lower EPBT than the conventional one and thus, on a long-term basis the solar system is proved to be more environmentally friendly (Lamnatou, Chemisana 2014).

Other critical factors are related with the electricity fuel mix adopted and in general with the source (electricity, natural gas, etc.) which is used e.g. for the calculation of the EPBT of a solar system. For some cases there are considerable differences between the electricity mixes of the countries. The contribution of fossil, nuclear and renewable energy sources on the total electricity mix influences parameters such as the total cumulative energy demand and CO_2 emissions (Dones et al. 2007).

The adoption of several scenarios for example for the output of the solar system (Lamnatou, Chemisana 2014) or for the impact of materials such as aluminium, copper, thermal fluid and galvanized steel (Ardente et al. 2005) is important for the elimination of the uncertainty which is associated with LCA studies. Alternative technologies such as ETC have been proposed (Hang et al. 2012) instead of using flat-plate collectors. However, the feasibility of these systems should be examined in terms of their cost. Moreover, other authors propose solar thermal systems which combine collection area and storage tank in one unit (Smyth et al. 2000)

Alternative materials, for example aerated concrete blocks for Trombe walls (Stazi et al. 2012),is crucial for the reduction of system impact and in general for the improvement of system environmental performance.

6.3 Durability and the payback time of the several types of BISTS

Previous studies show that PV systems (PV), hybrid photovoltaic and thermal system (PVT) and solar thermal collectors (STC) have a very small environmental payback time, compared with the service life of most equipment that is bounded between 15 to 20 years (Kim et al. 2014; Koroneos, Nanaki 2012; Tripanagnostopoulos et al. 2005). Ardente et al. (2005) concluded that the solar thermal collector can have both environmental and costs payback times lower than 2 years. In the case of PVT, Tripanagnostopoulos et al (2005) concluded that the best technology is the PVT with glazing (with or without reflectors) operating at the lowest temperature (25°C). In this case the GWP payback time was around 0.8 years.

The durability of components/materials is important and it is related to their ability to resist wear and tear on the building. The durability is also related with the environmental performance/impact of an installation since more durable components with longer lifetime mean less times of replacement or no replacement over the operational phase. The durability of some building materials can reach 50 years. It should be noted that for some cases the durability of the materials is also related with the climate (Berge 2009).

Recycling is also a crucial factor. By adopting recycling for materials with high impact such as aluminium, copper, steel considerable reduction of the environmental impact of a system can be achieved. Attention is needed for some specific cases e.g. energy recycling of painted products can lead to emissions of toxic pigment vapours (Berge 2009). Another issue is related with materials/components after their use phase is the end of system lifetime. Reuse of materials is interesting especially for materials/components which can be easily dismantled. The adoption of the appropriate disposal scenario (landfill, etc.) is also important. Disposal sites must ensure that there is no seepage of the waste into ground water. The most dangerous materials are those containing heavy metals (and other poisons) as well as plastics that are slow to decompose leading to problems (Berge 2009).

6.4 Health and fire safety issues

All new technologies can introduce new risks and in the building context fire risks are high ranking. However fires involving renewable energy technologies are quite rare (Shipp et al. 2013)). BISTC should be built using inflammable materials, as in fact this is already the case for ordinary STC. Another issue has to do with fire safety. For example borax and boric acid are used as fire retardants in building materials such as insulation made of cellulose fibre. Boron substances are moderately poisonous and in larger concentrations they affect plants and fish in freshwater. Ammonia also is an important element in ammonia phosphates and sulphates which are much used as fire retardants for plant-based insulation materials. Moreover, organophosphates are used primarily as fire retardants in foamed insulation products made with polyurethane and polyisocyanurate (often together with brominated compounds). For plastics, fire retardants such as chloroparaffins and brominated hydrocarbons are used up to 10% by weight (Berge 2009).

In the building sector, many materials are exposed to rain or humidity and their damage is associated with health risk especially when the materials are toxic. For some cases material decay could also increase the danger of fungal growth and other harmful agents while for other cases the decay of the materials is associated with allergies and other negative impacts for human health. There are some materials which have also considerable impact during their production (for some cases, emissions such as benzene, ethyl benzene, styrene, pentane and chlorofluorocarbons are quite likely) (Berge, 2009).

Health risks due to the incubation of systems with bacteria legionellae have been reported. Therefore when designing and using both a STC and a PVT system it is necessary to ensure protection against the proliferation of bacteria. In a solar hot water system, lukewarm water can remain for several days in the storage tank. Understanding both how a solar thermal system operates throughout the year and the temperatures for which the bacteria flourish it is possible to minimize the risks from hazardous bacteria. The *bacterium*, which causes Legionnaires' disease, is widespread in nature, mainly in water, flourishing at temperatures between 32 and 41°C. People often keep the temperature in their hot water tanks set low to prevent scalding and to decrease energy consumption in hot water heating. Nevertheless, guidelines (ASHRAE Guideline 12-2000)) recommend that to destroy the Legionnaires bacteria the temperatures in the hot water tanks should be heated to 60°C at least once a day.

7 Standardisation, Testing and Performance Evaluation

The most relevant standards concerning solar thermal façades are EN 12975 for collectors, EN 12976 for solar thermal systems with non-separable collectors and EN 13830 (curtain walling) for the façade. These standards are independent of each other and a standard for integrated façade collectors, especially without rear ventilation, does not exist yet. National building regulations for glazing or for the façade have to be observed. In the measurements specified by EN 12975 there is only one ambient temperature considered instead of different temperatures at the front and rear of the collector as is the case for integrated flat-plate systems. Customized absorbers or entirely new façade systems can be installed simply on small buildings. For taller buildings (three or more floors), fire safety regulations and further building laws have to be considered. These differ strongly in different regions. Proving that unique, customized installations are safe is considered to be too expensive and construction companies are not willing to guarantee for legal issues in case of damage. By the companies in our survey, this problem was rated more important than the actual construction process. For writing a new appropriate standard, our suggestion is to adjust EN 12975 with different temperatures in front of and behind the collector and to include building directives for construction products (e.g. CPD 89/106/EWG) as well. Homogenous international building directives could strongly contribute to the success of façade integrated systems. (Cappel et al. 2014)

8 Conclusions, Perspectives, Recommendations

Based on the literature about solar thermal LCA studies for buildings, it can be seen that these investigations regard mainly building-added configurations while few of them refer to passive solar walls which could be considered as real BI solar thermal systems. Thereby, there is a need for LCA studies about BI solar thermal systems since at future prospect these systems are expected to gain great interest in the building sector, providing several benefits in comparison with the traditional building-added configurations.

Usually the solar systems have higher initial impact in comparison with the conventional ones but on a long-term reference frame (during operational phase) this additional impact can be compensated. Thus, it is important to evaluate a solar system, and/or to compare it with a conventional configuration, on a long-term basis. However, it should be noted that future systems with fewer components and better building-integration characteristics (in comparison with the traditional solar thermal systems) could result in considerable reduction of the initial impact of the BI solar installations.

Since parameters such as solar radiation and electricity mix play an important role during the evaluation of the environmental profile of a solar system, the solar systems (solar thermal, etc.) show better environmental performance in countries with high solar radiation and electricity mixes with high impact. In the literature, most of the LCA studies about solar thermal systems for buildings are for warm climates. Nevertheless, this type of systems should be also evaluated under cold climatic conditions and for the case of countries with less solar radiation than the Mediterranean region.

On the other hand, it can be observed that most of the LCA works about solar thermal systems for buildings adopt embodied energy and CO_2 emissions for the evaluation of the systems. Thereby, from LCIA methodologies point of view, there is a need for further investigations based on methodologies such as EI99 and EPS 2002+. In this way, the studied systems can be examined based on their total ecopoints (e.g. with functional unit 1 produced kWh) on an endpoint or on a combined midpoint/endpoint approach.

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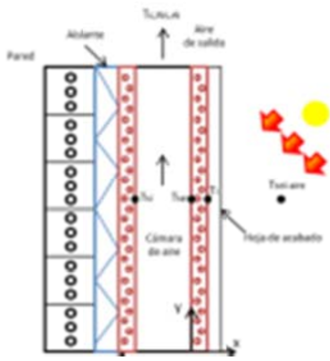
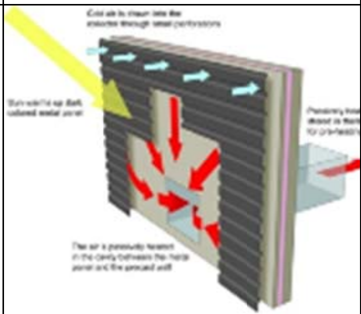
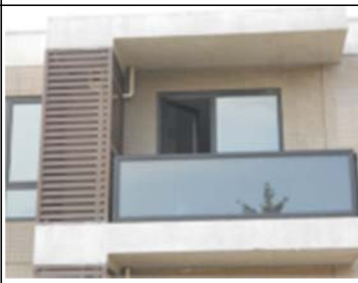
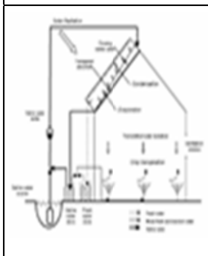
APPENDIX A

Table A1 BISTS applications and sources

	L. Aelenei, R.Pereira, H. Gonçalves, A.Rocha e Silva, Energy saving potential of a hybrid BIPV-T system integrated with heat storage material, 2nd International Conference on Sustainable Energy Storage, June 19-21, Trinity College Dublin, Ireland.		J.P. Jiménez, F. Fernández, J.M. Cejudo, MODEL OF DESICCANT VENTILATED FAÇADE FOR OUTDOOR AIR CONDITIONING VENTILATION, CLIMAMED VII. Mediterranean Congress of Climatization, Istanbul, 3-4 October, 2013
	Noguchi M, Athienitis A, Delisle V, Ayoub J, Berneche B. Net Zero Energy Homes of the Future: A case study of the ÉcoTerra™ house in Canada. Presented at the Renewable Energy Congress, Glasgow, Scotland, 19-25		http://solarwall.com/media/download_gallery/cases/CanadairBombardier_Y96_SolarWallCaseStudy.pdf
	Chungloo S, Limmeechokchai B. Application of passive cooling systems in the hot and humid climate: The case study of solar chimney and wetted roof in Thailand. Building and Environment 42 (2007) 3341–3351		Yang, Y., Wang, Q., Xiu, D., Zhao, Z. and Q. Sun "A building integrated solar collector: All-ceramic solar collector". Energy and Buildings (2013).62(15-17)
	M.Thameur.Chaibi. Greenhouse Systems with Integrated Water Desalination for Arid Areas Based on solar Energy. Doctoral thesis, Swedish University of Agricultural Sciences, Alnarp, Sweden.		http://daniel-libeskind.com/projects/villa-libeskind-signature-series

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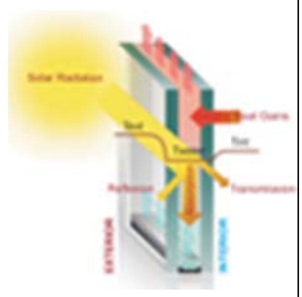
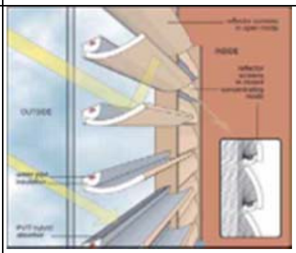
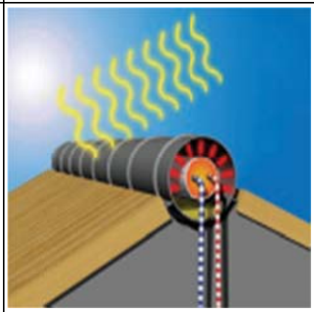
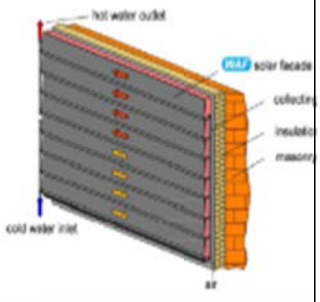
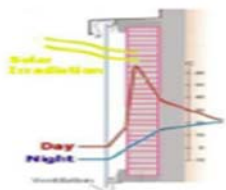
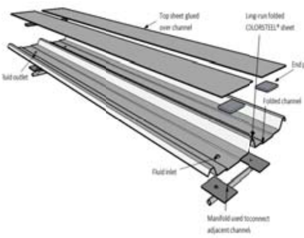
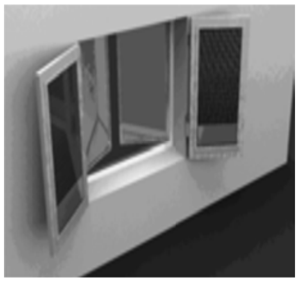
	www.Intelliglass.com		http://www.omsolar.net/en/index.html
	NSAI Agrément. Integra IDMK Flat Plate Integrated Collector NSAI, 1 Swift Square, Northwood, Santry, Dublin 9, Ireland (2010)		A. Fieber, H. Gajbert, H. Håkansson, J. Nilsson, T. Rosencrantz, B. Karlsson, Design, Building integration and performance of a hybrid solar wall element. Proceedings of ISES Solar World Congress 2003 Gothenburg, Sweden
	C.Cristofari, F.Motte, G.Notton, J.L.Canaletti (2013). A new energy concept to minimize electricity consumption in industry or buildings. Applied Mechanics and Materials, 330, 188-197.		Inventum B.V.
	http://www.kingspanpanels.co.uk/panels/products/insulated-wall-panels/sol-air-integrated/		http://www.waf-solarfassade.at/
	http://www.worldstainless.org/Files/issf/non-image-files/PDF/ISSF_Stainless_Steel_in_Solar_Energy_Use_Case_Study.pdf		IEA ECBCS Annex 50 Prefab Retrofit Demonstration project, Dieselweg 4, Graz

	Anderson, T.N., Duke, M. and Carson, J.K., 2013, “Performance of an unglazed solar collector for radiant cooling”, Proceedings of Australian Solar Cooling 2013 Conference, Sydney, April 2013		C.Cristofari, F.Motte, G.Notton, J.L.Canaletti (2013). A new energy concept to minimize electricity consumption in industry or buildings. Applied Mechanics and Materials, 330, 188-197.
	BUILDING INTEGRATED SOLAR THERMAL ROOFING SYSTEMS HISTORY, CURRENT STATUS, AND FUTURE PROMISE John Archibald American Solar Roofing Company		http://www.bio-tecture.net/downloads/commercial_casestudy.pdf
	Citrin Solar GmbH http://www.glesolar.com/applications/residential-options/domestic-hot-water		University of Wollongong, BlueScope Steel and Fraunhofer Institute, the Building Integrated Photovoltaic Thermal (BIPVT) system