COST Action TU1205 (BISTS)

Building Integration of Solar Thermal Systems

OVERVIEW OF BISTS STATE OF THE ART, MODELS AND APPLICATIONS

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PART I:

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 enable an understanding of 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, profiled 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 and 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 and 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:

BIPV	Building Integrated Photovoltaic
BISTC	Building Integrated Solar Thermal Collector
DEC	Desiccant and Evaporative Cooling
DHW	Domestic Hot Water
EPBT	Energy Pay Back Time
EPD	Environmental Product Declaration
ETC	Evacuated Tube Collector
FPC	Flat Plate Collector
GWP	Global Warming Potential
LCA	Life-Cycle Assessment
LCCA	Life-Cycle Cost Analysis
LCI	Life-Cycle Inventory
PV	Photovoltaic
PVT	Photovoltaic –Thermal

RES	Renewable Energy Systems
STC	Solar Thermal Collector
STS	Solar Thermal Systems

Active solar systems	Solar thermal systems with heat transport via a fluid transport (e.g. air, water) driven by forced convection (pump).
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.
Direct STS	Solar gains from the collector are directly transferred to the medium to be heated (e.g. in solar swimming pool collectors)
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 the STC, and the heat is transferred via an heat exchanger to potable water for hot water use in domestic sanitary appliances)
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)

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.

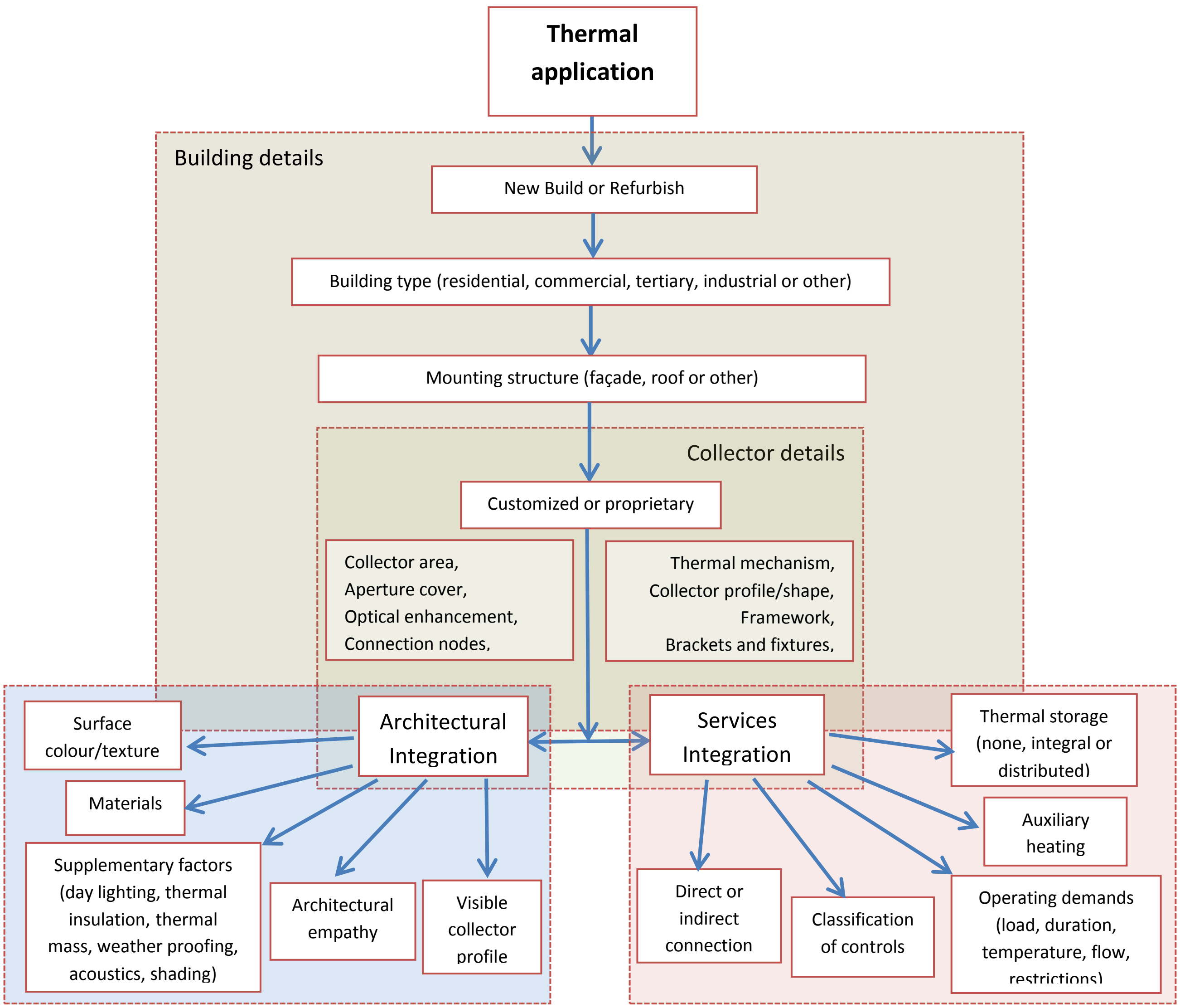


Figure 2.1. BISTS classification

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

BISTS deliver 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 and 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 domestic hot water (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 and 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.

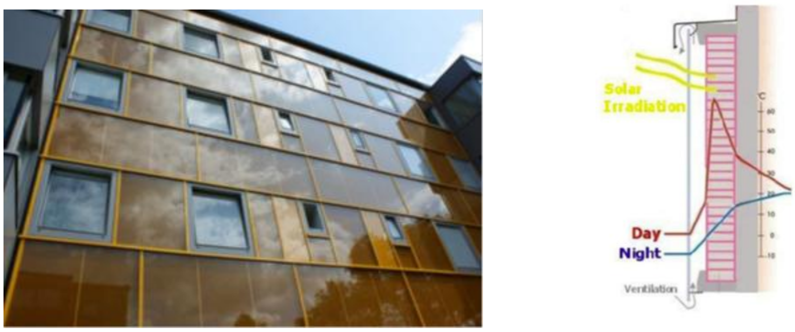


Figure 2.2. An indirect solar-comb construction BISTS, Dieselweg project, Graz

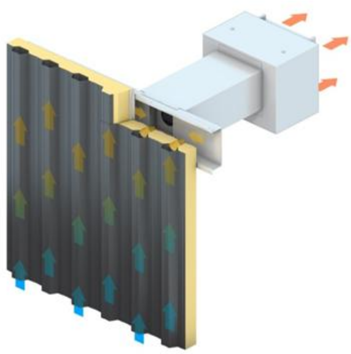


Figure 2.3. Solar air heating façade BISTS with auxiliary heating system

Figure 2.4. Roof integrated flat plate BISTS

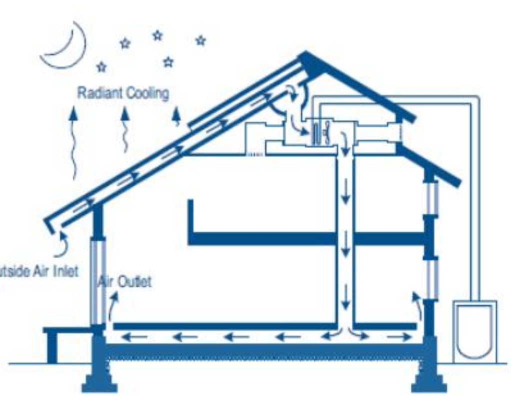


Figure 2.5. Radiant cooling via a reversed BISTS (OM Solar, 2014)

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.

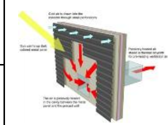
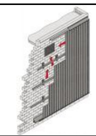
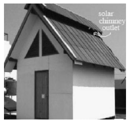
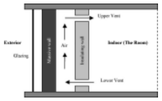
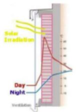
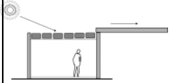
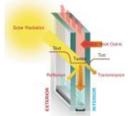
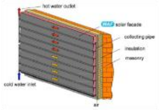
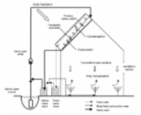
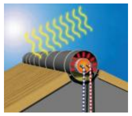
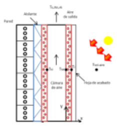
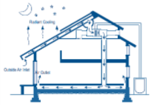
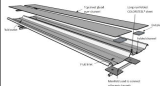
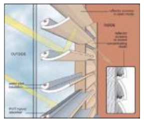
				Installed element					
				Façade		Roof		Other	
				New	Retrofit	New	Retrofit	New	Retrofit
OUTPUT	AIR	Air heating & ventilation	Active						
			Passive						
		Space heating	Active						
			Passive						
		Combined air and water heating	Active						
	WATER		Passive						
		Water heating	Active						
			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 in Appendix A 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 3-1 consisting 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).

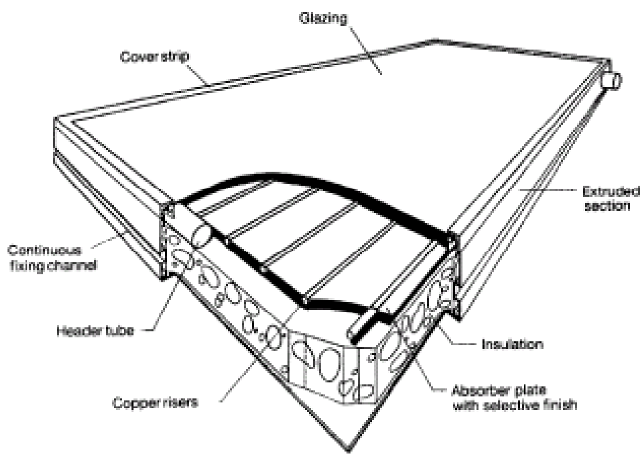


Figure 3-1: Typical Flat Plate collector (Kalogirou, 2004)

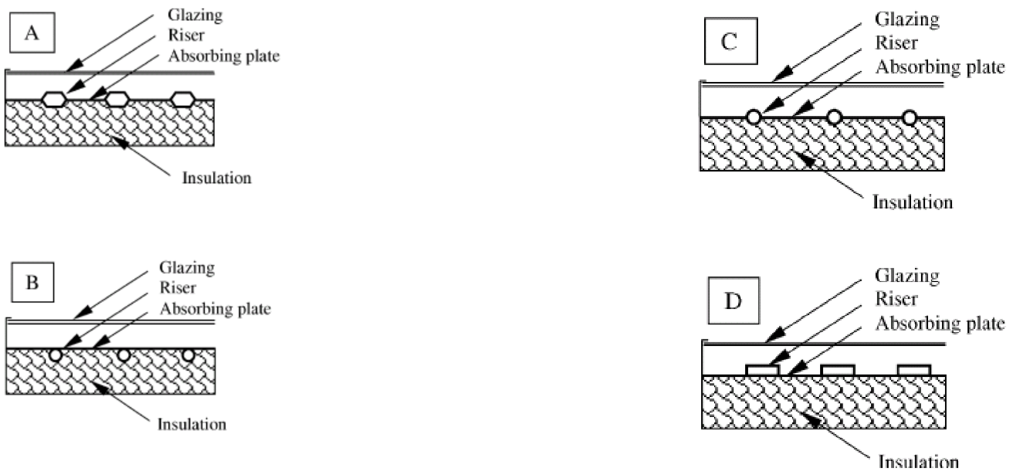


Figure 3-2 : Flat Plate collector absorber profiles and geometries (Kalogirou, 2004)

Vacuum tube collectors

Conventional 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/or windy days. Evacuated tube 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 are in good contact with the absorbing surface. The heat pipe collectors have 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.

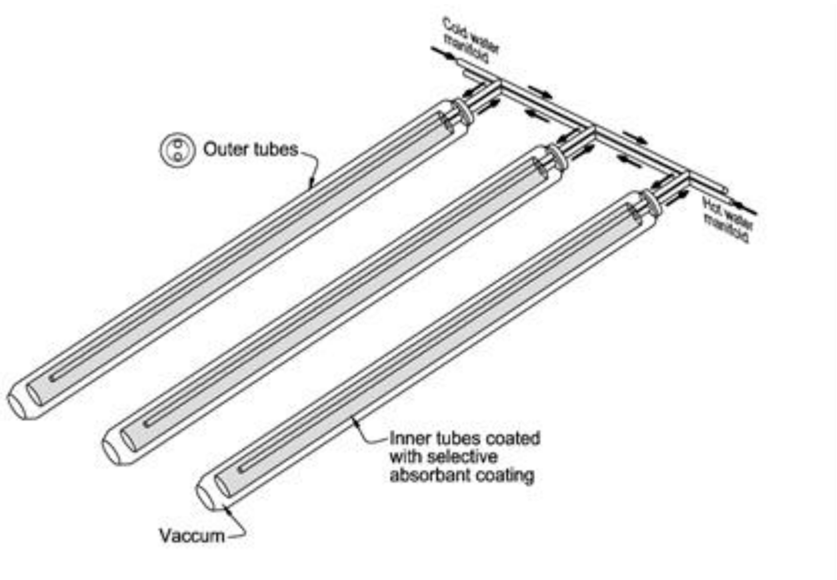


Figure 3-3 : Metal/glass water pipe evacuated tube solar collector (Smyth, 2005)

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, firstly the store itself contains potable water and therefore should be either 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 uses 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 by internal 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 and service domestic 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.

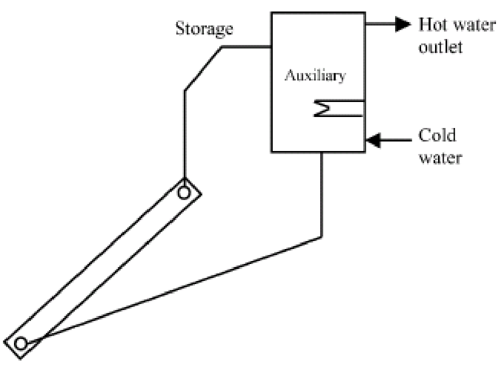


Figure 3-4 : Simple schematic of the thermosiphon system (Kalogirou, 2004)

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 auxiliary 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, reflector geometries (Tripanagnostopoulos and Souliotis, 2004) and thermal diodes has been investigated (Smyth et al., 2006). Transparent insulation materials have also been investigated (Goetzberger and 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 receiving vessel, thereby draining the collectors of the HTF. This allows the use of water as a HTF without the need for freeze 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.

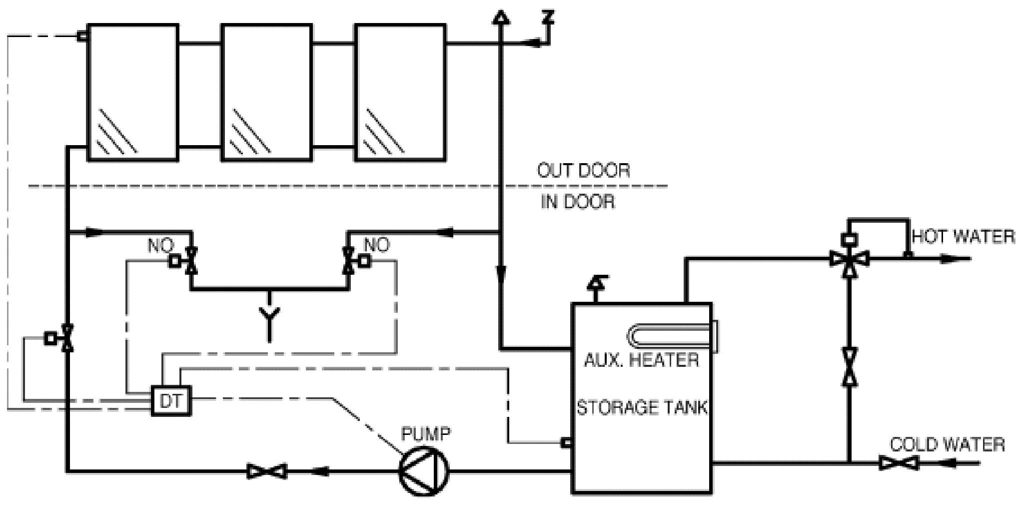


Figure 3-5 : Drain-back system (Kalogirou, 2004)

- Closed circulation (Pressurized)

In a closed system the collector circuit may be pressurized and therefore the boiling temperature of the fluid can be raised. A schematic of the system is shown in Figure 3-6. This allows higher operational temperatures and oxygen intrusion and thus corrosion in the closed circuit is much easier to control than in an open circuit. As the fluid is continually in the collector field including low temperature ambient conditions freeze protection is necessary in most cases. For SHWS the consequence is that the system is indirectly heating the potable water via a heat exchanger. The freeze risk depends upon the climate where the system is used. Freezing may even be prevalent in locations with a cooling dominated demand, especially in dry climates or high altitude locations. One option is the use of water-glycol mixtures as HTF (passive freezing protection), which have a lower freezing point, depending on the glycol concentration. Another option is active freezing protection, where circulating water in the collector field in winter time is heated by an auxiliary heating system or by hot water from the storage . 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.

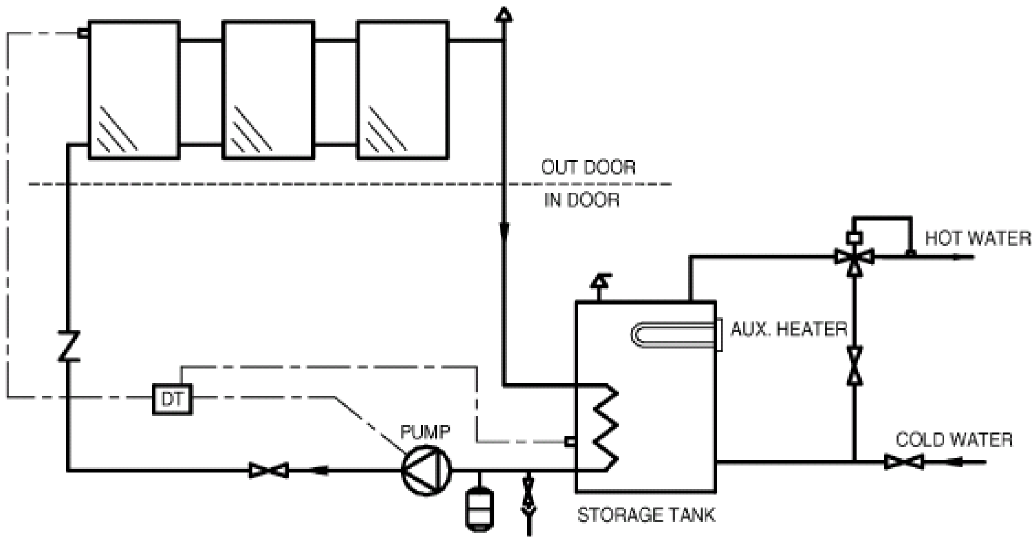


Figure 3-6 : Closed pressurized system (Kalogirou, 2004)

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 or sunspaces (Duffie and Beckman, 2008) where solar gains are captured directly by the building structural elements. The latter variants cannot be switched off (as in active systems) but with the use of solar control devices (such as shading elements), 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 greater 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 and 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 heated air handling units. Alternatively, the collector outlet air can be used to provide heat to other traditional building heating systems (e.g. gas fired air heaters, heat pump, etc.), thereby increasing their operational energy efficiency. Warm air delivered from the solar collectors can be stored directly via a range of appropriate techniques (greenhouses with thermal storage, 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 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 have the systems seem to be economically viable (Fisch et al., 1998; Lundh and 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 (Balcomb, 1983; Ochoa and Capeluto, 2008; Duffie and 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 in the conventional sense but by using shading systems the level of solar gain 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, as discussed previously, have been using a single glazing layer as an external cover for many decades (Duffie and Beckman, 2008). The efficiency of the solar wall was limited by the high thermal losses using only single glazing and 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 insulating 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 type of building material - through the massive wall into the interior. Windows and solar wall heating with transparent insulation work well together as the direct solar gain through the window can be of use immediately whilst the indirect gains from the solar wall reaches the space to be heated 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 insulating 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 finished 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).

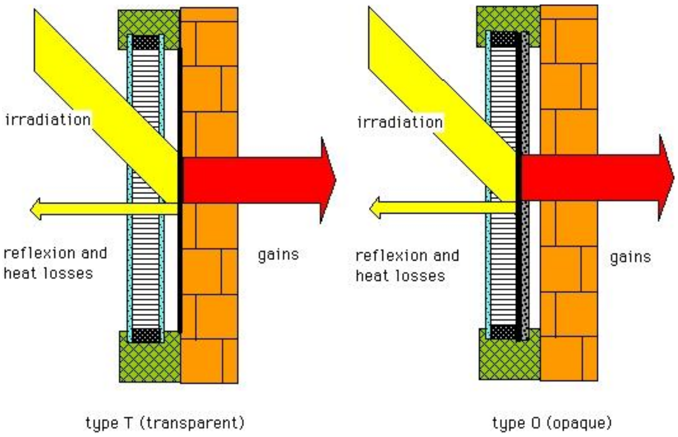


Figure 3-7 : Principle types T and O for solar wall heating with transparent insulation (type O can be vented in summer for effective overheating protection) (Platzer, 2000)

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 low compared to TIM systems 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 direct solar heating, but the insulation level will be increased without using excessive material thickness (Gap solution, 2014).

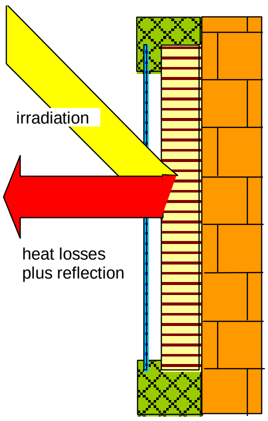


Figure 3-8 : Principle of solar insulation - solar gains and heat losses balance each other over heating season

3.3 Ventilation and cooling

Buildings need ventilation 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 and therefore obtaining the necessary 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. Unglazed 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. The Solar Wall® is a perforated wall used as a solar absorber. Air flowing through the wall is heated during the solar collection mode and can be used in conjunction with the building ventilation system. The same systems operating at night can be used for building cooling.

In cooling dominated climates the incoming air must be cooled in order to achieve comfortable supply conditions. Air conditioning ensures maintenance of constant air parameters such as temperature and humidity related to indoor comfort conditions in buildings. 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 andDöll, 2012; Balaras et al., 2007). Different solar collectors can supply heat with different temperature, for absorption system evacuated tube and concentrating solar collectors are preferred. With temperatures higher than 100°C it is possible to use double effect absorption chillers, COP it this case can be higher than 1. Adsorption chillers require a lower driving heat temperature, allowing the use of flat plate solar collectors. Lower temperatures influence the COP of a refrigerator. Typically the COP of an adsorption chiller with heat supplied from flat plate solar collector is around 0,5-0,6 (Cameron, 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). A disadvantage of DEC systems is the high water consumption that occurs in system. However, the 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 system 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 component solutions. When considering solar thermal systems, the competition for suitable roof or façade area with PV is an issue of much discussion. Therefore PV Thermal (PVT) collector solutions can offer an alternative option as they deliver solar thermal heat at levels 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. Unglazed 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 independent PV modules. Good examples of optimized collector solutions are in development (Dupeyrat et al., 2011a; 2011b). Figure 3-9 outlines the range and scope of BIPVT parameters of concern for buildings

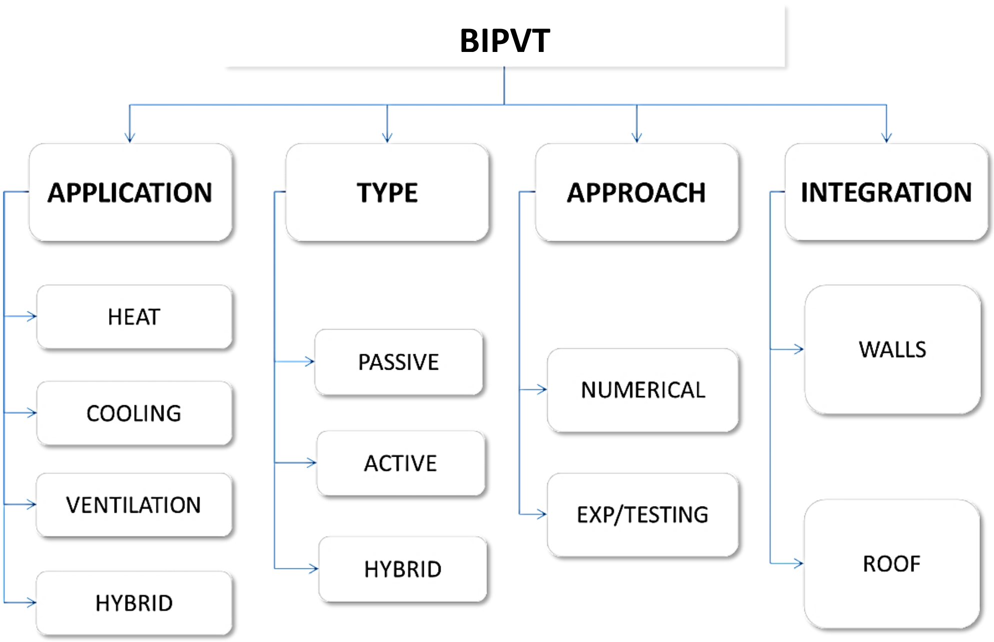


Figure 3-9 : BIPVT – Integration parameter classification

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, 2008). This leads to potential overheating problems for BIPV (Krauter et al., 1999). Common approaches to BIPV temperature mitigation and thereby useful heat extraction fall into two categories: natural ventilation and active heat recovery (Corbin and 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 and Sandberg, 1998) or serve as solar air collectors for preheating HVAC supply air (Corbin and 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) and/or 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 thermal 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 and 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 and 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 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). The BIPVT 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.

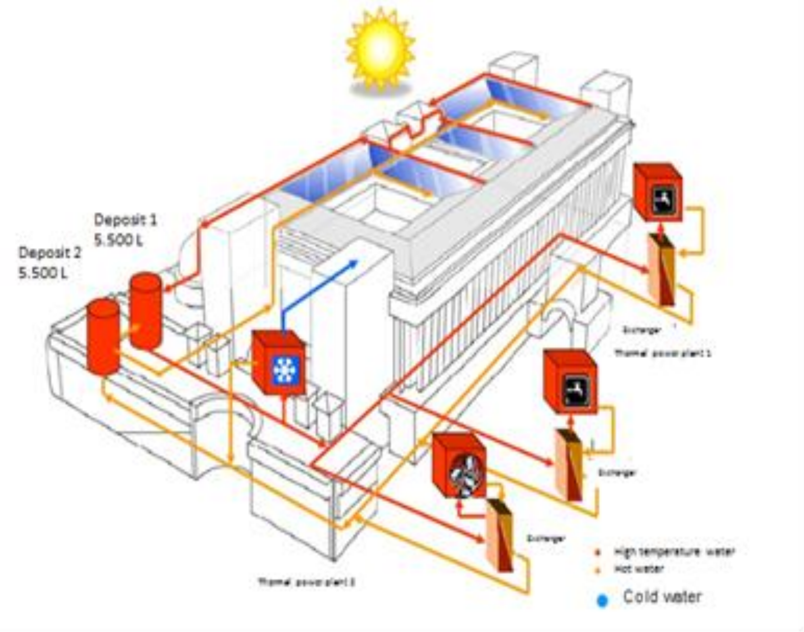


Figure 3-10 : A BISTS for hot water production with centralized storage and heating and cooling (via absorption chiller) (URBAN SOL PLUS, 2008)

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).

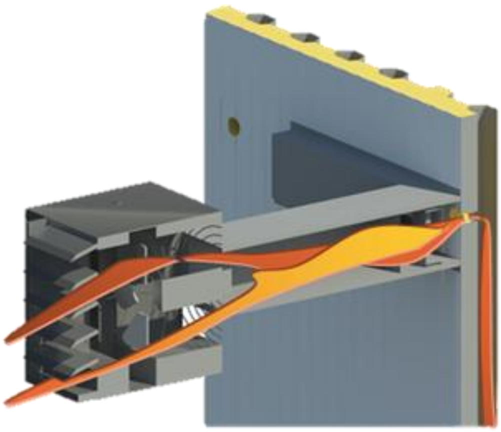


Figure 3-11 : Kingspan's Integrated Sol-Air Collector (ISAC) supplied complete with auxiliary heating system) (Kingspan, 2014)

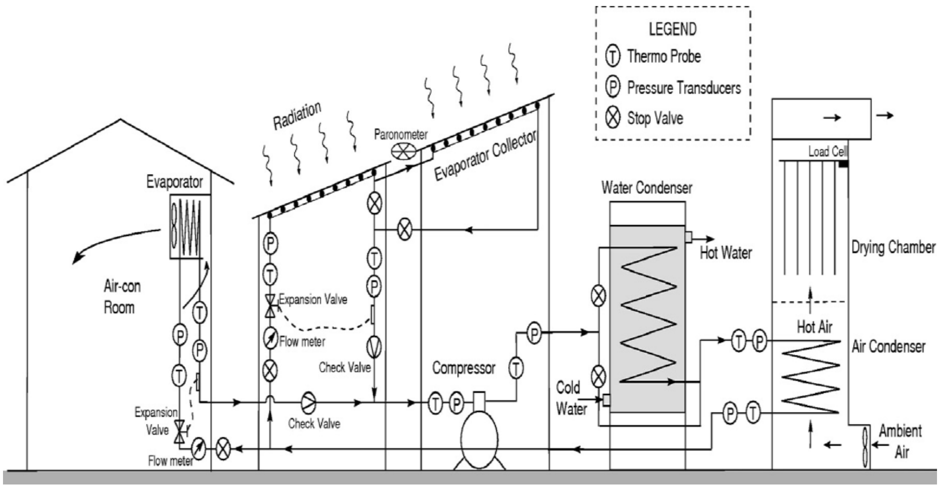


Figure 3-12 : Schematic diagram of a roof integrated (integral) solar heat-pump system (Zakaria and Hawlader, 2013)

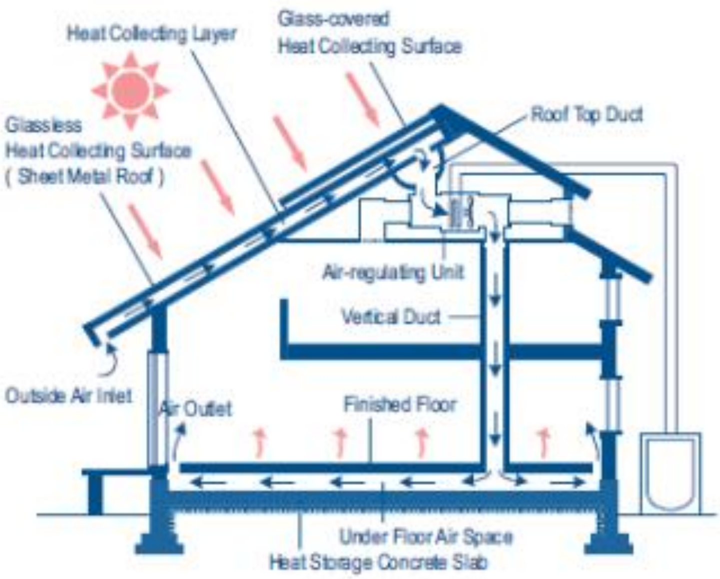


Figure 3-13 : The OM building concept in Japan with BISTS roof and warm air auxiliary heating system (Om Solar, 2014)

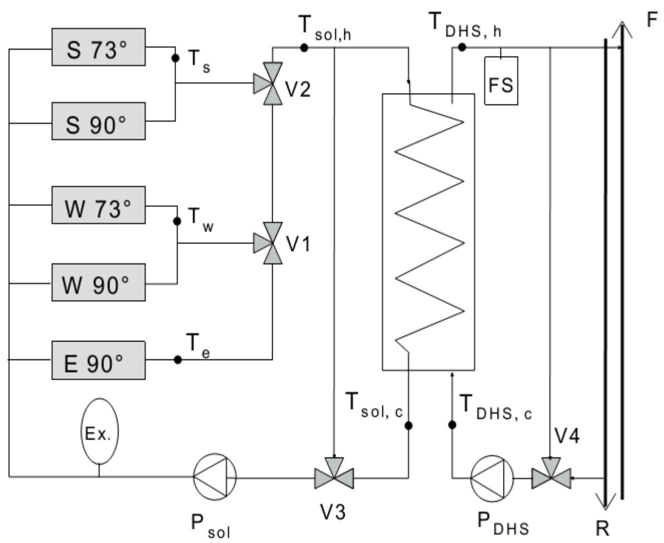


Figure 3-14 : Schematic diagram of the heat exchange interconnection of a multi-surface BISTS supplying a district heating scheme (Gajbert et al., 2005)

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 and 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 with new building envelope structures and components 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 construction industry. 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.
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 – $C_R \leq 30$ l/m²	Moderately favorable – 30 l/m² $\leq C_R \leq$ 70 l/m²	Favorable – $C_R \geq 70$ 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 – $C_F \leq 30$ l/m²	Moderately favorable – 30 l/m² $\leq C_R \leq$ 70 l/m²	Favorable – $C_R \geq 70$ 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 (1st 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 statement, to select an optimal solution for BISTS placement, the set of criteria, shown in Table 4.1. must 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 of up to 30° is also acceptable. For heating applications the solar yield is optimized with stronger inclination, with a 60° to 90° inclination recommended. Inclination may be also important in areas with high snow loads. The larger the inclination angle, the easier it is for snow to slide off flat plate collectors. Some studies and observations indicate that evacuated tubes, because of their shape and heat retention, take longer to shed snow (Appleyard and Konkle, 2007).

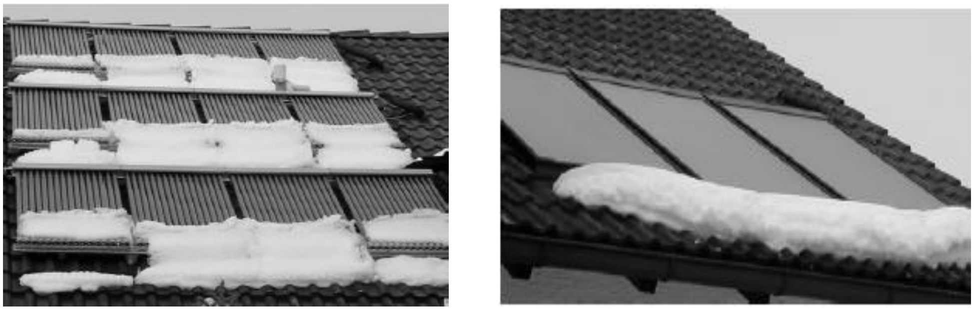


Figure 4.1. Snow shedding of flat plate collectors and the evacuated tubes.

It is not recommended to apply solar thermal panels on periodically shaded surfaces of the building envelope because it results in a lower system efficiency and may cause damage from thermal stress resulting in 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 and 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) (Appleyard and Konkle, 2007)

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 latter 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.

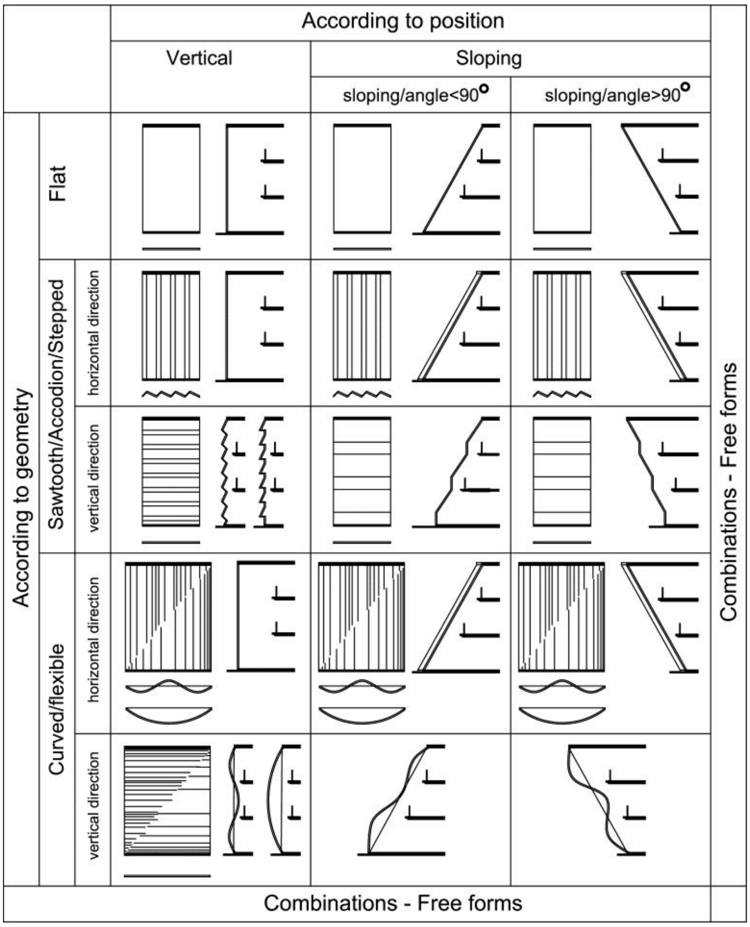


Figure 4.3. Form types of glass façades according to position and geometry of glazing surface (Krstic-Furundzic et al., 2012a).

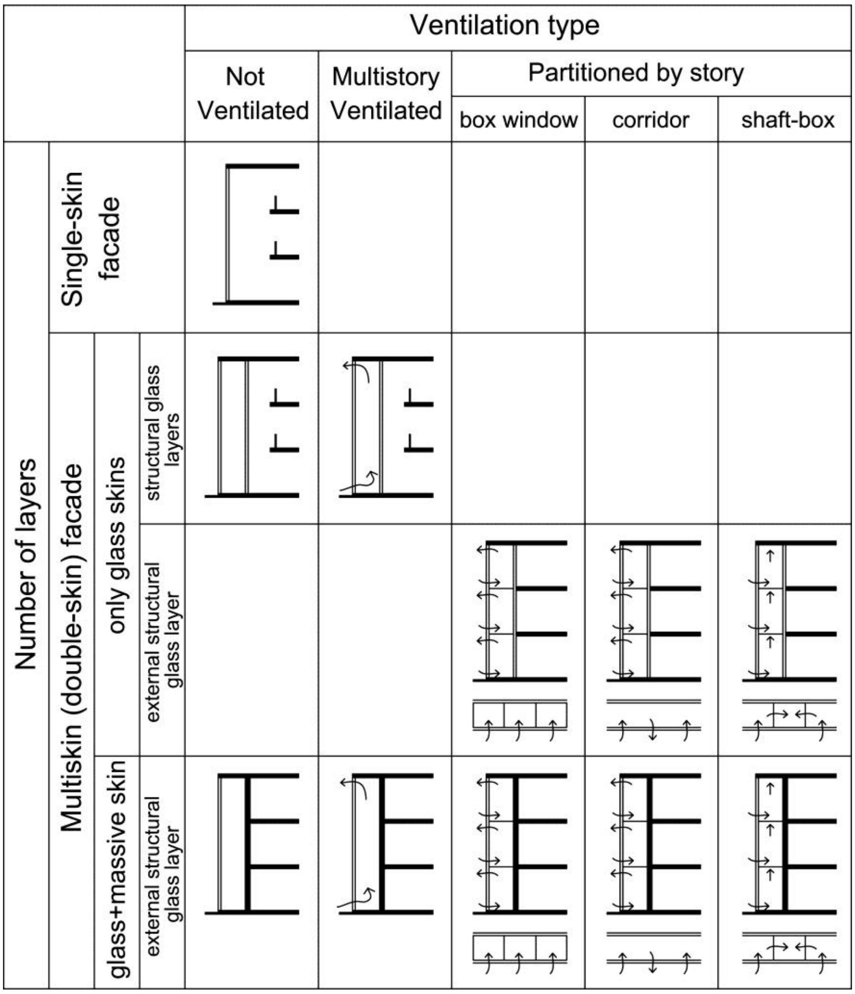


Figure 4.4. Assembly types of glass façades according to number of layers and ventilation type (Krstic-Furundzic et al., 2012a).

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.

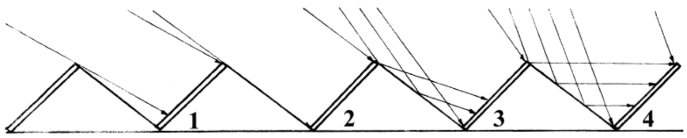


Figure 4.5. Effect of booster reflectors to collectors regarding the direction of solar rays (Tripanagnostopoulos et al., 2000)

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 multi-functional 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 and Roecker, 2007). For unglazed 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 and Rub, 2005). However the associated cost for bespoke products needs to be reduced, which requires an adaptation of the production processes.

Polymer collectors have been suggested as an alternative option (Lang, 2012). Polymer components could be manufactured more cheaply and flexibly thanks to the well-established process of extrusion, which could easily produce the exact dimensions needed to integrate collectors with buildings of all shapes and sizes. Components would be lighter to transport and easier to install, and could potentially come in a variety of attractive hues to do away with the ”any colour as long as it is black’ approach of conventional collectors” (Lee, 2005). A transparent polycarbonate (PC) twin wall sheet or hardened glass could be used as cover sheet. 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).

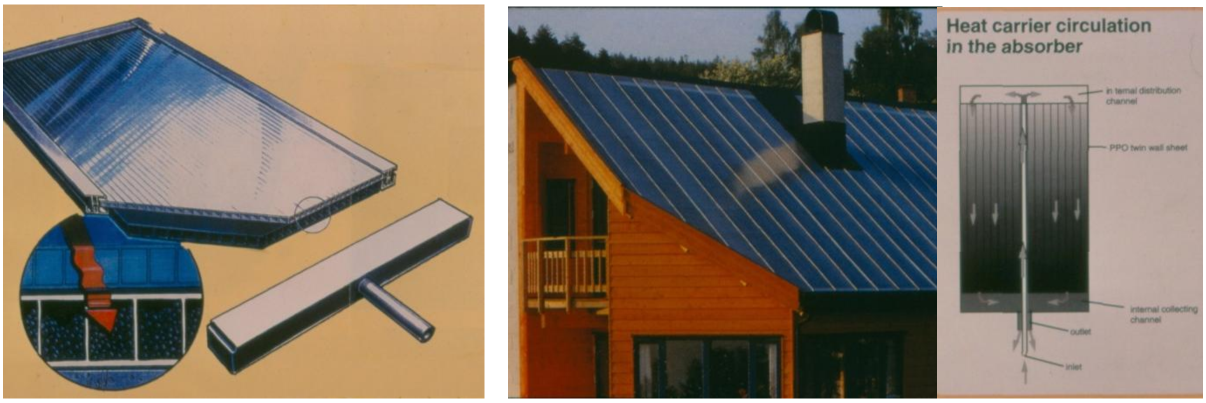


Figure 4.7. Building integrated STC made of polycarbonate twin wall absorber sheet filled with ceramic particles.

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 systems suitable for a multi-flat residential or office buildings, house space heating and 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 unglazed STC have large variations in terms of surface texture and finish such as corrugated, embossed, perforated etc. The surface can have a matt, glossy or structured finish (Probst and Roecker, 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 and 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 mechanism 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 and Kaan, 2011). Solar collectors should be designed with reference to the normal construction practices within the building industry. The following construction options for integrated STC modules within the building envelope are commonly used:

i. glazing layer (glazed flat STC)

ii. conventional 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 multi-functional elements or provide dummies as standard options (Probst, 2008). Façade integrated systems include vertical and tilted positions of glazed STC modules (Figure 4.8). Glazed solar thermal integrated façades are a type of curtain wall. STC 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).

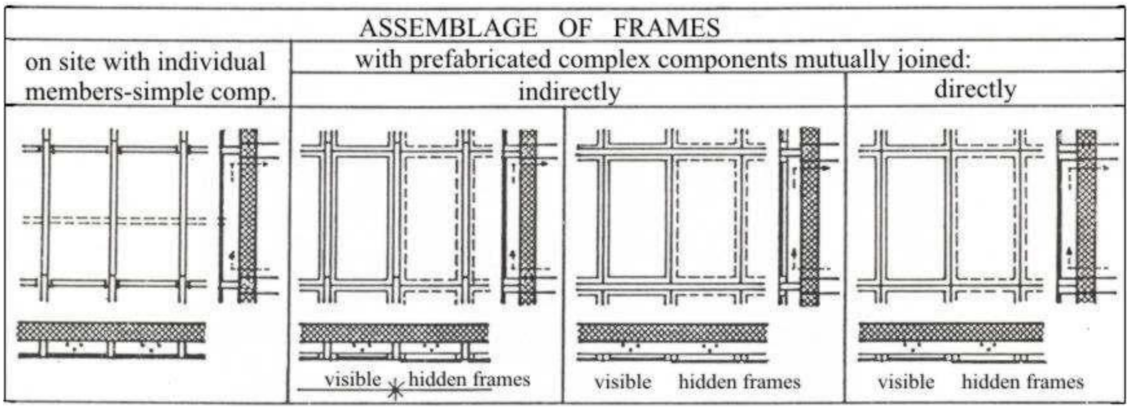


Figure 4.9. Suspended façade assemblage possibilities (Krstic-Furundzic, 2007)

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 multi-functional modules (M-modules) by using curtain wall technologies is acceptable as shown in Figure 4.10.

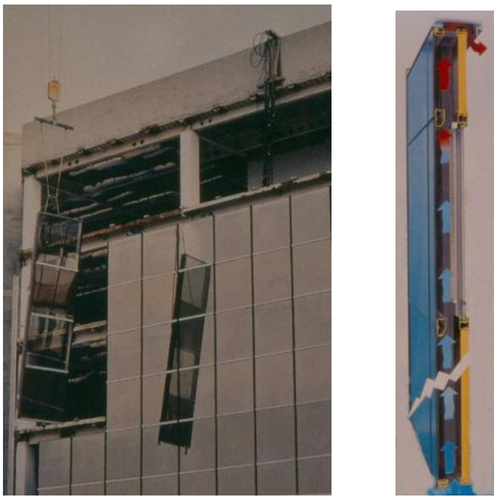


Figure 4.10. Hybrid Photovoltaic/Thermal façade constructed of prefabricated glass modules.

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 a customary solution in the case of solid, not transparent, roof concepts. Prefabricated solar thermal collectors are preferable for application on roof surfaces (Figure 4.11.) as the mounting process is easier with less installation time needed. In addition the quality of the collector finish achieved in the factory can be of a higher standard.

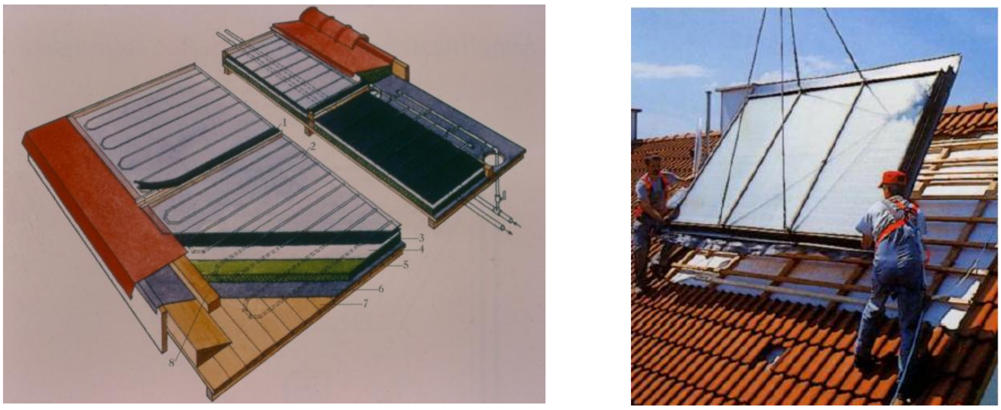


Figure 4.11. Roof integrated solar thermal collectors.

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.

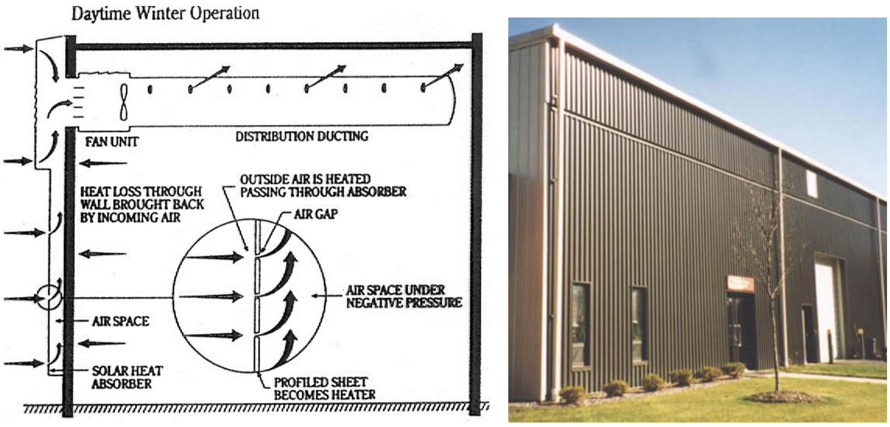


Figure 4.12. Construction as conventional façade cover, (SolarWall, 2014)

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 easily integrated into most building forms and very architecturally versatile as they can be styled, shaped, and designed in a variety of finishes and colours

Contemporary roofing technology refers to placement of roof tiles 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 coloured roof tile 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.

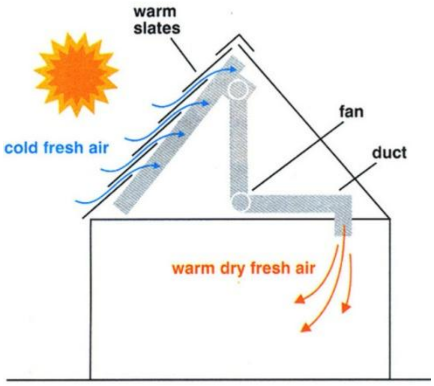


Figure 4.13. Construction as conventional roof cover – unglazed flat STC, Berwickshire, Scotland

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 the sun rays and overheating space. BISTS 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, allow a portion of the solar radiation depending on the season into the room.

Regarding structure and geometry, the 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 the building envelope becomes a changeable structure adapting to daily and seasonal changes - "alive" structure.

Figure 4.14. Solar thermal collector as shading device

Flat STC are preferable for overhangs as they provide added protection from rain and snow. If constructed of vacuum tubes it is just a shading device. For balcony railing construction, both types are suitable, but vacuum tubes enable better view of the surroundings (Figure 15), although issues relating to their physical strength must be considered.

Figure 4.15. Solar thermal overhang and balcony railing

5 Building Physics

The building physics of a building envelope are 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 standards 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 appropriate 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 the thermal solar collector glazing. Insulation in BISTS 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 to that 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 BISTS whereas for others (e.g. mineral wool) products being used will be slightly different from the variants used for building insulation only.

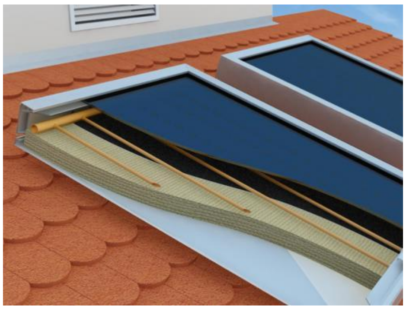


Figure 5.1. Solar panel thermal insulation (Canada Mortgage and Housing Corporation, 2014)

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 the correct product specifications must be used. Organic binders are being used in standard products which work well in building applications where temperatures below 60-80°C occur. Solar collectors may however reach much higher stagnation temperatures and therefore some of these materials have proved to be unsatisfactory in practice. This becomes noticeable due to the condensing of organic material on the inside of the collector cover due to the 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 offers long-term heat resistance up to 90°C and short-term heat resistance up to 250°C. Rigid polyurethane foam is non-aging, incombustible and is resistant to decomposition and pest damage.

5.2.3 Transparent/Translucent Insulation

Transparent or translucent insulating materials have a long history in scientific development (Platzer, 1994a; Stahl et al., 1984; Hollands, 1965). They have thermal insulating properties similar to that of mineral wool but permit the transmission of solar radiation to the absorbing element of a 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 aperture cover. The materials have also been able to withstand the high temperatures in the collector observed during stagnation (Rommel and Wittwer, 1988; Rommel and Wagner, 1992) or as use as stagnation prevention devices used to limit the collector temperature. Examples for stagnation prevention are thermotropic layers which turn from transparent to reflective white above a critical temperature. 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 (1994a; 1988).

Transparent insulation parallel to the absorber have been very successful in the development of heat insulating glazing with selective transparent coatings and noble gas fillings, used mainly in 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 almost invisible, with some remaining scattering reducing solar gains, but this 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.

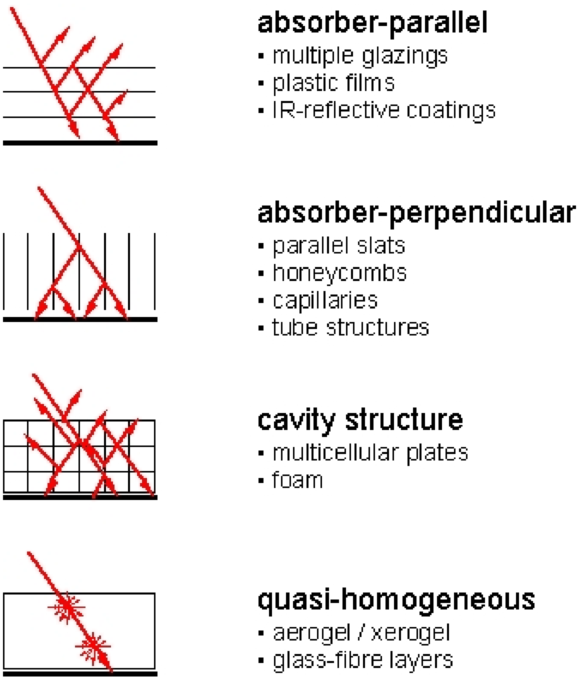


Figure 5-1. Classification of Translucent Insulation Materials (Platzer, 1988)

Honeycomb materials are light-guiding and very good convection suppression devices (Charters and 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 that related to mineral wool. This permits the 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, construction 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 building walls of 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 also 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 and Weiss, 2002). 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 assumed. 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.

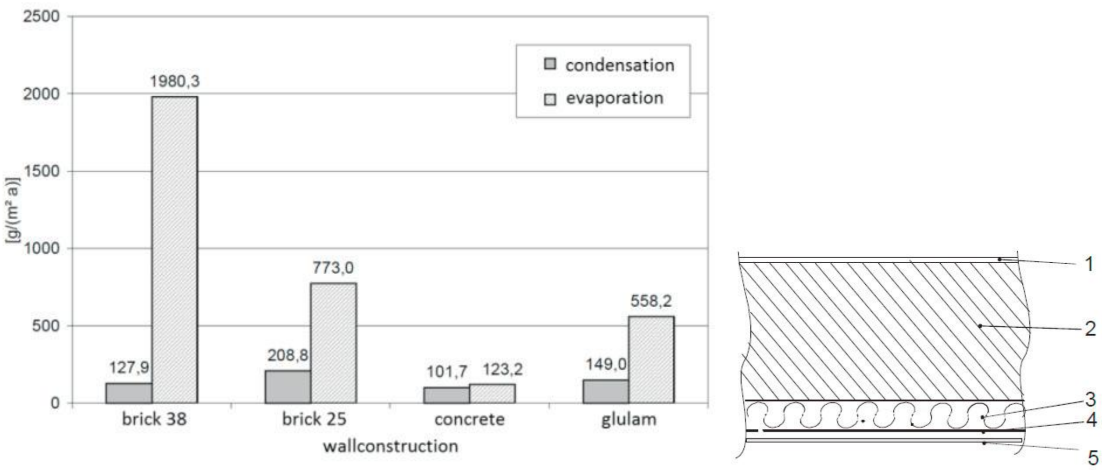


Figure 5-2. (left) Annual condensation and evaporation potential for different wall constructions, (Bergmann and Weiss, 2002). (right) Wall constructions: (1): interior plaster, (2): brick 38cm / brick 25cm / concrete, (3): insulation, (4): absorber, (5): glazing (Similar configuration for "glulam" with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

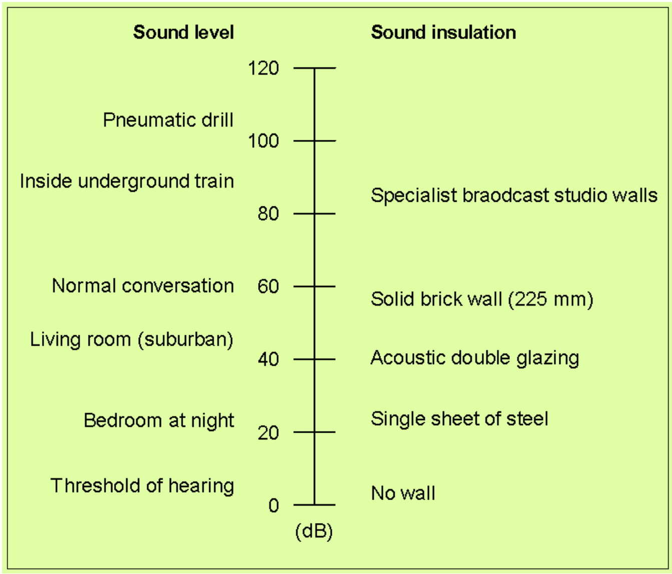


Figure 5.5. Typical sound levels and insulation values (Steel Construction Info Acoustics, 2014)

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

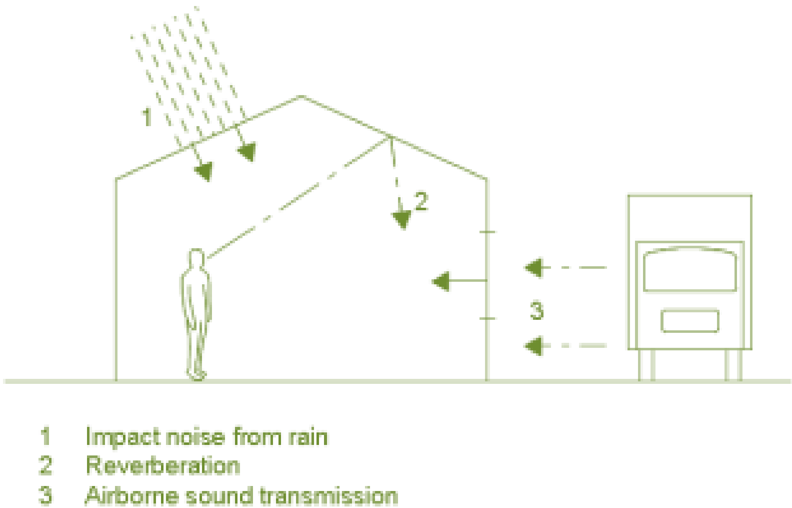


Figure.5.6. Categories of acoustic performance (Steel Construction Info Acoustics, 2014)

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. General regulations and standards exist for other EU countries (European Parliament 7/18/2002; ISO 140-3:1995; Rasmussen, 2006; 2010; 2013; Amundsen et al., 2011; Bradley and Birta, 2001; Olafsen and 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 buildings that have a user-intensive activity close to the glazed façades, such as in 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 and Nanaki, 2012). About two thirds of this energy use is related to the residential sector and the remaining third to commercial buildings. The largest proportion of this energy is used for water and space heating. Today, 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 sustainable manner. Life Cycle Analysis (LCA) or Environmental impact techniques are useful tools for the evaluation of an environmental profile of a solar installation. LCA and other Environmental impact techniques are important in the environmental sustainability of BISTS (Bojíc et al., 2014; Battisti and Corrado, 2005; Burch and 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 and 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 to the delivery of heat from a solar system. Although the context of the LCI data for BISTS is based on Swiss systems, it is accepted that this data is relevant throughout Europe as the technological level of the BISTS is consistent throughout Europe.

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 the near future BISTS manufacturers will make the specific environmental data related to their products publically available.

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

From the studies 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 material to the construction site. Likewise, the associated emissions of energy-related pollutants (like CO_2)may be viewed over their life-cycle leading to the notion of 'embodied carbon' (Hammond and Jones, 2008). Embodied energy and CO_2 emissions are of great interest and most of the previously presented studies are based on these issues.

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". 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 and Chemisana, 2014). The number of system components is crucial since more complicated systems are expected to have higher initial impact (during the 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 and Golden, 2009) as an alternative solution for the reduction of system embodied energy. Solar systems typically have a higher initial impact in comparison with conventional systems but on a longer-term reference frame (during use/operational phase) this additional impact can be compensated. By comparing the Energy Pay Back Time (EPBT) of a solar system 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 longer-term basis the solar system is proved to be more environmentally friendly (Lamnatou and Chemisana, 2014).

Other critical factors are related with the electricity/fuel mix adopted and its source (electricity, natural gas, etc.) used in 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 that relate to the output of the solar system (Lamnatou and Chemisana, 2014) or the impact of materials such as aluminium, copper, thermal fluid and galvanized steel (Ardente et al., 2005) is important for the elimination of uncertainty which has been associated with LCA studies. Competing solar collector technologies such as ETCs which can be proposed (Hang et al., 2012) over flat plate collectors should have the feasibility of such systems examined not just in terms of their cost, but their wider environmental accepatbility. Solar thermal systems which combine collection and storage tank in one unit (Smyth et al., 2000) have also been investigated.

Alternative materials, such as 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 payback period for BISTS

Previous studies show that PV systems, 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 and Nanaki, 2012; Tripanagnostopoulos et al., 2005). Ardente et al. (2005) concluded that the solar thermal collector can have both environmental and economic payback periods 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 Global Warming Potential (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 to the climate (Berge, 2009).

Recycling is also a crucial factor. By adopting recycling for materials with high a impact factor such as aluminium, copper or steel a considerable reduction in the environmental impact of a system can be achieved. Attention is needed for some specific cases such as the recycling of painted products which can lead to the emission of toxic pigment vapours (Berge, 2009). Another issue relates to the recycling of materials/components at the end of their operational life. The adoption of an appropriate disposal process (dismantling, reuse, 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)). BISTS should be built using inflammable materials, as is already the case for STC. Furthermore borax and boric acid are used as fire retardants in many building materials such as insulation made of cellulose fibre. Boron substances are moderately poisonous and in larger concentrations they can affect plants and fish in freshwater. Ammonia is also an important element in ammonia phosphates and sulphates which are also used as fire retardants for organic 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 whilst in 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 (emissions such as benzene, ethyl benzene, styrene, pentane and chlorofluorocarbons are quite likely) (Berge, 2009).

Health risks due to the incubation of bacteria legionellae in systems have been reported. Therefore when designing and using both STC and PVT systems 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 associated with hot water heating. 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 asking 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).

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PART II:

Review on modelling and simulation of building-integrated solar thermal systems

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Contents:

Abstract

In the present study, a literature review focusing on Building-Integrated (BI) solar systems is conducted. The review refers to systems which produce thermal, electrical or both thermal/ electrical energy. Emphasis is given on the BI solar thermal systems while the solar electrical and solar thermal/electrical systems are also included in order to have a more complete picture of the current literature. The results of the review show that in the literature the greatest part of the models are thermal and/or energetic simulations of BI Photovoltaic-Thermal (PVT) (or BI PV) and skin façades. Thus, there is a need for thermal and/or energetic modelling works about BI solar thermal systems, especially for models which give emphasis to the building (since the greatest part of the investigations give emphasis to the system itself). On the other hand, the optical-models are very few and certainly, more optical-modelling studies are needed since they could provide useful information for the behaviour of the BI solar thermal systems from the optical point of view.

1 Introduction

The building sector is an energy-demand sector and the use of renewable energy technologies could provide considerable benefits. Among renewable energy systems, solar energy technologies are promising especially for countries with high solar radiation. In the frame of this concept, several solar systems have been already tested and applied in buildings. Nevertheless, there is a potential for further development and this could be achieved by adopting solar systems which are integrated into the building envelope. This specific type of systems in the literature is known as Building Integrated (BI) solar systems. BI configurations are a new tendency in the building sector and they provide several advantages given the fact that they replace a part of the building (façade, roof, etc.). Among the BI systems, solar thermal are a recent development; thereby, there is a potential for further development and this could be achieved by investigating this type of installations e.g. by means of modelling.

The present work provides an overview in terms of modelling works about BI solar thermal systems. References from the literature about BI solar thermal configurations along with other systems (which produce electrical and thermal or only electrical energy) are cited, separated into groups, based on the type of the model (thermal, energetic simulation, etc.) and based on the specific characteristics of each system (skin façade, solar thermal collector, Photovoltaic-Thermal (PVT), etc.). In this way, a complete picture of the studies available in literature is provided while the gaps in literature are identified. It should be noted that few works about systems which are Building-Added (BA) (and not real BI) are also cited for certain cases when the system/or the model is of great interest. Moreover, in some categories, some general studies (e.g. about modelling of building components) are also cited.

In the literature there are no review works about the modelling studies in the field of BI solar thermal systems and thus, the present work is an innovative study. The results of the present investigation reveal which types of models/systems are available in the current literature and which types need further development. In this way, the present work provides useful information for example for academic/research purposes while models/systems which would be interesting for future investigation are also proposed.

2 Studies of Energetic Simulation (emphasis: building)

2.1 BI, Skin Façade

1. Ciampi M., Leccese F. and Tuoni G., Ventilated facades energy performance in summer cooling of buildings, 2003: Solar Energy 75(6), 491–502.

http://dx.doi.org/10.1016/j.solener.2003.09.010

Contexts	Outcomes
An analytical, simple method for design applications → evaluation of electrical energy savings in buildings	In all cases, the energy saving increases as the air duct width increases, The positioning of the insulating

Forced (with fan) and natural ventilation cases (stack effect) were examined Reference climatic conditions: outdoor air temperature = 28°C; indoor air temperature = 24°C; solar radiation intensity = 400 W/m^2	material close to the inner masonry wall is more efficient than the one close to the outer facing. The energy saving increases remarkably as solar radiation intensity increases; the bigger the solar radiation is the more efficient ventilated façades turn out to be from an energy saving point of view. The energy saving increases sensibly as the difference between the outdoor and indoor temperatures decreases. The energy saving is remarkably influenced by the wall outer surface thermal resistance value and by relative roughness of the slabs delimiting the air duct.

2. Goia F., Haase M. and Perino M., Optimizing the configuration of a façade module for office buildings by means of integrated thermal and lighting simulations in a total energy perspective, 2013: Applied Energy 108, 515 – 527.

http://dx.doi.org/10.1016/j.apenergy.2013.02.063

Contexts	Outcomes
A comprehensive approach (including heating, cooling and artificial lighting energy demand) was adopted → optimization of façade configuration. A methodology for the optimal transparent percentage in a façade module for low energy office buildings The investigation was carried out in a temperate oceanic climate (with different HVAC system efficiency) Façade module: single skin façade technology; two surfaces: a transparent part and an opaque part; the transparent surface was made of a triple glazing with low-E coatings (clear glass panes) and integrated external solar shading devices – i.e. a highly-reflective external venetian blind system (blind slate reflectivity: 80%) Aim of the search: to find the WWR (Window-to-Wall Ratio) of the façade module that minimizes the total energy demand of the building Integrated thermal-daylighting simulations The integrated thermal and daylight simulations were	The optimal configuration of the façade module was investigated for an office building characterized by a typical layout, located in Frankfurt (Germany) (belongs to temperate-oceanic climate) A daylighting calculation was performed at each heat-balance time-step when the sun was up. The electric lighting control system (continuous dimming control) was simulated to determine the lighting energy needed to make up the difference between the daylighting illuminance level and the design illuminance set-point

carried out by using the EnergyPlus software (calculations on hourly basis for the entire year).	

3. Liu M., Wittchen K.B., Heiselberg P.K., Development of a simplified method for intelligent glazed façade design under different control strategies and verified by building simulation tool BSim, 2014: Building and Environment 74, 31-38.

http://dx.doi.org/10.1016/j.buildenv.2014.01.003

Contexts	Outcomes
A simplified calculation method for intelligent glazed façade under different control conditions (night shutter, solar shading and natural ventilation) was developed to simulate the energy performance and indoor environment of an office room installed with the intelligent façade. The method took into consideration the angle dependence of the solar characteristic, including the simplified hourly building model developed according to EN 13790 to evaluate the influence of the controlled façade on both the indoor environment (indoor air temperature, solar transmittance through the façade and the illuminance level on a chosen point) and the energy performance of the room.	The results were evaluated by the Danish building simulation tool BSim and they showed good correlation for indoor air temperature and solar transmittance and acceptable correlation for illuminance level, energy demands of heating, cooling, lighting and ventilation between the simplified method and BSim. The authors noted that that simplified method is a reasonable reliable tool for the early stages of an office building design process, given the fact that the model is based on hourly calculation of an office in the whole reference year.

2.2 BI, Solar Chimney

1. DeBlois J., Bilec M. and Schaefer L., Simulating home cooling load reductions for a novel opaque roof solar chimney configuration, 2013: Applied Energy 112, 142–151.

http://dx.doi.org/10.1016/j.apenergy.2013.05.084

Contexts	Outcomes
Roof solar chimney (RSC) = a low cost passive ventilation technique for reducing the energy consumption for cooling buildings This study examined the performance and the level of energy savings by simulating a detached home in four climates with RSC, cross-ventilation, and standard ventilation strategies Each case was simulated by means of ESP-r for baseline and high efficiency construction, detached homes with a single story, three bedrooms, a 189 m^2 floor plan, high thermal mass constructions PVs were integrated into the surface of the solar chimney on the South-facing roof to improve the RSC	The authors noted that zonal building modelling is a coarse grid numerical approach and the program ESP-r was chosen (ESP-r creates a heat flux network and an airflow network. The two are coupled by defining common zones, and solved together) Climatic conditions: four climates were chosen for the simulation. The climates ranged from Pittsburgh (relatively cool and where many houses use window air conditioners), to Phoenix (hot, arid climate and more common central air conditioning). The other two locations chosen were Albuquerque and Atlanta

performance with their absorptive properties, and provide cooling to the reverse of the PV panels with the ventilation airflow To form the RSC, a gap under the external layer of the roof allowed airflow from the interior of the house to a plenum in the peak of the attic with vents to the outside while cross ventilation was aided with openings in the interior walls allowing flow between rooms. The ventilation gap was modelled by discretizing the RSC into 12 sections and calibrating the air-flow and convection coefficients with corresponding CFD models	(with cooling requirements in between those of Pittsburgh and Phoenix). Albuquerque is a dry climate while Atlanta is a wet one. According to IECC climate zone nomenclature, Pittsburgh is 5A (moist), Albuquerque is 4B (dry), Atlanta is 3A (moist), Phoenix is 2B (dry). Typical Meteorological Year 3 (TMY3) weather data from NREL was adopted for each location

2.3 BI, Solar Shades

1. Yao J., An investigation into the impact of movable solar shades on energy, indoor thermal and visual comfort improvements, 2014: Building and Environment 71, 24 – 32.

http://dx.doi.org/10.1016/j.buildenv.2013.09.011

Contexts	Outcomes
Climatic zone: hot summer and cold winter zone of China Investigated building: a six-story residential building (2100 m^2) in Ningbo city in hot summer and cold winter zone of China which was retrofitted with external movable solar shades Modelling: a south-facing room (a typical living room in China for relaxing and socializing with a comfortable illuminance level of 100-300 lux depending on types of activity); simulation software Energyplus; building performance simulation	The building simulation study indicates that movable solar shade not only improves indoor thermal comfort in summer but also reduces dramatically extremely uncomfortable risks.

2.4 BA, Solar Cooling/heating

1. Mateus T. and Oliveira A. C., Energy and economic analysis of an integrated solar absorption cooling and heating system in different building types and climates
2009: Applied Energy 86(6), 949–957.

http://dx.doi.org/10.1016/j.apenergy.2008.09.005

Contexts	Outcomes
Integrated solar absorption cooling and heating systems for building applications. The TRNSYS software tool was used as a basis for assessment.	An optimization of solar collector size and other system parameters was analysed based on the simulated results

Building types considered: residential, office, hotel TRNSYS models for a whole year in terms of combining cooling/heating and DHW applications were utilized New TRNSYS component types were created for the absorption chillers Three different locations/climates were examined: Berlin (Germany), Lisbon (Portugal), Rome (Italy)	By using an integrated solar system for combined heating and cooling, it is possible to save in terms of total costs and CO_2 emissions (this is particularly true for South-European locations). The single-family house and the hotel were the cases where the solar integrated system showed a higher economic feasibility. Based on that energy costs, Rome was the only city where it was possible to achieve a break-even situation. Compared to flat-plate collectors, vacuum tube collectors allowed a reduction in collector area between 15 and 50%, although, due to their initial cost, flat-plate collectors had higher economic viability. In order solar cooling (and heating) to become more competitive, it is necessary the initial costs for absorption chillers and solar collectors to be lower.

2.5 General studies

1. Srebric J., Chen Q. and Glicksman L.R., A coupled airflow-and-energy simulation program for indoor thermal environment studies, 2000: ASHRAE Transactions 2000; Volume 106, Part 1, p. 929.

Contexts	Outcomes
Coupled airflow-and-energy simulation program → calculated simultaneously distributions of indoor airflow and thermal comfort and heating/cooling load Application of the program: to study thermal environment in a house and an atrium CFD and energy analysis program ACCURACY	The coupled program is capable of studying the dynamic airflow, heating/cooling load, and thermal comfort simultaneously in a space on a personal computer

2. Zhai Z., Chen Q., Haves P. and Klems J.H, On approaches to couple energy simulation and computational fluid dynamics programs, 2002: Building and Environment 37 (8–9), 857–864.

Contexts	Outcomes
Integrated energy (finite difference) and CFD (finite volume) simulation: static and dynamic coupling strategies Case studies: office in Boston; indoor auto racing complex in Pittsburgh	The coupling strategies considered were implemented by using the EnergyPlus and MIT-CFD programs

3 Studies of Energetic Simulation (emphasis: system)

3.1 BI, Skin Façade

1. J. Hensen, M. Bartak, F. Drkal, Modeling and simulation of a double-skin façade system, 2002: ASHRAE Transactions 108(2), 1251-1259.

Contexts	Outcomes
Double-Skin Façade System The airflow modeling methods considered were the mass balance network method and CFD The authors noted that network method is more suited for this type of "everyday" design support work but there are important areas where the network method in general might benefit from CFD, or vice-versa	To predict the performance of Double skin façade system constitutes a nontrivial modelling and simulation exercise that should be based on a thorough methodology and good working practice Both the network method and CFD have their own advantages and disadvantages for modelling this type of natural and hybrid ventilation systems.

2. Patania F., Gagliano A., Nocera F., Ferlito A., Galesi A., Thermofluid-dynamic analysis of ventilated facades, 2010: Energy and Buildings 42(7), 1148-1155.

http://dx.doi.org/10.1016/j.enbuild.2010.02.006

Contexts	Outcomes
Ventilated façade performance Complete thermofluid-dynamic analysis Analytical method for design applications (natural and forced convection configurations) Two-dimensional system Fluent software: finite-difference numerical solution technique based on integration over the control system Simulation for the ventilated façade considering the following climatic conditions: indoor air temperature = 297 K, temperature of the air at the inlet of the duct = outdoor air temperature = 301 K	A steady calculation method, suitable for design applications, has been illustrated to study the energy performances of ventilated façades during the summer period. The authors of that work introduced the energy saving rate ''S'' to evaluate the energetic performance of the ventilated façade. The CFD results showed: - The energy saving S augments if the solar radiation increases and thus, for constant value of the absorption coefficient and the outdoor temperature, the choice of the ventilated façade was recommended in site with high values of solar radiation. - The increase of the external air temperature resulted in decrease of the energy saving rate S due to the reduction of the effects of ventilation of the structures. - The increase of the inlet velocity

	caused reduction of the air temperature inside the duct and increase of the energy saving rate S.

3.2 BI, Solar Chimney

1. DeBlois J. C., Bilec M. M. and Schaefer L. L., Design and zonal building energy modeling of a roof integrated solar chimney, 2013: Renewable Energy 52, 241–250.

http://dx.doi.org/10.1016/j.renene.2012.10.023

Contexts	Outcomes
Roof integrated solar chimneys use solar radiation to heat air and induce natural ventilation through a house → they can improve the performance of roof integrated PVs by removing heat absorbed by the panels and enhance buoyant free cooling at night Unobtrusive, integrated solar chimney design in a detached single family home A method for modeling it in the zonal building energy modeling program ESP-r was proposed to assist in evaluating the design and predicting the thermal dynamics in changing ambient conditions. The model discretizes the solar chimney by dividing it into several zones CFD is used to calibrate key model inputs A sensitivity analysis evaluates model sensitivity to several inputs and assumptions The mathematical model consisted of a heat balance for nodes at each surface and in each zone and a pressure-based airflow balance. The airflow network included buoyancy forces and losses in the channel, at the inlet and at the outlet, balanced over all of the nodes The CFD model was 2D, created in ANSYS Fluent (CFD model was 2 dimensional, because the air channel was symmetric with an aspect ratio of over 30) The CFD model was more physically accurate model of heat transfer and fluid flow than the heat transfer correlation and pressure-based network used in ESP-r The model adopted a steady-state assumption and temporally constant temperature boundary conditions for the walls	The natural convection correlation selected for the walls of the channel worked well for flow driven by natural convection, but poorly for other flow modes The RSC concept shows promise as a way of providing free cooling in a house throughout the day and night, without requiring major changes in the form of the house.

3.3 BI, Trombe Wall

1. Zalewski L., Lassue S., Duthoit B. and Butez M., Study of solar walls - validating a simulation model, 2002: Building and Environment 37(1),109 –121.

http://dx.doi.org/10.1016/S0360-1323(00)00072-X

Contexts	Outcomes
Four solar wall configurations were examined: composite solar wall, Trombe wall, Insulated Trombe wall, Non-ventilated solar wall Experimental installation → measurements about thermal transfer for model validation Model: finite difference method, heat transfer was considered to be one dimensional	The model can be used to study the effect of design parameters or new materials (important for the future development of solar walls) and to compare different types of solar walls. The model is also used to study the energy efficiency of solar walls for different locations/climatic conditions

3.4 BI, PVT

1. Matuska T., Simulation Study of Building Integrated Solar Liquid PV-T Collectors, 2012: International Journal of Photoenergy 2012, 8 pages.

http://dx.doi.org/10.1155/2012/686393

Contexts	Outcomes
Simulation study on combined heat/electricity production from given BIPV-T collectors for three typical applications (5°C: primary circuits of heat pumps; 15°C: cold water preheating; 25°C: pool water preheating) was conducted Climatic conditions examined: two different European climates (warm: Athens; moderate: Prague) Mathematical model of unglazed solar flat-plate hybrid PV-T liquid collector (PVT-NEZ) based on principle theory for energy balance of solar thermal collectors expanded for photovoltaic conversion Input parameters of the model: thermal, optical, electrical, geometrical properties of PVT collector parts, climatic conditions, operation conditions Output parameters of the model: usable electric and thermal power, output temperature of liquid, temperature of absorber surface (PV cell) Building envelope integrated installations were modelled with added adjacent envelope insulation	Main factors defining the quality of PV-T thermal performance are cooling fin quality (conductivity, thickness, and length) and bond conductance between riser pipe and cooling fin. Building integration brings a large improvement especially to low-tech PV-T collectors. While high-tech BIPV-T collector configuration shows negligible temperature difference between PV and liquid at nominal conditions A huge potential for roof applications of BIPV-T collectors instead of BIPV with 15% to 25% increase of electricity production in warm climate (Athens) and 8% to 15% increase in moderate climate (Prague). Associated heat production is from several times to 10 times higher than electricity production. Low-tech BIPVT collectors could contribute with reduced performance

layer of given heat resistance at the back side of PV or PVT collector with constant temperature behind considered (as interior temperature) The calculation approach of the PVT-NEZ model used external energy balance of PVT absorber (heat transfer from PVT absorber surface to ambient) and internal energy balance of PVT absorber (electric yield, heat transfer from PVT absorber surface to liquid); both balances were solved in iteration loops to find PVT absorber temperature (PV cell) and relevant heat transfer coefficients.	level but still with considerable improvement when compared to BIPV modules without cooling.

2. Pantic S., Candanedo L. and Athienitis A. K., Modeling of energy performance of a house with three configurations of building-integrated photovoltaic/thermal systems, 2010: Energy and Buildings 42(10), 1779–1789.

http://dx.doi.org/10.1016/j.enbuild.2010.05.014

Contexts	Outcomes
Theoretical and experimental study of energy performance of three different open loop air heating BIPVT systems that utilize recovered heat for home heating: Configuration 1: base case of unglazed BIPV with airflow under it; Configuration 2: addition of 1.5 m vertical glazed solar air collector in series with Configuration 1; Configuration 3: addition of a glazing over the PV The model developed was verified against experimental data from a solar research house for Configuration 1 A mathematical model has been implemented in MathCad 2001i for the three BIPVT configurations A control volume formulation has been applied The partial differential equation for air and rock temperatures was solved numerically by explicit finite difference method Region of the solar house: Concordia, Canada	Mathematical models have been developed for - Unglazed BIPVT roof. - Unglazed BIPVT roof connected to a glazed solar air collector - Glazed BIPVT roof The obtained relationships for the BIPVT system exiting air temperature as function of solar irradiance and air speed in PV cavity may be used for developing fan airflow control strategies to achieve desired outlet air temperature for different applications. For the case of Configuration 1, preheated air was suitable for HVAC system and domestic hot water (DHW) preheating. Higher outlet air temperatures of PV cavity suitable for DHW might be achieved by Configurations 2 or 3. With Configuration 2, significant outlet air temperatures were achieved in winter along with enhanced thermal efficiency making it suitable for coupling with a rockbed heat storage unit. Configuration 3 significantly reduced electricity production and may lead to excessively high PV temperatures.

3. Davidsson H., Perers B. and Karlsson B., Performance of a multifunctional PV/T hybrid solar window, 2008: Solar Energy 84(3), 365 –372.
http://dx.doi.org/10.1016/j.solener.2009.11.006

Contexts	Outcomes
A BI multifunctional PV/T collector was developed and evaluated: the PVT solar window was constructed from PV cells laminated on solar absorbers and it was placed in a window behind the glazing → to reduce the costs of the solar electricity, reflectors were added to focus radiation onto the solar cells	A model for the simulation of the electric and hot water production was developed: the model could perform yearly energy simulations where different effects such as shading of the cells or effects of the glazing could be included or excluded The simulation program was calibrated against measurements of a prototype solar window placed in Lund in the south of Sweden and against a solar window built into a single family house, Solgården, in Älvkarleö in the middle of Sweden TRNSYS was adopted for some cases

4. Delisle V. and Kummert M., A novel approach to compare building-integrated photovoltaics/thermal air collectors to side-by-side PV modules and solar thermal collectors, 2014: Solar Energy 100, 50 –65.

http://dx.doi.org/10.1016/j.solener.2013.09.040

Contexts	Outcomes
Case study of 40 m^2 south-facing roof located in Montreal, Canada Simulation was done for BIPV/T air system and side-by-side PV modules and liquid solar thermal collectors (PV + T) using TRNSYS A new methodology was developed to deal with the challenge of comparing different types of energy. In this novel methodology, the two systems are operated based on criteria for thermal energy usefulness and the thermal energy collected is transferred into water using a heat exchanger. The concept of equivalent useful thermal energy production was adopted to combine the electrical and the thermal energy produced. To demonstrate the usefulness of that approach, a case study for a residence was performed by the authors.	For a conversion factor of 2, the BIPV/T system was found to produce 5–29% more equivalent useful thermal energy than the PV + T system

5. F. Ghani, M. Duke, J.K. Carson, Estimation of photovoltaic conversion efficiency of a building integrated photovoltaic/thermal (BIPV/T) collector array using an artificial neural network, 2012: Solar Energy 86, 3378–3387.

http://dx.doi.org/10.1016/j.solener.2012.09.001

Contexts	Outcomes
BIPVT dimensions are related with specific roofing and energy requirements of the customer; thus, the issue of flow distribution and its effect on both thermal and PV performance it is important. In order to quantify the effect of flow distribution on PV output of a BIPVT array, a numerical approach was developed by authors in a previous work. That study was numerical and the authors calculated PV output. However, that method was time consuming and computationally intensive. To address this issue, the authors proposed in this paper an artificial neural network which can be used to approximate the PV yield of an array of specified shape operating under parallel/reverse flow in the manifolds and also with one or two fluid channels cooling each string of cells.	By approximating the yield for each scenario, the optimal configuration can then be selected. It was found that the neural network can be successfully trained for this specific case offering a fast alternative to the original numerical approach.

3.5 BI, PV

1. Yoo S.-H., Simulation for an optimal application of BIPV through parameter variation, 2011: Solar Energy 85(7), 1291–1301.

http://dx.doi.org/10.1016/j.solener.2011.03.004

Contexts	Outcomes
The efficiency of a BIPV system as a shading device was examined at different months Weather data: Suwon area, Korea The simulation program SOLCEL, for the calculation of a shading/sunlit area on solar cell module and façade, surface temperature of solar cell module, effective solar irradiance on solar cell module, the power generation of a BIPV as a shading device, was developed and validated.	The efficiency of the BIPV system as a shading device is seen to vary greatly in different months. The simulation and experimental results for over surface temperature of solar cell module vary slightly under a higher solar irradiance condition.

2. Electrical/Energetic simulation (emphasis: system)
Stamenic L., Smiley E. and Karim K., Low light conditions modelling for building integrated photovoltaic (BIPV) systems, 2004: Solar Energy 77(1), 37-45

http://dx.doi.org/10.1016/j.solener.2004.03.016

Contexts	Outcomes
Low irradiance efficiency of PV modules was examined (low light level dependence of PV module efficiency is very important for accurate modeling of BIPVs, especially in northern latitudes and in climates with significant cloud cover). A new model for photovoltaic module performance was developed based on the single diode model of a solar cell, but introduced a single lumped parameter to the ideal diode equation to characterize the non-ideal characteristics of the cell. The model was first applied to the open circuit voltage data collected for a solar module operating under conditions in which low irradiance contributed a large percentage of energy to the total annual energy production. Once the validity of the model was verified for modeling open circuit voltage the model was applied to a more comprehensive model which calculated the total power production on an hourly basis over several days.	The proposed model was able to accurately predict the actual energy production of a test system (at British Columbia Institute of Technology (BCIT)). Region of the experimental set-up: BCIT, Burnaby, Canada The model is capable of modelling the performance of photovoltaic systems that produce a large percentage of their total energy at low irradiance conditions.

3. Fara L., Moraru A.G., Sterian P., Bobei A.P., Diaconu A. and Fara S., Building Integrated Photovoltaic (BIPV) systems in Romania. Monitoring, modelling and experimental validation, 2013: Journal of Optoelectronics and Advanced Materials 15(1-2), 125-130.

Contexts	Outcomes
Performance analysis of a BIPV system developed in Romania and mounted on the building of the Polytechnic University of Bucharest (PUB) The estimation of the energy production of the BIPVs, on a short term period (two days), was considered Short-term solar irradiation forecasts are elaborated in two ways, based on meteorological experimental datasets Forecasting tests were run using Autoregressive Integrated Moving Average (ARIMA) models.	Artificial neural network (ANN) techniques were also evaluated (based on meteorological variables) in order to enhance the forecasts of solar irradiation

4. Muresan C., Ménézo C., Bennacer R. and Vaillon R., Numerical Simulation of a Vertical Solar Collector Integrated in a Building Frame: Radiation and Turbulent Natural Convection Coupling, 2006: Heat Transfer Engineering, 27(2), 29-42.

DOI:10.1080/01457630500397658

Contexts	Outcomes
Vertical double skin PV façade (a tall PV module located at a fixed distance from a vertical wall of a building): elementary study During winter, fresh air is aspired by the air supply system; during the summer, supporting thermal chimney effect so as to cool PV The collector is subjected to direct and indirect sun irradiation while the space between the wall and the collector forms a channel, at the bottom of which air is admitted and buoyancy-driven convection is developed Damping functions were inserted in the kinetic energy of the turbulence dissipation (ε) equation to account for viscous and wall-damping effects A finite volume scheme with a second-order discretization method for both advection and diffusion terms was applied; pressure correction method was adopted; the resolution was performed by using the SIMPLER algorithm Coupling of radiation heat transfer with conduction in the collector cover and overall coupling with thermo-aerodynamics phenomena in the air channel	Preliminary results of coupled heat transfer for the whole collector were proposed by using gray radiation properties. For that specific case, it seemed that the turbulent regime appeared very close to vertical channel outlet. From all of these results, it is was concluded that further work is needed in order to include realistic variations of radiation properties, including photoelectric effects and sun irradiation, so that a complete parametric study will allow extracting the best strategy to integrate PVs to buildings.

5. Mondol J. D., Yohanis Y. G., Smyth M. and Norton B., Long-term validated simulation of a building integrated photovoltaic system, 2005: Solar Energy 78, 163–176.

http://dx.doi.org/10.1016/j.solener.2004.04.021

Contexts	Outcomes
The PV array was roof mounted facing due south at an inclination 45° and was located in Ballymena, Northern Ireland The electrical and thermal performance of the BIPV system was predicted using TRNSYS. A new component model has been developed for modeling inverter output and modifications were made to standard TRNSYS types for global-diffuse correlation and PV module temperature Statistical analysis was performed with the measured and predicted data for three global-diffuse	Developed TRNSY type for inverter has been validated with measured data. The results revealed that modification of global-diffuse correlation and module temperature prediction improved the overall accuracy of the simulation model. The monthly error between measured and predicted PV output was below 16%. Over the period of simulation, the monthly average error between the measured and the predicted PV output was 6.79% while

correlations and four tilted surface radiation models to find those best for estimating the beam and diffuse components of the horizontal insolation and total, beam and diffuse components of insolation at the inclined PV surface, respectively Measured and simulated electrical PV outputs were compared on daily basis	the monthly average error between measured and predicted inverter output was found to be 4.74%.

6. J.-H. Yoon, J. Song, S.-J. Lee, Practical application of building integrated photovoltaic (BIPV) system using transparent amorphous silicon thin-film PV module, 2011: Solar Energy 85(5), 723-733.

http://dx.doi.org/10.1016/j.solener.2010.12.026

Contexts	Outcomes
An analysis has been carried out on the first practical application in Korea of the design and installation of building integrated photovoltaic (BIPV) modules on the windows covering the front side of a building by using transparent thin-film amorphous silicon solar cells. This analysis was performed through long-term monitoring of performance for 2 years. Electrical energy generation per unit power output was estimated through the 2 year monitoring of an actual BIPV system.	From simulating influencing factors such as azimuth and shading, the measured energy generation efficiency in the tested condition can be improved up to 47% by changing the building location in terms of azimuth and shading, thus allowing better solar radiation for the PV module. From the real application of the BIPV system, the installation of a PV module associated with azimuth and shading can be said to be the essentially influencing factors on PV performance Both factors can be useful design parameters in order to optimize a PV system for an architectural BIPV application.

7. T. Dwi Atmajaa, Façade and rooftop PV installation strategy for building integrated photo voltaic application, 2013: Energy Procedia 32, 105-114.

http://dx.doi.org/10.1016/j.egypro.2013.05.014

Contexts	Outcomes
Building integrated photo voltaic (BIPV) is an emerged research topic to optimize building component replacement using certain types of photo voltaic (PV) module. This paper conducts a strategic review on the	Recent calculations of the inclination angle of attaching the PV module in the selected walls indicates that an optimum angle in horizontal and vertical inclination.

optimum PV module installation to generate electricity from the building envelope. The façades and rooftops would be an object of building envelope to be deposited with a specific characteristic installation of PV module.	The calculation also uses installation distance to module length ratio to achieve a greater solar insulation on the PV modules. Other calculation also performed to observe effective load carrying capacity (ELCC) against PV penetration level to perceive the optimum PV penetration level for high ELCC without resulting operational problems.

8. D. Masa-Bote, E. Caamaño-Martín, Methodology for estimating building integrated photovoltaics electricity production under shadowing conditions and case study, 2014: RenewableandSustainableEnergyReviews31, 492–500.

http://dx.doi.org/10.1016/j.rser.2013.12.019

Contexts	Outcomes
The electricity losses due to shadows over PV generator have an impact on the performance of BIPV systems (electricity losses). In the frame of that work a methodology to estimate electricity produced by BIPV systems which incorporated a model for shading losses, was developed. The methodology was validated by means of one-year experimental data from two similar PV systems (BI on the roof) of a building which belongs to the Technical University of Madrid. The study included several weather conditions: clear, partially overcast, fully overcast sky.	The errors by the best performing model were less than 1% and 3% in annual and daily electricity estimation. The adoption of models which account for the reduced performance at low irradiance levels also improved the estimation of generated electricity. The authors noted that the proposed methodology is simple, easy-to-use and can provide fast/accurate results at low costs. Also it could be applied for PV systems which are not BI.

3.6 BI, CPV

1. E. F. Fernández, F. Almonacid, N. Sarmah, P. Rodrigo, T.K. Mallick, P. Pérez-Higueras, A model based on artificial neuronal network for the prediction of the maximum power of a low concentration photovoltaic module for building integration, 2014: Solar Energy 100, 148 –158.

http://dx.doi.org/10.1016/j.solener.2013.11.036

Contexts	Outcomes
Low concentration photovoltaic (LCPV) modules for BI are studied. The aim of that work was the development of an accurate model based on artificial neural networks (ANNs) to predict the maximum power (P) of a LCPV module for building integration	The model takes into account all the main important parameters that influence the electrical output of these systems: direct irradiance, diffuse irradiance, module temperature and

under real conditions.	the transverse and longitudinal incidence angles. The proposed model can be used for estimating the maximum power of a BI LCPV module with an adequate margin of error: R2 = 0.99. The ANN model had accurate performance for days in which the maximum power was mainly given by direct irradiance (clear days) and also for days in which the maximum power was mainly given by diffuse irradiance (cloudy days). Nevertheless, the performance of the artificial network based model had poorer results for the diffuse irradiance component than for the direct irradiance component. Despite this fact, the ANN based model can predict the maximum power of a BI LCPV module with an adequate degree of accuracy.

3.7 BA, Solar Cooling

1. K.F. Fong, C.K. Lee, T.T. Chow, Comparative study of solar cooling systems with building-integrated solar collectors for use in sub-tropical regions like Hong Kong, 2012: Applied Energy 90, 189–195.

http://dx.doi.org/10.1016/j.apenergy.2011.06.013

Contexts	Outcomes
The performance of solar cooling systems with building-integrated (BI) solar collectors was simulated and the results compared with those having the solar collectors installed conventionally on the roof based on the weather data in Hong Kong. Two types of solar collectors and the corresponding cooling systems, namely the flat-plate collectors for absorption refrigeration and the PV panels for DC-driven vapour compression refrigeration, were used in the analysis.	It was found that in both cases, the adoption of BI solar collectors resulted in a lower solar fraction (SF) and consequently a higher primary energy consumption even though the zone loads were reduced. The reduction in SF was more pronounced in the peak load season when the solar radiation was nearly parallel to the solar collector surfaces during the daytimes, especially for those facing the south direction. It was concluded that the use of BI solar collectors in solar cooling systems should be restricted only to situations where the availability of the roof was limited or insufficient when applied in sub-tropical regions like Hong Kong.

3.8 General studies

1. Athienitis A., Modeling and Simulation of Passive and Active Solar Thermal Systems, 2012: Reference Module in Earth Systems and Environmental Sciences
Comprehensive Renewable Energy, 357–417, Volume 3: Solar Thermal Systems: Components and Applications.

http://dx.doi.org/10.1016/B978-0-08-087872-0.00311-5

Contexts	Outcomes
That chapter presented major passive solar technologies and systems, followed by in-depth sections on their modeling (using both analytical and numerical models) More recent developments were described with a focus on BIPVs and net-zero energy solar homes	Various design methods were presented as well as an overview of the simulation techniques and programs suitable for active solar heating as well as cooling systems The software programs described briefly in that chapter included F-chart, TRNSYS and WATSUN

2. T. Hwang, S. Kang, J. T. Kim, Optimization of the building integrated photovoltaic system in office Buildings - Focus on the orientation, inclined angle and installed area, 2012: Energy and Buildings 46, 92-104.

http://dx.doi.org/10.1016/j.enbuild.2011.10.041

Contexts	Outcomes
This study aims to analyze the maximum electric energy production according to the inclination and direction of photovoltaic (PV) installations and the effects of the installation distance to the module length ratio. The annual solar insolation on PV panels was calculated for various façades of two buildings, and an analysis of different horizontal and vertical inclinations of PV panels was also conducted in consideration of the effects of panel shading from other panels and surrounding buildings.	As a result, the electric energy production due to the use of the PV system can cover approximately 1–5% of the electric energy consumption of a typical office building in Korea in terms of proper combinations of the following installation factors: inclination, module type, installation distance to module length ratio, and direction. The research estimated the proportion of power generation by BIPV systems according to different types of PV modules and installation methods. The data could serve as a useful reference for the application of BIPV systems in buildings.

3. S. Sharples, H. Radhi, Assessing the technical and economic performance of building integrated photovoltaics and their value to the GCC society, 2013: Renewable Energy 55, 150-159.

http://dx.doi.org/10.1016/j.renene.2012.11.034

Contexts	Outcomes
This paper assesses the technical and economic performance of PV technology integrated into residential buildings in the Gulf Cooperation Council (GCC) countries.	Through a systematic modelling analysis it is shown that the efficiency of PV system drops by 4-6% due to high range of module temperature and also a change in power output due to high ambient temperatures. Consequently, the outputs of horizontal and vertical PV modules are found to be less than estimates based on standard test conditions. Economically, this study shows that building integrated photovoltaic (BIPV) systems are not viable in GCC countries and cannot compete with conventional electricity sources on a unit cost basis.

4. W. Zhou, H. Yang, Z. Fan, A novel model for photovoltaic array performance prediction, 2007: Applied Energy 84, 1187–1198.

http://dx.doi.org/10.1016/j.apenergy.2007.04.006

Contexts	Outcomes
Based on the I–V curves, a novel and simple model was proposed. In order to validate the model, field measured data from one existing BIPV in Hong Kong was adopted and good agreements between simulated results/field data was found.	Five parameters were introduced to take account of all the non-linear effect of the environmental factors on PV module performance Model accuracy was demonstrated by comparing the predictions with the field data. The model was verified for several meteorological conditions (sunny, cloudy, four seasons). The results demonstrate acceptable accuracy of the model for modeling PV array outputs over various environmental conditions.

5. Kim J., Adaptive façade design for the daylighting performance in an office building: the investigation of an opening design strategy with cellular automata, 2013, International Journal of Low-Carbon Technologies 1-8.

doi: 10.1093/ijlct/ctt015

Contexts	Outcomes
The objective was the development of an innovative façade design strategy that comes from the	Each CA design value was tested under static and dynamic sky condition in

development of digital technology and dynamic daylight performance measuring methods. The parameters were studied through the computational process of cellular automata (CA) to generate the several alternative opening patterns on building façade.	order to analyze the quality and quantity of daylight and visual comfort over the year. The proposed CA system allowed changing the average opacity of building façade and tool advantage from the generative behavior for esthetics. The visualized daylight analysis maps with numeric data helped for the searching of the adaptive façade design.

6. T. Hong, C. Koo, J. Park, H. S. Park, A GIS (geographic information system)-based optimization model for estimating the electricity generation of the rooftop PV (photovoltaic) system, 2013: Energy, 1-10.

http://dx.doi.org/10.1016/j.energy.2013.11.082

Contexts	Outcomes
A sensitivity analysis on how the impact factors of the rooftop PV system affect its electricity generation was conducted. That study aimed to ultimately develop a GIS-based optimization model for estimating the electricity generation of a rooftop PV system.	Several impact factors were adopted in the sensitivity analysis. The result of this study showed that there were 1.12-, 1.62- and 1.37-fold differences in the annual electricity generation of the rooftop PV in South Korea due to the regional factor, the azimuth of the installed panel and the slope of the installed panel, respectively.

7. Lin Lu and Yang H. X., A study on simulations of the power output and practical models for Building Integrated Photovoltaic systems, 2004: Journal of Solar Energy Engineering 126(3), 929-935.

doi:10.1115/1.1701883

Contexts	Outcomes
A simple, practical, accurate model for describing the characteristics of PV power output was developed (describing I-V characteristics of PV modules according to the equivalent circuits of solar cells, by which an accurate but complicated model of the maximum power output (MPO) can be achieved).	Taking that MPO model as benchmark, two other application models from other studies were evaluated and examined. A simplified application model for describing the maximum PV power output was then derived from the results of the simulation. Once solar radiation on PVs and ambient temperature are known, the power output of BIPV systems or PV systems can be calculated accurately and easily.

8. S. Karthikeyan, G. Ravikumar Solomon, V. Kumaresan, R. Velraj, Parametric studies on packed bed storage unit filled with PCM encapsulated spherical containers for low temperature solar air heating applications, 2014: Energy Conversion and Management 78, 74 –80.

http://dx.doi.org/10.1016/j.enconman.2013.10.042

Contexts	Outcomes
(PCM) encapsulated spherical containers for low temperature solar air heating applications. Parametric analysis was performed using validated enthalpy based numerical model that considers the thermal gradient inside the PCM container.	The results of the simulations showed that the size of the PCM ball, fluid inlet temperature and mass flow rate of the heat transfer fluid (HTF) influenced respectively the heat transfer area in the packed bed, temperature difference between the HTF and PCM and the surface convective heat transfer coefficient between HTF and PCM balls. The poor thermal conductivity of the PCM had only negligible effect on heat transfer because of high surface convective resistance provided by the air. The influence of various parameters for the selected range of values were analyzed using the charging time, instantaneous heat stored and cumulative heat stored during the charging process.

4 Studies of Energetic Simulation (emphasis: building/system)

4.1 BI, Skin Façade

1. Saelens D., Roels S. and Hens H., The inlet temperature as a boundary condition for multiple-skin façade modeling, 2004: Energy and Buildings 36 (8), 825–835.

http://dx.doi.org/10.1016/j.enbuild.2004.01.005

Contexts	Outcomes
The results of numerical models for multiple-skin façades (MSFs) are very sensitive to inlet temperature → to illustrate this, a sensitivity study on mechanically and naturally ventilated façade was conducted by means of a numerical model (cell-centred finite volume method) - MSF model was also coupled to TRNSYS → energy performance analysis - MSF model and building model - Climatic conditions: Belgium, February	By analysing the influence of the inlet temperature, this work showed that a reliable energy assessment needs a correct implementation of the boundary conditions and modelling parameters. Measurements showed that the assumption of an inlet temperature equal to the interior or exterior air temperature was usually not valid. A sensitivity study revealed the significance of the inlet temperature as a boundary condition for numerical multiple-skin façade models. Models to estimate the inlet temperature should take the heating and cooling because of contact with the bounding surfaces and heating due to solar radiation. In addition, the effects of a change of the airflow rate have to be considered.

2. R. Høseggen, B.J. Wachenfeldt, S.O. Hanssen, Building simulation as an assisting tool in decision making Case study: With or without a double-skin façade?, 2008: Energy and Buildings 40, 821–827.

http://dx.doi.org/10.1016/j.enbuild.2007.05.015

Contexts	Outcomes
A planned office building in the city-centre of Trondheim, Norway, was adopted as case for considering whether a double-skin should be applied to the east façade in order to reduce the heating demand, thus making the double-skin façade a profitable investment. The building was modeled both with and without a double-skin façade (building energy simulation program ESP-r). That work described how a double-skin façade with controllable	Simulation results showed that the energy demand for heating was about 20% higher for the single-skin façade with the basic window solution compared to the double-skin alternative. Nevertheless, by switching to windows with an improved U-value in the single-skin alternative, the difference in energy demand was

windows and hatches for natural ventilation can be implemented in the simulation program.	almost evened out. The number of hours with excessive temperatures was not significantly higher for the double-skin alternative. However, the predicted energy savings were not sufficient in order to make the application of a double-skin façade profitable.

4.2 BI, Trombe Wall

1. Bojic M., Johannes K. and Kuznik F., Optimizing energy and environmental performance of passive Trombe wall, 2013, Energy and Buildings 70, 279 – 286.

http://dx.doi.org/10.1016/j.enbuild.2013.11.062

Contexts	Outcomes
Energy and environmental performance: buildings with and without Trombe walls Two Trombe walls were adopted at the south side of a "Mozart" house located in Lyon, France. The house satisfied the French thermal regulation The simulation was conducted by using EnergyPlus, Genopt and parametric algorithm	The results showed that the building with Trombe walls in Lyon, France, by using solar energy may save around 20% operating energy during heating compared to that used by the building without Trombe walls. The environmental impact of the buildings was also examined.

4.3 BI, PVT

1. Kim J.H., Kim J.T., A simulation study of air-type building-integrated photovoltaic-thermal system2012: Energy Procedia 30, 1016 – 1024

http://dx.doi.org/10.1016/j.egypro.2012.11.114

Contexts	Outcomes
TRNSYS simulation was performed The electrical and thermal performance of air type BIPVT system was evaluated The energy performance of a building was calculated considering air type BIPVT as a building envelop.	It was concluded from the simulation result that BIPVT system was more efficient compared to BIPV system without ventilation.

4.4 BI, PV

1. Chow T. T., Fong K. F., He W., Lin Z. and Chan A. L. S., Performance evaluation of a PV ventilated window applying to office building of Hong Kong, 2007: Energy and Buildings 39, 643–650.

http://dx.doi.org/10.1016/j.enbuild.2006.09.014

Contexts	Outcomes
An energy model of a PV ventilated window system was developed, based on TMY weather data for Hong Kong Energy model of the PV ventilated window: 2D computer model Performance analysis of application: small office: 3 m × 3 m × 3 m cubicle office within the perimeter zone of an office building; indoor temperature set points = 22^{o}C in winter (from November to April next year) and 25^{o}C in summer (from May to October) The simulation results on daylight saving were obtained by using EnergyPlus simulation software	The energy model of the PV ventilated window system was first introduced. Based on that together with TMY weather data for Hong Kong and the daylight simulation capability of the EnergyPlus program, the overall performance analysis was executed for different window orientations. It was found that a solar cell transmittance from 0.45 to 0.55 could achieve the best electricity saving.

2. J. Pérez-Alonso, M. Pérez-García, M. Pasamontes-Romera, A.J. Callejón-Ferre, Performance analysis and neural modelling of a greenhouse integrated photovoltaic system, 2012: Renewable and Sustainable Energy Reviews 16(7), 4675-4685.

http://dx.doi.org/10.1016/j.rser.2012.04.002

Contexts	Outcomes
Greenhouses can include added capabilities for the energy generation by the integration of photovoltaic solar modules in their cladding provided that the blocking effect of photo-synthetically active radiation is not significant for plants growing. This work describes the results of an experience carried out at Almería (South Eastern Spain), where it has been built and monitored a 1.024 m^2 pilot photovoltaic green house. The experimental setup has consisted of a green house roof 9.79% coverage ratio by means of 24 flexible thin film modules, installed in two different checker board configurations.	The obtained results indicate that, for the conditions of the undertaken experiment, they early electricity production normalised to the green house ground surface is 8.25 kWh/m^2, concordant to previous findings for the used type of modules. An artificial neural network model has been elaborated to predict the electricity instantaneous production of the system, showing the suitability of this modelling technique for complex and non linear systems, as it is the case of the constructively integrated PV plants, either in green houses and buildings, where both impinging radiation and system configuration are highly constrained by the pre-existing structures.

3. T.T. Chow, J.W. Hand, P.A. Strachan, Building-integrated photovoltaic and thermal applications in a subtropical hotel building, 2003: Applied Thermal Engineering 23, 2035–2049.

http://dx.doi.org/10.1016/S1359-4311(03)00183-2

Contexts	Outcomes
Comparative study of three different options in applying large-scale BIPVs in a coastal city at the South China Sea. The computational model was based on a 260 m^2, mono-crystalline Si PV wall of a 30-storey hotel. The numerical analysis was conducted by ESP-r building energy simulation software.	The results revealed that the different design options exhibit short-term electrical performance differences, but they have similar long-term electricity yields. Nevertheless, some configurations performed much better in terms of reducing building air-conditioning loads.

4. C. Hachem, A. Athienitis, P. Fazio, Energy performance enhancement in multistory residential buildings, 2014: Applied Energy 116, 9–19.

http://dx.doi.org/10.1016/j.apenergy.2013.11.018

Contexts	Outcomes
The effect of increasing residential density in multistory buildings on the overall solar potential and energy use of these buildings was examined. Hourly direct solar radiation was computed by EnergyPlus (ASHRAE model of clear sky applied to Montreal) The Equivalent One-Diode Model (or ''TRNSYS PV'' model, EnergyPlus) was adopted to perform electricity generation	Apartment buildings/passive solar configurations were adopted: low, mid-, high- rise. All integration of PV systems in façades, in addition to roof surfaces was considered. The study revealed that investment in advanced design of façades (such as folded-plate curtain walls) can substantially increase the production of electricity and it can achieve net zero and surplus energy status in building over eight stories high.

4.5 General Studies

1. Clarke J.A, Johnstone C., Kelly N. and Strachan P. A., The simulation of Photovoltaic-Integrated building facades, 1997: 5th IBPSA Conference: Sept. 8-10, Prague, Czech

Contexts	Outcomes
Extension to the ESPr system: simulation of façade and roof-integrated PVs The algorithms were for predicting electrical power output as a function of module characteristics, incident solar radiation and module temperature. The integration of the algorithm within ESP-r air and power flow network models, to facilitate hybrid photovoltaic system studies was described Building: initially located within the UK and then, in a warmer European climate corresponding to northern Italy	Integration with within the ESP-r → aspects of coupling: assignment of special behavior to multilayered construction nodes in order to transform some part of their absorbed solar energy to electricity; use of an air flow network to transport heat from nodes designated as PV cells and deliver this heat to intra-building locations via heat exchangers or directly; use of an electrical power flow network for modeling of local electricity use and co-operative switching with the grid

2. Kelly N. J., Towards a design environment for building integrated energy systems: the integration of electrical power flow modelling with building simulation, 1998: MSc thesis, Department of Mechanical Engineering. Energy Systems Research Unit University of Strathclyde, Glasgow, UK

Contexts	Outcomes
Power flow modeling: coupling the electrical network to the rest of the building model could be conducted by using 'hybrid' components that also exist in other energy subsystems of the building model. These hybrid components can supply the power flows necessary for the solution of the electrical network → integration of the electrical network solver into ESP-r flexible, modular simultaneous solution process	Component models for BI energy systems simulation: various component types could be added to ESP-r for use in the integrated simulation of the electrical network and BI energy systems: the electrical conductors and transformers which couple the control volumes in the electrical network; the hybrid load and the plant components which draw power from the electrical network, while simultaneously affecting thermophysical conditions in other parts of building network; the hybrid and the plant components could be used in the modeling of BI energy systems Verification of the electrical network solver and hybrid model calibration

3. Kim K. H. and Han S. H., Integrated Towers: High Performance Facades, 2012: Conference WREF 2012, CO, US, 13-17 May.

Contexts	Outcomes
The analysis was based on the case study of high-rise integrated towers located in two different climate zones: Aurora Tower in Kuala Lumpur, Malaysia located in Climate Zone 1A; New York Times building in New York City located in Climate Zone 4A That research adopted the integration of BIM (building information modeling) and energy simulation tool to facilitate workflow of 3D modeling and energy performance verification of building façades The work focused on three areas: heat gain, daylighting control benefits and solar energy potentials from building façades	The authors noted that integration of BIM and energy simulation tool provides timely efficient energy verification and offers a powerful framework toward solving many problems in contemporary building sustainability

4. M. Bojić, M. Miletić, D. Cvetković,
Optimization of size of overhangs with and without solar collectors, 2013: 26 th International Conference ECOS, Guilin, Guangxi, China, 2013, 16-19 July.

http://is.mfkg.kg.ac.rs/podaci/Dragan_Cvetkovic/106/D069final.pdf

Contexts	Outcomes
This paper presents the results of the optimization of the size of overhangs with and without solar collectors for two summer houses that operate during a cooling season in Serbia. The first house only has overhangs. The second house has overhangs covered by solar collectors. They are simulated and optimized by using EnergyPlus and Hooke Jeeves algorithm for their cooling season operation. Then, optimal depths of the overhangs are found.	The objective function serves to minimize the primary energy consumption needed for sanitary water heating and space cooling of the house, and amount of embodied energy in overhangs and solar collectors. Results show that overhangs depth depends on the use of solar collectors. Their depths also depend on their orientation.

5. N. Aste, R. S. Adhikari, L. C. Tagliabue , Solar integrated roof: Electrical and thermal production for a building renovation, 2012: Energy Procedia 30, 1042-1051.

http://dx.doi.org/10.1016/j.egypro.2012.11.117

Contexts	Outcomes
Solar renovation of a training Centre at Casargo, Lecco, Italy. The technology used for the roof refurbishment is an innovative system called TIS (Tetto Integrale Solarizzato); which means solar integrated roof. TIS is a modular covering system with the option to insert the various types of solar energy modules, providing most suitable dimension and configuration for a specific application.	The prototype of TIS system was presented. This paper presents the design details, energy performance and economic evaluation of solar integration roof of Casargo. The building is under monitoring phase. A comparison has been made between the monitored and simulated energy performance data.

6. S. A. Kalogirou, M. Bojic, Artificial neural networks for the prediction of the energy consumption of a passive solar building, 2000: Energy 25, 479–491.

http://dx.doi.org/10.1016/S0360-5442(99)00086-9

Contexts	Outcomes
Artificial neural networks (ANNs) were adopted for the prediction of the energy consumption of a passive solar building. Building thermal behavior was evaluated by using a dynamic thermal building (finite volumes and time marching).	The ANN modeling was able to predict the energy consumption of a building with acceptable accuracy. The application of ANNs revealed that it is possible to model such systems with a minimum amount of input data, thus providing the designer of such systems with the flexibility to test a number of systems quickly.

7. L. F. Sim, Numerical modelling of a solar thermal cooling system under arid weather conditions, 2013: Renewable Energy, In press.

http://dx.doi.org/10.1016/j.renene.2013.11.032

Contexts	Outcomes
A study about thermal cooling for an office (weather conditions: Doha, Qatar). The simulations were performed by using TRNSYS. Studied parameters: solar collector area, collector slope, tank volume, water flow rate, heat exchanger effectiveness.	The results revealed that the optimum system for 4.5 kW adsorption cooling required 23.4 m^2 evacuated tube collector titled at 24^o from horizontal with a water storage tank of 0.3 m^3. The adsorption cooling system can reduce the electricity consumption by 47% in comparison with a compression cooling system.

8. A. Colmenar-Santos, J. Vale-Vale, D. Borge-Diez, R. Requena-Pérez, Solar thermal systems for high rise buildings with high consumption demand: Case study for a 5 star hotel in Sao Paulo, Brazil, 2014: Energy and Buildings 69, 481–489.

http://dx.doi.org/10.1016/j.enbuild.2013.11.036

Contexts	Outcomes
Solutions for solar water installations in high rise buildings were studied. The integration of solar collectors into the building, hot water distribution installation and solutions to minimize the risk of exposure to Legionella, were examined. The requirements of solar thermal in developing countries were examined: solar hot water standards in Brazil (Sao Paulo). Software adopted: RETScreen	The proposed solutions for solar hot water systems for the case of high rise building applications minimize the issues with the pressure distribution due to the height of the building. A case study about a 5-star hotel clearly justified the installation of solar thermal systems in buildings with a high demand for hot water.

5 Studies of Thermal Simulation (emphasis: building)

5.1 BI, Skin Façade

1. Gratia E. and De Hendre A., Greenhouse effect in double-skin façade, 2007: Energy and Buildings 39(2), 199–211.

http://dx.doi.org/10.1016/j.enbuild.2006.06.004

Contexts	Outcomes
TAS software for building thermal analysis was used Identification of the factors that influence greenhouse effect → impact of these parameters on cavity temperature evolution Identified parameters: solar radiation level, cavity depth of the double-skin, glazing type, etc. A middle-size office building was examined Climatic data assumptions: Belgian standard days	The factors that influence the greenhouse effect are solar radiation level, orientation and shading devices use, opaque wall/window proportion of the interior façade, wind speed, colour of shading devices and of interior façade, depth of the cavity of the double-skin, glazing type in the interior façade and openings in the double-skin.

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

Contexts	Outcomes
A method for assessing the integrated energy performance of passive and active multi-section façade systems combined with lighting and thermal controls of perimeter building zones by using an open source language A thermal network approach was adopted to predict indoor thermal environmental conditions and annual energy consumption of perimeter zones equipped with combinations of passive and active façade systems such as selective glazings, translucent panels, motorized shades and blinds, in conjunction with daylight-linked lighting controls The model utilized anisotropic sky models for an accurate prediction of solar gains, variable angular glazing properties and non-linear interior and exterior convection and radiation heat transfer coefficients together with transient internal gains obtained from transient lighting simulation	A simple private office with one exterior window was adopted as an initial case study Experimental measurements (in full-scale laboratories with and without shading) were utilized to compare to simulation results in order to validate the model The model was expanded and generalized to include the impact of multi-sectional façades in order to evaluate the combined impact of glazing and shading configurations on energy demand/thermal comfort

5.2 General studies

1. Alemu A. T, Saman W. and Belusko M., A model for integrating passive and low energy airflow components into low rise buildings, 2012: Energy and Buildings 49, 148–157.

http://dx.doi.org/10.1016/j.enbuild.2012.02.002

Contexts	Outcomes
Passive airflow components which require simultaneous prediction of air temperature and flow rate were integrated into a coupled building ventilation and thermal model That model allowed the assessment of a combination of passive features such as solar chimney and wind induced earth-air tunnel for both natural and hybrid ventilation systems at the design stage → the model could facilitate the design of buildings with passive cooling features thus, minimizing the need for conventional cooling Mathematical model: a multi zone building ventilation and thermal model with integrated passive cooling features. The model was quasi steady state for each simulation hour. Separate wind and buoyancy driven airflow components (including solar chimney and wind induced earth-air tunnel were added into the multizone ventilation model The thermal model was a quasi-steady model applied to lightweight structure and thermal capacitance was ignored. The internal heat load, solar load and the heat transfer through walls, windows, roof, ground and openings were taken into consideration	The output of the model was compared with well validated TRNSYS-COMIS software for a naturally ventilated single zone building with a low and a high level large openings (space dimensions: 5 m x 5 m x 3 m height) A simulation was conducted for a single day (the first day of January using the TRNSYS weather database for Adelaide, Australia)

6 Studies of Thermal Simulation (emphasis: system)

6.1 BI, Solar Thermal Collectors

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

http://dx.doi.org/10.1016/j.renene.2012.04.049

Contexts	Outcomes
A new concept of a solar collector for water heating, patented, with high building integration, without any visual impact was presented Numerical calculations in Matlab by using a finite difference model and an electrical analogy were performed Thermal model: a nearly bi-dimensional model with the thermal transfers was developed; it was composed of a serial assembling of one-dimensional elementary models. Each model was based on a nodal discretization of the solar collector.	Good agreement between numerical and experimental results was found At low reduced temperature values, the thermal performances were found to be close to the conventional ones. However, the authors noted that it is necessary to optimize the shape of that collector in order to improve thermal insulation. This will be conducted by using the developed thermal model. The next step will be to include in that model a differentiation between direct and diffuse radiation and to develop correlations between the thermal coefficients and the environmental parameters (e.g. sky temperature correlated to the clearness index).

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

http://dx.doi.org/10.1016/j.apenergy.2012.08.012

Contexts	Outcomes
A new concept of flat plate solar collector is presented: its originality comes from its remarkable shape and from its integration into a rainwater gutter. The complete solar collector consists in several short modules connected serially.	A numerical model is developed in Matlab environment using a finite difference model and an electrical analogy. At last, the thermal model is validated from experimental data under various meteorological situations. The adequacy of the model with the experimental data is shown for various temperatures inside the solar collector

	and for the water temperatures.

3. Anderson T. N., Duke M., Carson J. K., The effect of colour on the thermal performance of building integrated solar collectors, 2010: Solar Energy Materials and Solar Cells 94(2), 350–354.

http://dx.doi.org/10.1016/j.solmat.2009.10.012

Contexts	Outcomes
Experimental and theoretical work One-dimensional steady- state thermal model based on the Hottel–Whillier–Bliss equations Region/climatic conditions: Auckland, New Zealand	The theoretical thermal efficiency of colored collectors was determined Having demonstrated and validated the design model of the colored solar collectors, it was examined the fraction of a typical domestic water-heating load that could be provided by the various theoretical colored collectors. An F-chart was constructed for the operation of the collectors in Auckland, New Zealand Low-cost coloured mild steel collectors could potentially provide noticeable contributions to domestic water heating loads. The performance of coloured solar collectors can be accurately modelled using a combination of experimental and numerical techniques. The use of coloured solar collectors will start to be an area that receives more attention than it has to date.

6.2 BI, Skin Façades

1. von Grabe J., A prediction tool for the temperature field of double facades, 2002: Energy and Buildings 34(9), 891–899.

http://dx.doi.org/10.1016/S0378-7788(02)00065-8

Contexts	Outcomes
Development and validation of a simulation algorithm for the temperature behaviour and the flow characteristics of double façades	It has been developed in order to obtain a tool which enables the energy consultant to make quick design decisions

2. Park C. S., Augenbroe G., Messadi T., Thitisawat M. and Sadegh N., Calibration of a lumped simulation model for double-skin façade systems, 2004: Energy and Buildings 36(11), 1117–1130.

http://dx.doi.org/10.1016/j.enbuild.2004.04.003

Contexts	Outcomes
Calibration of a simulation model of double-skin façade systems with controlled rotating louvers and ventilation openings The approach of the investigation was based on a parameter estimation technique and in situ monitoring of a full-scale element mounted on the south facing façade of an existing building The new approach was based on a postulated "minimalistic" lumped model which was calibrated on in-situ measurements	The lumped models for double-skin façade systems can be easily constructed based on a "grey box" approach, i.e., partly based on the lumped descriptions of dominant physical processes, and augmented by calibration parameters to make up for the simplifications. The model is very accurate in the prediction of the most relevant state variables, reliable for performance studies, and computationally light enough for model based optimal control.

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

http://dx.doi.org/10.1016/j.enbuild.2005.02.006

Contexts	Outcomes
Non-dimensional analysis is proposed as a method to analyze mechanically ventilated double glazed façade energy performance. The 12 non-dimensional numbers defined can be used to describe thermal and energy performance of interactive façade designs. A comparison between Nusselt number solved by experimental data and Nusselt calculated by the validated multivariable correlation function is reported in the present paper. Due to its wide validity field the proposed method can be used to analyze thermodynamic performances of glass double-skin façades with mechanical ventilation	Applying non-dimensional analysis to a mechanically ventilated double glass façade, a correlation between 12 nondimensional numbers has been obtained. Model has been validated using experimental data. The proposed method is useful to study thermal energy performances of mechanically ventilated double-skin façades for different climatic conditions, aspect ratio, shading device systems and also different thermo-physical characteristics of two glasses.

4. Coussirat M., Guardo A., Jou E., Egusquiza E., Cuerva E. Alavedra P., Performance and influence of numerical sub-models on the CFD simulation of free and forced convection in double-glazed ventilated façades, 2008: Energy and Buildings 40 (10), 1781–1789.

http://dx.doi.org/10.1016/j.enbuild.2008.03.009

Contexts	Outcomes
Double-glazed façades	In this work, several modeling tests were carried out on a well-documented

CFD Fluent software: flow and heat transfer modeling Undesirable building oveheating → Mediterranean climates	experimental test case taken from the open literature in order to obtain a suitable model of the aforementioned thermo-fluid-dynamics effects.

5. Pérez-Grande I., Meseguer J. and Alonso G., Influence of glass properties on the performance of double-glazed facades, 2005: Applied Thermal Engineering 25 (17-18), 3163-3175.

http://dx.doi.org/10.1016/j.applthermaleng.2005.04.004

Contexts	Outcomes
Glass properties influence on the performance of double-glazed façades Continental climate areas with warm summers (these façades increase dramatically the cooling requirements over summer months) → selection of appropriate glass	The thermo-fluid dynamics problem was solved by finite-volume commercial code, FLUENT, with a standard k–ε turbulence model By giving emphasis on the thermal balance, it was showed that an appropriate selection of the glasses forming the channel can reduce the thermal load into the building by almost an order of magnitude. It was also demonstrated that an appropriate use of the air stream flowing between the glass surfaces can improve global thermal balance.

6. Guardo A., Coussirat M., Egusquiza E., Alavedra P. and Castilla R., A CFD approach to evaluate the influence of construction and operation parameters on the performance of Active Transparent Façades in Mediterranean climates, 2009: Energy and Buildings 41(5), 534 –542.

http://dx.doi.org/10.1016/j.enbuild.2008.11.019

Contexts	Outcomes
Active Transparent Façades (ATF) Mediterranean climate → overheating Influence of construction/operation parameters of the ATF (such as optical properties of the materials, geometrical relations of the façade or flow stream conditions) in terms of energy savings, measured as a reduction of the solar load entering the building. Climatic conditions: Barcelona, Spain. CFD simulations: RNG k-epsilon turbulence model (when needed) and P1 radiation model; Fluent	The parameters that affect the most the reduction on solar load gain are related with the optical properties of the glass. An increase of the length-to-depth ratio causes a decrease on the ATF efficiency in terms of solar load gains.

software; 3D geometries.	

7. Nassim Safer N., Woloszyn M. and Roux J. J., Three-dimensional simulation with a CFD tool of the airflow phenomena in single floor double-skin façade equipped with a Venetian blind, 2005: Solar Energy 79(2), 193-203.

http://dx.doi.org/10.1016/j.solener.2004.09.016

Contexts	Outcomes
Modelling of a compact double-skin façade equipped with a venetian blind and forced ventilation The modelling was conducted by using CFD approach to assess the air movement within the ventilated façade channel. Three-dimensional airflow was modelled by using a homogeneous porous media representation, in order to reduce the size of the mathematical model. A parametric study was proposed, analyzing the impact of three parameters on the airflow development: slat tilt angle, blind position, air outlet position The commercial CFD tool FLUENT 6.0.20 was utilized, based on the finite-volume method and the SIMPLE solving algorithm	The CFD approach enables accurate computations of the velocity–pressure fields inside the channel of ventilated double-skin façades The global double skin façade model using the velocity averages and the airflow rates inside the channel of the double-skin façades will be derived from these CFD results

8. Pasut W. and De Carli M., Evaluation of various CFD modelling strategies in predicting air flow and temperature in a naturally ventilated double skin façade, 2012: Applied Thermal Engineering 37, 267–274.

http://dx.doi.org/10.1016/j.applthermaleng.2011.11.028

Contexts	Outcomes
This paper showed, through a sensitivity analysis, a good strategy for carrying out CFD simulation of double skin façades. The validation of the results was based on experimental data from the literature The paper provides a discussion about factors which are important in the simulation.	A CFD model for the natural ventilated double skin façade was developed. The model can be used to predict the airflow patterns, air temperature and air velocity distributions, and heat flux from gap into the room. The model was validated using experimental data collected in a full-scale double skin module test facility by Mai et al.

9. Jiru T. E. and Haghighat F., Modeling ventilated double skin façade - A zonal approach, 2008: Energy and Buildings 40(8), 1567-1576.

http://dx.doi.org/10.1016/j.enbuild.2008.02.017

Contexts	Outcomes
In the zonal approach, the DSF can be divided into a number of control volumes, using two or three-dimensional cells, which are usually larger than the cells normally used in CFD. The advantage of using the zonal approach is that the resulting systems of algebraic equations are smaller and much easier to solve than the CFD. The zonal models can provide information on airflow and temperature distribution in a ventilated space faster than CFD, but with more accuracy and detail than lumped and control-volume models. Application of zonal approach for modeling of airflow and temperature in a ventilated double skin façades (DSF). The zonal airflow equation, power-law, was employed to calculate the airflow through the shading device and cavities. The zonal energy equation was adopted to evaluate the temperature distribution in the DSF system. The predicted temperature distributions were verified by using measured values and parametric studies were conducted in order to identify the influence of height, flow rate and presence of venetian blinds on the inlet–outlet temperature difference. The case used for the development and the verification of the DSF models: experimental test cell at the Dipartimento di Energetica, Politecnico di Torino, Italy.	The zonal models can be used to assess the performance of the DSF system with venetian blinds. The results revealed that the zonal models can be used to assess the performance of the DSF system with venetian blinds. The zonal models provided more detailed information (which is not possible for the lumped and the control-volume models). Parametric study was also conducted in order to assess the influence of cavity height; inlet mass flow rate; and presence of venetian blinds on the outlet-inlet temperature difference. The result demonstrated that the influence of changing the values of each parameter was more apparent during the day than during the night. The DSF model developed can further be integrated into Building Simulation tool that includes HVAC plant and allows the evaluation of the use of control mechanisms in the DSF and their influence on the energy consumption of the HVAC system.

10. W.J. Stec, A.H.C. van Paassen, A. Maziarz, Modelling the double skin façade with plants, 2005: Energy and Buildings 37, 419–427.

http://dx.doi.org/10.1016/j.enbuild.2004.08.008

Contexts	Outcomes
Plants in office buildings can provide several advantages. These are mostly related with thermal, aesthetic, psychological, comfort level and sound attenuation. That research at TU Delft aimed in defining the thermal performance of the double skin façade with plants. A simulation model was developed and validated. After validating, the simulation model could analyze the influence of	The results revealed that In general plants created more effective shading system than blinds providing advantages such as: for the same solar radiation, the temperature raise of the plants was about twice lower than that for the blinds; the temperature of the plants never exceeded the temperature of

plants on the performance of the double skin façade. The simulation model was built by SimulinkTM. The thermal model was represented by the heat exchange between the layers of the façade.	35°C, when blinds could exceed 55°C; plants in the double skin façade reduced cooling capacity by almost 20%.

6.3 BI, Pipes

1. Albanese M. V., Robinson B. S., Brehob E. G. and Sharp M. K., Simulated and experimental performance of a heat pipe assisted solar wall, 2012: Solar Energy 86 (5), 1552–1562.

http://dx.doi.org/10.1016/j.solener.2012.02.017

Contexts	Outcomes
Simplified, thermal resistance-based computer models were developed to simulate the performance of direct gain, indirect gain and integrated heat pipe passive solar systems A computer model was developed to further investigate the feasibility of heat pipe integrated walls in a range of climates; a parametric study was conducted to determine the design features that have a significant effect on performance, a prototype heat pipe wall was constructed and tested to provide validation data MatLab codes were created to simulate hourly performance of the heat pipe system, as well as direct gain and concrete and water wall indirect gain systems; thermal network approach was adopted - An anisotropic model was utilized (three components: diffuse radiation – uniform, circumsolar, horizon brightening). Four cities were chosen to provide a range of insolation and temperatures: Albuquerque (New Mexico, the warmest and clearest of the four climates), Rock Springs (Wyoming, USA), Louisville (Kentucky, USA), Madison (Wisconsin, USA).	The heat pipe system provided substantial gains in performance relative to conventional direct and indirect gain passive solar systems and, thus, presents a promising alternative for reducing building energy use. Economic performance depends on the climate and the load to collector ratio, as well as a number of factors related to the costs of the system and of conventional heating.

2. Hassan M. M. and Beliveau Y., Design, construction and performance prediction of integrated solar roof collectors using finite element analysis, 2007: Construction and Building Materials 21(5), 1069-1078.

http://dx.doi.org/10.1016/j.conbuildmat.2006.01.001

Contexts	Outcomes
An integrated roof solar collector was designed The integrated roof solar collector consisted of a 6.35	The models were used to predict the optimum set of variables that can be used in buildings in order to achieve

mm single glass panel with a selective surface, followed by a 1-mm air-gap. The thermal collecting medium was a fluid (water with antifreeze) enclosed copper pipes. The pipes were laid within concrete cavities to minimize construction cost and time as well as to reduce convection losses. The copper pipes were connected together by means of a 1 mm copper plate absorber. 3D finite element models were developed to evaluate the thermal performance of the integrated roof solar collector.	adequate thermal comfort. Coupled conduction, forced convection, long wave thermal radiation modes of heat transfer were considered in the developed models. A specific location (Blacksburg, Virginia, USA) was modelled. ABAQUS software version 5.8 was used for finite element modelling of the solar roof panel.

3. Zhu Q., Xu X., Wang J. and Xiao F., Development of dynamic simplified thermal models of active pipe-embedded building envelopes using genetic algorithm, 2014: International Journal of Thermal Sciences 76, 258–272.

http://dx.doi.org/10.1016/j.ijthermalsci.2013.09.008

Contexts	Outcomes
New building envelope: active pipe-embedded building envelope → external wall (or roof) with pipes embedded in it (may include PCM) → advantages: utilizes directly low-grade energy sources for reducing building cooling/heating load and improving indoor thermal comfort. Dynamic, simplified thermal model of this structure with the thermal network structure of lumped thermal mass and the parameter identification of the simplified model based on frequency characteristic analysis. These resistances and capacitances are identified in frequency domain by using generic algorithm (GA) by comparing the frequency characteristics of the simplified model with the theoretical frequency characteristics of this structure obtained with Frequency-Domain Finite Difference (FDFD) method - Firstly, the FDFD model of this structure was established and the theoretical frequency characteristics under various disturbances were calculated for the reference of parameter identification. Then, an equivalent dynamic simplified thermal model with lump thermal network structure was developed and its frequency characteristics were also deduced and calculated. Finally, the GA estimator was adopted to identify	The optimal simplified model provides reasonable and accurate performance prediction whatever for the pipe-embedded light weight building wall, the pipe-embedded medium weight building wall, the pipe-embedded heavy weight building wall. The model accuracy may differ depending on the wall physical properties. The optimal model of the pipe-embedded light weighted wall may represent the theoretical frequency characteristics the best while the optimal models of the pipe-embedded medium weighted wall and the pipe-embedded heavy weighted wall present similar accuracy. In general, the simplified RC model is a good model for predicting the heat transfer performance of this structure.

these parameters of the simplified model for allowing the frequency responses of the simplified model to match the theoretical frequency responses by using the FDFD method. Performance prediction of this structure under realistic weather conditions, indoor air condition and circulating water temperature condition for practical applications (China).	

6.4 BI, Solar Chimney

1. Ong K. S., A mathematical model of a solar chimney, 2003: Renewable Energy 28(7), 1047–1060.

http://dx.doi.org/10.1016/S0960-1481(02)00057-5

Contexts	Outcomes
Analytical, physical model / thermal resistance network. A wall-type solar chimney was examined (a glass cover which with the other three solid walls of the chimney form a channel through which the heated air could rise and flow by natural convection). Steady-state heat transfer equations → matrix-inversion solution procedure.	The thermal performance of the solar chimney as determined from the glass, wall and air temperatures, air mass flow rate and instantaneous heat collection efficiency of the chimney are presented. Satisfactory correlation obtained.

6.5 BI, Trombe Wall

1. Jubran B. A., Hamdan M. A. and Manfalouti W., Modelling free convection in a Trombe wall, 1991: Renewable Energy 1 (3–4), 351–360.

http://dx.doi.org/10.1016/0960-1481(91)90044-P

Contexts	Outcomes
Numerical model for laminar, free convection flow in Trombe wall and a modified version of the conventional Trombe wall. Finite difference method.	The variation of fluid velocity, temperature and the average Nusselt number have been determined numerically for selected tilt angles of the glass wall for the modified version of the Trombe wall. It was found that there is a significant effect of the glass wall inclination on the average Nusselt number.

2. Ben Yedder R., Du Z.-G. and Bilgen E., Numerical study of laminar natural convection in composite Trombe wall systems, 1990: Solar & Wind Technology7(6), 675–683.

http://dx.doi.org/10.1016/0741-983X(90)90042-Z

Contexts	Outcomes
Natural convection problem in a composite Trombe wall solar collector. SIMPLER method was used (control volumes). Model for natural convention in cavities. Flow: steady, laminar, 2D.	The aspect ratio A has a small influence on the heat transfer and that other geometric parameters such as orifice position, channel size and width have important effects on the useful energy transmitted to the dwelling.

3. Koyunbabaa B. K., Yilmaz Z. and Ulgen K., An approach for energy modeling of a building integrated photovoltaic (BIPV) Trombe wall system, 2013: Energy and Buildings 67, 680–688.

http://dx.doi.org/10.1016/j.enbuild.2011.06.031

Contexts	Outcomes
A two-dimensional simulation model of a naturally ventilated BIPV Trombe wall system for winter period to be → applied to different locations with different climatic conditions, PV types, thermal mass samples, etc. The commercial CFD code Ansys CFX was adopted to model air flow and heat transfer with the Navier–Stokes equations. Ansys CFX based on finite volume technique. Validation of the model with experimental results of a BIPV Trombe wall built in Izmir, Turkey. An energy analysis for determining the performance of a BIPV Trombe wall integrated to the façade of a room was carried out (based on transient condition). CFD was used to predict temperature and velocity distribution in the test room model. The simulations for two-dimensional model of BIPV Trombe wall system were carried out for February 4–7th, 2008. Experimental set-up at Solar Energy Institute, Ege University Campus, Izmir, Turkey.	This study has shown the capability of a CFD code to predict the radiation, conduction and natural convection in a BIPV Trombe wall system. The k-epsilon turbulence model was used to conduct the CFD simulations on the meshed structure. Radiation heat transfer was modeled using Monte Carlo model.

6.6 BI, PVT

1. Anderson T.N., Duke M., Morrison G.L. and Carson J.K., Performance of a building integrated photovoltaic/thermal (BIPVT) solar collector, 2009: Solar Energy 83(4), 445–455.

http://dx.doi.org/10.1016/j.solener.2008.08.013

Contexts	Outcomes
A novel building integrated photovoltaic/thermal (BIPVT) solar collector was theoretically analyzed through a modified Hottel–Whillier model The model was validated with experimental data from testing on a prototype BIPVT collector. One dimensional steady state thermal model The electrical efficiency was calculated based on the difference between mean BIPVT temperature and Nominal Operating Cell Temperature (NOCT) (298 K).	The collector base material made little difference to the thermal efficiency of the BIPVT suggests that lower cost materials, such as steel, could be utilised for these systems. The disadvantage of using steel is that the electrical efficiency would be decreased marginally. Good thermal contact between the PV cells and the absorber needs to be made; this could be achieved using thermally conductive adhesives and will improve both the electrical and thermal efficiencies of the system. Increase in the transmittance/ absorptance product results in the greatest increase in thermal efficiency of all the parameters assessed, without greatly reducing the electrical efficiency. The use of unglazed BIPVT systems in conjunction with heat pumps could present interesting possibilities. Significant potential exists to utilise the low natural convection heat transfer in the attic at the rear of the BIPVT to act as an insulating layer rather than using additional insulation material. The use of this air layer would allow the material cost of such a system to be significantly reduced.

2. Ji J., Chow T. T. and He W., Dynamic performance of hybrid photovoltaic/thermal collector wall in Hong Kong, 2003: Building and Environment 38 (11), 1327–1334.

http://dx.doi.org/10.1016/S0360-1323(03)00115-X

Contexts	Outcomes
Based on the heat transfer analysis on a west-facing PVT collector wall with typical weather data of Hong Kong, a computational thermal model was developed. Based on the thermal model described above, a simulation program HYBRIDPV-1.0 (in FORTRAN) was developed.	The simulation program could determine the energy performance of PV/hot water collector system with any performance characteristic of PV panel, any climatic region and for any orientation of the collector wall → hourly TRY weather data in Hong Kong was used as a data input for the simulation program.

3. Ji J., Han J., Chow T. T., Yi H., Lu J., He W. and Sun W., Effect of fluid flow and packing factor on energy performance of a wall-mounted hybrid photovoltaic/water-heating collector system, 2006: Energy and Buildings 38(12), 1380-1387.

http://dx.doi.org/10.1016/j.enbuild.2006.02.010

Contexts	Outcomes
Façade-integrated BiPVT A numerical model was developed by modifying the Hottel–Whillier model, which was originally for the thermal analysis of flat-plate solar thermal collectors. Computer simulations were performed to analyze system performance. The combined effects of the solar cell packing factor and the water mass flow rate on the thermal and electrical efficiencies were examined.	The increase of working fluid mass flow rate is beneficial for PV cooling. System operation at the optimum mass flow rate improves the thermal performance of the system and meets the PV cooling requirement so that a better electrical performance can also be achieved.

4. Chen Y., Galal K. and Athienitis A. K., Modeling, design and thermal performance of a BIPV/T system thermally coupled with a ventilated concrete slab in a low energy solar house: Part 2, ventilated concrete slab, 2010: Solar Energy 84 (11), 1908–1919.

http://dx.doi.org/10.1016/j.solener.2010.06.012

Contexts	Outcomes
Modeling and design of a BIPVT system thermally coupled with a ventilated concrete slab (VCS) adopted in a prefabricated, two-storey detached, low energy solar house and their performance assessment based on monitored data. Climatic conditions: Canada (cold climate regions with cold but sunny winters).	A simplified three-dimensional, control volume, explicit finite difference thermal model was developed to simulate the thermal performance of the constructed VCS. The modelling approach can be applied to other types of VCS. The developed model is showed to be

	appropriate for design purposes and for study of control strategies.

5. Aelenei L. and Pereira R., Innovative Solutions for Net Zero-Energy Building: BIPV-PCM System – Modeling, Design and Thermal Performance, 2013: IEEE, IYCE 2013 Conference, 6-8 June, Siofok, Hungary.

http://dx.doi.org/10.1109/IYCE.2013.6604162

Contexts	Outcomes
Numerical thermal analysis of two different systems for integrating on building façade: BIPVT and BIPVT-PCM (Phase Change Material). A dynamic model was simulated using the real climatic data of winter time measured on the building site (Lisbon, Portugal). 1D numerical dynamic simulation model inside the control volume; fully finite difference scheme; programming MATLAB/SIMULINK® with SIMSCAPE® library.	The results revealed that the system using PCM decreased the temperature inside the air cavity and thus, the system was more stable due to the storage of solar gains as latent heat in the PCM wall. The thermal efficiency of the ventilated BIPVT was higher than the ventilated BIPVT-PCM because of the airflow at elevated temperature into the room. Nevertheless, after few hours, the two systems efficiencies appeared to be close to each other. That made PCM a reasonable option.

6. Ghani F., Duke M. and Carson J. K., Effect of flow distribution on the photovoltaic performance of a building integrated photovoltaic/thermal (BIPV/T) collector, 2012: Solar Energy 86(5), 1518-1530.

http://dx.doi.org/10.1016/j.solener.2012.02.013

Contexts	Outcomes
BIPVT: effect of flow distribution on PV performance A three step numerical analysis was conducted to model flow distribution, temperature variation, PV yield for a PVT collector of various design (manifold sizes), geometric shape (aspect ratio), operating characteristics in order to vary flow uniformity within the collector. CFD; FEA analysis → Heat transfer analysis → PV modelling. All simulations were conducted by using Autodesk Simulation Multi-physics 2012 software.	The results showed that the flow distribution within the collector will have a significant influence on the photovoltaic performance of a hybrid PVT collector. For the case where the flow distribution was most uniform, PV performance was improved by over 9% in comparison to a traditional PV collector operating under the same conditions. However, for poor flow the performance was only improved by approximately 2%. It was found that several parameters influence flow distribution: e.g. manifold to riser pipe ratio (a ratio of 4:1 was found to be ideal and that increasing to a 6:1 ratio offered negligible improvement). It was

	also found that array geometry (characterised by its aspect ratio in this study) is important for both flow distribution and PV yield. That study identified that optimal mass flow rate was dependent on array shape or aspect ratio.

7. Liao L., Athienitis A., Park K.-W., Collins M. and Poissant Y., Numerical study of conjugate heat transfer in a bipv-thermal system, 2005: ASME 2005, Orlando, Florida, USA, August 6–12.

Contexts	Outcomes
CFD study of a BIPVT system which generated both electricity and thermal energy. The conjugate heat transfer in the BIPVT system cavity was studied with a 2-D CFD model while the k-ε model was used to simulate the turbulent flow and convective heat transfer in the cavity, in addition to buoyancy effect. The longwave radiation between boundary surfaces was also modelled.	Experimental measurements: full scale outdoor test facility at Concordia University (Canada) showed good agreement with the CFD model. Average and local convective heat transfer coefficients were generated and PV panel average temperature and local cell temperatures were calculated and compared with the data from the experiments.

6.7 BI, PV

1. Fung T. Y. Y. and Yang H., Study on thermal performance of semi-transparent building-integrated photovoltaic glazings, 2008: Energy and Buildings 40(3), 341–350.

http://dx.doi.org/10.1016/j.enbuild.2007.03.002

Contexts	Outcomes
A one-dimensional transient simulation model, the Semi-transparent Photovoltaic module Heat Gain (SPVHG) model, for the thermal performance of the semi-transparent photovoltaic (PV) modules was developed and experimentally validated.	The SPVHG model can be applied for simulating various scenarios. Annual total heat gains through the semi-transparent BIPVs under different scenarios were simulated by means of the SPVHG model . Annual thermal performance (using the SPVHG model): climatic data for Hong Kong. The total heat gain follows the variation of solar radiation.

	The total heat gain through the PV module is dominated by solar heat gain. The effects of different parameters of the PV modules were also studied.

2. Charron R. and Athienitis A. K., Optimization of the performance of double-façades with integrated photovoltaic panels and motorized blinds, 2006: Solar Energy 80(5), 482–491.

http://dx.doi.org/10.1016/j.solener.2005.05.004

Contexts	Outcomes
Double-façades with integrated photovoltaics (PV) and motorized blinds. One-dimensional finite-difference thermal model is developed, with an algorithm that iteratively determines which convective heat transfer coefficient correlation to use for each surface inside the cavity using expressions that consider system characteristics and temperature distribution. Environmental conditions used in the model: representative of what would be experienced in Montreal, Canada.	A theoretical investigation of the performance of double façades with integrated photovoltaics and motorized blinds was presented for the case of forced ventilation. When the PVs were installed in the middle of the cavity, air flows on both sides, increasing PV section overall (thermal-electric) efficiency by about 25%, but lowered electricity generation by 21%. Integrating 0.015 m long, 0.002 m wide fins to the PV back plate resulted to a similar increase in efficiency without compromising electricity generation. The placing of the blind in the middle of the cavity increased the vision section efficiency by 5%. By adopting that approach to optimize performance can lead to combined thermal-electric efficiencies of over 60%.

3. Gan G., Numerical determination of adequate air gaps for building-integrated photovoltaics, 2009: Solar Energy 83(8), 1253-1273.

http://dx.doi.org/10.1016/j.solener.2009.02.008

Contexts	Outcomes
CFD software FLUENT (2005) was adopted for modeling of fluid flow and heat transfer around PV modules mounted on pitched roofs and in front of a	CFD has been used to predict the effect of air gap size on the PV performance in terms of cell temperature for a range of

vertical façade. Modelling was performed for realistic PV modules (type BP 485) and for a range of roof pitches and gap sizes. The modelling was two-dimensional for heat and fluid flow. In order to ascertain the reliability of CFD modelling, the model was validated for buoyancy-induced fluid flow and heat transfer in a tall open air cavity. The RNG k-e turbulence model was utilized for modelling turbulent air flow and heat transfer. Ambient air temperature was fixed at 20^{o}C while the incident solar radiation was first fixed at 1000 W/m^2 and then varied with inclination of roof mounted PV modules for an example location. A discrete transfer radiation model was adopted for modelling the radiation heat transfer from the modules to surroundings.	roof pitches and PV panel lengths at different solar heat gain levels. The CFD technique can be used to predict the required air gap for a given type of module and method of building integration.

4. N. Friling, M. J. Jiménez, H. Bloem, H. Madsen, Modelling the heat dynamics of building integrated and ventilated photovoltaic modules, 2009: Energy and Buildings 41(10), 1051-1057.

http://dx.doi.org/10.1016/j.enbuild.2009.05.018

Contexts	Outcomes
This paper deals with mathematical modelling of the heat transfer of building integrated photovoltaic (BIPV) modules. The experiment and data originate from a test reference module the EC-JRC Ispra. The set-up provides the opportunity of changing physical parameters, the ventilation speed and the type of air flow, and this makes it possible to determine the preferable set-up. The models are first order stochastic state space models.	The analysis has revealed that it is necessary to use non-linear state space models in order to obtain a satisfactory description of the PV module temperature, and in order to be able to distinguish the variations in the set-up. The heat transfer is increased when the forced ventilation velocity is increased, while the change in type of air flow does not have as striking influence. The residual analysis show that the best description of the PV module temperature is obtained when fins, disturbing the laminar flow and making it turbulent, are applied in the set-up combined with high level of air flow.

	The improved description by the model is mainly seen in periods with high solar radiation.

6.8 BI, Several systems

1. Sanjuan C., Suárez M.J., González M., Pistono J. and Blanco E., Energy performance of an open-joint ventilated façade compared with a conventional sealed cavity façade, 2011: Solar Energy 85(9), 1851–1863.

http://dx.doi.org/10.1016/j.solener.2011.04.028

Contexts	Outcomes
Open-joint ventilated façade (OJVF): a building system in which coating material (metallic, ceramic, stone or composite) is hanged by means of a metallic-frame structure to the exterior face of the wall, creating an air cavity between wall and slab → buoyancy effect and thus, ability to reduce cooling thermal loads. Phenomena produced on a typical open joint ventilated façade and comparison of its energy performance with that of a conventional sealed air cavity façade. The thermo fluid-dynamic behavior of both systems was analyzed with CFD. The numerical model employed a CFD code (FLUENT 6.3) to analyze the thermal and fluid dynamic phenomena taking place in OJVF. CFD software solved Navier–Stokes equations (including energy conservation equation) using finite volume method. 3D simulations were conducted. Climatic data: Madrid, Spain (Continental Mediterranean climate).	The three-dimensional CFD model developed to simulate a typical Open Joint Ventilated Façade has enabled a better understanding of the ventilation effect induced by the solar radiation in the air gap of the façade. Velocity profiles, together with temperature and heat flux distributions have been compared with those obtained in a conventional sealed cavity façade. The model has been also used to compare the thermal performance of both façades for the specific climatic conditions of Madrid (Spain).

2. Chen Y., Athienitis A. K. and Galal K. E., Frequency domain and finite difference modeling of ventilated concrete slabs and comparison with field measurements: Part 2. Application, 2013: International Journal of Heat and Mass Transfer 66, 957–966.

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.07.086

Contexts	Outcomes
Frequency response (FR) and lumped-parameter finite difference (LPFD) approaches for the thermal modeling of building-integrated thermal energy	The modelling techniques are applied to two kinds of VCS – one has air channel at the bottom of the mass (VCS-b) while

storage (BITES) systems. The results are compared to each other and with field-measured data from a solar demonstration house with a ventilated concrete slab (VCS).	the other kind has hollow cores as air channel (VCS-c). The explicit LPFD and FR models generate almost identical outcomes under periodic conditions. The accuracies of different discretization configurations and choices of time step were quantified. Time step of half an hour for FR models typically resulted in less than 3% error in the thermal performance. For LPFD models, discretization with Biot number less than 0.5 can reduce error to about 5%. Larger Biot number tended to overestimate the heat flow from air to the slab over time. For practical slab thickness (0.1-0.2 m), simulation results from 2-layer VCS-b and 3-layer VCS-c models with time step of half an hour showed errors less than 9%. LPFD simulation results under non-periodic conditions were presented for VCS-b and they were compared with field-measured data from a near net-zero energy solar house.

3. Palmero-Marrero A. I. and Oliveira A. C., Evaluation of a solar thermal system using building louvre shading devices, 2006: Solar Energy 80(5), 545 – 554.

http://dx.doi.org/10.1016/j.solener.2005.04.003

Contexts	Outcomes
Modification of existing louvre designs to integrate a solar collector in the shading device was performed → evaluation of a thermal solar system for water heating. A numerical model for the integrated solar collector was developed for different configurations and the collector efficiency was evaluated for each configuration. System thermal performance was obtained for the climatic conditions of: Lisbon (Portugal), Tenerife (Spain). The different configurations which were considered	In the models, steady state heat transfer was assumed (negligible thermal inertia) while the models consisted of 4–6 heat balance equations, depending on the configuration, stating that the sum of all incoming fluxes is equal to the sum of all outgoing fluxes.

for the integrated collector were: collector with tubes; collector with larger channels; collector with smaller channels and transparent cover area.	

4. Z. Wang, Z. Duan, X. Zhao, M. Chen, Dynamic performance of a façade-based solar loop heat pipe water heating system, 2012: Solar Energy 86, 1632–1647.

http://dx.doi.org/10.1016/j.solener.2012.02.031

Contexts	Outcomes
Study of a novel façade-based solar loop heat pipe (LHP) water heating system: theoretically and experimentally.	Two types of glass covers, i.e., double glazed/evacuated tubes and single-glazing plate, were adopted. The double-glazed/evacuated-tube system showed better performance than the single-glazing one.

5. Manz H., Numerical simulation of heat transfer by natural convection in cavities of facade elements, 2003: Energy and Buildings 35, 305 –311.

http://dx.doi.org/10.1016/S0378-7788(02)00088-9

Contexts	Outcomes
Heat transfer by the natural convection of air layers within vertical, rectangular cavities was examined for applications in building façade elements, such as insulating glazing units, double-skin façades, doors, etc. by using a CFD code (commercial CFD code FLOVENT, Version 3.1; finite volume method).	The presented method can be considered suitable for calculating convective heat transfer in tall, vertical cavities in different types of façade elements. That work included combination of an optical model for determining absorbed solar radiation in layers of façade elements such as glass panes, roller blinds, etc. with CFD modeling in order to increase the reliability of predictions of these elements thermal transmission and total solar energy transmission.

6.9 BA, Several systems

1. D. A.G. Redpath, P. Dalzell, P. W. Griffiths and N. J. Hewitt, Investigation of concentrating and nonconcentrating evacuated tube solar water heaters using 2D particle imaging velocimetry, 2014: International Journal of Low-Carbon Technologies.

doi:10.1093/ijlct/ctu004

Contexts	Outcomes
Under transient climatic conditions, solar water heaters with heat pipes are more effective in terms of capturing incident solar radiation (in comparison with other types of water heaters). Two configurations were studied: thermosiphon fluid flow and reflective concentrators.	A model manifold simulated the manifold of a heat-pipe evacuated tube solar water heater was presented. 2D-PIV revealed significant differences in flow patterns between the two manifold configurations which were confirmed by comparing Nusselt number. The five pin-fin system had Nusselt 2.1 times greater than that calculated at the same location in the 10 pin-fin configuration. The results showed that the incorporation of concentrators would have a small effect on the overall system efficiency but would reduce the frictional losses internally. The authors noted that further work is needed for the improvement of similar heat exchangers.

2. Sultana T., Morrison G.L. and Rosengarten G., Thermal performance of a roof integrated solar microconcentrating collector, 2011: ISES 5, 3494-3505, 30th ISES Congress, SWC 2011; Kassel; Germany; 28 Aug.- 2 Sept.

Contexts	Outcomes
Concentrating solar thermal systems for rooftop applications. Thermal performance of a new low-cost solar thermal micro-concentrating collector (MCT) which used linear Fresnel reflectors and it was designed to operate at temperatures up to 220°C. The modules of that collector were approximately 3 meters long by 1 meter wide and 0.3 meters high. Objective of the study: to optimize the design to maximize the overall thermal efficiency. Computational investigation of radiation and convection heat transfer in order to understand the heat loss mechanisms.	A computational model for the prototype collector was developed by using ANSYS-CFX. The numerical results were compared with experimental measurements. The efficiency of the collector was established on the basis of ray tracing and heat loss analysis.

6.10 General studies

1. Moshfegh B., Sandberg M., Investigation of fluid flow and heat transfer in a vertical channel heated from one side by PV elements, Part I – numerical study, WREC 1996, 248-253.

http://dx.doi.org/10.1016/0960-1481(96)88856-2

Contexts	Outcomes
Numerical study about fluid flow and heat transfer of buoyancy-driven convection between two vertical parallel walls, heated from one side. Both convection and radiation heat exchanges were taken into account as the heat transfer mechanisms by which the thermal energy is transferred into the air. A steady-state 2D model was adopted (finite element code).	Numerical results were derived for a channel (6.5 m height; different widths of the channel). The results showed the importance of radiation heat exchangers to the heat transfer mechanisms between channel walls.

2. G. Gan, S. B. Riffat, CFD modelling of air flow and thermal performance of an atrium integrated with photovoltaics, 2004: Building and Environment 39, 735- 748.

http://dx.doi.org/10.1016/j.buildenv.2004.01.027

Contexts	Outcomes
The thermal performance of an atrium integrated with PVs was evaluated. CFD was adopted for the prediction of air flow and temperature distribution in the atrium. CFD was then used to investigate the effect of ventilation strategies on PV performance. CFD package FLUENT was utilized.	The work showed that CFD is useful for optimising building ventilation systems to provide a comfortable indoor environment and effective cooling of BI PVs. For effective cooling of roof PVs, cool outdoor air should be supplied through an opening close to the roof or an air channel under the PVs. Increasing the ventilation rate can also reduce temperature and thus, improve PV performance, in particular if cool outdoor air is supplied via an opening close to the PVs.

3. G. Gan, Effect of air gap on the performance of building-integrated photovoltaics, 2009: Energy 34, 913–921.

http://dx.doi.org/10.1016/j.energy.2009.04.003

Contexts	Outcomes
Ventilation of PVs installed over or beside a building envelope can reduce module temperature and increase electrical conversion efficiency. A CFD method was adopted to assess the effect of the size of	It was found that PV mean PV temperature and maximum PV temperature associated with hot spots decreased with the increase in pitch

air gap between PV modules and building envelope on PV performance in terms of cell temperature for a range of roof pitches and panel lengths and to determine the minimum air gap that is required to minimise PV overheating. CFD software FLUENT was adopted.	angle and air gap. Mean PV temperature also decreased with increasing panel length for air gaps greater than or equal to 0.08 m whereas maximum PV temperature generally increased with panel length. In order to reduce possible overheating of PVs and hot spots near the top of the modules requires minimum air gap 0.12–0.15 m for multiple module installation and 0.14–0.16 m for single module installation depending on roof pitches.

7 Studies about Thermal Simulation (emphasis: building/system)

7.1 BI, Solar Thermal

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

10.1080/19401493.2013.766263

Contexts	Outcomes
Transparent solar thermal collectors (TSTCs) were studied Modelling challenges that arise when considering building façades and especially integrated TSTC systems were examined.	New transient systems simulation (TRNSYS) types were developed A simplified model was presented for comparison purposes. The overall performance of a building with façade-integrated TSTC was examined by considering a complete simulation model coupling the TSTC, building and heating, ventilation and air conditioning operation of the building. Possibilities for primary energy savings were investigated by using building mass as an additional thermal storage.

2. M. M. Hassan, Y. Beliveau, Design, construction and performance prediction of integrated solar roof collectors using finite element analysis, 2007: Construction and Building Materials 21, 1069–1078.

http://dx.doi.org/10.1016/j.conbuildmat.2006.01.001

Contexts	Outcomes
An integrated roof solar collector was designed to achieve ease of construction, energy efficiency, functional integration, composite behaviour, sustainability, reliability, flexibility, and cost effectiveness. Three-dimensional (3D) finite element models were then developed to evaluate the thermal performance of the integrated roof solar collector. Coupled conduction, forced convection, and long wave thermal radiation modes of heat transfer were considered in the developed models. A specific	Results showed that the integrated roof collector provides acceptable thermal performance by supplying approximately 85% of the building space heating and hot water requirements.

location (Blacksburg, VA) was modelled.	

7.2 BI, Trombe Wall

1. Nowzari R. and Atikol U., Transient Performance Analysis of a Model Building Integrated with a Trombe-Wall, 2009: Conference HTE'09, 20-22 August 2009, Moscow, Russia.

Contexts	Outcomes
Investigation of temperature behaviour of a hypothetical two-story building with a total floor area of 120 m^2 by modelling and simulation with TRNSYS program. A vented Trombe wall was adopted for the south façade of the ground floor and a direct gain window of area 6.5 m^2 was placed on the south façade of the First floor. It was assumed that the model building was located in Larnaca, Cyprus.	The simulation results obtained by TRNSYS for the hypothetical building integrated with a thermal storage wall: for January because it is one of the coldest months of the year.

7.3 BI, PVT

1. Chen Y., Athienitis A. K. and Galal K., Modeling, design and thermal performance of a BIPV/T system thermally coupled with a ventilated concrete slab in a low energy solar house: Part 1, BIPV/T system and house energy concept, 2010: Solar Energy 84(11), 1892–1907.

http://dx.doi.org/10.1016/j.solener.2010.06.013

Contexts	Outcomes
A quasi-two dimensional, control volume, steady state model for the simulation of the thermal performance of a BIPVT system, as well as a linear equation for predicting the temperature of the PVs and air at the outlet was developed based on measured data (the model and the equation could be applied to other BIPVT systems with similar configurations and they are useful in preliminary design and for control of air flow in the BIPVT system). During the initial design stage, the house was first analyzed without renewable energy use: based on HOT 2000 simulations, the annual gross space heating load (without solar gains) was evaluated Climatic conditions: Eastman, Quebec, Canada (a cold climate area).	A thermal model of the BIPV/T system suitable for preliminary design and control of the airflow is developed.

7.4 BI, PV

1. Mei L., Infield D., Eicker U. and Fux V., Thermal modelling of a building with an integrated ventilated PV façade, 2003: Energy and Buildings 35(6), 605–617.

http://dx.doi.org/10.1016/S0378-7788(02)00168-8

Contexts	Outcomes
Dynamic, finite element thermal model for ventilated PV façades combined with TRNSYS → complete thermal building model incorporating a ventilated PV façade and solar air collectors. Building with an integrated ventilated PV façade/solar air collector system. Building model validated with experimental data from a 6.5-m high PV façade on the Mataro Library near Barcelona.	A thermal building model is developed that include submodels of the ventilated PV façade and the additional solar air collectors. The modelled and the measured air temperatures were found to be in good agreement. The heating and cooling loads for the building with and without that ventilated façade were calculated and the impact of climatic variations on the performance such buildings was also investigated. The results showed that the cooling loads were marginally higher with the PV façade for all locations considered, while the impact of the façade on the heating load depended on the location.

7.5 BI, Several systems

1. Kuhn T.E., Herkel S., Frontini F., Strachan P. and Kokogiannakis G., Solar control: A general method for modelling of solar gains through complex facades in building simulation programs, 2011: Energy and Buildings 43(1), 19 – 27.

http://dx.doi.org/10.1016/j.enbuild.2010.07.015

Contexts	Outcomes
A new method (¨black box¨ model) for integrating complex façades in building simulation programs was developed. The method was designed to be used for complex façade components with nontrivial angular dependence. Complex façades: façades with prismatic layers, light re-directing surfaces, etc. → façade properties with complex angular dependence, façades with non-airtight layers, non-flat surfaces, etc. The method was implemented in ESP-r and the implementation was validated; the authors noted that	Advantage of the new method: only uses measurable quantities of the transparent or translucent part of the façade as a whole. General idea of the model: to describe every complex façade with a two-layer model → each of the two virtual layers has an effective solar absorptance with the desired angular dependence, between the two layers, there is a temperature-dependent thermal resistance.

the method could be implemented also in other detailed simulation programs such as DOE-2, EnergyPlus, TRNSYS or TAS thermal analysis software.	

7.6 BA, Space heating/water heating

1. Ji J., Luo C., Chow T.-T., Sun W. and He W., Thermal characteristics of a building-integrated dual-function solar collector in water heating mode with natural circulation, 2011a: Energy 36 (1), 566–574.

http://dx.doi.org/10.1016/j.energy.2010.10.004

Contexts	Outcomes
Building-integrated (added on the façade) dual-function solar collector in water heating mode with natural circulation was studied (modified collector). Dual function: passive space heating during cold winter; water heating over warm seasons (two independent modes). Dynamic numerical model for water heating performance and solar transmission though building façade / experimental validation (experimental set-up: collector prototype mounted on the exterior wall of a testing hot-box). Finite difference model. Heat flow through the front glazing: considered as one-dimensional. Water heating model for the collector; building façade model (coupling: collector model with building wall); space thermal load computations. Region/climatic conditions: Hefei, China. Based on practical air-conditioned room design conditions, numerical analysis was conducted to study water heating performance and to compare the solar transmission through building façade in different seasons with or without its presence.	A coupled numerical model has been developed for this building-integrated dual-function solar collector system. Through experimental validation, the numerical model was demonstrated, which is able to give accurate predictions. Over typical summer days, with the modified collector the daily cooling load of the room was reduced by 2%. The modified design did not lead to summer overheating (common in most of the traditional passive space heating systems). In addition, over typical summer days, water temperature in storage tank may exceed 40^{o}C (good for most of the hot water applications). During typical autumn days, the modified collector in water heating mode with natural circulation resulted in an increase of space cooling load but a reduction of space heating load. Furthermore, during typical autumn days, the water temperature can reach 48^{o}C with a thermal efficiency of 48.4% and a corresponding water heat gain at 6.57 MJ/m^2.

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

DOI: 10.1177/2041296710394243

Contexts	Outcomes
Two dynamic numerical models based on the finite-difference method. Region/climatic conditions: Hefei, China. A novel BI solar thermal system (BI dual-function solar collector) was proposed. The system had two independent operating modes: passive space heating mode and water heating mode (it used criteria to select the operating mode: during cold days it works in passive space heating and during warm season it works in the water heating mode). A testing system was established and it performed in thermosiphon water heating mode for heating of water. Two dynamic numerical models were presented for the two operating modes of the testing system. The experimental data were used to validate the two models.	For the thermosiphon water heating mode, it was proved by comparison of the experimental and simulated results that during the experimental periods, the prediction of the daily thermal efficiencies only had a maximal relative absolute deviation of 2.6% and the RMSD of the simulated result of the indoor temperature was around 0.4^{o}C. For the case of the space heating mode, the numerical model can also give accurate predictions but with higher deviation compared to the model for the system in the thermosiphon water heating mode.

7.7 General studies

1. Charvát P., Klimeš L. and Ostrý M., Numerical and experimental investigation of a PCM-based thermal storage unit for solar air systems, 2014: Energy and Buildings 68, 488–497.

http://dx.doi.org/10.1016/j.enbuild.2013.10.011

Contexts	Outcomes
Phase Change Materials (PCMs) for thermal energy storage in air-based solar thermal systems. Climatic conditions: Czech Republic. Model and experimental validation (paraffin-based PCM). Numerical model of the heat storage unit was implemented as a 1D transient heat transfer problem; TRNSYS 17 simulation tool was used for the numerical investigations; coupling between TRNSYS and MATLAB was adopted for the development of the numerical model of the heat storage unit; the numerical model developed in MATLAB was consequently recompiled with the use of C++ programming language to the form of the build-in TRNSYS module.	The results of the simulations demonstrated a good agreement with the experimental results. The model was adopted for a parametric study analysing the influence of certain parameters. The performed investigations revealed a potential of the use of latent heat thermal storage in air-based thermal systems with a narrow temperature operation range.

8 Studies of Energetic/Thermal Simulation (emphasis: building)

No available studies

9 Studies of Energetic/Thermal Simulation (emphasis: system)

9.1 BI, Solar Thermal

1. G. Notton, F. Motte, Chr. Cristofari, J.-L. Canaletti, New patented solar thermal concept for high building integration: Test and modeling, 2013: Energy Procedia 42, 43-52.

http://dx.doi.org/10.1016/j.egypro.2013.11.004

Contexts	Outcomes
A new concept of flat plate solar collector is presented: it has a remarkable shape and is integrated into a rainwater gutter. Several solar modules are connected serially or in parallel. A numerical model is developed in Matlab environment using a finite difference model and an electrical analogy. The thermal model is validated from experimental data under various meteorological situations. The adequacy of this model with the experimental data is shown for the water temperatures and for various temperatures inside the solar collector.	The developed model has a good accuracy with the measured data: the relative root mean square errors are around 5% for the water temperatures and from 4.6 % to 10% for the internal ones. The main advantage of this model is to be able to modify easily the characteristics and the form of the used materials.

9.2 BI, Skin Façades

1. D. Faggembauu, M. Costa, M. Soria, A. Oliva, Numerical analysis of the thermal behaviour of ventilated glazed facades in Mediterranean climates.
Part I: development and validation of a numerical model, 2003: Solar Energy 75, 217–228.

http://dx.doi.org/10.1016/j.solener.2003.07.013

Contexts	Outcomes
Despite the architectural interest of the glazed façades, in Mediterranean climate these systems are responsible for the overheating of the building. In these zones, double-skin envelopes made up of two layers of glass separated by an air channel in order to	A specific numerical code (for time-accurate simulations of the thermal and fluid-dynamic behaviour of ventilated and conventional façades) was developed. It was based on 1D-

collect or evacuate the solar energy absorbed by the façade are a design option that could resolve this issue.	discretizations and allowed the evaluation of the performance of the façades over the course of a year. The numerical results of each submodel were compared with the results of analytical models; both with reference situations and with experimental measures obtained in real-site test façade facilities (in different climatic conditions). The numerical code is a useful tool for the evaluation of the performance of different building façades. Different materials, orientations, geometries and climates can be tested in order to optimise designs/recommendations.

9.3 BI, PVT

1. Agrawal B. and Tiwari G. N., Optimizing the energy and exergy of building integrated photovoltaic thermal (BIPVT) systems under cold climatic conditions, 2010: Applied Energy 87(2), 417 – 426.

http://dx.doi.org/10.1016/j.apenergy.2009.06.011

Contexts	Outcomes
One-dimensional transient model was developed by using basic heat transfer equations. An analysis was carried in order to select an appropriate BIPVT system suitable for the cold climatic conditions of India. Climatic conditions: data for Srinagar city. Software "Matlab 7" to evaluate the performance and compute the useful exergy for all combinations of the BIPVT systems.	Performance analysis of a BIPVT system has been evaluated for four different parallel and series combinations under the cold climatic conditions of India. It is concluded that for a constant mass flow rate of air, the series combination is more suitable for the buildings fitted with BIPVT systems as rooftop.

2. Yang T., Athienitis A.K., A study of design options for a building integrated photovoltaic/thermal (BIPV/T) system with glazed air collector and multiple inlets,

2012: Energy Procedia 30, 177 – 186.

http://dx.doi.org/10.1016/j.egypro.2012.11.022

Contexts	Outcomes
Open loop air based BIPVT system having single inlet. Experiment was performed inside the lab under	The simulation results showed that the application of two inlets on a BIPVT collector increased thermal efficiency

indoor simulator at Concordia University, Canada. A control volume model was developed to validate the experimental results. Improved designs of the BIPV/T system with multiple inlets and other means of heat transfer enhancement are examined by means of the simulations.	by around 5% and increase electrical efficiency marginally. An added vertical glazed solar air collector improved thermal efficiency significantly while the improvement was more significant with wire mesh packing in the collector.

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

http://dx.doi.org/10.1016/j.enbuild.2009.07.013

Contexts	Outcomes
An experimentally validated CFD model of a new BIPVT collector was investigated to examine the effect of active heat recovery on cell efficiency and to determine the effectiveness of that device as a solar hot water heater. A parametric analysis indicated that cell efficiency can be raised by 5.3% and water temperatures suitable for domestic hot water use are possible. Thermal and combined (thermal plus electrical) efficiencies were found to be 19% and 34.9%, respectively. A new correlation was developed for relating electrical efficiency to collector inlet water temperature, ambient air temperature and insolation that allowed cell efficiency to be calculated directly. In terms of the experimental set-up: the novel experimental collector was originally designed and constructed for the 2007 U.S. Solar Decathlon by the University of Colorado Solar Decathlon Team while the collector had 41 PV panels suspended above an array of tube-fin absorbers. Two models were developed to evaluate the performance of the BIPV/T collector under different operating conditions. A collector cooled by natural convection was the base case for cell temperature comparison. That model represented a standard BIPV where PVs are mounted close to the roof surface. The second, a collector with a liquid-cooled tube-fin absorber into the cavity, simulated active heat recovery. The collector geometry simulated in both models matched with the physical characteristics of components in the physical test array. A CFD package was adopted for the simulations.	The proposed BIPVT collector demonstrated potential for providing increased electrical efficiency of up to 5.3% over a naturally ventilated BIPV roof, reducing negative effects of integration into building façade. This collector provided hot water for domestic use or hydronic space heating with no additional roof space requirements. The total efficiency of the collector was predicted to be 34.9%. A new correlation was developed for relating PV cell efficiency to collector water inlet temperature, ambient air temperature and insolation. That correlation allowed cell efficiency to be predicted based on readily available and easily measured quantities. Standard methods for characterizing solar hot water collectors were also applied to determine the important collector properties from which thermal efficiency can be calculated. The numerical model was well validated and demonstrated good agreement with the experimental data from a full-scale test collector.

4. H.M. Yin, D.J. Yang, G. Kelly, J. Garant, Design and performance of a novel building integrated PV/thermal system for energy efficiency of buildings, 2013: Solar Energy 87, 184–195.

http://dx.doi.org/10.1016/j.solener.2012.10.022

Contexts	Outcomes
A building integrated multifunctional roofing system has been designed to harvest solar energy through photovoltaics (PVs) and heat utilization while minimizing PV efficiency loss and eliminating the material and labor redundancies of conventional PV systems.	The performance analysis indicates that the proposed solar roofing system provides significant advantages over the traditional asphalt shingle roof and PV systems without cooling.

5. T.T. Chow, A.L.S. Chan, K.F. Fong, Z. Lin, W. He, J. Ji, Annual performance of building-integrated photovoltaic/water-heating system for warm climate application, 2009: Applied Energy 86(5), 689-696.

http://dx.doi.org/10.1016/j.apenergy.2008.09.014

Contexts	Outcomes
Through computer simulation with energy models developed for this integrative solar system in Hong Kong, the results showed that the photovoltaic/water-heating (PVW) system is having much economical advantages over the conventional photovoltaic (PV) installation. The system thermal performance under natural water circulation was found better than the pump-circulation mode.	Through computer simulation with energy models developed for this integrative solar system in Hong Kong, the results showed that the photovoltaic/water-heating (PVW) system is having much economical advantages over the conventional photovoltaic (PV) installation. The system thermal performance under natural water circulation was found better than the pump-circulation mode.

6. L. Liao, Y. Poissant, M. Collins, A. K. Athienitis, L. Candanedo and K.-W. Park, Numerical and experimental study of heat transfer in a BIPV-thermal system, 2007: Journal of Solar Energy Engineering 129(4), 423-430.

Contexts	Outcomes
A CFD study was conducted for a BIPVT. The heat transfer in the BIPVT cavity was studied with a 2D CFD model. The realizable k-ε model was adopted to simulate turbulent flow and convective heat transfer in the cavity, including buoyancy effect and long-wave radiation between boundary surfaces was also modeled. A particle image velocimetry (PIV) system was employed to examine fluid flow in BIPVT cavity and provide partial validation for the CFD model. Average and local convective heat transfer coefficients were generated with the CFD model using	Cavity temperature profiles were calculated and compared to the experimental data for different conditions. A good agreement was observed. Correlations of convective heat transfer coefficients were generated for the cavity surfaces. Local heat transfer coefficients, such as those presented, are necessary for the prediction of temperature distributions in BIPVs.

measured temperature profile as boundary condition.	

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

http://dx.doi.org/10.1016/j.solener.2013.12.040

Contexts	Outcomes
Energy models for two systems: Unglazed Transpired solar Collector (UTC) only; UTC with PVs, were developed. CFD simulations were performed. The energy models were validated with measurements (outdoor two-story test building at Purdue University, USA). Good agreement between the model prediction and the experimental data was observed.	Correlations for the average Nu related to exterior and interior convective heat transfer and the effectiveness were obtained, for the first time, for the configurations considered (UTCs with trapezoidal-shaped corrugation and small perforation suction; UTCs with PVs), through validated CFD simulations (high resolution grids; RNG k–ε turbulence closure model). The authors note that a detailed discussion of the energy performance of their system is presented in a second paper (Part 2) which is an extension of that work.

8. S. Li, P. Karava, Energy modeling of photovoltaic thermal systems with corrugated unglazed transpired solar collectors – Part 2: Performance analysis, 2014: Solar Energy, In press.

http://dx.doi.org/10.1016/j.solener.2013.12.041

Contexts	Outcomes
This paper which is an extension of the previous one (part 1) outlined all the factors that affect the thermal performance of PVTs integrated with UTCs and examined the impact of several parameters (corrugation geometry, plate orientation, incident turbulence intensity).	The findings of that study revealed that the ‘vertical’ installation of the plate greatly enhanced exterior and interior convective heat transfer due to the combined effects of the corrugation, wind speed, suction velocity and buoyancy, for the configuration of UTC only. Increasing the turbulence intensity increased the exterior Nu. Optimizing the geometry can greatly improve the energy performance of UTC systems. Improving the energy performance through optimizing the geometrical parameters for UTCs with PV panels was less effective.

9. Chow T. T., He W., Chan A. L. S., Fong K. F., Lin Z. and Ji J., Computer modeling and experimental validation of a building-integrated photovoltaic and water heating system, 2008: Applied Thermal Engineering 28(11–12), 1356-1364.

http://dx.doi.org/10.1016/j.applthermaleng.2007.10.007

Contexts	Outcomes
A dynamic simulation model of a BI PV and water heating system was developed. The numerical model was developed based on the finite difference control volume approach while the integrated use of energy balance and fluid flow analysis allowed the prediction of system dynamic behavior under external excitations such as changes in weather, water consumption and make-up conditions. The validity of the model was verified by comparing its predicted operating temperature changes and system daily efficiencies with the measured data acquired from an experimental rig at the City University of Hong Kong.	The use of multi-nodal scheme is considered most useful in apprehending the underlying physical processes. The integrated use of energy balance and fluid flow analysis allows the prediction of the system behavior in a comprehensive manner.

9.4 BI, PV

1. A. Kane, V. Verma, Performance Enhancement of Building Integrated Photovoltaic Module using Thermoelectric Cooling, 2013: International Journal of Renewable Energy Research 3(2).

http://www.ijrer.com/index.php/ijrer/article/view/588

Contexts	Outcomes
In order to cool BIPV, a thermoelectric system was developed. Thermoelectric module was attached at the back of PV module (cooling mode). Initially mathematical modeling of individual systems was performed. Then the dynamic model of BIPV/Thermoelectric system with consideration of temperature of PV panel temperature was developed.	The results of the simulations revealed that the proposed cooling method improved PV efficiency but at the cost of minimal power loss. The detailed analysis of the model showed that performance and life enhancement of BIPV could be achieved with 10°C cooling without loss of power.

2. Mei L., Infield D., Eicker U., Fux V., Parameter estimation for ventilated photovoltaic façades, 2002: Building Services Engineering Research and Technology 23(2), 81-96.

doi: 10.1191/0143624402bt033oa

Contexts	Outcomes
The estimation of thermal parameters which describe the performance of ventilated PV façades integrated	A direct numerical approach was developed in order to identify the

into buildings was examined.	parameters that describe heat transfer processes. The method allowed the heat transfer coefficients to be obtained (directly) from data measured on an operational ventilated PV façade. The results were compared with values which were taken from conventional practice.

9.5 BI, PCM for passive solar walls

1. K. Darkwa, P.W. O´Callaghan, Simulation of phase change drywalls in a passive solar building, 2006: Applied Thermal Engineering 26, 853 –858.

http://dx.doi.org/10.1016/j.applthermaleng.2005.10.007

Contexts	Outcomes
Integration of phase change materials (PCMs) into building fabrics: composite PCM drywall samples (i.e. randomly-mixed and laminated PCM drywalls) were studied in a model passive solar building. Thermal simulations for a room were performed numerically by finite difference method based on the fixed mesh method.	Laminated PCM sample with a narrow phase change zone was capable of increasing minimum room temperature by about 17% more than the randomly-mixed type. Even there was some display of non-isothermal phase change process the laminated system was proved to be thermally more effective in terms of evolution and utilization of latent heat. Further heat transfer enhancement process was required for the development of the laminated system.

9.6 BA, PVT

1. Tonui J.K., Tripanagnostopoulos Y., Performance improvement of PV/T solar collectors with natural air flow operation, 2008: Solar Energy 82, 1–12.

http://dx.doi.org/10.1016/j.solener.2007.06.004

Contexts	Outcomes
An analytical model was developed in Fortran90 to evaluate induced airflow rate and PVT system temperature for natural airflow. Three configurations were studied: Reference; with thin metal sheet in the middle of the air channel (TMS); with fins in the middle of the air channel (FIN). These low-cost modifications in the air channel were made in order to improve heat extraction.	Model estimated the outlet air temperature within ± 2^0C for all configuration. The air mass flow rate was also calculated by this model. The air mass flow rates which were evaluated by the model for the three configurations were in agreement with the results reported for ventilated PV façades by other researchers. The model results revealed that the

	modified systems had better thermal efficiency for every parameter considered with the FIN system giving better performance than the TMS system but both contributed positively towards enhancing heat extraction from PV module for better electrical and thermal energy production.

2. Kalogirou S.A, Tripanagnostopoulos Y., Industrial application of PV/T solar energy systems, 2007: Applied Thermal Engineering 27, 1259–1270.

http://dx.doi.org/10.1016/j.applthermaleng.2006.11.003

Contexts	Outcomes
TRNSYS simulations were performed for hybrid PVT solar systems for domestic hot water applications both passive (thermosiphonic) and active. Prototype model was manufactured at University of Patras (Greece), using polycrystalline silicon (pc-Si) and amorphous silicon (a-Si) combined with water heat extraction unit. Simulations were performed using Typical Meteorological Year (TMY) data from Nicosia (35^0), Athens (38^0) and Madison (43^0). TRNSYS model calculated the energy and cost of hybrid PVT system with thermosiphon and forced water flow.	The results revealed that the electrical production of the system with polycrystalline solar cells was more than the amorphous one but the solar thermal fraction was slightly lower. A non-hybrid PV system gave about 25% more electrical energy but the present system covered also, depending on the location, a large percentage of the thermal energy of the industry considered.

3. Kalogirou S.A, Tripanagnostopoulos Y., Hybrid PV/T solar systems for domestic hot water and electricity production, 2006: Energy Conversion and Management 47, 3368–3382.

http://dx.doi.org/10.1016/j.enconman.2006.01.012

Contexts	Outcomes
TRNSYS simulation were performed for PVT systems, for three locations at different latitudes: Nicosia (35^o), Athens (38^o) and Madison (43^o). In that study, the authors considered a domestic thermosiphonic system and a larger active system suitable for a block of flats or for small office buildings.	The results revealed that a considerable amount of thermal and electrical energy was produced by the PVTs and the economic viability of the systems was improved. The electrical production of the system with polycrystalline solar cells was more than that employing the amorphous ones, but the solar thermal contribution was slightly lower. A non-hybrid PV system produced about 38%

	more electrical energy, but the present system covered also a large percentage of the hot water needs of the buildings considered. The TRNSYS results gave an account of the energy and cost benefits of the studied PVTs with thermosiphon and forced water flow. As a general conclusion, the overall energy production of the units was increased and the hybrid units had better chances of success. This was also strengthened by the improvement of the economic viability of these systems, especially for applications where low temperature water, like hot water production for domestic use, was also required.

4. Garg H.P., Adhikari R.S., Conventional hybrid photovoltaic/thermal (PV/T) air heating collectors: steady-state simulation, 1997: Renewable Energy 11(3), 363-385.

http://dx.doi.org/10.1016/S0960-1481(97)00007-4

Contexts	Outcomes
Performance analysis of a conventional PVT air heating collector was performed. A simulation model was developed while various performance parameters were calculated for single-glass and double-glass configurations. The results were presented to show the effect of various design and operational parameters on the performance of a system. The authors noted that these results are useful for designing such systems more scientifically; however, final selection of design and operational variables must be based on system cost-effectiveness.	The use of single- and double-glass covers in a PVT air heating system depends on the range of the temperatures for which the system is designed. The system efficiency increased with increase in collector length, mass flow rate, cell density and decreased with increase in duct depth for both configurations.

9.7 General studies

1. G. Notton, C. Cristofari, M. Mattei, P. Poggi, Modelling of a double-glass photovoltaic module using finite differences, 2005: Applied Thermal Engineering 25, 2854–2877.

http://dx.doi.org/10.1016/j.applthermaleng.2005.02.008

Contexts	Outcomes
A simulation model (finite differences) for a double-glass multi-crystalline PV module was developed and validated by using experimental data. The simulation model was based on various thermal hypotheses,	The authors considered as convective coefficient: - Only the forced convective one - The highest value between free and

particularly concerning the convective transfer coefficients and various hypotheses found in the literature were tested (the best one was accepted).	forced one - The sum of two coefficients: free and forced Using the developed modelling procedure, the cell temperature was estimated with a root mean square error of 1.3^{o}C.

2. Kalogirou S.A., Use of TRNSYS for modeling and simulation of a hybrid pv–thermal solar system for Cyprus, 2001: Renewable Energy 23, 247–260.

http://dx.doi.org/10.1016/S0960-1481(00)00176-2

Contexts	Outcomes
Modelling and simulation of a PVT system was performed. The system consisted of a normal PV panel at the back of which a heat exchanger with fins was embedded. The advantage of that system was that the PV operated at a lower temperature and thus, more efficiently and also hot water was produced at the same time as electricity. The PV system consisted of a series of PV panels, a battery bank and an inverter while the thermal system consisted of a hot water storage cylinder, a pump and a differential thermostat. The system was modelled by TRNSYS, for typical meteorological year (TMY) conditions for Nicosia, Cyprus. The main component of the TRNSYS deck file constructed was Type 49, accompanied by other additional components required for the model.	The results revealed that the optimum water flow rate of the system was 25 l/h. The hybrid system increased mean annual efficiency of the PV system from 2.8% to 7.7% and in addition covered 49% of the hot water needs of a house, and thus, increased the mean annual efficiency of the system to 31.7%.

3. Bergene T., Løvvik O.M., Model calculations on a flat plate solar heat collector with integrated solar cells, 1995: Solar Energy 55(6), 453-462.

http://dx.doi.org/10.1016/0038-092X(95)00072-Y

Contexts	Outcomes
A detailed physical model of a PVT system was developed and algorithms for making quantitative predictions regarding the performance of the system were presented. The model was based on an analysis of energy transfers due to conduction, convection, radiation and predicted the amount of heat that can be drawn from the system and the (temperature-dependent) power output. Emphasis was given on the dependence of the fin width to tube diameter ratio.	In that study they showed that a PVT system was interesting with respect to system efficiency while algorithms that can be used in computer simulations were presented. The model predicted the performance of the system fairly well with system efficiencies, thermal plus electrical, about 60-80%. However, the authors mentioned that direct comparisons with relevant experiments

	were difficult as the system parameters relevant to the proposed model were not explicitly stated in the description of the experiments. As possible applications they proposed a domestic system for combined production of electricity and low temperature heat (for example as a pre-heater in a hot water system) and a large-scale system that it could be interesting regarding production of hydrogen and fresh water.

4. A. S. Yadav, J.L. Bhagoria, A CFD based thermo-hydraulic performance analysis of an artificially roughened solar air heater having equilateral triangular sectioned rib roughness on the absorber plate, 2014: International Journal of Heat and Mass Transfer 70, 1016–1039.

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.11.074

Contexts	Outcomes
A numerical investigation to analyze the 2D incompressible Navier–Stokes flows through the artificially roughened solar air heater for relevant Reynolds number (from 3800 to 18,000) was conducted. Finite-volume-based numerical method was adopted. The commercial finite-volume based CFD code ANSYS FLUENT was utilized to simulate turbulent airflow through artificially roughened solar air heater. RNG k–e turbulence model was used to solve transport equations for turbulent flow energy and dissipation rate.	For a given constant value of heat flux (1000 W/m^2), the performance of the artificially roughened solar air heater was strong function of Reynolds number, relative roughness pitch and relative roughness height. The optimum configuration of the roughness element for artificially roughened solar air heater was evaluated.

5. J. Xamán, G. Álvarez, L. Lira, C. Estrada, Numerical study of heat transfer by laminar and turbulent natural convection in tall cavities of façade elements, 2005: Energy and Buildings 37, 787 –794.

http://dx.doi.org/10.1016/j.enbuild.2004.11.001

Contexts	Outcomes
Laminar and turbulent natural convection flow in a 2D tall rectangular cavity heated from the vertical side was studied numerically (finite volume method). Fluid flow and heat transfer by natural convection in a tall cavity using laminar and turbulent k–ε models was examined.	This study will help to have more accurate heat transfer parameters for several applications: façade elements, insulating units, double-skin façades, etc.

6. S. Farah, W. Saman, and M. Belusko, Chapter 79 Integrating Solar Heating and PV Cooling into the Building Envelope, 2013: A. Håkansson et al. (Eds.): Sustainability in Energy and Buildings, SIST 22, pp. 887–901, Springer-Verlag Berlin Heidelberg.

DOI: 10.1007/978-3-642-36645-1_79

Contexts	Outcomes
A new 1D, steady-state BI solar collector model was developed, incorporating PVT and thermal (PVTT) collectors connected in series. In summer, the PVT collector was air-cooled and the collected heat was discarded to the surroundings while thermal collector heated the water for domestic use. In winter, both PVT and thermal collectors were water-cooled producing domestic hot water. The presented BI collector incorporated an unglazed PVT collector and a glazed thermal collector, connected in series to form one PVTT collector. The PVTT collector was cooled by water or simultaneously by two fluids (air and water). The cooling fluid tube or channel was bounded by stiffened corrugated roof metal sheet and absorber. The roof metal sheets were available in different profiles and they were made from aluminum or coated steel. These profiles can be easily modified to allow the installation of the absorber over a trough space and the installation of the PV laminate and the glazing of the PVT and thermal sections respectively.	For the same total collector area and for the same PVT section characteristics, PVTT was found to be better than PVT by reducing the summer operating temperature. That temperature reduction avoids collector thermal stresses and provides modest electrical power output improvement; however, this small improvement is associated with a more complex collector.

10 Studies of Energetic/Thermal Simulation (emphasis: building/system)

10.1 BI, Solar Collectors

1. L. Gao, H. Bai, X. Fang, T. Wang, Experimental study of a building-integrated solar air heating system in cold climate of China, 2013: Energy and Buildings 65, 359–367.

http://dx.doi.org/10.1016/j.enbuild.2013.06.014

Contexts	Outcomes
A series of experiments were carried out under real transient outdoor conditions to investigate thermal performance, color effect and energy savings of a building-integrated solar air heating system based on unglazed transpired collectors (UTCs). The average efficiency of black UTC was 77.64% and 68.92% under high and low air flow rate respectively, which are higher than most glazed flat-plate collectors. Collector's surface color had an effect on its thermal performance.	Design heating load of a reference building in Harbin can be reduced by 6.4% due to reduced wall loss with the application of UTC. With better coordination with architectural design at early stage in a project, this building-integrated solar air heating system can be both esthetically and technically viable in cold climate of China.

10.2 BI, Skin Façade

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

http://dx.doi.org/10.1016/j.enbuild.2007.04.002

Contexts	Outcomes
The primary parameters for a double skin façade (DSF) design were examined: an integrated and iterative modeling process for analyzing the thermal performance of DSF cavities with buoyancy-driven airflow by using a building energy simulation program (BESP) along with a CFD package, were adopted. A typical DSF cavity model was established and simulated. The model was validated using measured data from Dirk Saelens (Vliet Test Cell in Leuven, Belgium).	The energy performance and potential influential factors of such DSF were investigated. The modeling was used to develop correlations for cavity airflow rate, air temperature stratification, and interior convection coefficient that can provide a more accurate energy analysis of a DSF with buoyancy-driven airflow within an annual building energy simulation program.

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

http://dx.doi.org/10.1016/j.enbuild.2013.10.016

Contexts	Outcomes
Development of an artificial neural network (ANN)-based temperature control method to keep energy efficient indoor thermal environment in buildings with double skin envelopes.	The prediction accuracy of the ANN model for indoor temperature was proved. That accuracy supported the applicability of that ANN model. The developed ANN model has the potential to be successfully applied to temperature control method for buildings with double-skin envelope systems over summer.

10.3 BI, PVT

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

http://dx.doi.org/10.1016/j.apenergy.2012.02.079

Contexts	Outcomes
Building integrated semitransparent photovoltaic thermal system was considered to the roof of a room for analytical and numerical studies. One dimensional heat conduction equation in quasi steady state was considered. No temperature stratification in the air of room and semitransparent PV module was also assumed. The room was considered as thermally insulated. The meteorological data was for Pune (India) Matlab 7.1 software was used. Six different type PV module was considered to perform comparison work on the basis of energy and exergy analysis.	Cell efficiency decreased with increase in cell temperature. The efficiency was found to be 16.0% for HIT (PV cell on top of a crystalline silicon (c-Si) cell) and 6.0% for a-Si (thin amorphous silicon). HIT produced maximum annual electrical energy (810 kW h) → suitable for generating electrical power. Si produced maximum annual thermal energy (464 kW h) → suitable for space heating applications. An annual overall thermal energy (2497 kW h) and exergy (834 kW h) was maximum for the HIT PV.

2. A. K. Athienitis, J. Bambara, B. O'Neill, J. Faille, A prototype photovoltaic/thermal system integrated with transpired collector, 2011: Solar Energy 85, 139–153.

http://dx.doi.org/10.1016/j.solener.2010.10.008

Contexts	Outcomes
Combination of BIPV/T and UTC systems for building	The value of the generated energy –

façades is considered in this paper – specifically, the design of a prototype façade-integrated photovoltaic/thermal system with transpired collector (BIPV/T). A full scale prototype is constructed with 70% of UTC area covered with PV modules specially designed to enhance heat recovery and compared to a UTC of the same area under outdoor sunny conditions with low wind. The orientation of the corrugations in the UTC is horizontal and the black-framed modules are attached so as to facilitate flow into the UTC plenum. The BIPV/T concept is applied to a full scale office building demonstration project in Montreal, Canada	assuming that electricity is at least four times more valuable than heat – is between 7% and 17% higher. Also, the electricity is always useful while the heat is usually utilized only in the heating season. The ratio of photovoltaic area coverage of the UTC may be selected based on the fresh air heating needs of the building, the value of the electricity generated and the available building surfaces.

10.4 BI, PV

1. Thevenard, D., Review and recommendations for improving the modelling of building integrated Photovoltaic systems, 2005: IBPSA Conference, Montreal Canada 15-18 Aug.

Contexts	Outcomes
The models for photovoltaic (PV) systems currently in ESP-r prove very useful in estimating the electrical and thermal impact of BIPVs (they represent well the impact of PVs on the building thermal energy balance) but they may lack in accuracy in the prediction of the system energy production → To achieve both goals it is suggested to improve the PV models in ESP-r, taking into account all phenomena affecting the power output of PV modules: solar radiation intensity, cell temperature, angle of incidence, spectral distribution, uncertainty in manufacturer ratings, ageing, mismatch, soil and dirt, snow, partial shading, diodes, wiring → This would provide a more realistic estimate of the probable PV output over its lifetime. It is suggested to implement three models: a simple model based on constant efficiency, a one-diode equivalent model with explicit temperature dependency of the parameters, the Sandia model for cases when detailed modeling is required. PVs in ESP-r are modeled as an active material which can be located at any node inside a construction.	In the conclusion, the author noted that the current ESP-r PV model was adequate to predict the impact of PVs on building thermal energy balance, but may lack in accuracy to predict the energy production of the PV system. To achieve both goals at once it was suggested to improve or rewrite the PV models in ESP-r.

10.5 BA, Several systems

1. Bakker M., Zondag H.A., Performance and costs of a roof-sized PV/thermal array combined with a ground coupled heat pump, 2005: Solar Energy 78, 331–339.

http://dx.doi.org/10.1016/j.solener.2004.09.019

Contexts	Outcomes
A 25-m^2 PVT system and ground coupled heat pump was simulated with TRNSYS. The ground loop heat exchangers were modeled by using Eskilson´s model, implemented in TRNSYS type 81. This model assumed that ground thermal properties were homogeneous, which was justified as long as the model was only used to describe long-term processes.	This system could cover 100% total heat demand of newly built Dutch one family dwelling. Based on ten-year average energy balance of the reference system, the PVT was able to cover nearly all (96%) of its own electricity use (including pumps, electrical heater, and heat pump). The system was able to cover 100% of the heat use for space and tap water heating: the former was fully covered by the ground source heat pump by using PVT supplied heat, while the latter was partially covered by the PVTs, and partially by the heat pump.

2. F. A. Ghaith, R. Abusitta, Energy analyses of an integrated solar powered heating and cooling systems in UAE, 2014: Energy and Buildings 70 (2014) 117–126.

http://dx.doi.org/10.1016/j.enbuild.2013.11.024

Contexts	Outcomes
Viability of using the integrated Solar Heating Cooling (SHC) systems in residential buildings in UAE, by studying the thermal performance and potential energy savings, in addition to the economical and environmental aspects such as payback period and reduction in CO_2 emissions. This work involves integration of the absorption chiller with solar thermal collectors to provide a continuous cooling.	The obtained results for the fully solar powered system, showed that about 159 kWh and 126 ton/year savings were achieved in the Annual Energy Consumption (AEC) and CO_2 emissions, respectively. The maximum solar penetration of 20% was found to be optimum as it reduced AEC by 176 kWh and cut off CO_2 emissions by 140 ton/year with a payback period of 4 years.

11 Studies of Optical Simulation (emphasis: building)

No available studies

12 Studies of Optical Simulation (emphasis: system)

12.1 BI, Several systems

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

http://dx.doi.org/10.1016/j.buildenv.2013.09.003

Contexts	Outcomes
Both direct and diffuse fluxes of transmitted, reflected and absorbed solar and visible radiation within a multilayer glazing/shading system was presented. An algorithm or determining solar and visible optical properties of venetian blinds was also described, so that this type of system can be handled as a homogeneous layer of the fenestration system. Net radiation method for solving the radiant energy exchange within a multilayer system. Numerical, analytical, experimental results: comparison. Climatic conditions: Southern European regions (Lisbon, Portugal).	Model can be used for different sun profile angles and venetian blind geometries, suitable for comparing different glazing/venetian blind solutions and devising blind control strategies. Design charts were developed to help designers and users in enhancing the thermal and daylighting indoor conditions by adjusting the slat orientation of venetian blinds. The knowledge of the solar and visible optical properties of different glazing/shading systems is crucial in identifying the most effective sustainable strategies to improve the fenestration system performance, regarding building energy consumption and indoor comfort issues.

2. Wiegman J. W. E. and van der Kolk E, Building integrated thin film luminescent solar concentrators: Detailed efficiency characterization and light transport modeling, 2013: Solar Energy Materials and Solar Cells 103, 41–47.

http://dx.doi.org/10.1016/j.solmat.2012.04.016

Contexts	Outcomes
An inorganic thin film luminescent solar concentrator (LSC) was characterized experimentally. Application: as windows in buildings → building integrated (BI) LSCs.	The model can be used to calculate the LSC light transport efficiency as a function of window size, which only needs the easily measurable linear attenuation as input. That modelling related BI-LSC efficiency to window colour.

3. Baldinelli G., Double skin façades for warm climate regions: Analysis of a solution with an integrated movable shading system, 2009: Building and Environment 44(6), 1107–1118.

http://dx.doi.org/10.1016/j.buildenv.2008.08.005

Contexts	Outcomes
Glass double skin façade equipped with integrated movable shading devices. Three different modelling levels: optics of materials, fluid dynamics of the double skin façade and building energy balance. Aim: optimization of energy performance over winter as well as over summer. 3D CFD model made of two opaque walls with an inlet (bottom) and outlet (top) opening in the external wall; buoyancy driven flow regime. Climatic data: central Italy.	The simulation of façade performances with a CFD model for the winter configuration (shading closed) showed the instauration of a buoyancy induced flow inside the gap, producing the doubly beneficial effect of diminishing the heat dispersion through external walls and preheating the air for ventilation purposes.

4. A. Kerrouche, D.A. Hardy, D. Ross, B.S. Richards, Luminescent solar concentrators: From experimental validation of 3D ray-tracing simulations to coloured stained-glass windows for BIPV, 2014: Solar Energy Materials & Solar Cells 122, 99–106.

http://dx.doi.org/10.1016/j.solmat.2013.11.026

Contexts	Outcomes
Luminescent solar concentrators (LSC) are promising for BIPV (providing variety of colors, etc.). Ray-trace modeling: design, performance evaluation, optimization of LSCs. The study included 70 samples – both square and circular LSCs, containing five different fluorescent organic dyes.	Comparison of 3D ray-tracing modeling results with experimental data. 3D ray-trace results showed good agreement with the experimental measurements → confidence in the use of modeling for future larger LSCs for BIPVs.

5. Sellami, N., Mallick T.K., Design of nonimaging static solar concentrator for window integrated photovoltaic, 2012: 8th International Conference on Concentrating Photovoltaic Systems, CPV 2012; Toledo; Spain; 16 April 2012 through 18 April 2012.

DOI: 10.1063/1.4753845

Contexts	Outcomes
A solar concentrator for building integration (compact, static, able to collect maximum solar energy) was developed. The novel concentrator was designed for Window Integrated Concentrated PV (WICPV).	The concentrator was optically optimised (for different incident angles of the incoming light rays). Evaluating the best combination of the optical efficiency and the acceptance angle, 4x concentrator built from dielectric material, with total internal reflection was optimised. It was found to have a constant optical efficiency of 40% for an acceptance angle equal to 120° (-60°, +60°) and an optical concentration ratio (OCR) equal to 1.6x. This enables capture of the sun rays all day long (both direct and diffuse light). Higher OCR's were achieved for different dimensions of the solar concentrator; nevertheless, the acceptance angles were relatively low. Experimental results validated optical model results with a variation of less than 5%.

12.2 BA, Low-concentration evacuated-tube solar collector

1. G. Li, G. Pei, Y. Su, J. Ji, D. Wang and H. Zheng, Performance study of a static low concentration evacuated tube solar collector for medium-temperature applications, 2014: International Journal of Low-Carbon Technologies Advance Access, 1-7.

doi: 10.1093/ijlct/ctt083

Contexts	Outcomes
Experimental and optical analysis of a static low-concentration evacuated tube (LCET) solar collector for medium-temperature applications was performed. The LIGHTTOOL software was used for ray tracing to evaluate the LCET solar collector optical performance at different incident angles.	The ray tracing on the single LCET revealed that the overall average optical efficiency could reach 76.9% between 0 and 60° incident angles, a very attractive value for medium temperature applications.

13 Studies of Optical/Thermal Simulation (emphasis: building/ system)

13.1 BI, Several systems

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

http://dx.doi.org/10.1016/j.enbuild.2012.05.011

Contexts	Outcomes
Transparent solar thermal collectors (TSTC) → collector model with an advanced calculation of the transmission of diffuse radiation and a connection to the building → allows analysis of collector gains and g value. The model was implemented as a TRNSYS Type and a coupled simulation between a collector and a room was presented for different façade constructions. An HVAC system was presented together → possible reductions of primary energy Frankfurt was chosen for the meteorological data.	A new Type 871 was developed which is capable of modelling transparent solar thermal collectors in a very detailed way while opening the door to coupled system simulations with a building and an HVAC system. The validation of the models has been successful.

2. D. Saelens, W. Parys, J. Roofthooft, A. Tablada de la Torre, Reprint of "Assessment of approaches for modeling louver shading devices in building energy simulation programs, 2014: Energy and Buildings 68, Part C, 799–810.

http://dx.doi.org/10.1016/j.enbuild.2013.11.031

Contexts	Outcomes
A ray-tracing method was developed to describe the global solar transmittance of louver shading devices. The developed method was integrated in the dynamic building energy simulation program TRNSYS to assess the cooling demand as well as the required peak cooling power in a south oriented office room. The proposed integrated approach allowed the calculation of the solar transmittance for each time step. For the shading device a two-dimensional angular and time dependent model was adopted. Building simulation model: simulations were	The use of a simplified implementation of SFs is possible within acceptable margins by implementing average results from ray-tracing calculations.

conducted for a typical moderate Belgian climate.	

3. Baruchi I., Chorin M. B., Freedman B. and Sovran I., Modeling of building integrated low concentration photovoltaic glazing windows, 2010: Proceedings of the SPIE 7785.

DOI: 10.1117/12.861524

Contexts	Outcomes
A transparent PV double glazed unit which exhibited three main features - concentrating direct solar rays on PV cells, allowing a viewer to see through the window a non-distorted image and having good thermal isolation properties, was developed.	A model which simulated seasonal and day/night variations of the optical and thermal behavior of the window as a function of installation location was presented. The outputs of the model included PV power generation and the change in the required power for heating/cooling due to the elimination of direct irradiation into the room. That outputs were utilized to optimize the optical design in order to achieve best overall energy saving performance.

4. H. Manz and Th. Frank, Thermal simulation of buildings with double-skin façades, 2005: Energy and Buildings 37, 1114–1121.

http://dx.doi.org/10.1016/j.enbuild.2005.06.014

Contexts	Outcomes
Highly glazed commercial buildings with double-skin façades may overheat during summertime; thus, in order to optimize thermal comfort and minimize cooling loads, the thermal behaviour of these buildings requires careful investigation at the design stage. Complex physical phenomena (optical, thermodynamic, fluid dynamic processes are involved).	Three level modelling, design method for the whole building with double-skin façades. Static coupling between CFD and building energy simulation. These three levels are: modelling the optics of the layer sequence of the double-skin façade by a spectral method, modelling thermodynamics and fluid dynamics of the double-skin façade by CFD, modelling building by a building energy simulation tool.

14 Studies about other types of simulation

14.1 Exergy analysis (emphasis: system)

D. Fiaschi and A. Bertolli, Design and exergy analysis of solar roofs: A viable solution with esthetic appeal to collect solar heat, 2012: Renewable Energy 46, 60-71.

http://dx.doi.org/10.1016/j.renene.2012.03.013

Contexts	Outcomes
Solar Roof (SR): ducts on the bottom side of copper roofs to collect a fraction of the absorbed solar radiation; an innovative solar collector with high aesthetic value. Basic proposed system: Unglazed Solar Roof (USR). Additional system: Glazed Solar Roof (GSR).	USR showed 30-60% efficiency. GSR performance showed significant improvement only over cold seasons; Compared with a commercial reference flat plate collector (FPC) model, the efficiency of USR was reduced by 20% over the whole operating field. The exergy efficiency curves showed optimization at temperatures well above those in flat plate collectors. Integration with a domestic hot water system showed a potential yearly solar fraction of 53% with USR and 60% with GSR.

14.2 Energetic/lighting simulation (emphasis: building/system)

M. Janak, Coupling building energy and lighting simulation, 1997: proceedings BS1997

http://www.ibpsa.org/proceedings/BS1997/BS97_P036.pdf

Contexts	Outcomes
A new method of direct run – time coupling between building energy simulation and global illuminance simulation was presented. Direct coupling at the time step level between ESP-r and RADIANCE offers building energy simulation with access to an internal illuminance calculation engine, and thereby, enabling modelling of the complex interactions between artificial lighting control and the rest of the building energy domain in a fully integrated way.	The method of direct run - time coupling between building thermal and lighting simulation was proved to be promising. It allows explicit modelling of important interactions between artificial lighting control and the rest of the building energy domain. If a short time step and sub - hourly solar irradiance or illuminance climate data are adopted, relatively realistic dynamic behaviour of the lighting control can be predicted.

14.3 Emergy analysis (emphasis: building/system)

F. Meillaud, J.-B. Gay, M.T. Brown, Evaluation of a building using the emergy method, 2005: Solar Energy 79, 204–212.

http://dx.doi.org/10.1016/j.solener.2004.11.003

Contexts	Outcomes
Emergy is the energy of one kind, usually solar energy, which is required to make a service or product. Emergy methodology was adopted and the application was a building. The LESO (Solar Energy Laboratory, Swiss Federal Institute of Technology, Lausanne) was considered. The authors noted that emergy was the most appropriate methodology to evaluate their system, because each type of flow (monetary or information) could be taken into account. The experimental LESO building is 3-stories containing faculty/students offices and a workshop. A PV installation was situated on the roof. The building was constructed in 1981 with different solar façades. A homogenous south façade, replacing these units, was built in 1999 in accordance with sustainable development strategies and a drastic reduction of the use of non-renewable energy. Units adopted: J_{em} = emergy per unit time (sej/year, solar emjoules per year).	The yearly emergy consumption/production of a building was evaluated. This building was constructed according to special environmental considerations, such as important the use of passive gains and it had low energy consumption (232 MJ/m^2 year). Considering only energy and materials inputs, electricity was the largest input to the system (2.7E16 sej/year). The total emergy of the material inflows was 1.7E16 sej/year, paper being the largest material input (5.7E15 sej/year). The specific emergy (per mass) of some common building materials was also evaluated and compared to non-renewable energy.

14.4 Sunlight simulation (emphasis: system)

A. Márquez-García, M. Varo-Martínez, R. López-Luque, Toolbox engineering software for the analysis of sunlight on buildings, 2013: International Journal of Low-Carbon Technologies.

doi: 10.1093/ijlct/ctt062

Contexts	Outcomes
Shadow, irradiance, daily radiant exposure functions were presented (created by using Visual Basic). Those functions allowed the calculation, in an easy and fast way, the daily radiant exposure in each point of a façade in an urban environment.	The developed tool can improve the method for establishing the best part on a façade to set a generation device, e.g. PV panels or solar thermal collectors.

15 Conclusions

In the frame of the present study, a literature review focusing on BI solar systems is conducted. The review includes systems which produce thermal, electrical or both thermal/electrical energy. Emphasis is given on the BI solar thermal systems while the other two types of configurations (electrical; thermal/electrical systems) are also included in order to have a more complete picture of the studies which have been done and the studies which are needed to be conducted as a future prospect.

In the field of energetic simulations of BI solar systems, there are more than 30 studies. Most of these investigations regard BI PV, BI PVT and skin façades while there are few studies about passive configurations (solar chimney and Trombe wall), BI Concentrating PV (CPV) and solar shades. Thus, it can be seen that there is a need for energetic simulations of BI solar thermal configurations, especially of active solar thermal systems which could provide hot air and/or water for building energy needs. Also it would be interesting the development of models about BI CPVT (Concentrating PV/Thermal) or BI CT (Concentrating Thermal) systems provided that low-cost and simple configurations will be selected. In general terms, most of the energetic simulations give emphasis to the system itself; thereby, there is a need for more studies which give emphasis to the building.

In the area of thermal simulations of BI solar systems, there are more than 35 studies. Most of these works are about BI PV, BI PVT and skin façades while there are few studies about BI solar thermal collectors, solar chimneys, Trombe walls and pipes integrated into the building. Thereby, there is a need for thermal simulations of BI solar thermal collectors since there are no more than 5 studies in this type of systems. As it was previously mentioned, the development of models about BI CPVT or BI CT systems could also be examined as well as systems which include heat storage solutions for example with PCM. Also in the field of thermal simulations the greatest part of the investigations gives emphasis to the system and consequently, there is need for more studies which give emphasis to the building.

Moreover, there are more than 20 studies which combine energetic and thermal simulation. In that field, there is also the same tendency: the greatest part of the works is about BI PVT while there are only few studies (no more than 2) about BI solar thermal systems. It should be noted that some of the BI PVT and BI solar thermal systems of these works include transpired collectors. Consequently, in a future prospect, energetic/thermal modelling studies about BI solar thermal configurations (with/without concentration, with/without PCM, etc.) could provide useful information. In the same way with the two previous categories, there is a need for studies which give emphasis on the building.

Concerning optical and optical/thermal simulations, there are no more than 10 studies (with emphasis on the system and on the building/system). These studies regard multiple configurations such as thin-film luminescent solar concentrators, PV windows, skin façades and systems with louver shading. Thus, it can be seen that there is a gap in the literature in the field of optical models and further developments are needed since optical simulations could provide useful information for the behaviour of the BI solar thermal systems. Also for this category, there is a need for more studies which give emphasis on the building. Finally, it should be noted that in the literature there are also some models which regard other types of simulations such as emergy and exergy.

Conclusively, in the current literature the greatest part of the models are thermal and/or energetic simulations of BI PVT (or PV) and skin façades and thereby, there is a need for thermal and/or energetic models about BI solar thermal systems (models which give emphasis to the system itself but also models which give emphasis to the building are needed). On the other hand, the optical-modelling studies are very few and certainly, more optical-modelling investigations are needed since they could provide useful information about the behaviour of the BI solar thermal systems from optical point of view.

PART III:

Investigation of new applications for innovative BISTS

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1 General Background

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 the generated greenhouse gas emissions. Using Renewable Energy Systems (RES) such as solar thermal systems in buildings to cover water heating, space heating, cooling and other energy needs, is essential to achieving these challenging targets. 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. Until recently however, most of solar thermal collector systems were mounted on building roofs i.e. were superimposed on the building structure, with no attempt to incorporate them into the building envelope. This method of integration provides no savings by substituting existing building elements. In many instances the collector systems are actually seen as a foreign element of the building roof. Many architects, irrespective of the potential benefits, object to this use of renewable energy systems due to this fact alone. It is therefore necessary to develop systems and techniques that allow easy and real integration within the building envelope while proving good aesthetic appearance and blending into the form of the building architecture in the most cost effective way.

When superimposing a solar thermal system on a building structure it is possible to achieve architectural integration and provide good aesthetic appearance. However a solar thermal system is considered to be truly building integrated (i.e. a Building Integrated Solar Thermal System – BISTS), if for a building component this 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, like in the case of replacing with BISTS one of the walls in a double wall façade. BISTS should provide a combination of the following:

- Mechanical rigidity and structural integrity.
- Weather impact protection from rain, snow, wind and hail.
- Energy economy, such as useful thermal energy, but also shading and thermal insulation.
- Fire protection.
- Noise protection.

It is essential that BISTS provide flexibility on a wide range of characteristics that affect the building aesthetics. These include employed material and surface textures, colour of the absorber, shape and size of the units and methods for interconnection and thermal storage options. The ideal BISTS should achieve good thermal performance, cost effectiveness, good aesthetics and overall public acceptance.

Three types of mounting for BISTS can be identified:

- Installation either on a horizontal or tilted (pitched) roof.
- Vertical or sloped façade installation.

- Vertical Installations as balcony railings (balustrades) or fences.

Further classifications is whether the STS is or not accessible from within the building and transparent or translucent collectors (e.g. incorporated in a glazed façade) “Warm façade” or in front of a wall “Cold façade”.

2 Water Heating BISTS

2.1 Introduction

Water heating BISTS are the bigger sector of building integrated solar thermal systems. However until recently, in many of the cases the collector was just superimposed on the building structure rather than being and integral part of it. This was partly due to the fact that very few collectors existed in the market that allowed sufficient architectural and structural flexibility for integration. One of the main restrictions for the integration of such collectors in a building structure is the presence of a transparent glass cover which can reduce reliability and increase maintenance requirements cause injury in the case of of breakage. As a result some of the available solar thermal collectors currently made for building integration are unglazed (e.g. WAF, Solar Energie, all ceramic collector) or utilise thick glazed tiles for cover (Soltech Sigma). Evacuated tube collectors are a good BISTS solution as they offer easy integration onto a roof, façade structure or a balcony balustrade or fence. However in the cases of facade, balustrade or integration as a fence they need to be installed within protective structures or use toughened glass for the tube.

The water inlet and outlet arrangements are a very important factor influencing the suitability of the system for building integration. Traditional solar water heating collectors require lengthy pipe connections between outlet and inlets of adjacent units which in many cases cannot be integrated into a roof or façade structure. Purpose designed systems as BISTS have special arrangements or mechanisms that allow simple, reliable and architecturally seamless interconnection of the collector units on a roof or on a façade.

2.2 Review of Water heating BISTS

Solar water heating systems and their suitability for building integration BISTS is discussed in the following sections through actual demonstrations and case studies.

2.2.1 Solar Thermal Façade by WAF

The WAF Fassadensysteme Company in Austria, has developed a solar thermal façade system that enables natural energy generation via the external walls of the building (WAF, 2014). The absorber material is aluminium with solar varnish coating. The principle of operation of the solar thermal façade is described in Figure 2.1. The innovative design and surface coating, guarantee a cost efficient and visually appealing integration into the building façade.

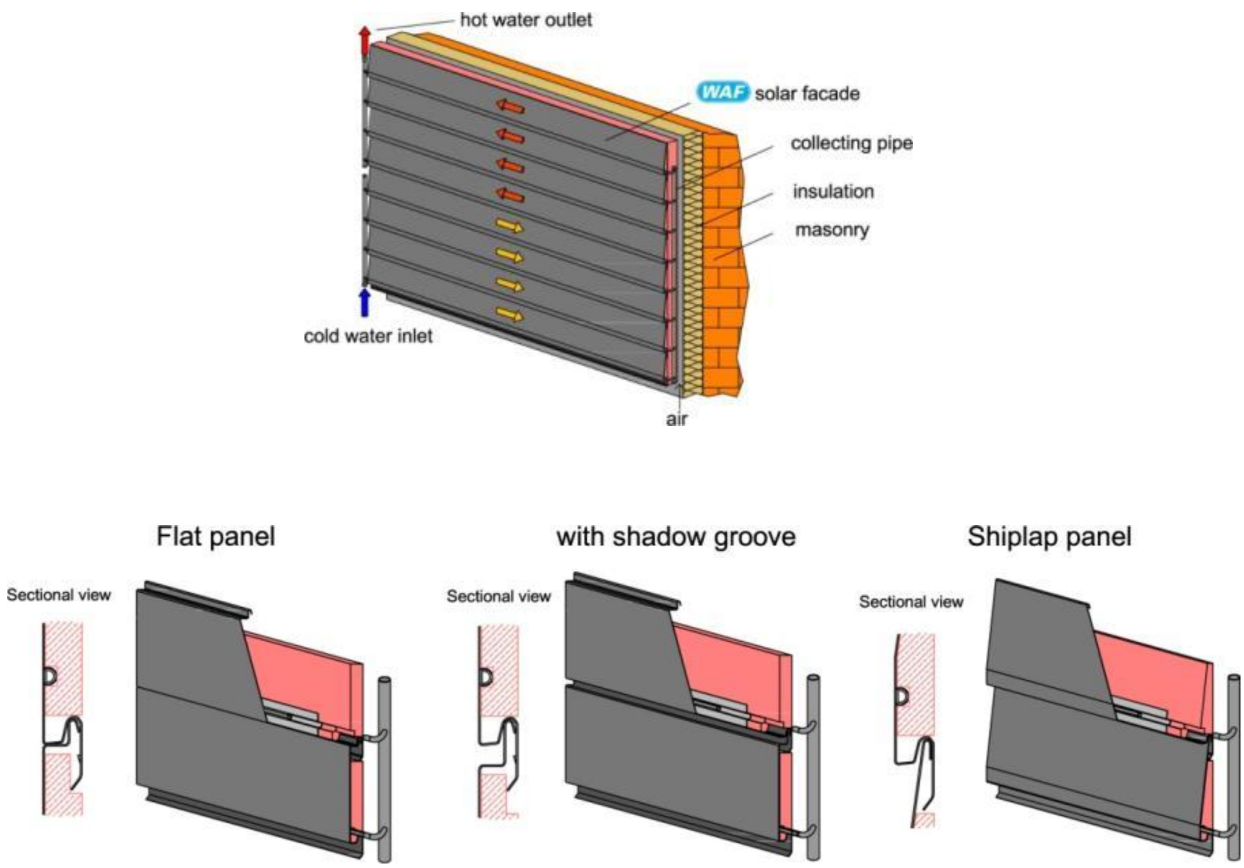

Figure 2.3 Solar Thermal Façade by WAF.

The WAF Solar facade combines energy generation with thermal insulation for the building and requires low maintenance due to its simple structure. The solar system works on the same principle as conventional solar thermal collectors. A heat transfer medium, in general a water-glycol mixture, passes through the solar circuit behind the facade elements. Thanks to a selective solar varnish coating, solar energy is optimally converted into thermal energy.

The structure of a solar facade is different from conventional, uncovered solar systems, mainly because of the connection between the lamella and the pipe. The metal sheet and the copper pipe are laser-welded to the lamella, which ensures optimum heat transfer. Furthermore, the pipe is pressed into the metal sheet and flattened on one side. This results in a larger surface area of direct heat transfer.

The insulation of the WAF solar facade mainly consists of a PUR insulation board (l=0,03W/mK), which minimizes convective heat losses through the back panel (figure 2.2). In order to avoid air pockets between the pipe and the insulation, PU foam is used for filling possible cavities. In addition, 50mm of mineral wool are used for insulating, among others, the collector pipes.

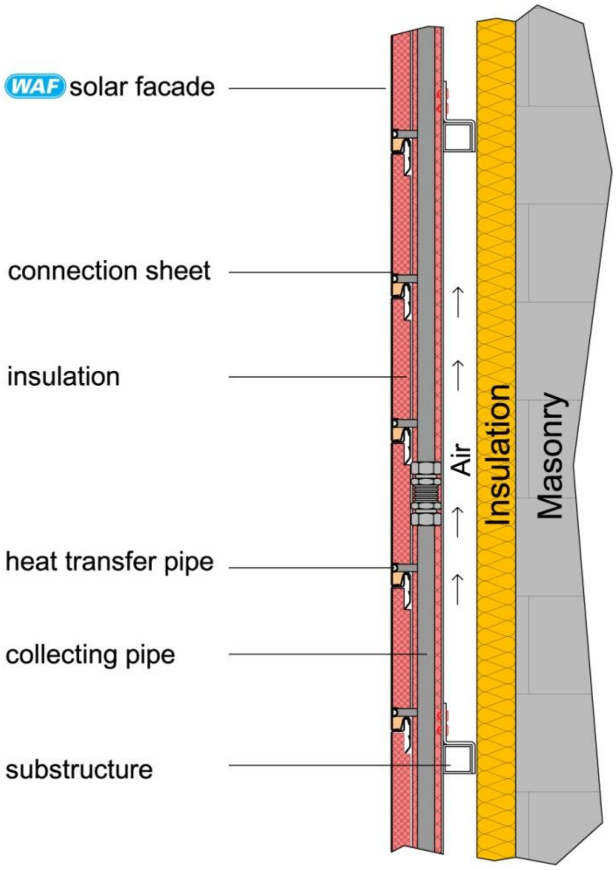

Figure 2.2 The structure of the WAF Solar Thermal Façade.

The coating of the lamella consists of a special solar varnish with a very good degree of absorption (black: 86%) and emission (black: 36%). At the same time, this solar varnish is extremely weather resistant. The individual lamellae are connected via the WAF click system, allowing for easy self-assembly.

The optimum thermal delivery of the WAF solar facade lies within that of low-temperature range. In order to achieve the facade's highest efficiency, the fluid temperature should be between 35°C and 45°C. In this range of temperature, preheating of drinking water, energy provision for low temperature heating or low temperature process heat can be provided.

2.2.2 Flat plate collector by Energie Solaire

Energie Solaire in Sierre, Switzerland produce a flat plate STS which can be easily integrated onto building roofs and facades (Solaire Energie, 2014). The absorber is made from two sheets of cushion stainless steel which are bonded together (figure 2.3). The working fluid (e.g. water) flows in the gaps formed between the two cushion sheets.

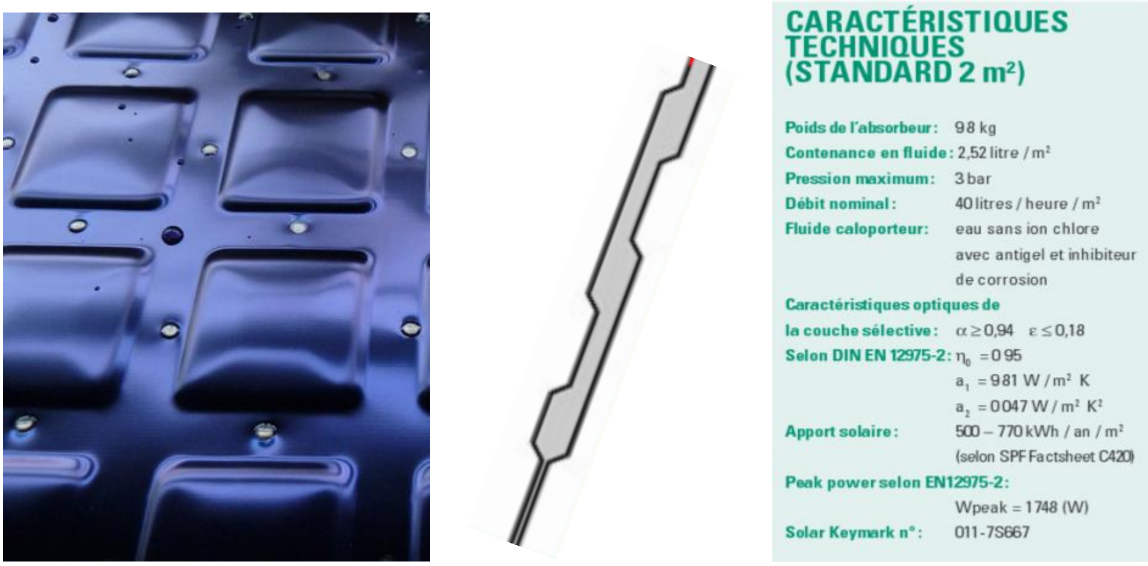

Figure 2.3 The absorber of the flat plate collector made by Energie Solaire.

This collector can be directly integrated on a roof or façade while its hidden face is thermally insulated (figure 2.4). The selective absorber coating is designed to withstand all weather achieving emissivity of below 0.18 and absorptivity above 0.94. The absence of glazing allows this collector to be integrated with ease on a wide range of building roofs including non-flat (curved) ones and facades (figure 2.5). In addition, the integration of the collector on a roof acts just like a conventional roof, providing a waterproof and durable cover. The collector has good aesthetics is efficient and economic, and ideally suited to large installations requiring water up to 50 °C.

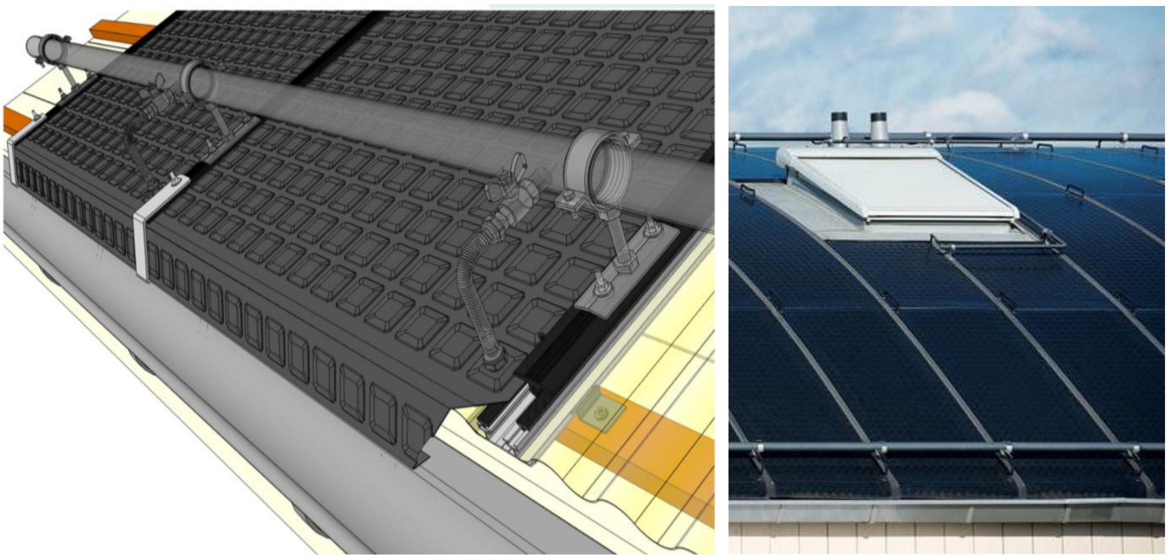

Figure 2.4 The collector of Energie Solaire as a BISTS on roofs.

Figure 2.5 Examples of the Energie Solaire solar collector as a BISTS on different types of buildings.

2.2.3 Soltech Sigma – Roof BISTS

Soltech Energy Company created an efficient and simple solar thermal system for single domestic as well as for large residential and commercial buildings (Soltech, 2014). The system is modular and designed for easy roof integration as demonstrated in figure 2.6. Instead of traditional roof tiles made from concrete or clay, the SolTech tiles are made of glass which covers the SolTech developed liquid based absorber modules. The tiles are interconnected on the roof to form a complete solar thermal collector system. The produce thermal energy is stored in a tank which is connected to the building's central heating system. The Soltech Sigma has excellent aesthetics compared to traditional roof integrated solar thermal collectors (Figure 2.7)

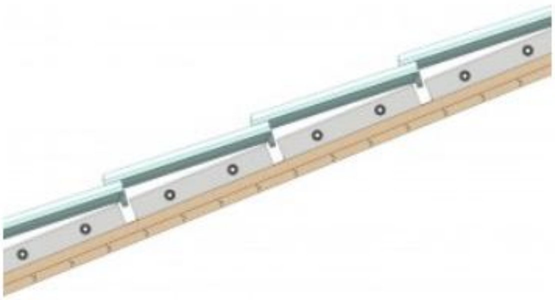
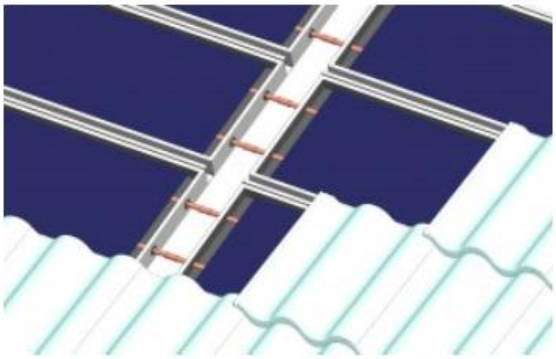

Figure 2.6 Soltech Sigma Smart Roof.

Figure 2.7 The Soltech Sigma Smart Roof solar collector integrated on a domestic building roof.

2.2.4 Universität Stuttgart, IBK 2 – Façade system

The University of Stuttgart (IBK2, 2014) has developed a facade system which uses integrated evacuated tube collectors to generate solar heat at a high temperature, and provide semi-transparent light and protection against the sun for indoor areas without impairing the view. The system is particularly suitable for offices and other functional buildings with a large number of windows. It can also be used as an architectural design element for facades (figure 2.7).

The high-performance evacuated tubes are equipped with perforated parabolic mirrors and which are integrated into a unitised façade (figure 2.8). The mirror bundles the direct irradiation of the sun and part of the diffuse light onto the evacuated tubes, in so doing reducing solar gains and therefore the associated cooling requirement of the building by between 70 and 90 %. By varying the pattern and size of the perforations on the mirrors, the interplay between collector yield, sun protection and room lighting can be optimised or customised. From the inside of the building, the sunlight appears reduced, is evenly distributed and is not causing discomfort to the human eyes.

20 mm thick laminated safety glass cover panel is used to provide the required safety in contrast. Simulations have shown that the choice of glass has a greater influence than the perforation of the reflector mirror on the energy yield of the system.

By using evacuated tubes the system is modular and can be installed on building facades of different sizes (figure 2.9). For architectural, geometric, technical and visual reasons, the horizontal alignment – as with sun protection blinds – has proven to be the most suitable.

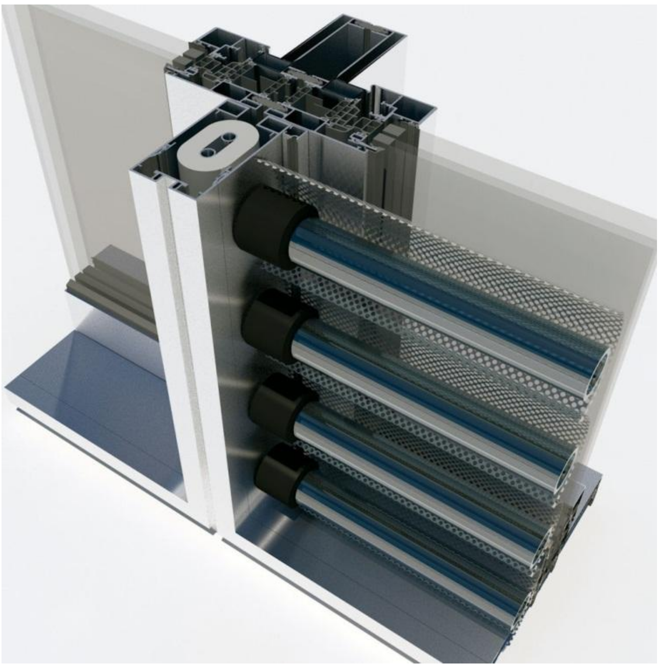

Figure 2.8 The BISTS using evacuated tubes and perforated parabolic mirrors developed by University of Stuttgart.

Figure 2.9 The of University of Stuttgart BISTS on a building façade.

2.2.5 Roof and facade BISTS – Citrin Solar

The roof and facade of the solar collector manufacturing facility of Citrin Solar in Germany are integrated with an active water heating BISTS (Citrin Solar, 2014).

The collector system used is a commercial product mainly for roof application but in this case it is also used as a façade system which also provides solar shading (figure 2.10). The installation consists of 70 collectors of 1,849 m^2 of total surface area. The façade was chosen for collector installation in order to maximize winter yield and avoid solar gain related overheating in summer. A 17,000 lt tank is used for storage of the produced thermal energy.

The installation aims to provide thermal energy for under floor heating of the 3000 m^2. The floor heating is covered with a thick concrete layer of the floor plate which serves as an additional energy storage. The BISTS performance data based on long term monitoring has shown that the total energy production from solar in 2010 was 70,000 kWh.

Figure 2.10 Roof and facade BISTS on the Citrin Solar factory (Germany).

2.2.6 Residential Building – Belgrade

This is a refurbishment case where the BISTS is added to the architectural image of the building and creating a visible surface change (Golic et al., 2011). The system installed is an active water heating system installed on the south facing façade and the roof of the building. A number of collector units have also been installed on the facades to provide solar shading.

The roof integrated collectors are mounted at 40° slope and cover an area of 100 m^2. The collectors integrated vertically on the facade cover an area of 90 m^2 while the collectors integrate at a 45° in parapets cover 120 m^2 of surface area. Finally solar panels were integrated as solar shades in horizontal position cover 55 m^2 of surface area.

The motivation of the project was to show different design solutions and benefits from the solar thermal collectors' integration on a multi-occupancy housing building. At yearly basis, the design variants of solar thermal collectors' integration can produce thermal energy from min 21,475.5 kWh (sun shading) to max 49,269.5 kWh (roof). Thermal energy production per m^2 varies from min 356.8 kWh/m^2 (parapet) to max 492.7 kWh/m^2 (roof).

2.2.7 Residential Building – China

A respectively small installation of BISTS can be seen in a new residential building in China where ceramic solar collectors act like a balcony (Yang et al., 2013).

All ceramic solar collectors (figure 2.11) were used, with ceramic raw materials mainly meaning porcelain clay, quartz, feldspar etc. Although most ceramic products have a certain requirement of whiteness, all-ceramic solar collectors have black or fuscous colour without whiteness requirement. Therefore, raw material with higher Fe can be used. The all-ceramic collector manufacturing process generally consists of four basic stages, preparation of raw materials, shaping, drying and calcining.

Figure 2.12 shows the integration of the all ceramic solar thermal collector onto the roof of the building and onto the balcony as a balustrade. In the case of roof integration the collector is directly mounted onto the roof structure and shares its insulating material to reduce heat loss from the back. When the ceramic collector is mounted as a balcony balustrade, it has increased thermal losses due to the lack of back insulation compared to the roof integrated system. However due to its location and mounting arrangement it is far easier to inspect and maintain.

Figure 2.11 The all ceramic solar thermal collector

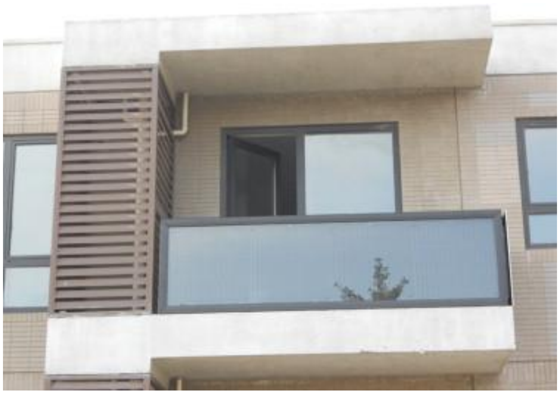

Figure 2.12 The all ceramic collector as a roof integrated system (left) and integrated as a balcony balustrade (right).

2.2.8 Residential Building – Holland

This is a new residential building in Holland where a passive water heating BISTS is installed on its roof. The system is called Eco-Nok and it has a special design and use.

The Eco-Nok is an integral roof mounted Integrated Collector Storage (ICS) solar water heating system available in connected modules (see Figure 2.13). Each module has a water capacity of 26 litres, is 1.5 m long with diameter of 270 mm. The module's effective collection area is 0.36 m^2 or 1.03 m^2 for a typical 3 module unit. The annual energy collection for a 3 module installed along the apex ridge in Holland is 2.1 GJ.

Figure 2.13 Eco-Nok ICS solar water heating collector.

The Eco-Nok uses unique, patented ICS technology based on heat pipe (thermal diode) operation and is typically mounted in the apex ridge of pitched roof. Several modules may be linked together and can directly preheat feed water to the hot water cylinder (HWC) or indirectly via a pumped circuit to the HWC heating coil. The Eco-Nok is CE certified and can provide up to 50% annual savings on hot water energy consumption according to the Dynamic System Testing method for a typical Dutch household equating to around 125 and 250 m^3 per year in natural gas.

2.2.9 School building – New Haven, USA

A passive solar thermal water heating system which also provides solar shading (awning) is integrated onto the new Science and Technology building of a school in New Haven (BIO Tecture, 2014). The system is fully integrated to the architectural concept of the building (see Figure 2.14). The use and production of energy from the BIST system is monitored and presented to students and this makes the building itself a teaching tool.

Figure 2.14 New Science and Technology building, New Haven.

The system is essentially an awning with horizontal blinds, which act as a solar thermal system, facing south and has a slope of 45° in order to take full advantage of the location and orientation of the building. The blinds are metallic in black colour.

2.2.10 Residential building – Florida, USA

The BIST water heating system in this residential building is installed as a balustrade (see Figure 2.15). The gross area of the collector used is 1.737 m^2 and the fuel capacity is 64 litres. The GLE SHP310 glazed solar water heater unit consist of in-line evacuated tube batch collector with 650 mm long tubes of 125 mm diameter (GLE Solar Energy, 2014). The thickness of the tube glass is 4 mm and the absorber tube is made from stainless steel, coated with graded Al-N/Al.

The GLE solar evacuated tubes are much larger than in conventional evacuated tube collectors and therefore create larger units. The framing of the tubes is designed to be integrated into existing fence, handrail and balustrade features providing aesthetically integrated appearance.

Figure 2.15 GLE solar evacuated tubes in residential building in Florida.

The performance data for the BIST system were obtained through measurements and tests in accordance with ISO 9806. The unit was evaluated by the Solar Rating & Certification Corporation (SRCC) in accordance with SRCC OG-100. The performance rating of the system on the building showed that in warm climate the energy produced from water heating per panel per day with medium radiation is 2.9 kWh/m^2 while for cool climate the energy from space and water heating is 1.6 kWh/m^2 per day.

2.2.11 Residential Building – Ireland

The Integra In-roof **Integrated Solar Collector** is installed in new residential buildings in Ireland (figure 2.16). Its construction and appearance is similar to that of conventional flat plate collector units. The Integra collector consists of a double header manifold absorber construction and the riser pipes are ultrasonically bonded to the absorber plate which are brazed to the top and bottom manifolds.

Figure 2.16 The Integra In-roof Integrated Solar Collector installed onto the roof of a new domestic dwelling in Ireland.

The collector must be fixed to a roof that meets the requirements of I.S. ICP 2:2002 Irish code of practice for slating and tiling. Each collector is mechanically fixed to the roof trusses with four aluminium brackets. The Integra collector was tested for impact resistance in accordance with EN 12975-2:2006.

2.2.12 Office Building – Switzerland

The South facing façade of the Centre ď entretien des Routes Nationales (CeRN) in Switzerland, is covered with the Solaire Energie unglazed solar thermal collectors which act as a multifunctional material (figure 2.17). The North facing façade of the building is covered with stainless steel elements of the same geometry but not thermally active.

Figure 2.17 The BISTS integrated onto the façade of the Centre ď entretien des Routes Nationales (CeRN) in Switzerland.

The south façade consists of stainless steel solar collectors. The collector consists of two sheets of stainless steel which are assembled back to back with their peaks and edges shifted in such a way relative to one another so the fluid can flow through the resulting voids (Nivo, 2014). This method provides a uniform flow of water and heat transfer is particularly effective since the fluid is in contact with almost the entire surface of the collector sheet. The collector area is 576 m^2 and they are pre-fabricated off-site and assembled on-site. The 576 m^2 of thermal solar collectors produce 288,000 kWh/year.

2.2.13 Solar fence – JET Solar

The Jet Solar Fence (JSF) is solar water heater mounted in a fence configuration with optional privacy slats mainly used as a solar pool heater (figure 2.18). JSF was designed to be installed into an existing fence or used to hide the equipment pad, anywhere there is sun exposure (GLE Solar, 2014).

Figure 2.18 The JET Solar Fence (JSF) installed in a domestic building in USA.

The water vessel is made of high-grade marine stainless steel; there is a manifold that runs the length of the unit, and heating tubes are welded to the manifold, where they are covered with a glass evacuated tube. The direct pool water is pumped in the lower corner of the unit; the water then flows through each heat collection tube, and heated water flows back out. Both the inlet and outlet are located together for ease of plumbing.

2.2.14 Residential building – China

A very large scale passive water heating BIST system is installed in a new residential building in China. It is a complex of apartment buildings called 'Garden Utopia' Project in the Chinese city of Dezhou (Global Solar Thermal Energy Council, 2012).

The project used 504 vacuum tube collectors placed horizontally into a massive metal casing in the form of a wave, which covers all the rooftops of the buildings, as well as horizontal vacuum collectors placed in orthogonal frames to the facades. The domestic hot water tanks are placed on the balconies behind an element with horizontal vacuum tubes. The tubes are placed in front of all the 20 storey building (figure 2.19).

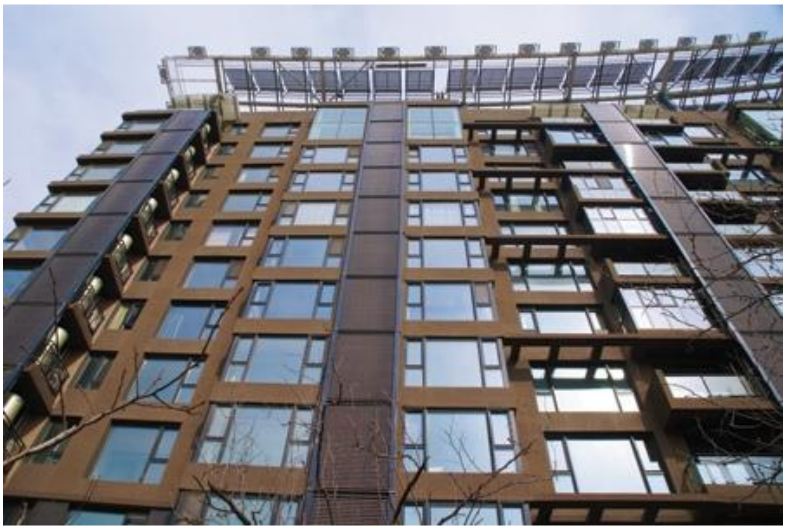

Figure 2.19 Evacuated tube solar thermal collectors horizontally integrated onto the façade of a building in the Garden Utopia' Project in the Chinese city of Dezhou.

The solar fields composed of vacuum tubes with a gross collector area of about 1400 m^2 that utilize the sun on the roof and feed a central heating and cooling system running through the entire building complex.

The system proved to be very viable as the flat owners save up to 75% of annual energy costs in their new accommodations.

2.2.15 Solar Hybrid Shades in residential building – Hollywood, USA

This building combines three functions of BIST systems; water heating, shading, and natural cooling (BIO TECture, 2014).

Special software was used to finalize their design, taking into account various factors such as the size and the distance between the tubes in order to shade the building without obstructing the view, but according to proper thermal performance. The system consists of 5 specially designed boxed with horizontal evacuated tubes placed on the south side of the building. The total area of the collector is 18.5 m^2.

Figure 2.20 The BIO TECture solar hybrid shades integrated onto a domestic building in Hollywood, USA.

With the integration of passive and active solar technologies, the house offers thermal comfort all year round without the need of air conditioning. In the southern side of the building, the BISTS has functions both as blinds for shadings as well as solar thermal system that provides hot water for household needs for hot water and floor heating. It is important to mention that the thermal solar collector is invisible, fully integrated and does not distract from the clean architectural lines of the building (figure 2.20).

This small 18.5 m^2 hybrid façade shield preheats water to reduce energy costs (by up to 30 %). The natural cooling concept of this project reduces the heat gain by an average of 4.8 % and 18.9 % peak demand reduction.

2.2.16 Non-rectangular solar collectors for roof or wall integration

The work done by Visa et al. (2013) presents a novel concept of solar-thermal arrays with variable geometry, based on non-rectangular collectors; different shapes and sizes are analysed and their adaptability for developing arrays with various geometries for integration on roofs or walls is discussed. Two “unit” shapes are proposed (equilateral triangle and isosceles trapeze), based on which various geometries can be developed; the size range of the collectors is discussed, along with the tubes’ design for the inner circulation of the water based working fluid. Several examples of façade and roof integrated arrays are presented, outlining the versatility of the proposed solution.

According to Visa et al. (2013), for building up a façade with a high flexibility degree in terms of shape and design, the solar-thermal collectors should be different than the regular “rectangle” shape; still, a “unit” shape should be found, based on which the other geometries can be derived and in this view, highly symmetric geometries are preferred. Additionally, the unit shape should not be too large, as increasing the dimensions reduces the coverage degree of small facades. On the other hand, the hydraulic limitations impose an inferior size limit, below which pressure drop in the tubes is significant. Preliminary calculations showed that polygonal geometries with sides of 70-120 cm may suite the purpose.

Basically, these pre-requisites are well satisfied by the equilateral triangle allowing to further building up isosceles trapeze and regular hexagons (with the corresponding increased dimensions). On the other hand, if compact larger assemblies are required, the better choice for the unit shape is the isosceles trapeze, with the advantage of reducing the costs (as compared to three interconnected equilateral triangles) and increasing the reliability, but having the drawback of a single colour of the collector.

For the triangle unit the obvious solution is with the in-/outlet on the corners, Figure 2.21a. This is a feasible approach especially for serial connections of a limited number of FSTC. In-field studies on commercial FSTC showed that there is a limited number of collectors that can be serially interconnected (up to 5) and above this limit the efficiency drastically drops as the in/out temperature difference is too low. Considering the reduced size of the novel triangle collectors, preliminary estimations showed that the number of serially connected collectors can be higher but it is limited. An alternative is proposed, that allows parallel or serial connection with the same likelihood, based on the in-/outlet that are positioned close to the mass centre of the collector, Figure 2.21b. The closed loop type of the tubes design allows, according to the unit size and tubes diameter, various geometries, insuring a high collection degree of the heat delivered by the absorber plate. Calculations showed that for a 1/2” tube, a distance of 10…12 cm is enough for avoiding heat losses between the absorber plate and the working (liquid) fluid.

The serpentine in Figure 2.22a is mounted inside a collector that can have four in/outlet connections; according to the mounting requirements on each of the trapeze basis one will be blinded, leaving a regular one-to-one inlet/outlet. The novel design proposed in Figure 2.22b derives from the traditional parallel tube design but has significantly enhanced heat coverage of the absorber plate. Combinations of these two serpentine types are also possible using tubes with different diameters for hydraulic equilibration.

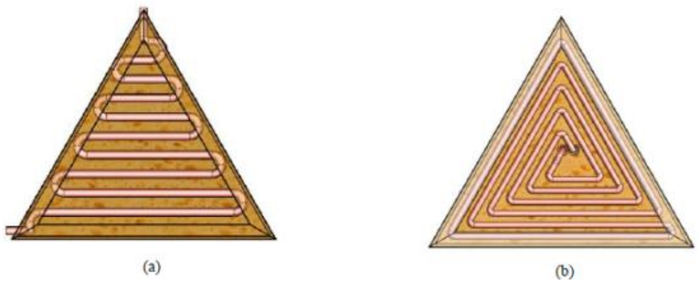

Figure 2.21 Tubes design for the triangle shape unit: a) inlet/outlet on the corners and b) inlet/outlet in the mass centre.

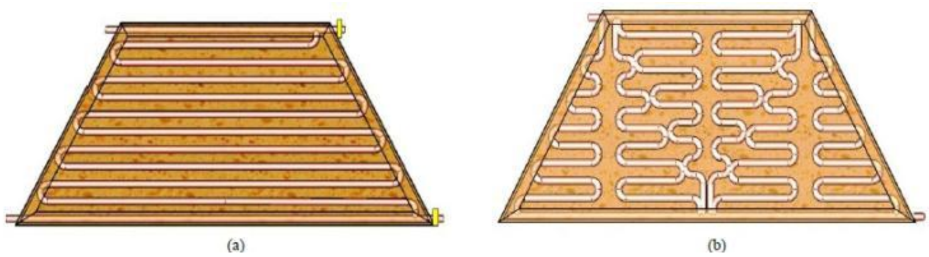

Figure 2.22 Design of the tubes in the trapeze unit shape a) serpentine b) novel design.

The tube design for the water-based working fluid can follow the regular serpentine type but alternative solutions are presented, that insures large heat coverage and allows serial and parallel connections in various positions and assemblies. The non-conventional shapes are completed with coloured glazing or absorber plate, leading to a practical infinite variety of solutions that can be implemented on blocks of flats, residential or office buildings and are supporting the more extensive development of sustainable communities.

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3 Air Heating BISTS

3.1 Introduction

Air heating BISTS are a type of building integrated solar thermal system, using air instead of water (the most usual) as fluid. The major difference between air and water based collectors is the need to design an absorber that overcomes the heat transfer penalty caused by lower heat transfer coefficients between air and the solar absorber and the lower density of the air, which requires large volume of air to be circulated.

A number of different solar air collector designs have been build. They differ according to the cover transmissivity, the type of the absorber, the type of coating and the air flow pattern.

Air BISTS are mainly used for space heating. However, when hot water is also required for domestic uses, the same collectors can be used. In this case air is circulated through air collectors and via ductworks is directed to an air-to-water heat exchanger. Through the heat exchanger, heat is transferred to the potable water, which is also circulated through the heat exchanger and returned to the storage tank (Kalogirou, 2004). Air BISTS can also heat the building ventilation air and improve indoor air quality.

The main advantages of air collector systems are that air medium does not need to be protected from freezing or boiling, is non-corrosive, and is free. Additionally, other advantages include the high degree of stratification which can occur inside the absorber of the system and which can lead to lower collector inlet temperatures and higher efficiencies.

The disadvantages are that air handling equipment (ducts and fans) needs more space than liquid piping and pumps and air leaks are difficult to detect. Air BISTS would also incur higher parasitic power consumption (electricity used to drive the air fans) compared to systems using water or oil liquids. Another disadvantage is that air collectors are operated at lower fluid capacitance rates and thus with lower values of F_R than the liquid heating collectors.

The SolarWall system, the solar cooling system and the SunMate solar air heating system are commercially available air BISTS. The main aspects of these three systems along with the highlights of some of the projects which use them are presented in the following sections.

3.2 SolarWall systems

The SolarWall air heating system is a custom engineered solution containing several internal and external components (SolarWall, 2013a). A basic component is the exterior metal cover which is the visible wall part attached on the internal framing design. Special vent-slit perforated collector panels are installed several centimetres from a south facing wall other wall orientations are also possible), creating an air cavity. The SolarWall cladding (transpired solar collector) is heated by the solar radiation from the sun, and ventilation fans create negative pressure in the air cavity, drawing in the solar heated air through the exterior panel perforations.

There are many variations to the SolarWall technology, based on the energy requirements of the building or on the objective of the customer. The conventional single-stage SolarWall systems (figure 3.1) can be styled, shaped and angled in a variety of colours and the 2-Stage SolarWall systems (figure 3.2) might be used for higher temperatures. The two systems are presented in Figures 1 and 2 respectively.

In cold countries, on a sunny day, the air entering the air handling unit will already be heated, from 16-38°C for a conventional SolarWall system and 20-55°C for a 2-Stage SolarWall system.

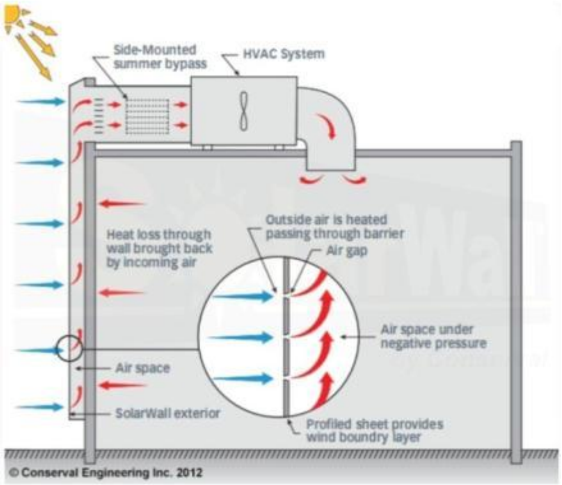

Figure 3.1 Single stage SolarWall® patented system with Rooftop HVAC.

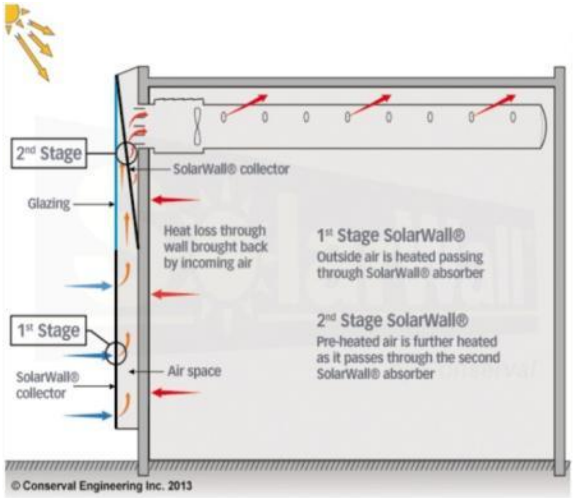

Figure 3.2 2-Stage SolarWall patented system ® with Interior Fan.

Many other manufacturers produce cladding for solar walls that come in various shapes and colours. One such manufacturer is ATAS International, Inc. who informs us that the cladding cost is comparable to a brick wall and that the typical payback is 3 to 8 years. The cladding collects solar energy at a typical efficiency of over 60%, reduces annual CO_2 production by 200 to 300 kg/m^2 of collector and utilizes metal components that contain recycled material and are recyclable at the end of their life cycle.

The SolarWall system displaces 20-50% of the traditional heating load and corresponding greenhouse gas (GHG) emissions. They allow high life-cycle cost savings and require no maintenance over their 30 year lifespan.

3.3 The Kingspan Integrated Sol-Air Collector

The system in this project is called Kingspan façade solar air heater and involves a *BISTS* integrated on a commercial building's façade (Kingspan, 2014). The Kingspan Integrated Sol-Air Collector is a modified Kingspan insulated composite panel. On a typical panel, five crowns are left un-insulated, creating profile voids beneath the crowns (Figure 3.3).

Incident solar radiation on the panel's outer steel skin is absorbed leading to a rapid temperature rise inside the channel. Fresh air drawn into the channels at low level is heated and supplied into a supply plenum at the top of the panel. Additionally, an auxiliary heating system provides top-up heating when necessary.

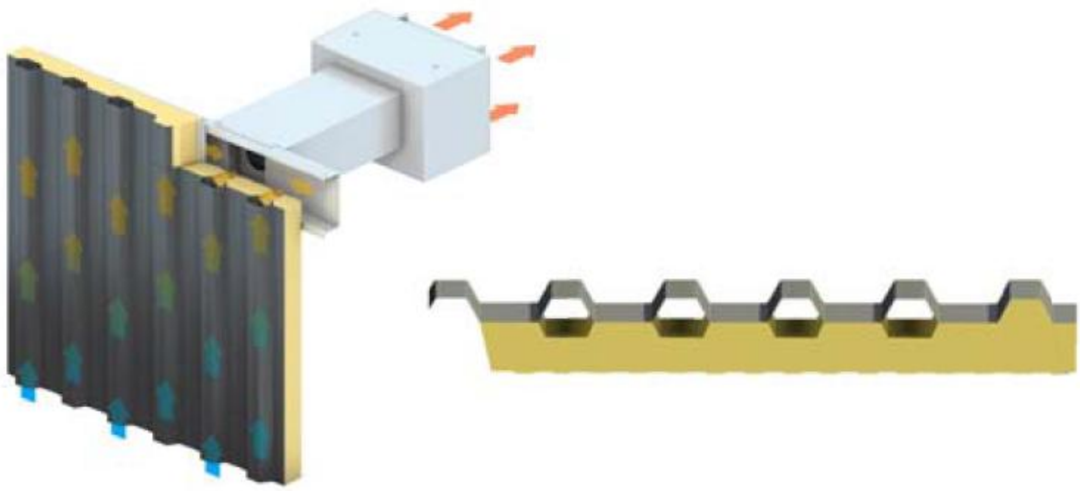

Figure 3.3 Schematic of the Kingspan Integrated Sol-Air Collector (ISAC).

Due to its easy and rapid system installation and dual functionality, thereby involving reduced material and labour costs, the Kingspan Integrated Sol-Air Collector was an ideal choice to provide solar pre-heated air to an occupied area in the building used as case study; a large supermarket warehouse. The ergonomic building envelope solution suited perfectly with the architectural features required by the portal frame and panel clad structure, requiring minimal on-site fabrication of the system structure and ideal for this new build project.

3.4 Solar Cooling Systems

The solar cooling systems remove energy from the room air to cool a building without the use of compressors or refrigeration systems (see Figure 3.4**Error! Reference source not found.**). This echnology is partly based on nocturnal sky radiation, which can cool a roof by as much as 10°C below ambient temperature on a clear night. As warm night air touches the cooler surface of the patented NightSolar® system (SolarWall, 2013b), it transfers its heat to the surface, which cools the air. The chilled air is then drawn in through perforations in the collector and enters the HVAC unit via an economizer cycle. This cooling has the ability to reduce the use of conventional air conditioning from sunset to sunrise. During the daytime, the NightSolar® system reduces daytime heat gains normally received through the roof. Field monitored NightSolar® installations show as much as 50% overall cooling savings on buildings using existing fans and economizers.

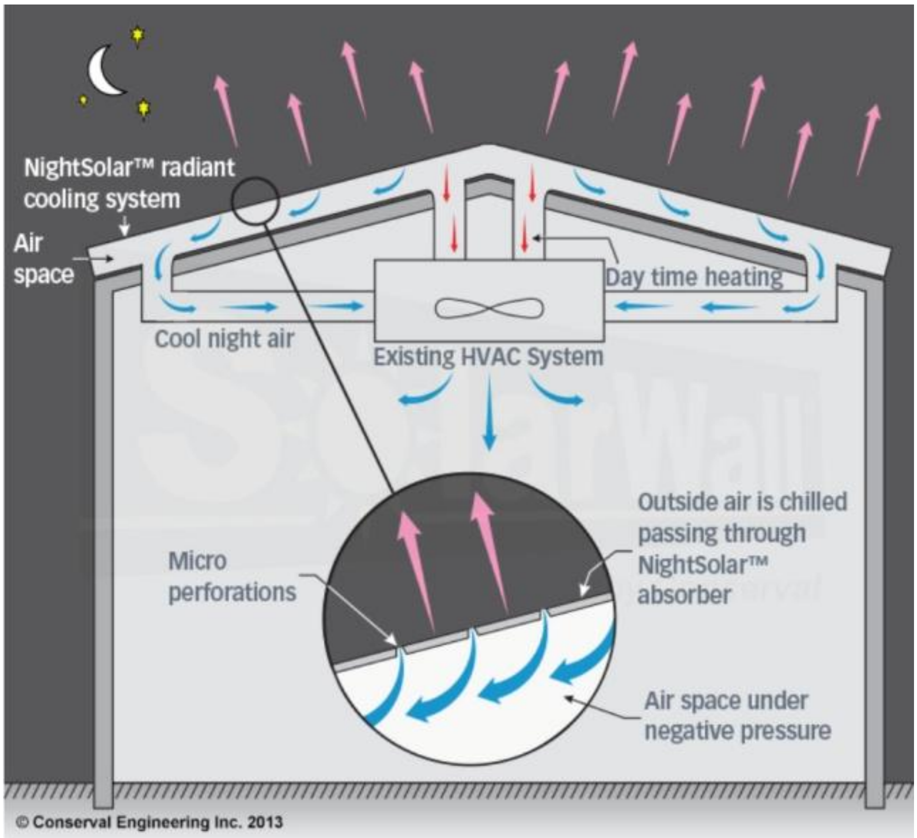

Figure 3.4 NightSolar® system showing the principle of operation.

3.5 The SunMate™ Solar Air Heating Collector

This system offers an environmentally friendly, low-cost air heating option. The SunMate™ draws cool air from the building, channels it through the absorber plate, where it is warmed by energy from the sun, and circulates it back into the building. A built-in thermostat automatically turns on the fan when the absorber plate reaches 42° C and shuts the fan off when the plate cools to 32°C. This system is built from heavy-duty, stainless steel and aluminium components providing long life with no maintenance (Environmental Solar Systems, 2014).

A single panel can heat up about 75 m^2 of room area. Its double-sealed solar glass eliminates air infiltration and the polyisocyanurate insulation results in low heat loss. The unit runs with an 8.5 W fan that can be powered by a 20 W solar module.

The panel dimensions are 60 cm x 120 cm or 60 cm x 180 cm and can be installed on an external wall or roof as shown in Figure 3.5. Parallel installation allows the integration of multiple panels for heating larger areas. The unit is covered with TiNOX, a highly selective absorber coating, that has high absorption (95%) and low emissivity (5%). It converts 90% of all solar radiation into heat.

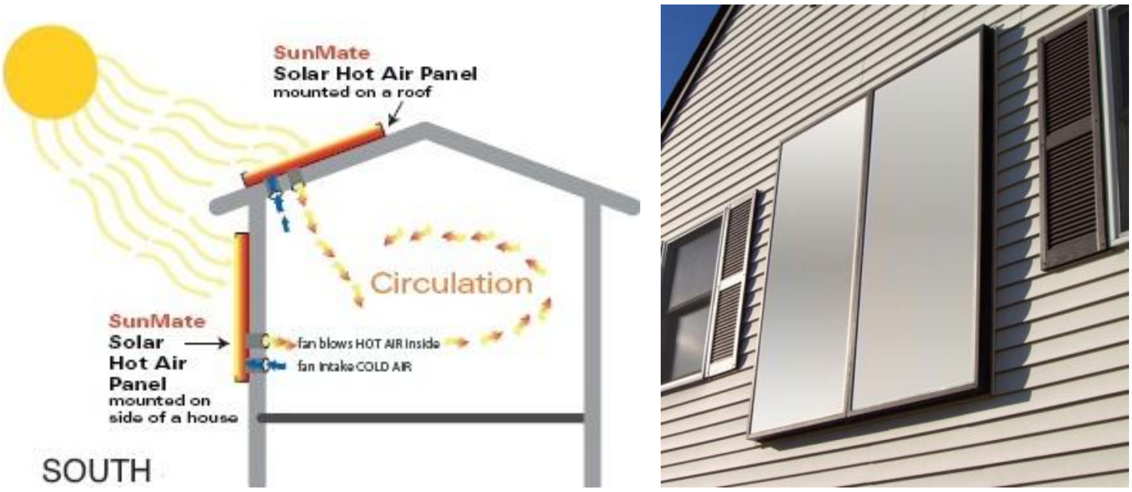

Figure 3.5 The SunMate™ Solar Air Heating Collector.

3.6 Air BISTS projects

Air heating BISTS are widely used and there are many examples of case studies for discussion. Some examples are presented in the following sections.

3.6.1 Commercial Building – Doncaster, UK

The Kingspan ISAC system has been integrated on the façade of a commercial building (figure 3.6) in Doncaster, UK, to provide solar pre-heating to a floor space area of 645m^2 having a conditioned volume of 11,483m^3. The solar-heated air flow rate for the building was calculated at 89m^3/hr per m^2 of collector panel, requiring an effective collector area of 72.8 m^2. Given that each panel has an effective area of 0.583m^2, a total panel area of 124.8m^2 was required. To fit the building's south façade, above proposed light wells, the total Kingspan Integrated Sol-Air Collector system required was 8.95m high and 14.4m long (128.2m^2).

Figure 3.6 The Kingspan ISAC on the façade of a commercial building in Doncaster, UK.

Based on the 128.8m^2 of Sol-Air system installed on the south elevation façade and the 14.4m of linear plenum and HVAC duct, an estimation of the solar derived energy delivered, CO_2 reduction, final material cost, annual financial savings and payback period have been determined (Table 3.1).

Table 3.1 Solar Air Savings – Kingspan.

Total energy demanded by the building	66.32 MW/hr
Total predicted energy delivered by Solar-Air	13.14 MW/hr
Estimated annual savings	653 £/year
Total cost of Solar-air system	2661.6 £
Payback period	5 years
CO_2 annual reductions	2.36 tCO_2/ year

3.6.2 Residential Building – Japan

This is an OM solar integrated dwelling application (Figure 3.7) (OM Solar, 2014). The OM solar concept building was developed to provide a completely different prefabricated house from those offered by traditional Japanese home manufacturers. The solar system consists of a glass covered heat collector having an area of 16m^2, a metal solar heat collector having an area of 11m^2, an under floor storage of 64m^3, and hot water tanks with a total storage of 300 litres. The system supplies a volume flow rate of fresh air of 600m^3/h.

During the solar heating mode, fresh outdoor air enters a channel under the roof and flows upwards. The air is heated on contact with the metal roof sheet, passing through an upper glazed section (to improve collection) whereupon the heated air enters roof top duct and is mechanically forced through the air regulating unit. The temperature controlled air is directed down into the space to be heated via underfloor channels between the floor and the concrete slab before finally being diffused into the room through floor diffusers. In the summer cooling mode, outdoor air is drawn through the roof channels at night-time, sub cooled using radiant cooling, and as with the heating mode, directed into the space to be cooled via the underfloor channels.

Figure 3.7. OM solar integrated dwelling.

The OM solar system has been very successful and has been replicated in various forms throughout Japan in over 20,000 homes. The modelled heating load of the house for a year shows that 59% of the annual heating energy can be supplied by the solar heat (OM system).

3.6.3 Industrial Building – Montreal, Canada

The first example is a large air heating BISTS is installed in a new Canadair industrial building in Montreal in 1996. It was the largest air heating system in the world (SolarWall, 2014a).

The solar installation was integrated on the extensive renovations that were needed to improve the indoor air quality and the appearance of the aged buildings of the industrial complex. The architect overseeing the renovation project selected the blue-grey colour for the SolarWall collector and contrasted it with a white colored canopy, which also acts as a manifold to ensure an even distribution of incoming air across the entire solar collector area (figure 3.8). The overall intention was to redesign the building so that it was energy efficient and aesthetically attractive. As it was proved, the depreciation of €210,265 (in 1996 prices), came in just 1.7 years which is very short remarkable payback time.

Figure 3.8 The SolarWall BIST in the Canadair industrial facility in Montreal, Canada.

The system is installed on two sections of the complex. The total surface of the solar panels is 8826 m^2 plus an additional 1700 m^2 canopy. It is basically a second shell which is mounted on the outer walls of the building and heats the air and then circulates it inside the building. The system has a metallic dark colour and it can be fabricated on site.

The performance analysis of the system was made through detailed simulations and measurements. As shown by the CANMET's monitoring report, the annual energy from the solar system is around 12,531 GJ/yr (SolarWall, 2014a).

3.6.4 Research facilities – Colorado, USA

The Research Support Facility (RSF) is the first Zero Energy Building of its kind and is a showcase for high performance sustainable design (Archdaily, 2011). Designed to use 50% less energy than a standard office building, incorporates a number of green innovations such as the solar air heating system (SolarWall, 2014b).

Two SolarWall systems are integrated on the south façade of a new building in Colorado (see Figure 3.9). The anthracite-colored solar panel, cover over 802.68 m^2 and preheat the fresh air vent using the sun. The aim was to reduce heating costs and GHG emissions.

The SolarWall system at the RSF is projected to deliver over 238 MWh (856 GJ) of thermal energy each year. The estimated reduction in GHG emissions is over 53 tonnes of CO_2 per year.

Figure 3.9 RSF building in Colorado: SolarWall façades.

3.6.5 Avon Theatre – Ontario, Canada

This is a refurbishment case of a theatre with air BISTS installation. SolarWall air heating system was installed to strengthen the conventional heating system (SolarWall, 2014c). The system was integrated and diversified architecturally an orthogonal volume, participating in the architectural concept of the building (figure 3.10). It is basically a second shell which is mounted on the outer walls of the building, and heats the air and then forces it inside the building.

Figure 3.10 The SolarWall BIST in the Avon theatre building, Ontario, Canada.

The SolarWall solar air heating system preheats the incoming air before it reaches the HVAC system, thus lowering the traditional heating load and reducing the GHG emissions. The black SolarWall system of the Avon Theatre consists of three large walls, one in the west (166 m^2), one in the south (218 m^2) and one to the east (104 m^2). There is a total 488 m^2 covered area with SolarWall system.

The system is expected to reduce the GHG emissions by 59 tonnes per year and the gas consumption by 28,000 m^3 per year. The reduction of the costs for heating are around $7,000 per year.

3.6.6 Public School – Canada

Air BISTS is mounted on the Dr David Suzuki Public School in Ontario. The system creates a second shell which is mounted on the outer walls of the building and heats the air and then leads it inside the building (SolarWall, 2014d).

A 16 m^2 SolarWall system is located on the south oriented wall of the second level of the building. The solar system was integrated seamlessly to the innovative façade (figure 3.11). A pipeline connection from one of the air handling units, gathers the outside air and leads it into the SolarWall system where it is preheated using the solar energy, before entering the air conditioner unit during the heating season.

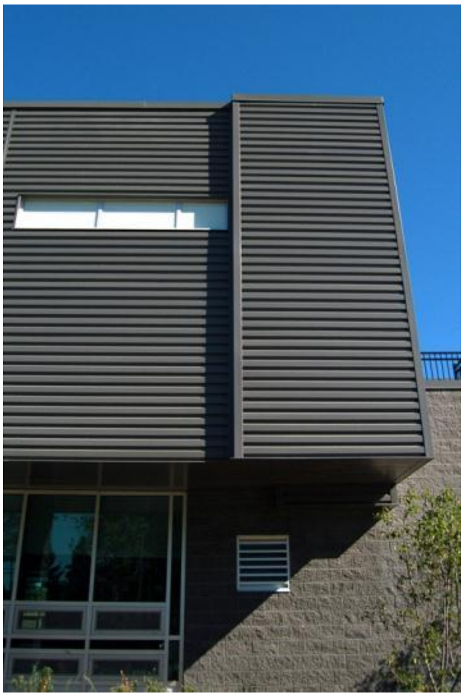

Figure 3.11 The SolarWall BIST in the Dr David Suzuki public school, Ontario, Canada

3.6.7 Public Building – Erlangen, Germany

Air SolarWall technology was chosen for several reasons for the Erlangen City Hall in Germany (SolarWall, 2014e). Apart from its ability to provide energy savings and significantly reduces of $CO_{2,}$ the system requires no maintenance and has no moving parts. This was an extremely important issue, because the system was placed above the ground level and therefore it would not be easily accessible after the completion of the construction. It is basically a second shell which is mounted on the outer walls of the building and heats the air and then leads it inside the building.

The architect integrated 150 m^2 of panels between 6th and 14th floor of the office building. The design (see Figure 3.12), is eye-catching and manages to fulfil both aesthetic demands and the production of hot air.

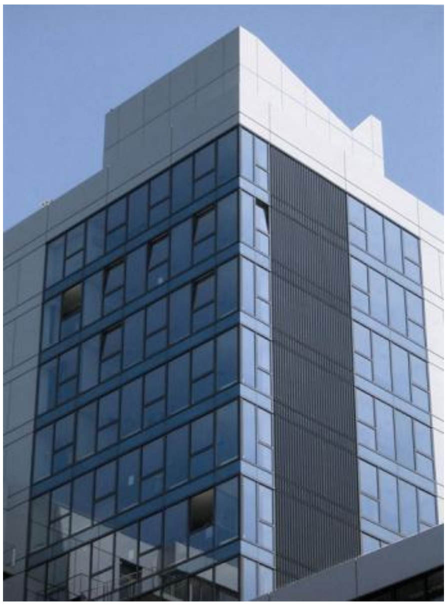

Figure 3.12 The SolarWall in the Erlangen City Hall, Germany.

The system is used on an average of 60 hours per week and preheats 3000 cfm of ventilation air that is used in the building. Regarding the reduction of emissions, the solar system eliminates nearly 30 tonnes of CO_2 emissions per year (SolarWall, 2014e).

3.6.8 Industrial Building – Colorado, USA

An air heating BISTS is mounted on the outer walls of the FedEx building in Colorado, creating a second shell heating the air and then leads it inside the building (SolarWall, 2014f).

Figure 3.13 The SolarWall on the FedEx building in Colorado, USA.

Because of the many trucks that pass through the facility, the building was placed in the same category as car parks. Therefore it has requirement for ventilation of 0.14 cfm/m^2. The heating for this volume of air using conventional methods should be prohibitively expensive. So the Colonial Red Solar Wall system was chosen to preheat the ventilation air. The BISTS installed has a total area of 465 m^2.

A red colour was chosen for the system to make an architectural statement. The red area (BISTS area) is connected to the rest of the building as a horizontal red line which is wrapped around it (figure 3.13). The installation of the system was integrated to the building and looks as a part of the texture of the building.

The solar investment provides 2,300 million BTUs of thermal energy in the building each year. The system also includes three solar fans offering 45,000 cfm of hot air ventilation throughout the building. The solar system allows savings about $12,000 per year (in gas prices 1996) and now these numbers are higher.

The increase in lease payments for the SolarWall installation was $400 per month, while FedEx saw a decrease of $1000 per month in energy costs. This means that the company made direct savings of around $600 per month. Finally, the system prevents 127 tonnes of CO_2 from being released to the environment each year.

3.6.9 Residential Building – Manitoba

Fred Douglas Place is a complex of apartments which has a big required volume of ventilation air during the long and cold winters of Winnipeg. The heating of this air by conventional means is very expensive and this is why they used the SolarWall system (SolarWall, 2014g). This is a benefit for old high-rise buildings because the system can work both for protection from the rain and as a solar ventilation system.

Figure 3.14 The SolarWall installation on the Fred Douglas Place multi-residential building, in Manitoba, Canada.

The SolarWall system is basically a second shell which is mounted on the outer walls of the building and heats the air and then leads it inside the building. The design is consisted of six columns, five facing south and one facing west, integrated on the tall building between the windows (figure 3.14). The system is Metro Brown and extends to 330.27 m^2 at 14 floors.

The overall system is sized to heat 17,000 cfm of fresh air and is expected to save 228 MWh (820 GJ) of natural gas and hold over 40 tonnes of carbon dioxide per year from the environment. It is also expected to save over $9150 per year in heating costs. The system is expected to be depreciated in 7.7 years.

3.6.10 Airport Building – Canada

This BISTS application, besides the energy savings, adds to the architectural image of the building as the system is mounted on the outer walls of the building. It is basically a second shell which is mounted on the outer walls of the building and heats the air and then leads it inside the building. The architect Carol Kleinfeldt of KMA won the 2007 Solar Thermal Project of the Year Award from the Canadian Solar Industry for innovative building design with the technology of SolarWall (SolarWall, 2014h). The SolarWall system is one of the defining features of the new Fire and Emergency Services Training Institute at Toronto Pearson International Airport.

The all-black system is integrated on the front façade of the building (see Figure 3.15). The perforated solar system is about 240 m^2 and delivers between 3800-6800 cfm (6460 – 11560 m^3/h) of heated air. An additional 250 m^2 of not perforated metal cladding was installed in the wall just behind the SolarWall system to match the front. The SolarWall system contributed, to the building could win the LEED points in categories EAc1 (Energy Efficiency) and MRc4 (Recycled Content).

Figure 3.15 Greater Toronto Airport Authority – SolarWall system.

3.6.11 Commercial Building – Leicestershire

The building is carbon neutral and has the largest SolarWall system in Europe which has been instrumental in the designing of a carbon neutral building of its size (SolarWall, 2014i). The building is a commercial building for Marks & Spencer distribution centre in Leicestershire. The system is integrated into the building and was designed to be an attractive addition to the south façade (figure 3.16).

Figure 3.16 The SolarWall installation on Marks & Spencer distribution centre in Leicestershire, UK.

The SolarWall system is 4,330 m^2 and heats a large building using solar energy instead of fossil fuels. Overall the system, divided into 4 sections and is placed between the staircases, is equal to the size of 16 tennis courts. The system of M&S is expected to provide 1.1 GWh energy savings. This is a staggering amount of renewable energy produced on site by a solar technology, and will provide a basis for comparison, since the building is equivalent to the total energy used for two typical M&S stores. This will result on the elimination of over 250 tonnes of CO_2 annually. Overall, the SolarWall technology in this building successfully covered the environmental and economic requirements. The large reductions in GHG emissions through energy production using renewable technology is acheved at reasonable cost.

3.6.12 Public Building – South Dakota, USA

The architects placed a SolarWall heating and ventilation system for the two new community centres in Rapid City. The dark bronze metallic coating was used as an architecture feature of the two buildings.

The architects wanted to maintain a consistent look for the two buildings, so the same coating was used on the walls, but only the two southern walls were used as solar air heaters. Approximately 900 m^2 of panels have been installed in total in both buildings of the community centre. The actual area of the solar collectors on both buildings is 115 m^2 and 90 m^2.

3.6.13 Public Building – Minnesota, USA

The Conserval Engineering in collaboration with the Architectural Resources Inc, developed a solution that integrates 115 m^2 SolarWall panels on the renovated building. The metal panels were used at two levels for preheating the air used for ventilation of the office space, reducing both energy costs and emissions of CO_2.

The system saves about $3,100 per year (in gas prices for 2007) and will provide a hedge against the escalation of energy prices. The system will also displace more than 16 tonnes of CO_2 per year and will produce more than 202 MBtu (213 GJ) of energy per year.

3.6.14 Industrial Building – France

Another air BISTS application is the one in Toyota Motor Manufacturing in France. The 400 m^2 SolarWall solar air heating system (integrated in the ventilation system) was designed to help Toyota to achieve some of its ambitious green goals. The TMMF choose to decorate its system with the logo of the sun at the top corner of the panel, to emphasize the fact that the wall is actually a solar collector (see Figure 3.17).

Figure 4. Toyota Motor Manufacturing SolarWall system.

As can be seen from Figure 3.17, the system is basically a second shell which is integrated on the outer walls of the building and heats the air before it enters the building.

The system yields positive results and increases the temperature of the air entering the building by up to 9°C during the coldest months of the year. It is estimated that the facility would result annual energy savings of up to 25 % compared with the conventional heating methods, with CO_2 emissions reduction around 20 tonnes per year.

3.6.15 Commercial Building – Aurora, Colorado, USA

The metal sheets forming the outer southern wall of the Supercentre, serve dual purposes as they can also act as a solar air heater. There are about 745 m^2 grey coloured SolarWall panels (SolarWall, 2014j).

The metal panel is heated in the sun and the ventilation fans draw the heated air from the surface of the wall through the perforations in the panel and guide it in the special designed ventilation channels (figure 3.18). Then, the heated air is distributed throughout the building.

The system is basically a second shell which is mounted on the outer walls of the building and heats the air which is afterwards driven inside the building.

The natural heating of fresh air means that less natural gas is required to heat the ventilation air to maintain a high level of indoor air quality. Additionally, the wall also serves as a solar shield, reducing solar gains and hence the need for cooling in summer. The SolarWall panels reduce the annual energy consumption in the Wal-Mart Supercentre by 1,325 million BTUs (388,000 kWh) and save the store about $20,000 per year (gas prices for 2005).

Figure 3.18 The SolarWall installation on the Supercentre commercial building in Colorado, USA.

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4 BISTS for Heating-Cooling-Shading (H-C-S)

4.1 Intro on BISTS for H-C-S

The integration of solar thermal collectors into the envelope of buildings can significantly increase the cost effectiveness of solar thermal systems due to the combination of weather protection, photovoltaic (PV) generator, solar thermal collector, thermal insulation, shading and mounting elements.

This section presents the main aspects of building integrated solar systems for heating, cooling and shading and highlights and summarises some of the projects which use solar systems for this purpose.

4.2 Review of H-C-S BISTS

Krauter et al. (2000) presented combined photovoltaic and solar thermal systems for façade integration and building insulation. Three cooling options were tested. The first had passive air cooling, the second active air cooling, and the third water circulation. Base case was the PV mounted directly on the insulation layer (no cooling). Heated water could have domestic use, and increases the efficiency of the PV panels by 9%. Prototypes could be mounted directly on insulation layer, but keeping the cooling gap if needed. Experimentation was used to verify calculations.

Sandberg and Moshfegh (2001) made a study of air flow and thermal performance using different outlet configurations of a photovoltaic façade with air gap embedded to a vertical building façade. The results showed some disagreement with measured data due to lack of higher precision measurements, but only at high aspect ratios of the cavities.

Mei et al. (2003) carried out a thermal modelling of a building with an integrated ventilated PV facade /solar air collector system. The incident solar radiation heating the PV elements preheats the ventilation air within the facade ventilation gap. The TRNSYS modelling data were compared with experimental data of a ventilated PV façade in a Spanish Library. The results showed a good agreement between experimental and simulated data for PV generation, heating and cooling. From both measurement and simulation, it was verified that the PV facade outlet air temperature reaches around 50 ºC in summer and 40 ºC in winter. In winter, for Barcelona, 12% of heating energy can be saved using the pre-heated ventilation of the air.

Ji et al. (2003) studied the dynamic performance of hybrid photovoltaic/thermal collector wall in Hong Kong. A computational thermal model was used for analysing the annual performance of facade-integrated hybrid photovoltaic/thermal collector system for use in residential buildings. The applications of EPV (film cell) and BPV (single silicon cell) panels in this hybrid photovoltaic/hot-water system were investigated. A west-facing PV/T collector wall with typical weather data of Hong Kong was studied. Simulation results based on test reference year data showed that the annual average electric efficiencies of the hybrid EPV/T and BPV/T modules were 4.3% and 10.3% for a west-facing panel. The annual efficiencies of the water heating systems were 47.6% (for EPV) and

43.2% (for BPV), respectively. The overall thermal efficiencies are 58.9% and 70.3% respectively, which are better than the conventional solar collector performance. The corresponding number of days in a year when the water temperature in the storage tank reached 45ºC and above was 195 and 217 for EPV and BPV respectively. Compared with a normal concrete wall, the reduction of space heat gain through the two kinds of hybrid PV/T collector wall can reach 53.0% and 59.2%, respectively.

Chow et al. (2003) made a theoretical study for PV performance in high rise buildings in a hot humid region. An imaginary 30-storey hotel was modelled with a thin strip PV wall (260 m^2) running along the entire height of the building. Three options were studied on how to apply the panels for energy output and thermal performance: top and bottom cavity openings, open at all sides, and direct mount on the wall. The first two options work effectively as a double façade. The option with all sides open generated the least heat gain.

Kalogirou (2004) made a survey of the various types of solar thermal collectors and applications. He described the various types of collectors including flat-plate, compound parabolic, evacuated tube, parabolic trough, Fresnel lens, parabolic dish and heliostat field collectors. Additionally he presented the typical applications of the various types of collectors.

Palmero and Oliveira (2006) presented the modification of existing louvre designs to integrate a solar collector in the shading device of a south facing window (Figure 4.1). The evaluation of a solar thermal system for water heating is assessed. A numerical model for the integrated solar collector was developed for different configurations and the collector efficiency is quantified for each configuration. The economic and environmental viability of the system is assessed.

The economic analysis for a solar louvre system providing 200 l of hot water per day, led to a payback period of 6.5 years for Lisbon and 5.5 years for Tenerife (comparison with conventional heating with gas) (Palmero and Oliveira, 2006). The life cycle analysis showed that the louvre area that leads to maximum savings (in costs) is equal to about 9 m^2 for a system life of 20 years (2290€ for Lisbon and 1364€ for Tenerife). Savings in CO_2 emissions for a solar louvre system with a collector area of 4.5 m^2 and a life period of 20 years, savings are equal to 8.6 tons of CO_2 (Lisbon) and 12 tons (Tenerife).

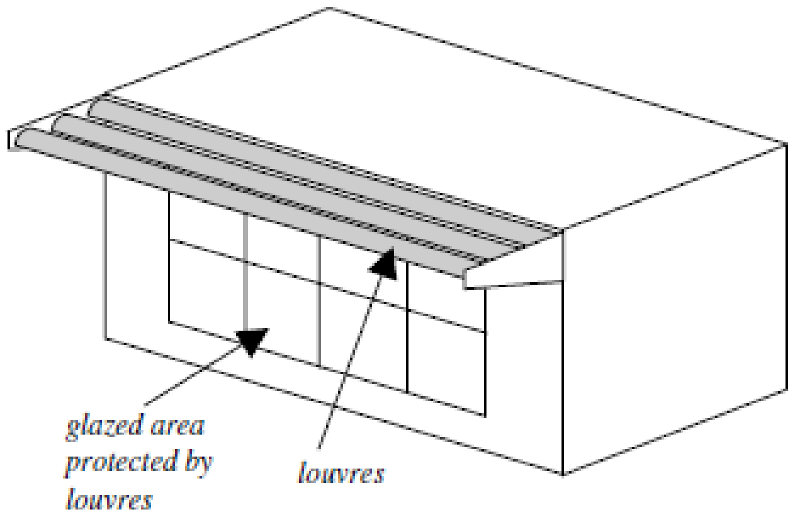

Figure 4.1 Use of a solar louvers collector to protect glazed surfaces (Palmero and Oliveira, 2006).

Guiavarch and Peiportier (2006) studied the efficiency of photovoltaic collectors according to their integration onto the buildings. Two positions were studied: independent on a sloped roof (single housing) and vertical on a façade (social housing) (see Figure 4.2). For unventilated PV modules in Paris the efficiency is 14%. Using PV with the cavity increases efficiency to 20% (due to reduced energy to heat inside). Authors note that proper integration of the panels in the building improves their life-cycle balance.

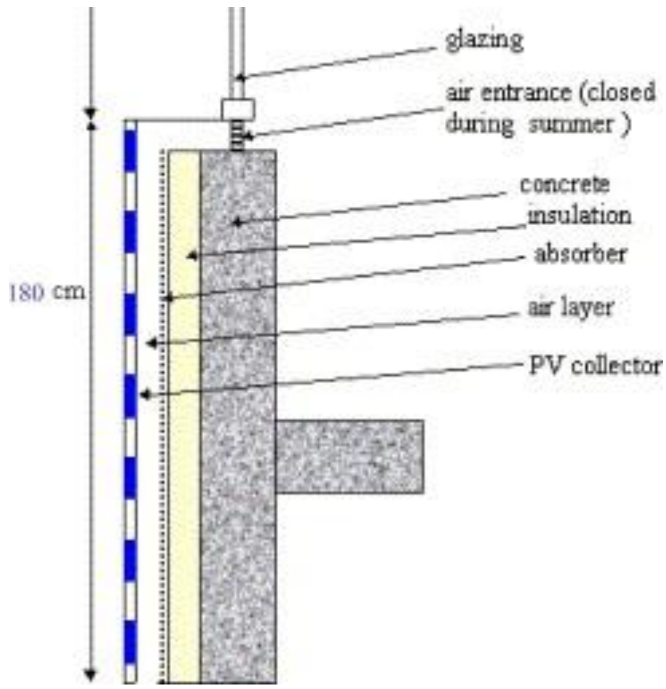

Figure 4.2 PV collector integrated in the facade, side view (semi-transparent PV collector preheating the ventilation air) (Guiavarch and Peiportier, 2006).

Sparber et al. (2007) presented an overview on worldwide installed solar assisted cooling systems including systems with a cooling power over 20 kW. Technical properties of the plans are listed and the dimensioning of single components is discussed. The list counts 81 installed large scale solar cooling systems, eventually including systems which are currently not in operation.73 installations are located in Europe, 7 in Asia, China in particular, and 1 in America (Mexico). 60% of these installations are dedicated to office buildings, 10% to factories, 15% to laboratories and education centres, 6% to hotels and the left percentage to buildings with different final use (hospitals, canteen, sport centre, etc.). Within 56 installations absorption chillers are used, within 10 adsorption chillers and within 17 Desiccant Evaporative Cooling (DEC) systems are used. Among the DEC installations, only 2 systems use a liquid regenerator (DEC liquid). The overall cooling capacity of the solar thermally driven chillers amounts to 9 MW 31% of it is installed in Spain, 18% in Germany and 12% in Greece.

Fraisse et al. (2007) carried out a study on the energy performance of a photovoltaic/thermal (PVT) collector combined with a Direct Solar Floor. The annual operating costs for a solution including an electrical auxiliary system (house heating and DHW) are presented. The annual photovoltaic cell efficiency is 6.8% which represents a decrease of 28% in comparison with a conventional non-integrated PV module of 9.4% annual efficiency, due to a temperature increase related to the cover. Without a glass cover, the efficiency is 10% which is 6% better than a standard module due to the cooling effect. The study shows that focusing on energy savings on the auxiliary consumption (house heating and DHW), the 16 m^2 of thermal collector are equivalent to 29 m^2 of hybrid covered PVT component with a low emissivity (Cov-LE-PVT). For an area of 32 m^2, the thermal savings and the photovoltaic production are higher. Considering the oversize of the combined system for the summer, temperature level reached by the PV cell is higher than 100ºC for the covered PVT component. It is referred that under such conditions, the middle term behaviour of the cells is unknown. The research led to the design of a water PVT prototype with a glass cover.

Palmero and Oliveira (2007) evaluated the integration of solar louvre collectors into a cooling system using a water-fired absorption chiller. The system performance was assessed and the results show that with such a system, comfortable indoor thermal conditions can be guaranteed. The system may also lead to energy savings when compared with conventional cooling. The solar louvre collector was integrated in an existing aluminium built louvre, with a width of 25 cm. The louvre solar collection (transparent) area is equal to 60% of the louvre area. Three different scenarios were considered: windows without any shading, use of solar louvres for shading, and use of solar louvre collectors coupled to the cooling system. Without louvre shading indoor temperature can reach values above 30°C. With louvre shading (and no cooling system) indoor temperatures are lower, but uncomfortable conditions are frequent. With louvre shading only, the percentage of time with thermal discomfort (Tair > 26°C) is equal to 13% for the lower area and to 39% for the higher area (29% for the intermediate area). When louvre collectors and a cooling system are used, there are comfortable conditions all the time, with indoor temperature always below 26°C. The difference in indoor temperature, comparing the use or no use of a cooling system, varies between 1.3 and 3.3°C. The initial cost of the solar louvre cooling system is reduced, when compared to a solar cooling system using conventional flat-plate collectors, because of the lower additional cost of the louvre collector – louvre collector cost minus normal louvre cost (167 €/m^2). In order to obtain a similar performance with selective flat plate collectors, a collector area of 7m^2 (350 €/m^2) would be necessary (instead of 12.5m^2). The initial investment would be higher for the flat-plate collectors (2450 €/m^2), if louvers are also used just as shading devices, than for the louvre collectors (2088€/m^2).

Jakob (2008) presented the development and investigation of the thermally driven ACS 08, a novel single effect, silica gel/water adsorption chiller with nominal cooling capacity of 7.5 kW, developed by SorTech AG for solar cooling. Small compact adsorption chillers seem to be an attractive option for thermally driven air-conditioning. The results of the field test of prototypes carried out in 2007 were encouraging. Therefore, since March 2008 SorTech AG has introduced a small adsorption chiller ACS 08 with a chilled water capacity of 7.5 kW and since June 2008 a larger system ACS 15 with 15 kW into the market. Currently, the chillers are produced in a small series and the market response is very positive.

Palmero and Oliveira (2010) made a research on heating and cooling requirements of buildings with solar louvre devices. A general study of the effect of louvre shading devices applied to different façades of a building was carried out. Building energy requirements for a building in the cooling and heating seasons are quantified for different window and louvre areas, under different climatic conditions (Europe, Africa and America). The results showed that the use of louvre shading devices in the building leads to indoor comfortable thermal conditions and may lead to significant energy savings, in comparison with a building without shading devices.

Park et al. (2010) investigated the electrical and thermal performance of a semi-transparent PV module that was designed as a glazing component. The results showed that the power generation of PV module decreased about 0.48% per 1 ºC increase in the indoor test (standard test conditions except temperature) and decreased approximately 0.52% per 1 ºC increase in the outdoor test (under 500 W/m^2 of irradiance). It was also found that the property of the glass used for the module affected the PV module temperature followed by its electrical performance. Athienitis et al. (2010) designed and installed a prototype photovoltaic/thermal system (an unglazed transpired collector, UTC) at the top of a university building in Montreal, Canada. The system is placed as facade walls of the machinery room (top floors) of a University building (Figure 4.5). They carried out calculation procedures, prototype testing and installation of a transpired solar thermal collector with PV panels and air cavity (288 m^2 installation with 384 building-integrated PV modules covering about 70% of the UTC). Air is solar-heated and collected, reducing energy consumption. Further energy reductions are achieved by the PV panels. The system has a peak power output of 24.5 kW and preheats up to about 7.5 m^3/s of fresh air for the building occupants. According to the study the thermal efficiency in the combined system is 7 to 17% higher than a standalone system, due to the electricity generated by the PV.

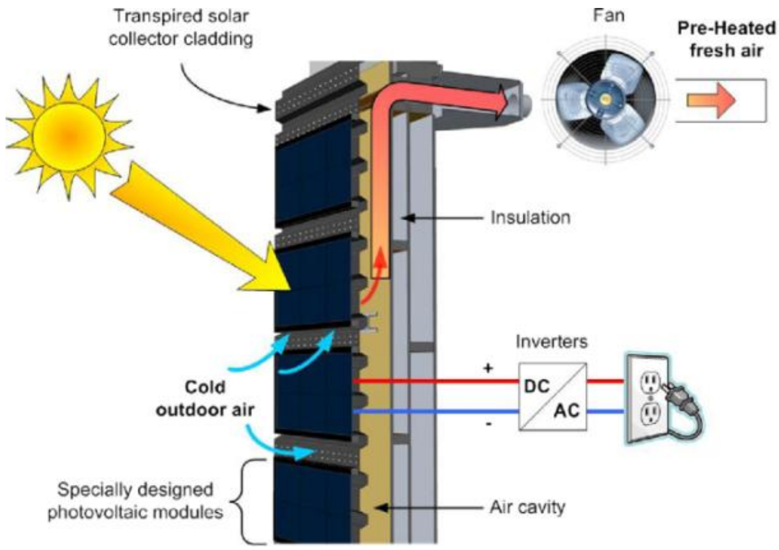

Figure 4.5. Concept schematic for BIPV/T system (top) and BIPV/T demonstration project (bottom) in a university building in Montreal (top floors) (Athienitis et al., 2010).

Ramirez-Stefanou et al. (2011) made an optical and experimental investigation of a low concentration line axis solar thermal collector employing symmetric and asymmetric CPC geometries. A low concentrating solar thermal collector using a dielectric asymmetric compound parabolic concentrator (DACPC) was designed, fabricated, modelled and evaluated using outdoor conditions. Using simulation and experimental evaluation the DACPC collector performance was determined. At slope β=30° the average optical efficiency of direct beam was 44.3% having a total energy collected of 0.758 kWh/m^2 from 9:22 to 15:15. For sloped angles of 60° and 90° the average optical efficiencies for direct beam were 93% and 86%, respectively. The total collected energy was 1.591 kWh/m^2 for β=60° and 1.266kWh/m^2 for β=90°. For the 21st of December simulation of the system showed a 93% optical efficiency of direct beam and a total energy collection of 1.322 kWh/m^2. Optical efficiency of diffuse beam was 54.5 % for all cases. Outdoor experimental characterization of the DACPC collector during July and August showed that the average collection efficiency is 65%. Slope angles of 45° and 60° had collection efficiencies of 61.8% and 62.4% under 675 W/m^2 and 426 W/m^2, respectively. The serpentine arrangement had a collection efficiency of 50.1%, which was 7% greater than the parallel arrangement at the same solar conditions. The maximum temperature achieved by the DACPC collector was 80.2 ºC under stagnation with an average solar radiation of 760 W/m^2. Under 110 W/m^2 for a period of time of about 50 minutes the maximum temperature reached was 30.3 ºC.

Maurer et al. (2011) investigated, through simulation using TRNSYS, heating and cooling in high-rise buildings using façade integrated transparent solar thermal collector systems (TSTC). The central HVAC system was integrated the TSTCs into a collector network supplying a central thermal storage buffer. The buffer supplies heat to the heating devices as well as an absorption chiller and is one of the core elements of the HVAC system. To cover the loads that cannot be met by the solar collectors /absorption chiller, a compression chiller is used on the cooling period and a gas boiler on the heating season. The study shows that simplified transparent collector models cannot reproduce the complex behaviour of the solar transmission and the heat transfer to the building interior adequately. Even an advanced simplified model with carefully chosen parameters underestimates the annual collector gain by 15%. The quality of the approximation of the collector gain decreases with an increasing fraction of diffuse radiation.

Bambara et al. (2012) made a performance evaluation of a Building Integrated Photovoltaic/Thermal System. They concluded that Building Integrated Photovoltaic/Thermal (BIPV/T) systems may be combined with Unglazed Transpired Collectors (UTC's) to produce useful heat while generating simultaneously electricity from the same surface.

Davidsson et al. (2012) investigated a PV/T hybrid solar window on a system level. The solar window is a PV/T hybrid collector with tiltable insulated reflectors integrated into a window. It simultaneously replaces thermal collectors, PV-modules and sun shading devices. The building integration of a PV/T hybrid solar system on a window lowers the total price of the construction since the collector utilizes the frame and the glazing in the window. The reduction of the thermal losses due to the insulated reflectors is beneficial, but the blockage of solar radiation that would otherwise heat the building passively limits the performance of the solar window. To investigate the sum of such complex interaction a system analysis has to be performed. TRNSYS simulations have been carried out and a building with the solar window was compared to a building with a solar collector on the roof. The roof collector was of the same size as the absorbers of the solar window. The building with the roof collector was equipped with an energy efficient window, half the size of the solar window. The building system with individual solar energy components, i.e. solar collector and PV modules, of the same size as the solar window, uses 1100 kWh less auxiliary energy than the system with a solar window. However, the solar window system uses 600 kWh less auxiliary energy than a system with no solar collector. The solar window produces 35% more electric energy per cell area compared with a PV module installed vertically on a south wall. Increasing the insulation on the reflectors and absorbers and using a glazing with a lower U-value and a slightly lower solar transmittance the annual auxiliary energy need then dropped by 900 kWh compared with the original solar window. The results were comparable to the case where the solar collector was installed on the roof.

Yang et al. (2012) presented an all-ceramic building integrated solar collector in China. They presented a very resistant modular system with different dimensions. The collector consists of a ceramic collector with glass, encased in concrete modules. It can be used as substitute of secondary structure such as railing. Ceramic material is presented as alternative to conventional systems.

Caponetto et al. (2013) proposed an innovative solar thermal façade for the refurbishment of an existing tower building, to satisfy the heating and cooling needs of an existing apartment tower located in Sicily. The proposed setup consists of a stackable system of modular panels called TMF (Tube-Mirror-Frame) each made up of evacuated tube solar collectors coupled with concentrating aluminium mirrors. In terms of expected results, system modelling has shown that for the specific building, the proposed solar system can fulfil about 26% of heating demand and 69% of cooling demand, if the building fabric is left untouched, whilst if the building fabric is improved 69% and 95% of the original heating and cooling energy demand could be fulfilled by solar heating and cooling.

Chemisana et al. (2013) carried out a study on building integration of concentrating systems for solar cooling applications. The analysis, using TRNSYS simulation program, compared two cooling systems, integrated in the South façade of a three-floor building (Figure 6.5), with and without solar concentration, during a typical summer day. According to the study presented the investment and operation costs of the solar concentrating cooling system can be reduced significantly due to the lower rejected heat in the double-effect chiller. The results show that the solar concentrating cooling system options can cover between 22% and 39% of the cooling demand depending on the tracking limits of the reflectors. These performances have been compared with the ones of two reference solar cooling systems (RSCS), with the same cooling load. The solar concentrating cooling system options needs 85% to 90% less solar collector absorber area than the reference low-temperature solar cooling system options. The solar concentrating cooling system options need between 3 and 4.6 times the aperture area of the respective reference low-temperature solar cooling system options because of the relatively low levels of the solar irradiation over the South façade of the building in summer.

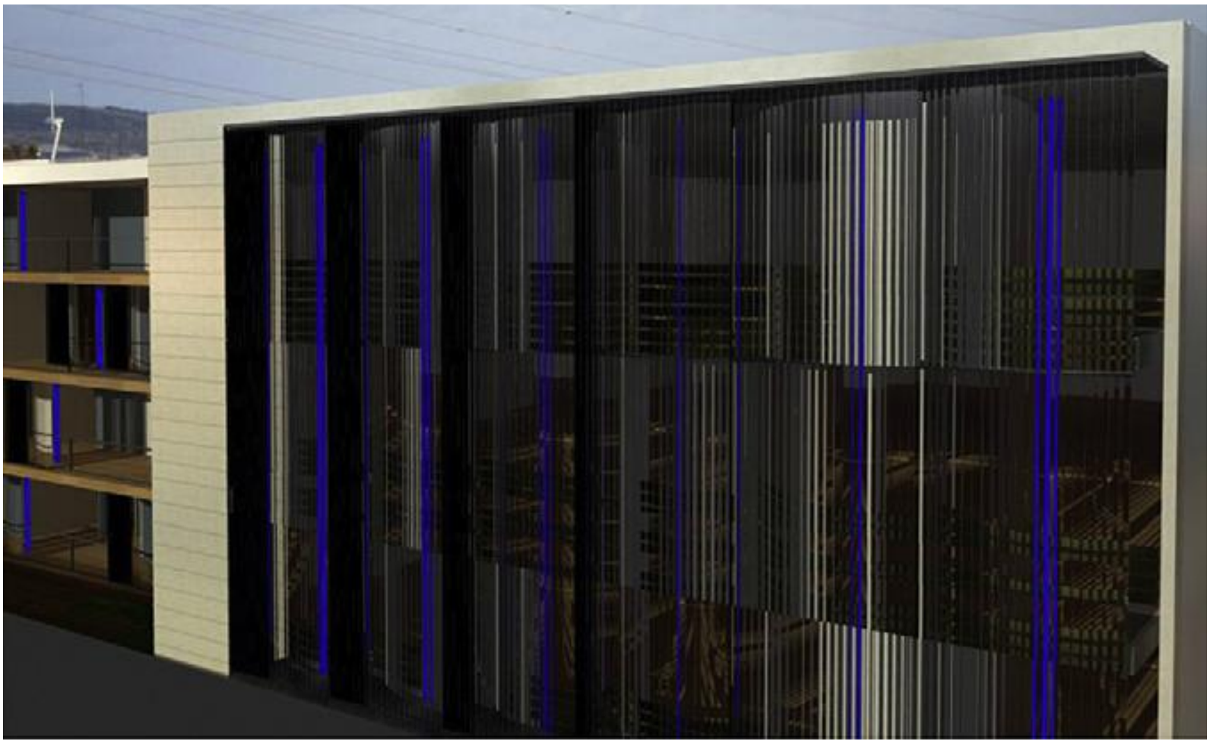

Figure 6.5 Architectural design of the building integrated concentrating system. The blue lines behind the Fresnel reflectors indicate the position of the receptors which are installed on the facade (Chemisana et al., 2013).

Hussain et al. (2013) made a literature review on photovoltaic/thermal collectors. The review presented different achievements in the area of applied and theoretical BISTS with or without power generation. Section 5 focuses on façade-integrated or vertical collectors.

Macia et al. (2013) investigated the influence parameters on the performance of an experimental solar-assisted ground-coupled absorption heat pump in cooling operation. The study describes a novel experimental facility consisting in a solar-assisted absorption ground coupled heat pump (GCHP) and a TRNSYS model of the facility. Results show that the optimum working generator temperature for the heat pump, in terms of its best COP, is not the best working temperature in terms of the Global Efficiency of the whole installation. For a fixed generator temperature results showed that the lower the temperature of condenser is, the higher are the Global Efficiency of the installation and the heat pump COP. If the temperature at the inlet of the condenser decreases from the nominal 28ºC to25ºC, both Global Efficiency and the heat pump COP increase its magnitude roughly by 30%.

Vakiloroaya et al. (2013) made an experimental study to investigate the inherent operational characteristics of a new direct-expansion air conditioning system combined with a vacuum solar collector. Simulation results were compared with experimental data collected from a test rig equipped with sensors and data logging devices for validation of the mathematical models. Results showed sufficient accuracy of the derived models for predicting the system performance. To reject the additional heat amount obtained from the water storage tank, a slightly larger condenser is used. With not much change in the manufacturing cost, the effect of the condenser size on the energy consumption is analysed to show the system's overall cost effectiveness. The novel design is promising for increasing the system average energy efficiency while fulfilling the cooling demand with a higher coefficient of performance. Results show an average monthly energy saving between 25% and 42%.

Ghaith and Abusitta (2014) carried out analysis of an integrated solar powered heating and cooling systems in United Arab Emirates. They developed a mathematical thermal project to represent the fully integrated solar heating and cooling system and it was used to determine the useful energy for two selected building configurations based in UAE: fully solar cooling powered one-floor office building; and hybrid four-floor residential building, at different percentages of solar penetration. For the office building a fully solar-powered integrated cooling system was compared with an electrical conventional air-cooled chiller and for the residential building the hybrid cooling system was compared with 100% conventional air cooled chiller of 366 kW capacity with existing solar heating system for DHW used only in winter season. The results show that about 159 kWh and 126 ton/year savings were achieved in the Annual Energy Consumption (AEC) and CO_2 emissions, respectively. Additionally they performed numerical studies on the integrated SHC system of the residential building and concluded that the maximum solar penetration of 20% was found to be the optimum as it reduced AEC by 176 kWh and cut off CO_2 emissions by 140 ton/year with a payback period of 4 years.

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5 PVT BISTS

5.1 Introduction on PVT BISTS

The PV modules that are combined with thermal units, where circulating air or water of lower temperature than that of PV module is heated, constitute the hybrid photovoltaic/thermal systems and provide electrical and thermal energy, increasing therefore the total energy output from PV modules (Tripanagnostopoulos, 2007).

The PV/T solar systems can be effectively used in the domestic and in the industrial sector, mainly for preheating water or air. The water-cooled PV modules (PV/T water systems) consist of a water heat exchanger in thermal contact with the PV rear side and are suitable for water heating, space heating and other applications (Figure 5.1a). Air-cooled PV modules (PV/T air systems) can be integrated on building roofs and facades and apart of the electrical load they can cover building heating and air ventilation needs (Figure 5.1b). PV/T solar collectors integrated on building roofs and facades can replace separate installation of thermal collectors and photovoltaics, resulting to cost effective and aesthetic application of solar energy systems. An additional glazing for thermal loss reduction (Figure 5.1c, Figure 5.1d) increases thermal output but decreases the electricity production due to the additional optical losses, (Tripanagnostopoulos, 2007).

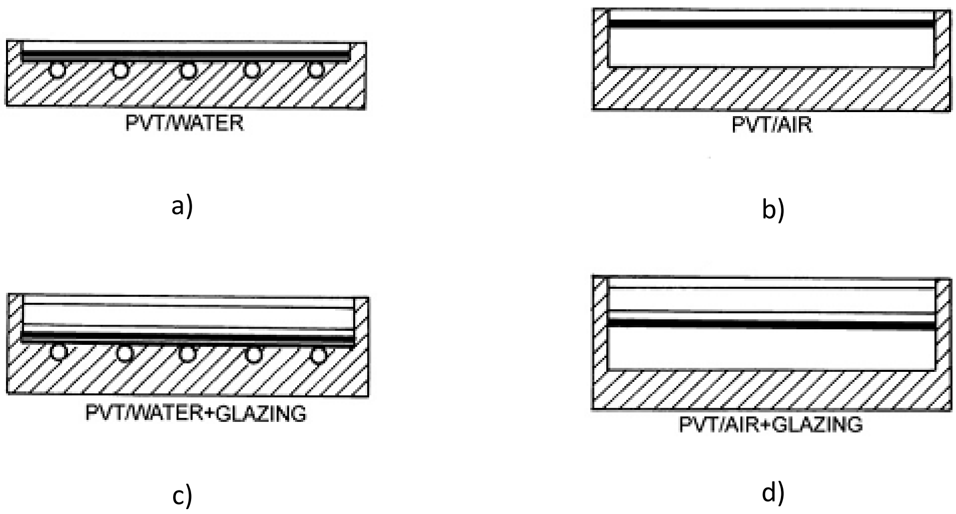


Figure 5.1 Cross section of the main PV/T geometries, a) PVT/water (unglazed) b) PVT/air (unglazed) c) PVT/water with glazing d) PVT/air with glazing.

Water-cooled PV/T systems are practical systems for water heating in domestic buildings but their application is limited up to now. Air-cooled PV/T systems have already been applied in buildings, integrated usually on their inclined roofs or facades. These systems keep the electrical output at a sufficient level, covering building space heating needs during winter and ventilation needs during summer, also avoiding building overheating (Tripanagnostopoulos, 2007).

The PVT/water collectors have more limitations in system design and operation than the PVT/air collectors. This is due to the necessary heat exchanger element, which should have good thermal contact with PV rear surface, while in PVT/air systems the air is heated directly from the front or/and the back surface of PV modules. But on the other hand the air heat extraction is less efficient than the water one, due to the low density of air and improvements are necessary to make PVT/air system efficient and attractive for real applications (Tripanagnostopoulos, 2007).

In BIPV/T systems solar collector can be installed on the roof as a roofing material and to walls as a wall material. Therefore the cost of building construction can be reduced as well as the building payback period (Hussain et al.2013).

Agrawal and Tiwari (2013) concluded that a mono-crystalline silicon BIPV/T system was the most suitable choice for high demand energy efficiency but limited mounting space, like in multi-storey buildings. But, from an economic point of view, amorphous silicon BIPV/T system was the best choice, suitable for urban and remote places.

The facade and tilted roof integrated PV/T systems are more effectively insulated on their rear surface, compared to the ones installed on horizontal roof, as they are attached on the facade wall or the tilted roof. The additional thermal protection increases the thermal efficiency of the system, but the lower thermal losses keep PV temperature at a higher level, therefore they are operating with reduced electrical efficiency (Tripanagnostopoulos, 2007). Smaller size PV and PV/T systems, using aperture surface area of about 3–5 m^2 and water storage tank of 150–200 l, can be installed on one-family houses, but larger size systems of about 30–50 m^2 and 1500–2000 l water storage are more suitable for multi-flat residential buildings, hotels, hospitals, industries, etc. An interesting building application of solar energy systems is to use linear Fresnel lenses as transparent material of atria, sunspaces, etc, to control lighting and temperature of these spaces, providing also electricity and heat and cover building energy needs (Tripanagnostopoulos, 2007). Further work on improving efficiency, cost reduction and building integrated application of PV/T technology seem to be very important in order to obtain optimal performance of the collector.

5.2 Review of PVT BISTS

5.2.1 Hybrid solar system integrated on roof

Yin et al. (2013) proposed energy system that seamlessly integrates novel hybrid solar panels into the building structure as a building integrated photovoltaic/thermal system (BIPV/T), and adaptively uses several operating modes to optimize panel and system performance as the environmental conditions vary seasonally and daily. The system is also designed to be customized to different climates and building configurations. Using a highly efficient panel design and optimized operating modes, excellent panel and system-wide energy and cost efficiencies can be achieved.

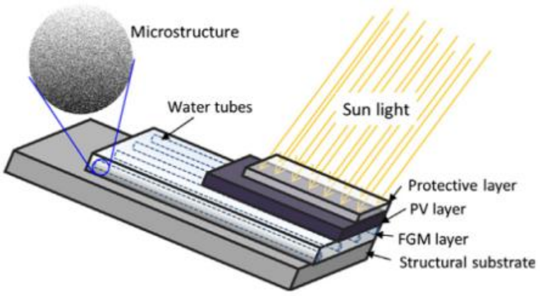
The overall approach towards designing and manufacturing a multifunctional high-performance roof for sustainable buildings has to start with the recognition and specification of the various performance parameters, such as architectural requirements, aesthetic appearance, mechanical strength and durability, thermal efficiency, material compatibility, moisture migration, and material sustainability.

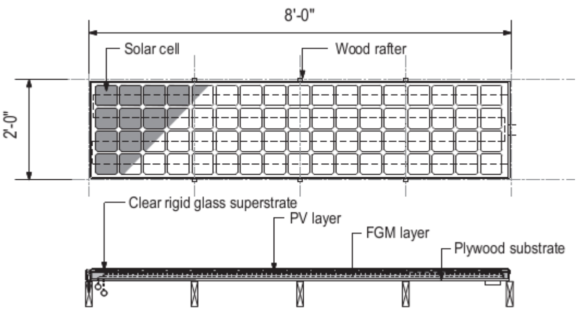
In Figure 5.2a, a novel hybrid solar roofing panel is proposed to perform the multiple functions of both a roof structural component and an energy harvesting device. The cross section of the residential system with the integrated hybrid solar panel is presented at Figure 5.2b. The innovations illustrated above create the following synergistic benefits of energy generation and savings:

increased PV efficiency, free heating supply, reduced cooling demand, efficient in all climates, snow and ice removal.

The substrate of the panel is designed to be integrated into the building skin, allowing the panel to serve as both structural sheathing and waterproofing. This eliminates the material redundancies of current industry standard designs and the embodied carbon associated with those materials. The integration of the panel into the building skin also eliminates the waterproofing concerns associated with the roof penetrations required to mount conventional panels on a sloped surface (Yin et al. 2013).

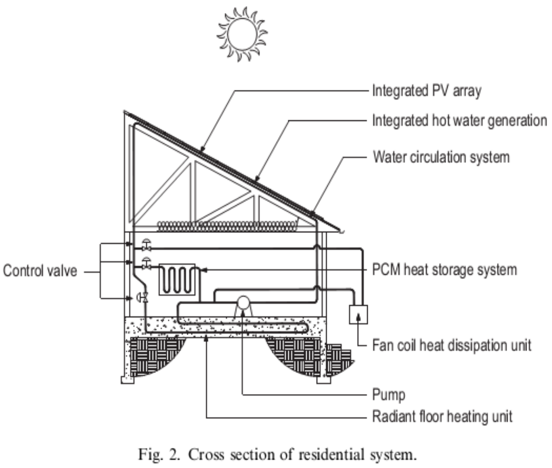
Figure 5.2c shows the design of the proposed BIPV/T panel. An example of the systems integration into a traditional residential architecture is illustrated in Figure 5.2d.

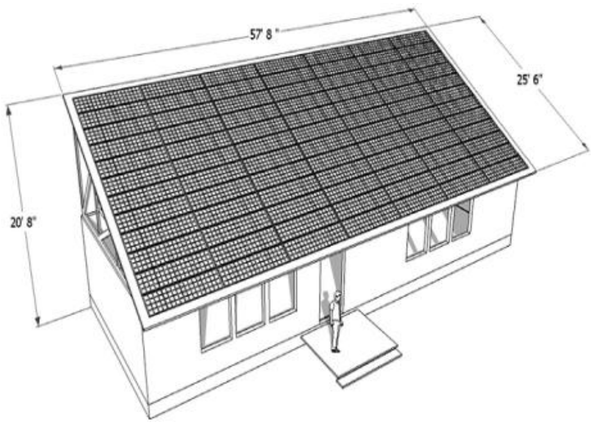




c)

a)





b)

d)

Figure 5.2 Hybrid solar system integrated on roof, a) Novel hybrid solar roofing panel, b) Cross section of the residential system with the integrated hybrid solar panel, c) Design of the proposed BIPVT panel: top view (upper) and section view (lower), d) Plan of BIPVT roof-gross area (135 m^2), BIPVT net area (125 m^2).

Based on the design philosophy, the benefits of this novel building integrated roofing system are:

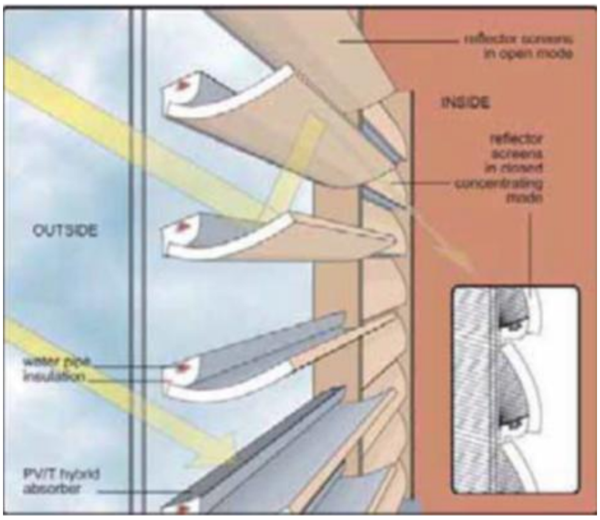
- High efficiency conversion of solar energy reduces or eliminates the need for conventional grid power and the need for heat in winter,

- A holistically designed building envelope and the removal of heat from the roof will drastically reduce energy use by minimizing the need for cooling in summer and
- The total amount of materials needed to construct the combined roof and alternative energy system is reduced as redundant functions are eliminated. This reduces the carbon foot print of the system and the other environmental impacts associated with the building materials.

The cost and performance analysis indicates that the proposed hybrid solar panel exhibits great potential for significant system energy benefits with a small additional investment (Yin et al. 2013).

5.2.2 Building-integrated multifunctional PV/T solar window

The solar window is a PV/T hybrid collector with tiltable insulated reflectors integrated into a window. It simultaneously replaces thermal collectors, PV-modules and sunshade (Davidsson et al. 2013). The building-integrated multifunctional PV/T solar window, which is constructed of PV cells laminated on solar absorbers placed in a window behind the glazing, is developed and evaluated (Figure 5.3).



a)

b)

c)

Figure 5.3 Building-integrated multifunctional PV/T solar window a) Solar window at Lund in the south of Sweden, b) the prototype solar window, c) the solar window in Solgarden, Sweden with closed reflectors.

To reduce the cost of the solar electricity, tracking reflectors were introduced in the construction to focus radiation onto the solar cells. The reflectors render the possibility of controlling the amount of radiation transmitted into the building. The insulated reflectors also reduce the thermal losses through the window. The system is a visible element in the exterior of the building and particularly in the interior and its performance is directly connected to the user behaviour, due to the operation of the reflectors which can be switched between a closed, concentrating mode or an open transparent mode (Figure 5.3) (Fieber et al. 2003).

One of the basic ideas behind the design was to express the building integrated solar energy system architecturally in an attractive maximally exposed way. The curved concentrating geometry is decorative and expresses the capturing nature of a solar energy system. The backside facing the interior could be covered with any surface material suitable for the interior context. The modular nature of reflectors, with no connection to the energy distribution, makes it possible to exchange them for alternative surface, thickness or reflecting geometry. The concave front facing the window will be slightly visible from the exterior and the mirror like surface might be the most critical aesthetically property for a wider acceptance. However, the curved mirror can generate interesting optical expressions in the façade. The overall impression of the façade will hence change when approaching it. The mobility of the reflectors also contributes to a dynamic façade expression.

The performance of a 1 m^2 prototype of the system regarding its sun shading and U-value properties and its photovoltaic and active thermal output has been monitored (Fieber et al., 2004). For a two panel anti-reflective window the U-value is reduced from 2.8 to 1.2 W/m^2K with the reflectors close, calculated from measurements in a guarded hot-box according to ISO 8990. The annual transmittance through the window is estimated to 609 kWh/m2 of which approximately 10% is expected to be delivered by the PV modules. About 20% will be delivered as active solar heat and 30% as net passive space heating.

Performance of the system has been analysed separately for passive gains, active thermal gains and PV electricity yield. According to a proposed regulating schedule passive gains are estimated to 210 kWh/m^2 annually. The performance of the fully concentrated PV/T absorber is estimated to 79 kWh/m^2 of electricity, and at least 155 kWh/m^2 of heat for domestic hot water. Production costs for the Solar Window excluding the glazing are estimated to approximately €250/m^2.

A model for simulation of the electric and hot water production was developed and it was able to perform the yearly energy simulations for different features, such as the shading of the cells and/or effects of the glazing can be included or excluded. The simulation can be run with the reflectors in active, passive, up right and horizontal positions. The simulation program has been calibrated against the measurements on a prototype solar window placed in Lund, Southern Sweden and against a solar window built into a single family house at Solgarden, Central Sweden. The results obtained from the simulation showed that the solar window annually produces about 35% more electric energy per unit cell area as compared to a vertical flat PV module (Davidsson et al. 2013, Tyagi et al. 2012).

The building integration lowers the total price of the construction since the collector utilizes the frame and the glazing in the window. When it is placed in the window a complex interaction takes place. On the positive side is the reduction of the thermal losses due to the insulated reflectors. On the negative side is the blocking of solar radiation that would otherwise heat the building passively. This limits the performance of the solar window since a photon can only be used once. To investigate the sum of such complex interaction a system analysis has to be performed (Davidsson et al. 2012).

5.2.3 Hybrid thermal insulating PV façade element

The HYTIPVE was one of 4 PV/T prototyped and tested under the 'steady state' solar simulator at Laboratorio Fotovoltaico at Universidade Federal do Rio de Janeiro. The HYTIPVE is designed to be a vertically mounted PV/T unit that combined power and heat generation with improved building envelope insulation (Krauter, 1999).

The HYTIPVE is a thermal insulating PV façade with an integrated cooling system that consists of a SOLON PV module mounted on a propylene mat and a 12.5 cm layer of mineral wool. The thermal insulation was attached directly to the back of the PV/T panel in order to achieve a thermal insulation of k=50.32 W/Km^2 in accordance with WSV 95 regulation. The heated water can also be used for thermal applications (directly of combined with solar thermal systems). The prototype module was 1205 mm long and 545 mm wide.

The HYTIPVE offers a cooling effect of about 20°C compared to conventional PV curtain facades, and is in the same range as that found for active ventilated structures (max 18°C). Based on the measured performance of the HYTIPVE the integral water cooling/heating system allowed an electrical yield that was 9% higher than that found for conventional PV facades.

5.2.4 Office Building – Lisbon, Portugal

The motivation of the project was to design a service building with low energy consumption, integrating renewable technologies (solar thermal and photovoltaic) and passive systems for heating and cooling (Gonçalves and Cabrita, 2010). The aim was to increase the area of solar heat gains with the south solar façade, as a direct gain system for heating; External shading devices in the south oriented windows; Photovoltaic façade for electric use; Heat recovery by natural ventilation in the photovoltaic façade for indoor environmental heating; Natural ventilation.

Solar XXI is a 3 storey building with 1500 m^2 net floor area and 1200m^2 of conditioned floor area. Multictystalline silicon, amorphous silicon and CIS thin film PV modules installed on the south façade of the building with a total collection are of 100 m^2 (5.25 m^2 per system). The PV/Wall ratio of the south façade is 24% and the Window/Wall ratio 34%. The peak power installed is total 12 kW and the energy produced is 31 kWh with 40% contribution to building load.

The heat released in the process of converting solar radiation into electrical power is successfully recovered (natural convection) transferred into adjacent rooms, as a heating strategy for the improvement of the indoor climate during heating season in the day time hours. In the mid-season months, the system can function as a fresh air pre-heating system in which air is admitted from outside through the lower vents, which heats thereafter in the air gap of BIPV-T before transferred directly into the room by natural convection through the upper internal vents (figure 5.4).

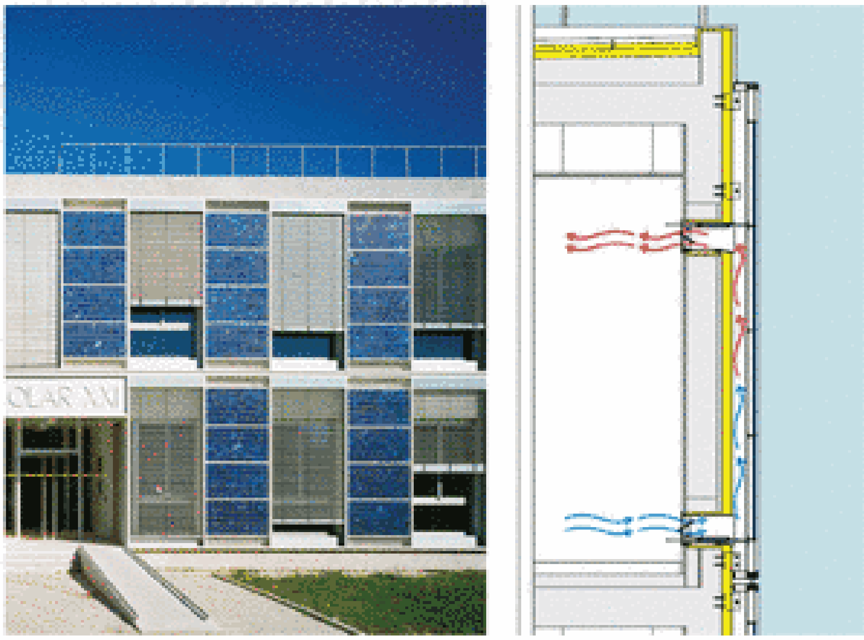


Figure 5.4 The building integrated solar PV/Thermal façade of the Solar XXI building in Lisbon, Protugal.

During cooling season is important to extract the heat from the modules to the environment. Therefore, the most used functional situation is the extraction of the heat to outside through the two external vents, in this situation the internal vents are closed. Another option in terms of functional use, is the evacuation of the hot air from the room through.

The system's viability was tested through modelling and simulation tools. The simulation program developed by the Department of Energy of the USA, EnergyPlus, has been used to study and analyse the dynamic thermal performance of the building.

The performance analysis shown that the solar savings fraction was 40% and the solar gain factor 75%. Solar XXI building is considered a very high efficient building, with a difference in energy performance 1/10 regarding a standard Portuguese office building. From the Net ZEB goal perspective, the building, may be currently considered, a "plus (electric) Energy Building" and a "nearly Zero Energy Building" in terms of the overall building energy consumption.

5.2.5 Institutional Building – Beijing, China

The complex of the 2008 Beijing Olympic Village was required to use 75% less energy compared to conventional Chinese buildings. To achieve the demanding energy goals, the developer of the Olympic Park was instructed to incorporate innovative green technologies.

The integrated SolarWall and PV/T systems can produce 20 kW thermal energy power (figure 5.5).

Figure 5.5 Beijing Olympic Village, China.

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6 Combined BISTS for Heating Cooling and Shading

6.1 Review of Combined BISTS

There are few examples of demonstrations of combined BISTS presented in this section.

6.1.1 Residential Building – Graz, Austria

The project's motivation was to obtain a reduction of the heat demand in about 90% and also diminish the greenhouse gas emissions (IEA ECBCS, 2014). Furthermore, is intend to get a reduction in operating costs for space heating and DHW-preparation, avoiding an increase in rents, also allowing lower monthly charges for the tenants. The name of the building is Dieselweg 3-19 and houses 204 apartments. The net floor area of the building is 14520 m^2 (Figure 6.1).

The renovation concept was the essential improvement of the thermal envelope with prefabricated façade modules. The integration of a series of components into the prefabricated façade module system like windows, ventilation devices and solar thermal collectors. The implementation of a new and innovative solar-active energy concept.

Figure 6.1 Dieselweg 3-19/ Graz, Austria.

Solar thermal collectors were integrated in all south and southwest façade. The roof carport was also covered with collectors, and additional collectors were installed on the roofs of the five single buildings. Generally there are about 3 m^2 of collectors per apartment. Heat storage tanks (5 m^3) are installed in the basement and supplied by the solar thermal plant and a ground water heat pump. The heat distribution is done by small heating pipes, inserted in XPS insulation boards and mounted on the existing walls; these are warmed from the outside.

The system proved to be very viable as shown in Table 6.1.

Table 6.1 System Viability.

		Before	After
Running Costs	Heating	Before renovation about €2.00 m^2 net floor area/month	After renovation about €0.11 m^2 net floor area/month
	DHW	Before renovation about €0.40 m^2 net floor area/month	After renovation about €0.10 m^2 net floor area/month

6.1.2 Commercial Building – Lisbon, Portugal

This is the Caica Geral de Depositos bank's headquarters building in Lisbon where a solar thermal system is integrated on a pitched roof (Figure 6.2). The building has a total floor area of 173,600 m^2 with a rectangular shape and consists of 15 floors (Caica Geral de Depositos, 2014).

The solar thermal system used in the CGD central headquarters consists of 158 solar collectors with a total area of 1600 m^2. The panels were manufactured off-site and subsequently placed on the roof of the building over a wooden structure. The roof on the south side would be a prime location, but CGD opted not to use it due to concerns about visual impact.

In total, there are energy savings of more than 1 GWh/year corresponding to 5% of the global building consumption (Caica Geral de Depositos, 2014). CGD invested 1 million euros in this project and foresees to recover the investment in 8-10 years through the savings made on the electricity bill. With the solar thermal plant, the building annually saves more than 1 GWh of electricity, equivalent to avoiding each minute of operation the emission into the atmosphere of about 1 kg of CO_2.

Figure 6.2 Integration of STC in pitched roof.

6.1.3 Commercial Building – Satteins, Austria

The head quarter of the Austrian solar collector producer AKS DOMA Solartechnik was at the opening in spring 1999, one of the first buildings with CO_2 neutral energy supply. Glazed flat plate water collectors were integrated in the façade of a building which is used as an office building and production hall (Basnet, 2012).

The solar system is a combined system, contributing to both domestic hot water preparation and space heating. The integrated solar collectors are directly south oriented and cover an area of 80 m^2 with water heat store of 950 litres capacity (Figure 6.3).

The energy and electricity demand for the offices with 479 m^2 and the production hall with a floor area of 1,389 m^2 is covered exclusively from renewable energies. The heat distribution in the office building is performed via a wall heating system. The production hall is heated via a floor heating system integrated in the concrete floor. The concrete floor (90 cubic meters) is used both as a radiator as well as a heat store. As a result of the excellent thermal insulation of the building and the corresponding dimensioning of the wall- and floor heating systems, the system can be operated with very low flow temperatures. These low supply temperatures offer ideal conditions for the operation of the solar thermal plant.

Figure 6.3 Solar integrated system in the AKS DOMA Solartechnik building in Austria.

6.1.4 Office Building – Ljubljana, Slovenia

An area of 24 m^2 of solar collectors are integrated on the south façade of the building 15° towards east (Figure 6.4). For the first time, semi-transparent solar thermal façade collectors run a sorption chiller in a real building. The slat structure of the absorbers allows visual contact to the exterior while accounting for good solar thermal gains at the same time. The collectors are the wall of a staircase and support the building services for real offices in the building.

The cost of the double skin façade elements increases only by 10-15% when a semi-transparent absorber is included. At the same time the shading provided by the collector reduces the cooling load (Maurer, 2012).

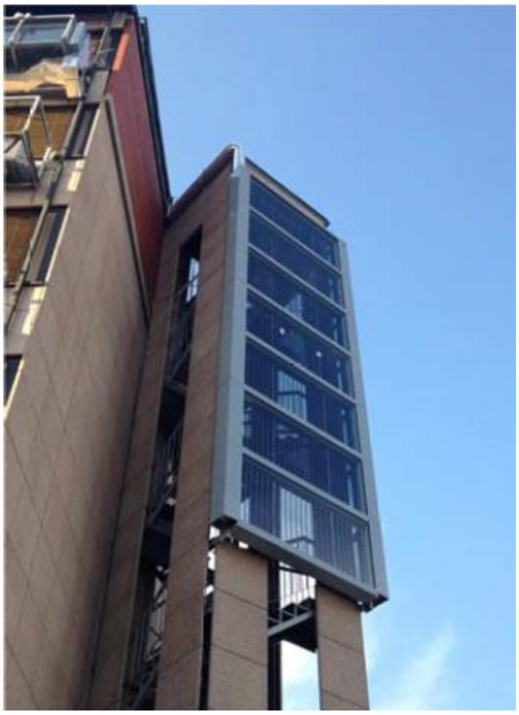

Figure 6.4 Integrated solar system in office building in Ljubijana.

6.1.5 Residential Building – Paris, France

Eco-friendly architecture is becoming a priority to almost many of the architects and designers worldwide. One of the architects that join with the whole world in designing structures with saving the earth in mind is the Philippon-Kalt Architects, whom had designed the first building for social housing in Paris that has solar panels. The agency Philippon-Kalt just delivered, opposite the station Barbès, the first building of social housing in Paris with a facade solar panels (Figure 6.5).

Seventeen social housing units for lower income have been created in a very constrained environment with a willingness to implement innovative environmental techniques. The facade shows its solar panels on the Boulevard de la Chapelle, and capturing solar gain free to provide 40% of domestic hot water needs. A control system to verify the system performance of solar water heating. Robin Sun sensors, in the absence of technical advice, were the subject of a notice of the specific area of operation. Double skin, double use, solar panels reflect the image a powerful instrument panel, atypical in the scope of protection of historic monuments. It preserves the privacy of passengers' views of dwellings from the Skytrain and offers private balconies protected from the noise of the Boulevard de la Chapelle by forming trellis acoustic masks (Architizer, 2014).

Figure 7 The solar thermal glass in the Boulevard de la Chapelle.

The solar thermal glass is supplied on racks made from waste wood or specially designed metal A-frames (against consignment). Each solar thermal glass is separated from the next one by foam sheeting or protective cork separators. These low adhesive separators must be removed from the glass by the joiner/façade specialist during installation. Each tube exiting from the glass comprises a 50mm-long split silicon sleeve. That sleeve allows the dilation of the tubes after the reconstitution of the sealant with silicone and aluminium adhesive strips after the possible drilling of holes in the connector. Each solar thermal glass sheet comprises on one side 2 copper tubes, each with a diameter of 8*7mm. These tubes must be perfectly circular and exit perpendicularly from the glass on 100mm. The tubes that exit in dependence of the module dimension on the side or top of the glass. Upper and lower copper tubes are closed with removable yellow stoppers.

The modules are wrapped to the racks with a polyethylene film. Beyond the polyethylene film, at the bottom of the module situated at the exterior a thin wood plate (OSB) protect them. The modules are maintained to the rack with a one way or reusable girth.

The standard width is 1016 mm (glass rand). The upper and lower pipe who goes out of the glass on the side adds between 25 mm (which is the minimum cupper dimension to connect or disconnect) and 100 mm (standard delivery length) to that width. The height of the lower copper pipe axis is located 51 mm from the bottom of the glass.

6.1.6 Residential Building – Warsaw, Poland

A residential building in Warsaw, Poland uses a BISTS for combined hot water supply and central heating (figure 6.6). The building was designed to use solar energy by passive and active systems. The building has a buffer space at south side which provides high solar gains during autumn, winter and spring. In summer buffers limits heat gains to living space of the building.

The primary heat source of the building is a heat pump with vertical ground heat exchangers. The flat plate solar collectors with collection area of 10.92 m^2 are oriented on the south side of the roof in a slope of 38°.

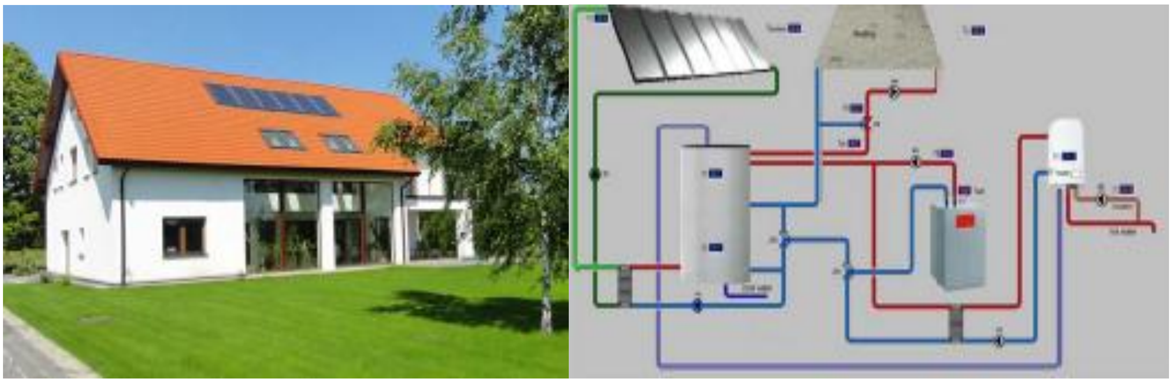

Figure 6.6 Combi BISTS in residential building in Warsaw, Poland.

The solar heating system provides 30% of space heating and hot water of annual demand. At this point it should be noted that from April to September there is no need for space heating and DHW is accomplished by solar heating system in 95%.

The system has been operated for 1.5 year. Running costs are mainly connected with electric energy consumption of 7.6 MWh/year which corresponds to 800€/year. The following graphs in Figure 6.7 and 6.8 show the useful energy from the solar collectors through one year and the energy used from the solar collectors. It is obvious that in summertime, the useful energy collected is much bigger than the amount of energy needed to be consumed.

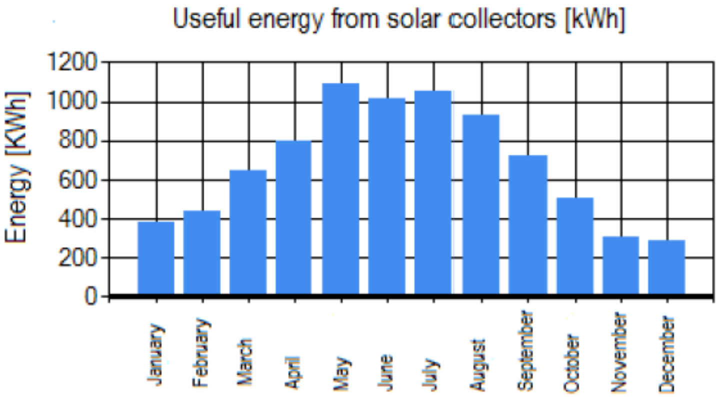

Figure 8 Useful energy from solar collectors – residential building, Warsaw, Poland.

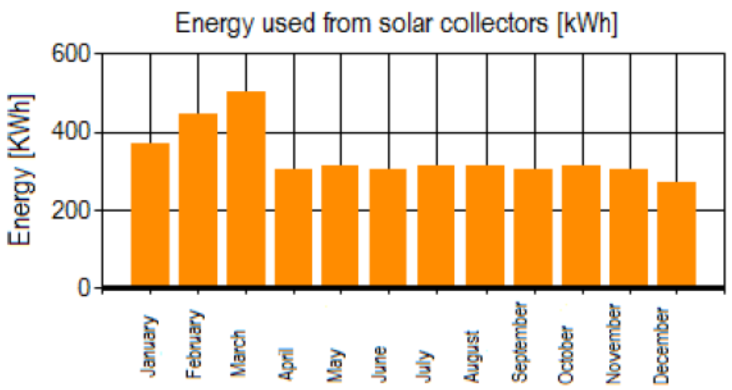

Figure 9 Energy used from solar collectors – residential building, Warsaw, Poland.

6.1.7 Residential Building – Ajaccio, France

This is t church rectory building in Corsica, France where combined BISTS applied for several purposes as shown in Figure 6.9 (Motte et al., 2013). This residential house is composed of four small apartments. Two Integrated Solar Domestic Heat Water systems are installed in these apartments. One is integrated on a metal porch roof and one into the gutters. The area of the gutter solar collector and a part of area of the solar metal porch roof are connected to one tank for two apartments (rural tourism houses –collector area 1.80 m²). The other part of area of the solar metal porch roof is connected to another tank for the others apartments (church rectory - collector area 2.02 m²/ 43°tilted). The usages of these apartments are different: Two of them are for tourist's location, booked half the year and the other are used all the year.

The thermal solar collector is totally invisible from the ground level thanks to the drainpipe integration; it is arranged so it can also be used on north oriented walls (being oriented south into the drainpipe). The drainpipe preserves its role of rainwater evacuation. The plumbing connecting the house to the solar collector are integrated in the vertical drainpipe. An installation consists in several connected modules. There are two collector versions integrated in this house:

a) A flat plate one with from top to bottom, a thermal module is composed by a glass, an air layer, a highly selective absorber and an insulation layer. First, the cold fluid from the tank flows through the interior insulated tube and then in the upper tube in thermal contact with the absorber. Each module is about 1 m length and 0.1 m in width (individual houses).
b) A vacuum solar collector into the gutter. The vacuum tubes are in 2.0 m length in direct flow and heatpipe version. The tube diameter is 56 mm, the wall thickness of the cladding tube is 1.8 mm. The installation consists in several connected sets of of 2 vacuum tubes.

Figure 6.9 Combined BISTS application in Corsica.

Moreover, three solar air collectors integrated in a shutter contribute to the heating of the house and allow to maintain a comfortable air temperature. The ambient air enters into the solar collector assisted an air fan which is electrically supplied by a PV module. The ambient air is heated in a multi-wall polycarbonate sheet which is transparent on one side (facing the sun) painted black on the back to act as a solar absorber. The hot air is then introduced in the apartment.

Using the vacuum version of the H2OSS solar collector on the rural tourism houses, the energy output is estimated at 1155 kWh/year (for collector area of 1.80 m²) and the solar fraction is 48%. The environmental impact of the system for installations on rual tourism houses and a Church rectory are shown in figure 6.10 (Cristofari et al., 2013).

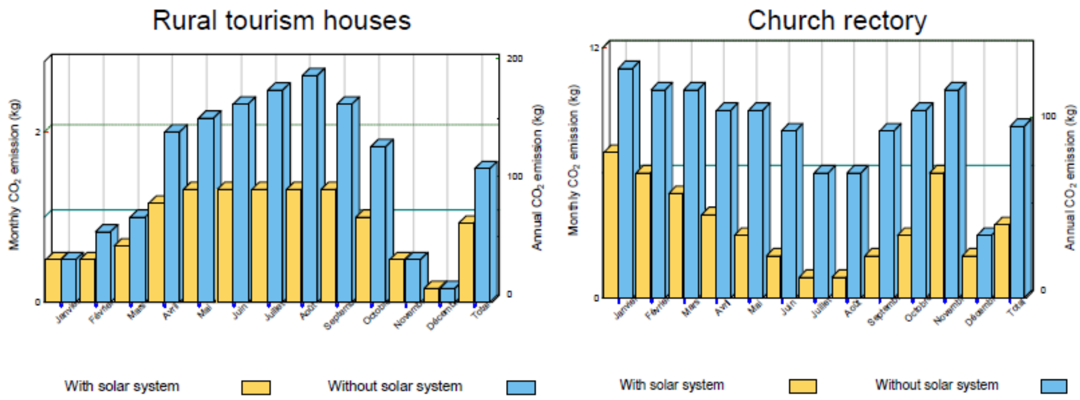

Figure 6.10 Avoided CO_2 emissions for the vacuum solar collector H20SS.

6.1.8 Asphalt solar collector incorporating carbon nano-tubes for combine HW and space heating

The system installed on this building is an asphalt carbon nano-tube roof integrated solar water heating collector. The Lawell Asphalt Caron Nano-Tube (ACNT) solar water heating collector is a building integrated solar collector designed to offset traditional roofing elements. The concept is being developed by a roofing contractor as an additional product range that they can offer commercial and industrial clients, both as a pre-heat for domestic hot water or air space heating systems. The system is fully integrated into the roof (flat structures only) and is envisages to cover an entire roof surface covering the entire building footprint. The collector will not be visible from an architectural perspective.

The ACNT collector design is based upon a simple and robust concept of using asphalt to create the solar absorptive surface. A serpentine coil of copper tubing is embedded within the asphalt to act as the heat transfer fluid channelling element. The prototype was made from asphalt that contained carbon nano-tubes. The presence of the carbon nano-tubes is intended to increase the solar collector performance by:

1) Improving the solar absorption and emittance characteristics of the absorber materials by making them partially spectrally selective.
2) Improving thermal conductivity.

The asphalt was set into a wooden tray base and was uncovered (Figure 6.11). The finished active absorbing surface of the collector was 1.605 m x 0.600 m.

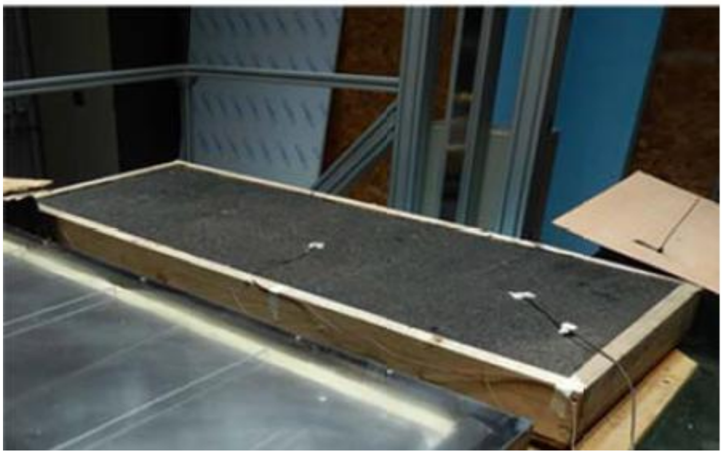

Figure 6.11 The asphalt in the wooden tray for the ACNT roof solar water heating collector.

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7 BISTS linked to other systems

7.1 Introduction on BISTS linked to other systems

Building Integrated Solar Thermal Systems (*BISTS*) typically refer to systems whereby systems are fully integrated within the building architecture, often substituting or complementing traditional building elements such as roofs, windows, walls, *etc.* Given their interaction within the built environment and the degree of skill required by the designer, architect or engineer they are so far not very common, especially compared to the more conventional types of solar collectors such as the free-standing thermosiphonic, roof installed systems, which are basically a plug and play system requiring little design thought and added once the building design (and construction) has already been completed.

In this context, it is even far less common to find building integrated solar thermal systems linked with other systems such as heat pumps or thermally activated chillers. For one, the design aspect is cumbersome, laborious and highly technical, involving the design and installation of multiple mechanical systems. Secondly capital cost especially where the building layout and the thermally activated chillers are involved is still very much on the high side

This section presents the main general aspects of *BISTS* linked with other systems and highlights and summarises some of the projects which have specifically looked at this aspect.

7.2 Review of BISTS linked to other systems

The *BISTS* linked to other systems are presented in the two main sections; *BISTS* linked to heat pumps and *BISTS* linked to thermally activated chillers. Further demonstrations of *BISTS* linked to other systems are presented later in the review.

7.2.1 BISTS with heat pumps

Technically the scope of a *BISTS* integrated with a heat pump is not too different from *BISTS* technologies aimed at air or water heating directly. The only difference is the fact that through the use of a heat pump a higher Coefficient of Performance (COP) can be attained compared to the case of a *BISTS* heating air or water directly. In most cases there is the additional requirement of a compressor as *BISTS* technologies integrated with heat pumps require a higher net input energy compared to a stand-alone *BISTS* heating air or water directly. However, the considerably high achieved COP and consequent high energy yield justify the need for the extra component.

Although many examples where solar collectors coupled with heat pumps exist; few are those examples where the solar collectors were effectively fully integrated in the building design. Most systems found in literature are in fact effectively solar collectors coupled with heat pump systems, with a very low degree of integration of the solar collector panels within the building architecture. Only few examples are available if we consider only *BISTS* linked with heat pumps where a certain degree of integration in the building architecture was achieved.

The two examples which follow are therefore two particular case studies where the solar collectors were fully integrated in the building design. The first covers the integration of a solar thermal system in the retrofitting of a building in China; the second is a concept design for a sustainable prefabricated villa.

Building Space Heating with a Solar-Assisted Heat Pump Using Roof-Integrated Solar Collectors in Tianjin, China

The first example is a solar assisted heat-pump whose evaporator was effectively designed as a solar-collector integrated composite roof structure. The building described in detail by Yang et al. (2009), consists of a refurbished 3-storey villa (Figure 7.1) measuring approximately 820m^2 whose solar roofing collector encased within the roof structure serves to absorb solar radiation similar to the scope of an evaporator in a normal heat pump. To complete the loop the internal radiant heat floors serve as the condenser of the whole building heat pump where heat is wilfully rejected into the space to be conditioned.

Figure 7.10 Refurbished Villa.

The solar-collector roof is sloped at an angle of 25° and is aligned east to west. Heat collecting devices in the form of copper tubing carry the fluid to be heated inside the evaporator side of the whole building heat pump setup (practically the whole roof). The roof was finished with EPS board for insulation and the whole roof covered in concrete on top of which ceramic roof tiles were placed (Figure 7.2) (Yang et al. 2009). The copper tubes installed underneath the roof tiles are invisible from the outside, hence fully integrated in the building architecture.

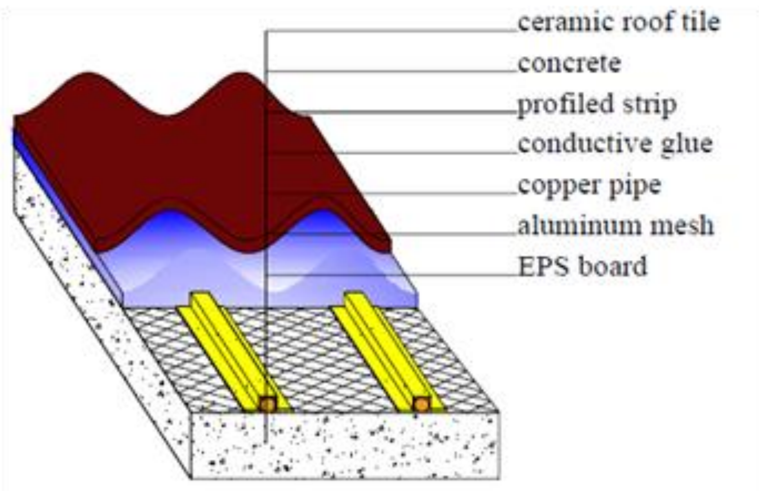

Figure 7.2 The arrangement of the solar collector.

The results for this particular project are drawn from both simulations carried out using eQuest and real measurements done on the built project. Specifically the experimental results show that the system implemented in this case can provide comfortable conditions with average and maximum COP of 2.97 and 4.16 respectively.

The Libeskind Villa

The second example of *BISTS* integrated with a heat pump comes from a concept design by Architect Daniel Libeskind (Rheinzink. 2009). The building (Figure 7.3) makes use of a purposely designed solar collectors and conventional ground source collectors which combined, form the energy source for the installed reversible heat pump.

Figure 7.11 The Libeskind Villa.

In order to heat the indoor environment, the heat pump collects heat from the earth through the ground source collectors. In summer the heat source is augmented through the use of solar collectors (designed as standing seams which complements the building architecture) (Figures 7.4 and 7.5) passing heat to the ground thus increasing the source temperature. In case of a large heat demand inside the Libeskind Villa, the output of both systems can be combined.

Figure 7.4 Standing seam solar energy absorbers integrated into the roof.

Figure 7.12 Finished roof texture.

The heat pump utilising the solar and ground source energy to heat the Libeskind Villa is also a reversible-cycle heat pump with performance factors in the order of 4.5 and calculated Seasonal Performance Factor (SPF) of 4.8. The reversible aspect of the heat pump, therefore its cooling cycle, is achieved by effectively reversing the cycle and channelling the indoor heat off into the ground and at extreme temperatures, through the solar thermal collectors integrated in the building texture. Table 7.1 summarises the expected energy results for the building extracted directly from the Rheinzink Brochure (Rheinzink. 2009).

Table 7.2 Energy Building Data.

Heating energy consumption of the building	28 MWh/yr
Storage and distribution losses	2 MWh/yr
Total thermal energy consumption of the building	30 MWh/yr
Solar collector orientation	- 90° (East)
Solar collector pitch	30°
Solar collector surface area	34.2 m² (38x0.9m²)
SPF of the heat pump according to the manufacturer	4.4
SPF of the heat pump (Actual)	4.8
Primary energy demand of the heat pump	16,900 kWh/yr
CO_2 emissions by the heat pump	4.0 t/yr
Avoided CO_2 emissions when compared to conventional gas condensing boilers	3.6 t/yr

Given the specific surface texture and thought design, the building integration in this second case study can be considered as fully integrated, as the solar collectors form a permanent feature which specifically aims to improve the building architecture.

7.2.2 BISTS with Thermally Activated Chillers (TAC)

TAC are heating and cooling heat operated devices which given their versatility in using various heat sources are especially popular when cooling loads are the predominant space conditioning load. They are particularly useful when coupled with either solar collectors or Combined Heat and Power (CHP) systems. Although various working principles exist, the most common commercially available TAC system is the absorption chiller which makes use of the affinity of two liquids (such as lithium bromide/water or ammonia/water) to produce a process similar to that of a conventional vapour compression heat pump cycle. The fact that waste heat from a CHP or heat from a renewable source is being used enhances the green credentials of such a device.

Similarly to the case where solar collectors are integrated with heat pumps, a lot of case studies exist where solar collectors were used to power TAC, especially absorption coolers. However, again few are those case studies were an effective effort was done to integrate the solar collectors within the building architecture.

Solar Heating & Cooling fed through a Solar Thermal Building Integrated Facade

In this proposed refurbishment an innovative solar thermal façade is being proposed to satisfy the heating and cooling needs of an existing apartment tower located in Sicily (Caponetto et al., 2013). The proposed setup consists of a stackable system of modular panels called TMF (Tube-Mirror-Frame) each made up of evacuated tube solar collectors coupled with concentrating aluminium mirrors (Figure 7.6). The operating temperature of the water emerging from such a setup is expected to reach 120°C, thus useful for both direct heating and cooling using an absorption chiller. Such a setup is proposed to cover 490m^2 on each of the almost windowless East and West façades, and 450m^2 on the South façade.

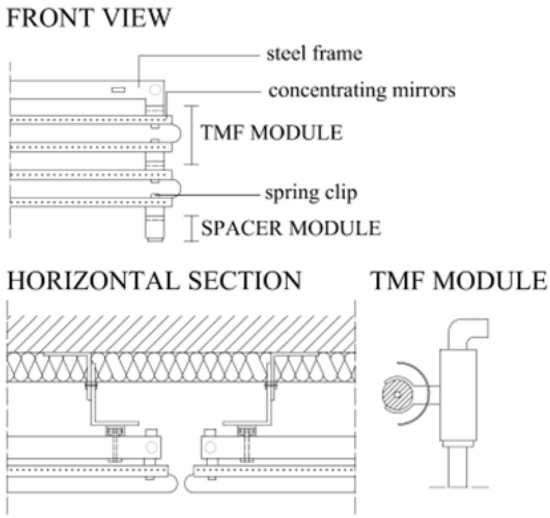

Figure 7.13 Design of a panel made by Tube mirror frame module.

Aesthetically, the design is being proposed such that the original shape and layout of the façade are retained and possibly enhanced (Figure 7.7).

In terms of expected results system modelling has shown that for the specific building, the proposed solar system can fulfil about 26% of the heating demand and 69% of the cooling demand, if the building fabric is left untouched, whilst if the building fabric is improved 69% and 95% of the original heating and cooling energy demand could be fulfilled by solar heating and cooling.

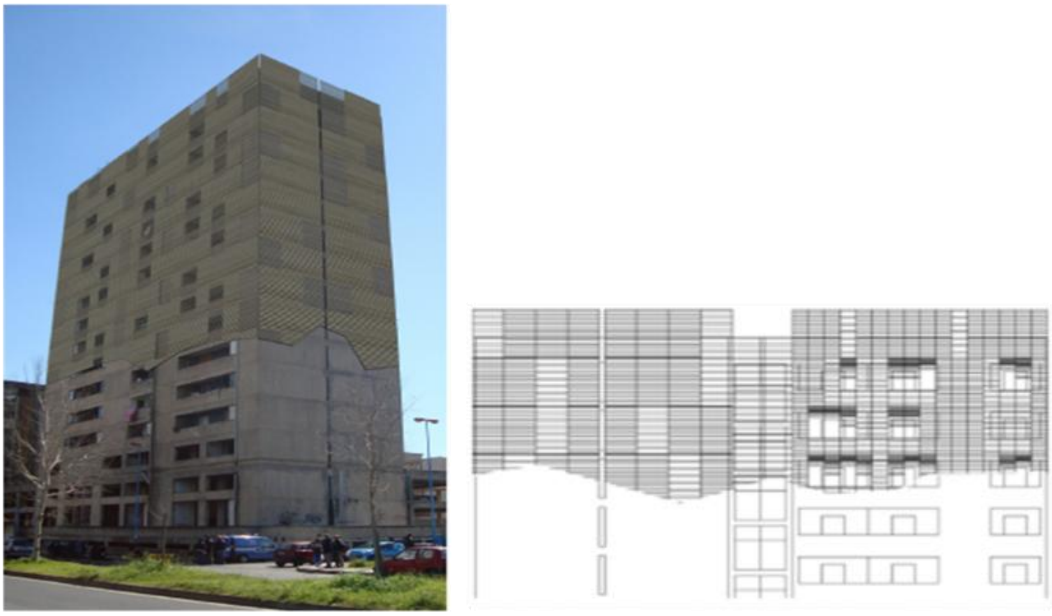

Figure 14.7 Proposed Building – Current façade and simulation of the new proposed solar thermal cover.

7.2.3 Other linked BISTS case studies

Government Building – Ontario, Canada

The SolarWall system installed in the Health Canada building, replaces 12,300m^3 of natural gas per year, saves 390GJ of energy per year and the savings in CO_2 are about 23 tonnes/year (SolarWall, 2014).

After running various simulations, it was determined that the southern and the eastern walls of the building would be the most advantageous for saving energy and money, through solar heating. Consequently, Health Canada chose these two walls to install the SolarWall system. It is basically a second shell which is mounted on the outer walls of the building, used to heats the incoming fresh air supply before being led inside the building.

The workshops require a large volume of ventilation and hot air which can be very costly. 185 m^2 of SolarWall panels are installed in the upper part of the building, over the existing brickwork. The system is designed so that the panels are curved around the building, creating a visually appealing façade (see Figure 7.8). Bronze panels were selected to match the system with the overall appearance of the rest of the building.

Figure 15 Health Canada building, Ontario.

The SolarWall system is connected to the existing air intake system on the east wall to supply 14,000cfm of ventilation air. This preheated air is passed to the building through the HVAC system, and is then distributed through conventional methods to all of the various laboratories.

Commercial Building – Malmo, Sweden

This is the Kockum Fritid building in Malmo where a large façade was covered by solar collectors for water heating and district heating. The installation of the 1050m^2 large plate collectors with antireflection treated and frosted glass was carried out as a replacement of the existing old façade and they have been given an interesting design, well integrated in the building (Figure 7.9).

Figure 16 Façade integrated collectors at Kockum Fritid in Malmo.

The five collectors are divided into three subsystems, which are integrated in the facades in directions close to east, south and west and tilted at 90° and 73°. The control system allows cooperation of the five collectors. The areas, azimuth angles and tilted angles of the collectors are shown in Table 7.2.

Table 7.2 Areas and azimuth angles of the collectors installed.

Direction	Azimuth angle, α_z	Collector tilt, β	Collector area (m^2)
East	-98°	90°	181,6
South	-8°	90°	371,2
South	-8°	73°	221,6
West	82	90°	112,4
West	82	73°	163,4

The solar thermal system works as any other conventional production unit in the district heating system in Malmö, with the exception that the production cannot be predicted. It is therefore very important that the system is robust and provides a high availability, in order not to cause disturbances like the discharge of low-temperature water into the district heating net. The system is therefore highly automated, remote-controlled and requires minimal maintenance. A condition for the success of this solar thermal system is the carefully planned location, which makes it possible to keep the heat losses from the system very low. The solar system is situated in the outer parts of the district heating system where only relatively low temperatures are required. Also, it is very close to an area where the buildings were designed to maintain thermal comfort using the minimum temperature of 65°C from the district heating system.

Simulations of the energy output of each of the collectors were performed using WINSUN, a simulation program for solar collectors (Gajbert, 2005). The TRNSYS based simulation program WINSUN was used for the simulations of solar gains from the different collectors. The program calculates the theoretical monthly energy output from the solar collectors using climatic data from Meteonorm as input data. The program also uses the monthly operation temperatures of the collectors, parameters of the collector performances and orientations, climatic data and certain other surrounding conditions. It returns the monthly energy output for the period.

Measured data from the solar thermal system from the period 2002-07-01 to 2003-06-30 have been analysed and used for simulations. Figure 7.10 shows the measured and simulated results of the total monthly energy output from the solar thermal system. Each collector was simulated separately. Input data of the performance parameters of the collectors are received from the manufacturer who had the collectors tested by SP Technical Research Institute of Sweden. Monthly mean flow weighted operation temperatures in the collectors were derived from measurements and used as input in the simulation program. The average operational temperature over the year was calculated at 63°C. During the investigated period the system delivered 189,000 kWh to the district heating system, *i.e.*, 180kWh/m² of collector area, with a peak power of 0.3 MW. The Coefficient of Performance, *i.e.*, the thermal energy produced per unit (kWh) electricity used for the system operation, *e.g.* pumps, *etc.* was 24, according to the measurements. The results from the simulations show an expected energy output of 183,000kWh/year, *i.e.,* 174kWh/m2/year, which is a divergence of only 3% from the measured output.

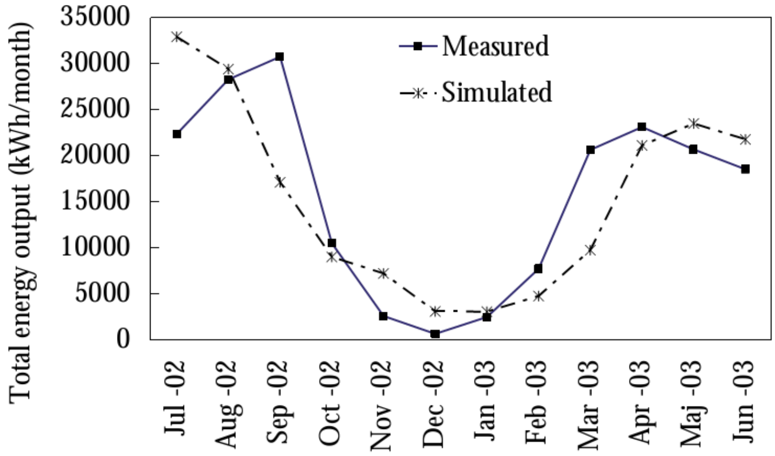

Figure 17 Measured and simulated results of the total monthly energy output from the solar thermal system.

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8 Thermal Energy Storage (TES) for BISTS

8.1 Introduction

Thermal energy storage (TES) is the technology that allows the storage of thermal energy (heat and cold) for later use (Cabeza, 2012). TES allows overcoming mismatch between energy generation and use in terms of time, temperature, power or site (Mehling and Cabeza, 2008). Solar applications, including BISTS, require storage of thermal energy for periods ranging from very short duration to annual storage.

Advantages of using TES in a solar energy system are the increase of the overall efficiency and better reliability, but it can also lead to better economics, reducing investment and running costs, and less pollution of the environment and les CO_2 emissions (Dincer and Rosen, 2002).

In general, storage concepts have been classified as active or passive systems (Gil et al., 2010). An active storage system is mainly characterized by forced convection heat transfer into the storage material. The storage medium itself circulates through a heat exchanger (the heat exchanger can also be a solar receiver or a steam generator). This system uses one or two tanks as storage media. Active systems are subdivided into direct and indirect systems. In a direct system, the Heat Transfer Fluid (HTF) serves also as the storage medium, while in an indirect system, a second medium is used for storing the heat. Passive storage systems are generally dual-medium storage systems: the HTF passes through the storage only for charging and discharging a solid material.

Thermal energy can be stored using different methods: sensible heat, latent heat and thermochemical energy storage (Cabeza, 2012).

Sensible storage is the most common method of heat and cold storage. Here energy is stored by changing the temperature of a storage medium (water, air, oil, rock beds, bricks, concrete, or sand). Latent heat storage is when a material stores heat while at phase transition. Usually the solid-liquid phase change is used. Upon melting, while heat is transferred to the storage material, the material still keeps its temperature constant at the melting temperature, also called phase change temperature.

The main advantage of using TES with BISTS is the success of converting an intermittent energy source in meeting the demand (usually also intermittent but at different periods of time) (Cabeza, 2012). In addition TES components integrated into buildings can replace traditional components reducing overall cost. The proximity of the storage to the energy supply system can also provide further economies in the form of reduced power and equipment requirements. Effective, efficient and low-cost TES systems can be the key factor influencing the economic viability of BISTS. The following sections present a review of TES methods/technologies which can be used with the range of BISTS reviewed in the previous sections of this document. In some of the cases the TES system is part of, or incorporates, a BISTS, which demonstrates the interdependence and common features of the two technologies.

8.1.1 Passive systems – Solar Wall

Sustainable energy system design offers credible and innovative strategies to overcome environmental energy crises (Saadatian et al., 2012). Solar walls offer feasible technique for the exploitation of directional flow of heat in buildings. This article reviewed state-of-the-art concepts, applications and significance of solar walls for energy savings in buildings. Detailed operational framework of various solar-wall configurations, technology and efficiency as building component was discussed. Need for this sustainable energy design in buildings and constraints associated with their realisation were reported to aid proposed future research work. Sustainable design based on passive solar technique reduces annual heating demand through the use of various architectural instrumentalities such as solar walls (Saadatian et al., 2012), (Koyunbaba, xxxx), (Quesada, 2012) and many others (Saadatian et al., 2012). Solar walls often referred to as storage walls or solar heating walls (SHW) (Xiande et al., 2008), (Hami et al., 2012) help reduce building energy consumption. A solar wall is an important green architectural feature that aids the ventilation, heating and cooling of buildings (Saadatian et al., 2012).

The technology that underlies solar wall configuration encompasses the use of sun facing wall (solar wall) to conventionally heat up air for ventilation purposes, which is essentially needed to provide thermal comfort in buildings (Zamora and Kaiser, 2009). This is achieved through the absorption of solar radiation during daylight and the release of the energy absorbed to the interior during the night. The operation strategy facilitates the use of excess energy absorbed during the sun's peak hours by the building's occupants when it is most needed (Saadatian et al., 2012).

According to Saadatian et al., (2012), classification, solar walls are divided as follows:

Standard solar wall (Trombe wall)

Standard solar wall comprises a compartment of glass and air space that is separated by the wall from the outdoor environment (Gan, 2008), (Mekhilef et al., 2011). This type of solar wall was invented by Edward Morse, an American engineer, and was patented in 1881. Classic solar wall was popularized by Felix Trombe (a French engineer) and Jacque Michel (French architect) in late 1950s and 1960s. Their innovative work on solar walls led to the modified versions that are currently referred to as Trombe wall. Classic solar wall involves the use of materials of high heat-storage capacity such as bricks, concrete, stone and adobe with colour-textured external surface (usually black) to improve the absorption rate of heat energy and are glazed, with air gap between the glass and wall (Saadatian et al., 2012).

The solar wall surface absorbs direct and diffuse solar radiation as the sun shines and conveys the absorbed heat energy towards the thick storage mass interior wall by either convection or conduction when the sun sets. The air space between the sunfacing wall and the glass, often in the range of 3–6 cm, gradually releases absorbed heat energy and stores it as thermal mass. The heat-transfer mechanism from the sun is basically through radiation and convection, which is essentially used to increase thermal comfort level of building occupants. Customarily, conventional airflow is produced through solar buoyancy effect. However, diversified modifications on the size and shape of classic solar walls can be designed. Commercially modified solar walls are incorporated with gypsum-lined board with layers of masonry exterior and gypsum board. This design conventionally induces buoyancy-driven natural ventilation. A dark coloured, 2 m^2 commercially modified solar wall having 14 cm air gap can induce 20–90 m^3/h of air ventilation (Khedari et al., 1998). The design incorporates air gap between different layers, although different components can be integrated into the classic solar wall to enhance its performance (Saadatian et al., 2012).

Green building and sustainable architecture are new techniques for addressing the environmental and energy crises (Saadatian et al., 2012). Trombe walls are regarded as a sustainable architectural technology for heating and ventilation. This article reviews the application of Trombe walls in buildings. The reviews discuss the characteristics of Trombe walls, including Trombe wall configurations, and Trombe wall technology. The advantages and disadvantages of this sustainable architectural technology have been highlighted, and future research questions have been identified.

Solar walls have been studied for decades as a way of heating building from a renewable energy source (Zalewski et al., 2012). A key ingredient of these wall is their storage capacity. However, this increases their weight and volume, which limits theirs integration into existing building. To alleviate this problem, storage mass is replaced by a phase change materials. These allow to store a large amount of energy in a small volume, which brings the possibility of retrofit trough use of light prefabricated module.

This article presents an experimental study of a small-scale Trombe composite solar wall. In this case, the phase change material was inserted into the wall in the form of a brick-shaped package. While this material can store more heat than the same volume of concrete (for the same temperature range), it shows a very different thermal behavior under dynamic conditions. A particular attention is focused on the delay between the absorption of solar radiation and the energy supplied to the room. The energy performance of the wall from heat flux measurements and enthalpy balances are also presented.

Stazi et al., (2012) presented a study on the behaviour of solar walls in a residential building under a Mediterranean climate, in terms of energy performances and thermal comfort all year round. The aims of this study are: the investigation of Trombe wall's thermal behaviour; the evaluation of solar wall's influence on heating and cooling energy needs and indoor thermal comfort; the analysis and optimization of solar wall's behaviour in an accommodation varying the envelope insulation level.

In order to do that, various activities were carried out: a series of monitoring campaigns in different seasons; dynamic simulations with software EnergyPlus; calibration of the model with experimental data; parametric analyses on the interaction between solar walls (on the southern side) and different types of building envelopes (on the other exposures) varying the insulation level according to recent standards.

The results demonstrated that solar wall provides heating energy savings and thermal comfort in winter and intermediate seasons. A significant improvement of the solar wall's performances can be obtained using double glazing. In summer solar walls determine an increase in cooling energy needs and risk of overheating. The use of solar wall's shading and ventilation reduces such drawbacks and leads to indoor conditions within comfort range. (Briga-Sa et al., 2014). The improvement of energy performance in buildings can be achieved through the integration of a Trombe wall system. The literature review reveals that more research work is still required to evaluate the real impact of this system on the building thermal performance. The study here presented aims to define a calculation methodology of the Trombe wall energy performance, based on ISO13790:2008(E), adapted to the Portuguese climatic conditions. The massive wall thickness, the ventilation system and the external shutters influence in the system thermal performance is demonstrated. It was concluded that the highest contributions to the global heat gains is given by the heat transfer by conduction, convection and radiation. However, the existence of a ventilation system in the massive wall has a significant role in the thermal performance of the Trombe wall, which contribution increases with the increasing of the massive wall thickness. It was also applied the Portuguese thermal regulation to a residential building with this system. It was concluded that energy heating needs can be reduced in 16.36% if a Trombe wall is added to the building envelope. The results also showed that the proposed methodology provides a valid approach to compute the Trombe wall thermal performance.

Solar water wall

Solar water wall is a type of solar wall that works on an operation principle similar to that of classic solar wall. The distinction between the two is that while masonry is used for heat storage in classic solar wall, water storage/reservoir is used in solar water wall (Tyagi and Buddhi, 2007). The use of water in place of heat is more effective for indirect heat gain and as a result has drawn the interest of most passive heating designers. The enhanced performance realised through the use of water in place of air is based on the concept that surface temperature of water retains heat more than air, which is used in masonry, and as a result, heat is reflected on the glazing surfaces, which is needed for environmental responsive building design for thermal comfort (Saadatian et al., 2012).

In this type of solar wall, glazing is installed at the front of water storage medium, which facilitates the flow of solar radiated heat as water distributes the absorbed heat by convection from solar water wall through to the building rooms. In order to absorb more heat from incident solar radiation, the surfaces of the solar wall exteriors are darkened. Most solar wall layers are separated with thin film concrete wall that acts as an insulator in the interior and in turn increases the wall's efficiency (Saadatian et al., 2012).

As a result of high specific heat capacity of water (C), which is higher than most building materials such as concrete, bricks, adobe and stone, more heat energy is conserved using water. In addition, the transfer of the absorbed heat energy to the interior space using water is faster than air, which is used in classic solar wall systems.

However, in cold climate, the need arises to insulate the glass layers to prevent heat loss from the sun-facing warm wall to the exterior. The solar water wall can function as a cooling and heating medium for building apartments, which is part of sustainable architectural micro-element in building design. However, liquids such as water are more difficult to handle than solid materials such as the ones used in masonry. As a result, solar water wall is not widely adopted by stakeholders compared to classic solar walls (Saadatian et al., 2012).

Solar transwall

A transwall is another type of solar wall. A transwall is a transparent modular water wall. A transwall plays an aesthetic role by providing visual access to a building's interior. In addition, it provides thermal gain from solar radiation. This wall is built on a metal frame that holds a water container constructed from glass walls and a semi-transparent absorbing plate that is positioned between the walls. The semi-transparent plate absorbs 4/5 of the solar energy and transmits the rest of the energy inside.

Therefore, this type of wall uses the direct and indirect gain systems and is suitable for locations where daytime temperature is high (Al-Karaghouli and Kazmerski, 2010). Convective heat transfer in a transwall lessens the efficiency of this type of wall. However, installing transparent baffles overcomes this deficiency. To increase the viscosity of the water and to prevent microorganisms from growing in the water, gelling and bio-inhibiting agents should be added to the water (Al-Karaghouli and Kazmerski, 2010).

Composite solar wall

The composite solar wall, which is also known as the Trombe–Michel wall is another type of solar wall, which consists of several different layers (Ji et al., 2011), (Marinosci et al., 2011). These layers include a semi-transparent cover, a mass heating wall, a closed cavity, a ventilated air cavity and an insulating panel. Composite solar walls are considered a remedy for two deficiencies of solar walls: (a) heat loss during cloudy winter days and (b) undesired heat inputs during hot weather (Zhai et al., 2011).

The composite solar wall functions as follows. The first layer, which is transparent, dispatches the majority of the gained solar beams. Consequently, the storage wall absorbs a portion of the gained solar energy and heats up. The mass wall stores and transmits part of the absorbed energy into the building's interior. This energy transfers into the room by convection through the ventilated channel. In addition, a small portion of the energy is transmitted by conduction from the wall into the room. These free solar gains must be distinguished from direct solar gains.

The advantages of composite solar walls are as follows: (a) users can control the rate of heating by controlling the airflow into the ventilated channel and (b) the composite solar wall's thermal resistance is extremely high because the walls and ventilated channel are insulated. One disadvantage of a composite solar wall is that the wall requires a mechanism to prevent reverse thermo-circulation, which occurs when the storage wall becomes colder than the ambient air of the building's internal space. This problem can be solved by inserting a plastic film in the vent, which functions as a thermal diode (Zalewski et al., 2012).

A group of scholars based in France, compared the classic solar wall with the composite solar wall using TRNSYS software and validated it by experiential testing to analyse the walls' efficiencies. The results demonstrated that the composite solar wall performs better during winter, particularly in cold or cloudy climates (Jibao et al., 2007a -2007b).

Fluidised solar wall

Fluidised solar wall operational principle is based on the classic solar wall; however, in place of air gap between the solar wall and glazing as found in classic solar wall, highly absorbent, low-density fluid is used in fluidised solar wall (Tunc and Mithat, 1991). A fan is used to convey the solar heat captured by the absorptive fluid and are been driven by heated air to the occupants rooms. The operation involves the use of filters at the top and bottom of the air compartment to prevent the entrance of fluidised particles into the living rooms (Sadinemi et al., 2011). A group of Turkish scholars compared classic solar wall with fluidised solar wall theoretically and experimentally and found that fluidised beds provide limited distinctive procedure for solving governing equations based on air as the working fluid.

Findings showed that fluidised solar walls perform better than classic solar walls due to the heat-transfer mechanism used, which involves direct contact of fluid with the particles (Tunc and Mithat, 1991).

8.1.2 Active systems

Core Activation

Thermal mass activation consists of using building structure components such as walls, ceiling or floors as a storage unit. In this case, the activation is directly done inside the material by the use of pipes or ducts connected to a BISTS.

Ceiling/floor

A ventilated concrete slab (VCS) was implemented in a nearly zero energy solar house by Chen et al. (2010). The VCS was designed as a thermal storage component to store solar thermal energy for heating purposes. The system is actively charged through a building integrated photovoltaic/thermal (BIPV/T) system located in the roof, where the air is the heat transfer fluid (Figure 8.1). Then, the heat stored is passively released to cover the heating demand of the building. Data registered during the commissioning of the building showed that the VCS can store from 9 to 12 kWh during a clear sunny day.

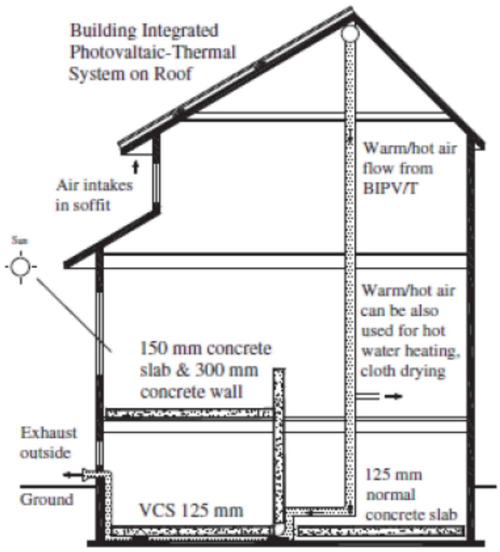

Figure 8.1 Scheme of the VCS linked with BIPV/T system.

In a new study, Jin and Zhang (2011) included phase change materials (PCM) on the surface of a concrete slab radiant floor. The system proposed consists of two layers of

PCM which have different melting temperatures. Each layer is used to store energy and release it in the peak period either for heating or cooling purposes. The optimal melting temperature for both PCM were defined with a numerical model described in the paper, being 38°C and 18°C for heating and cooling respectively. Moreover, the energy release when adding PCM layers is increased by 41% for heating and 38% for cooling.

Wall

Fraisse et al. (2006) studied the integration of a solar air collector in a timber frame house and a heavy ventilated internal wall. The heat supplied by the collector is circulated through the concrete wall cavity charging the internal wall with solar energy.

Several operational modes referring to the air circulation, open or closed loop, were studied with numerical simulations. The authors conclude that the closed loop (Figure 8.2) integrated collector with the heavy internal wall is much more efficient due to its independence from the ventilation system.

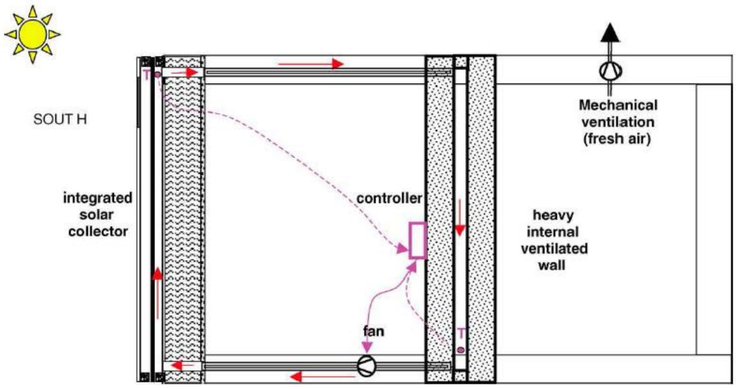

Figure 8.2 Diagram of a closed loop mode in winter.

Suspended ceiling

Storage components located in the suspended ceiling such as radiant panels or water panels which have at least an active charge.

Roulet et al. (1999) presented the design of radiant panels filled with water used for cooling and heating. The panels are made of stainless steel and the water inside them is directly in contact in 98% of the panel surface. Although radiant ceilings are mostly used for cooling, these radiant panels are designed also for heating with low temperature sources, such as heat pumps or active solar systems. Depending on the building requirements radiant panels could be placed on the ceiling or the walls and in some cases it could be an efficient solution to control the indoor temperature (Figure 8.3).

Figure 8.3 Heating and cooling ceiling in a meeting room.

A new thermally activated ceiling panel based on gypsum with microencapsulated PCM was presented by Koschenz and Lehmann (2004). The study presented the panel as an alternative for the building refurbishment, hence the authors focused on minimizing the panel thickness as well as providing good storage capacity. The system can be coupled to renewable energies, such as solar energy o geothermal, for heating or cooling office buildings. Simulation study and laboratory tests carried out determined that a 5 cm layer gypsum panel with 25% of PCM by weight to maintain a comfortable room temperature in standard office buildings.

8.1.3 External solar façade

Double skin facades which act as an external storage component for heating or cooling purposes.

Sensible heat storage

Fallahi et al. (2010) discussed the integration of a thermal mass into a DSF in order to reduce the risk of overheating and increase the system efficiency in both winter and summer periods. A numerical model was developed to demonstrate that the use of thermal mass in the air channel enhances the energy savings from 21% to 26% in summer and from 41% to 59% during winter.

Latent heat storage

Costa el al. (2000) developed eight prototypes to evaluate experimentally the thermal performance of VDSF in different European climates (Southern, Central and Northern climates). In one prototype (M3) a PCM layer was included in the inner skin; however, due to the small amount of PCM (4 cm), no significant improvements were found due to its use.

Gracia et al. (2012) tested experimentally the thermal performance of a ventilated facade with macro-encapsulated PCM in its air chamber. During the heating season facade acts as a solar collector during the solar absorption period (Figure 8.4). Once the PCM is melted and the solar energy is needed by the heating demand, the heat discharge period starts. This discharge period is performed until no more thermal energy is needed or can be provided by the system. The authors registered a reduction of the 20% in the electrical energy consumption of the installed HVAC systems because of the use of this solar ventilated facade.

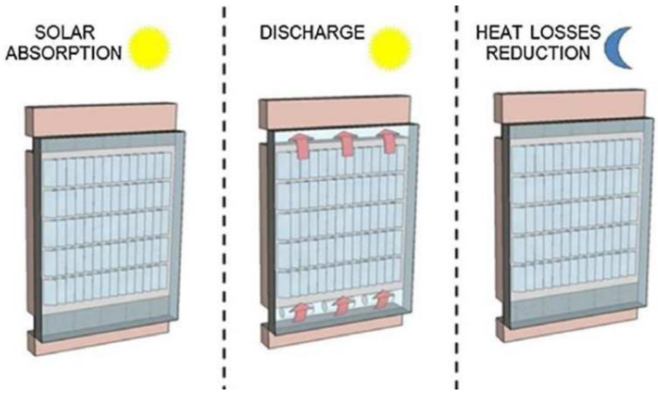

Figure 8.4 Operational mode for the system during winter.

Diarce et al. (2013) investigated numerically and experimentally the thermal performance of an active ventilated facade with PCM in its outer layer. The behaviour of this system was compared against traditional constructive systems. It was shown that the PCM led to a significant increase in the heat absorption during the phase change thermal range. It was also demonstrated that the thermal inertia of the ventilated facade with PCM was higher than that of the different evaluated traditional systems.

8.1.4 Water tanks

Storage water tanks are a common component of solar thermal systems offering in most cases small size, diurnal thermal energy storage. Larger size, weekly, monthly or seasonal storage can be achieved by integrating the tanks in the structure of the building and sometimes replacing traditional components of the building structure.

Integrated in the building

Water tanks from solar systems have been integrated in the building in several projects. For example, in Das Sonnenhaus, a water tank has been architecturally integrated in the living area (Figure 8.5) (Hasan et al., 2014).

Figure 8.5 Solar water tank integrated in a living room.

In Regensburg, the first fully solar-heated solid house was built (Hasan et al., 2014) (Figure 8.6). The total heat supply of the house is covered by a 38,500 l solar storage without additional heating.

Figure 8.6 Solar water tank integrated in a solar building in Regensburg.

One more example is a Zero Energy House Nature Park Information Centre located in Germany. It has 110 m^2 of solar thermal collectors and one buffer storage of 22,000 l which cover the energy demand (Figure 8.7).

Figure 8.7 Solar water tank integrated in a zero energy house nature park information centre.

8.1.5 Examples of single dwelling Seasonal TES (STES)

Central Continental Climate

A number of companies located in Switzerland and Germany have created “products” which integrate solar collectors and buffer/STES systems in single dwellings.

Josef Jenni built a purely solar heated home in 1989 in Oberburg, Switzerland, which uses 84 m^2 of solar collectors in combination with 118 m^3 of storage capacity in three storage tanks (92, 13, 13 m^3) to heat a house of 130 m^2 (Figure 8.8). His company Jenni Energietechnik supplies storage tanks for buildings with at least 50% solar heating (Jenni, 2014).

The storage tanks manufactured by Jenni Energietechnik have been adopted by two German suppliers as the basis for their new energy-efficient homes (Figure 8.9). Solifer, who supply the Energetikhaus 100, which is proposed to be the “first turnkey affordable all year solar house” by the company promoting the product (Energetichaus, 2014). The first house which was built in 2006 is reported to have a combined DHW and space heating solar fraction of 95% through the use of 69 m^2 of solar collectors on the south facing roof in combination with a 28 m^3 buffer storage tank (Goswami, 2009). The other company Promassivhaus (promassivhaus, 2014), which is a partnership of 50 construction companies, offers five different variants of dwelling all of which have a combined solar fraction in excess of 50%.

Figure 8.8 Energetikhaus 100 solar panels.

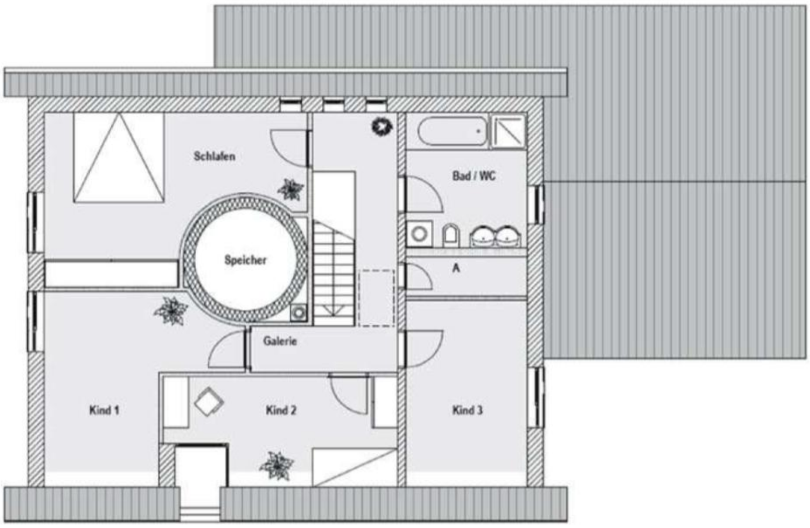

Figure 8.9 Location of tank 'Speicher' within Energetikhaus 100.

An analysis of a building integrated sensible seasonal thermal energy store has been conducted by Simons and Firth (2011). The apartment building is located in a lowland region of the Canton of Berne in Switzerland. The STES was designed and built prior to construction of the apartment building which was constructed to the Minergie-P standard.

The STES consists predominantly of two components: the seasonal thermal energy storage vessel of volume 205 m^3 (which is partially underground) and the flat plate solar collector of 276 m^2. The STES vessel is an insulated mild steel cylinder containing steel heat exchanger coils in addition to three stainless steel boilers which are used to heat the potable DHW (Domestic Hot Water).

The three boilers are placed at different levels within the storage vessel, only one of which is used at any one time. The stored water cools from the bottom and, once the water temperature drops below a certain threshold, the higher boiler is used to achieve the desired temperature. The flat plate solar collectors form the whole south-facing side of the roof and are specifically designed to function as the roofing cover. Only the glass and rubber seals are externally exposed which allows the structural elements to be constructed of timber.

The STES has been shown to be successful in meeting the heating and hot water demands throughout the year. In respect to energy demand, the analysis undertaken by Simons and Firth has shown that over a relatively short lifetime of 40 years, the total non-renewable primary energy used in producing, operating and disposing of the STS is far lower than any of the other heating systems used in the comparison and so on this aspect the initial investment is justified.

Using a range of lifetime scenarios it was found that the solar thermal system displays potentially significant advantages over the other systems considered (air-source heatpump, ground-source heat pump, natural gas furnace, oil furnace and a wood-pellet furnace) in terms of reductions for purchased primary energy (from 84 to 93%) and reductions in GHG emissions (from 59 to 97%). However, the solar thermal system was shown to have a higher demand for resources (a factor of almost 38 compared with the natural gas system considered).

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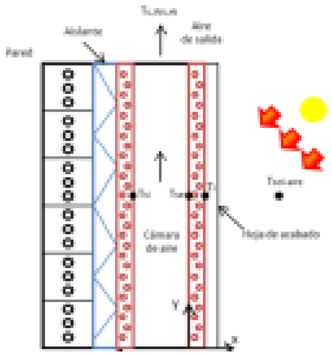
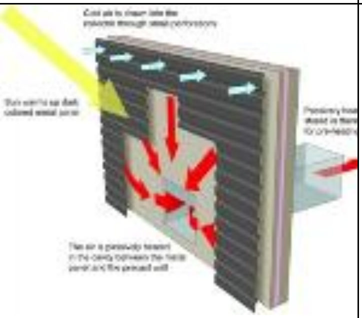
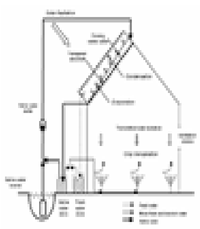
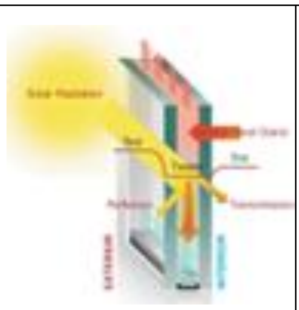
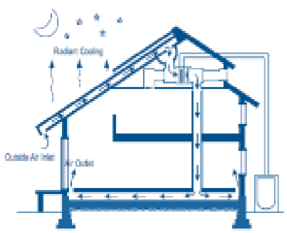
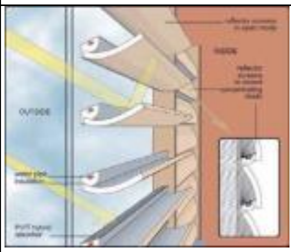
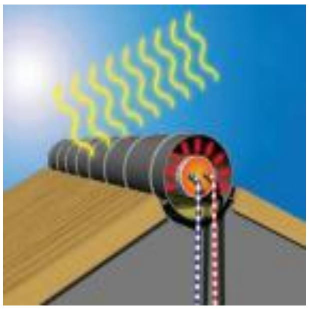
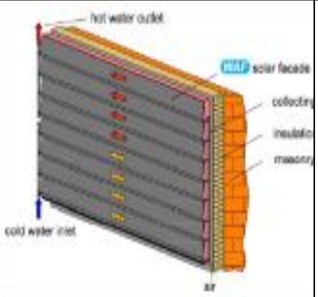
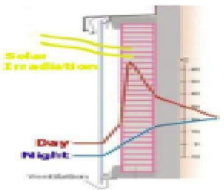
APPENDIX A

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. 2003		http://daniel-libeskind.com/projects/villa-libeskind-signature-series

	www.IntelligIass.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

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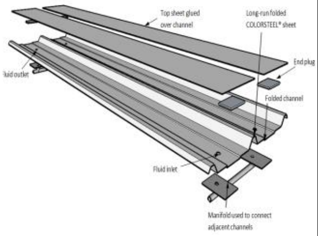
<td>
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<td>Anderson, T.N., Duke, M. and Carson, J.K., 2013, “Performance of an unglazed solar collector for radiant cooling”, Proceedings of Australian Solar Cooling 2013 Conference, Sydney, April 2013</td>
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