EU COST Action TU-1205

Building Integration of Solar Thermal Systems (BISTS)

Deliverable 3.1 –

Review of current STS and the suitability of integration onto building structures for domestic, commercial and industrial buildings

Working Group 3 –
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.

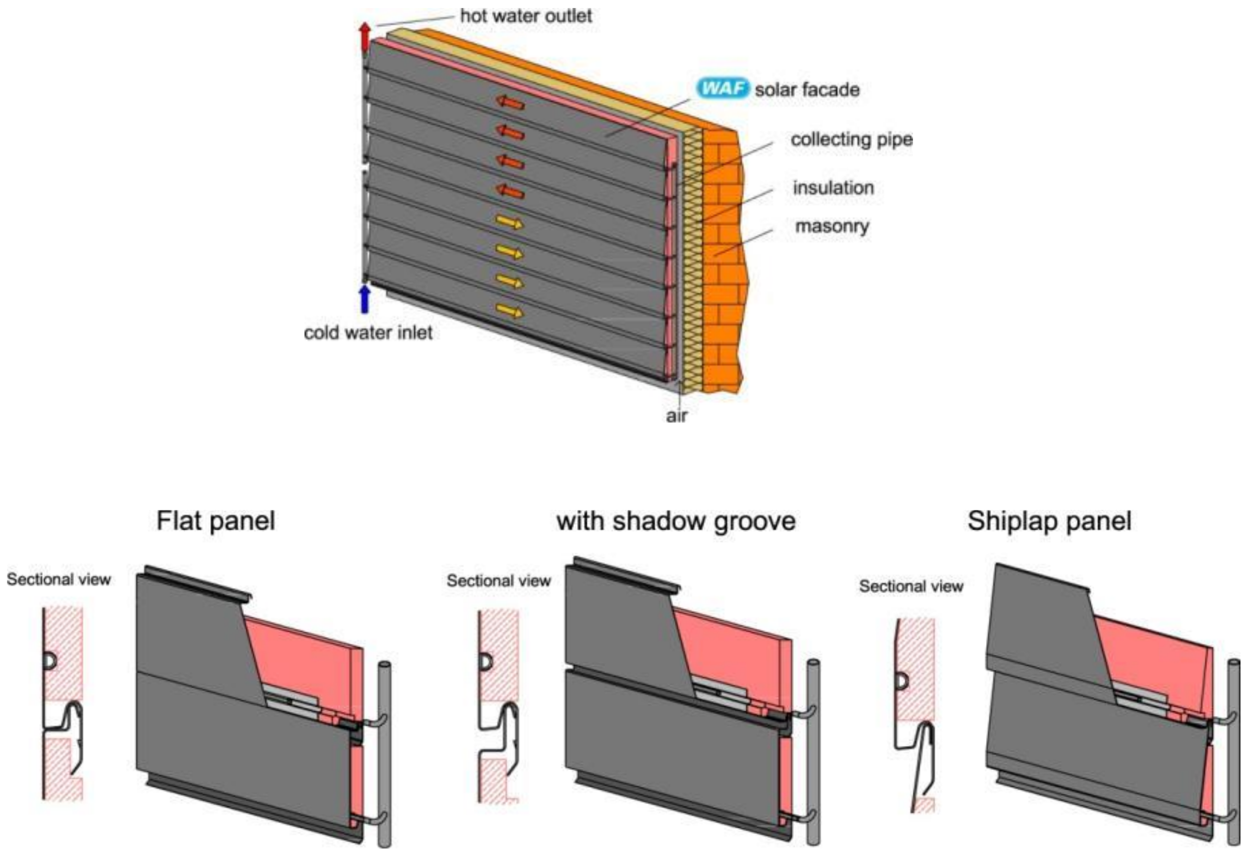


Figure 2.1 Solar Thermal Façade by WAF.

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.

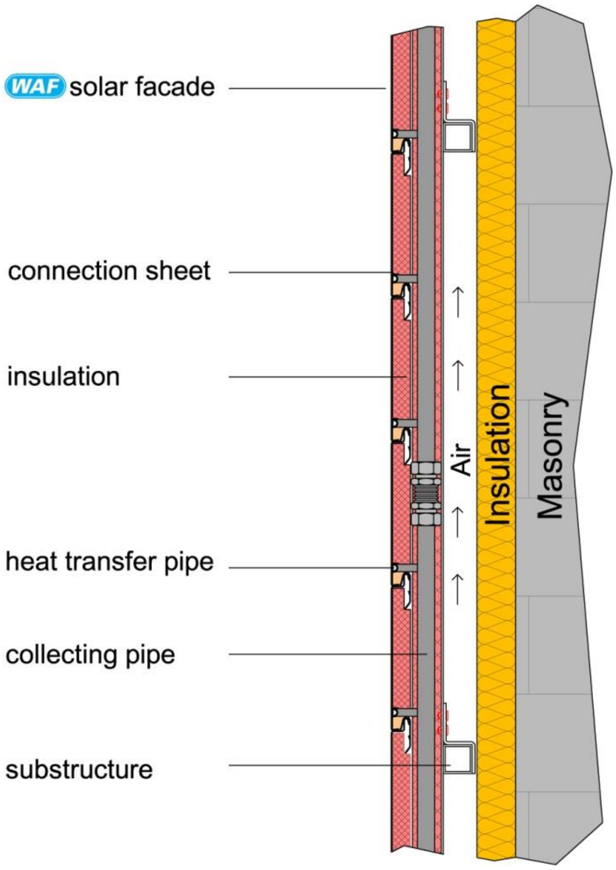


Figure 2.2 The structure of the WAF Solar Thermal Façade.

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.

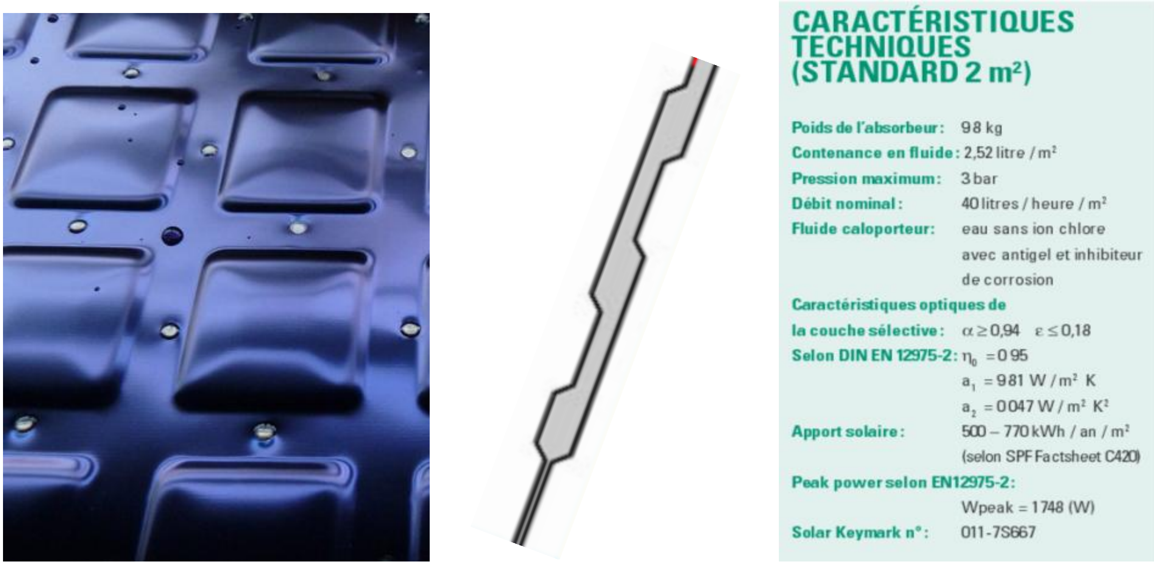


Figure 2.3 The absorber of the flat plate collector made by Energie Solaire.

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.

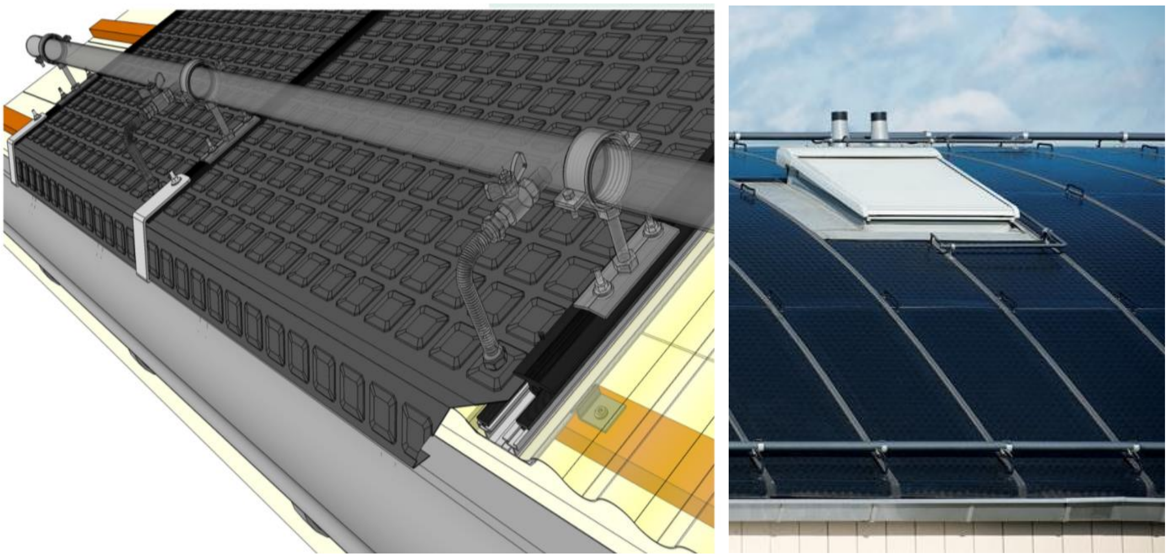
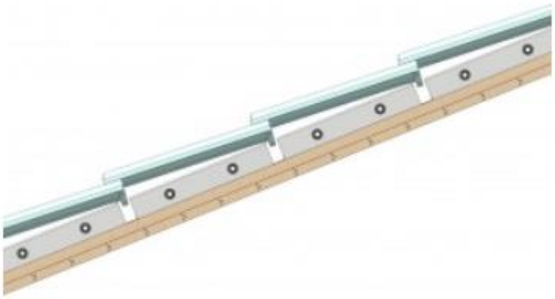


Figure 2.4 The collector of Energie Solaire as a BISTS on roofs.

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)



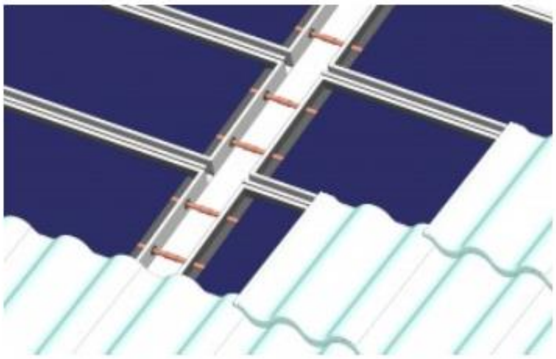


Figure 2.6 Soltech Sigma Smart Roof.

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.

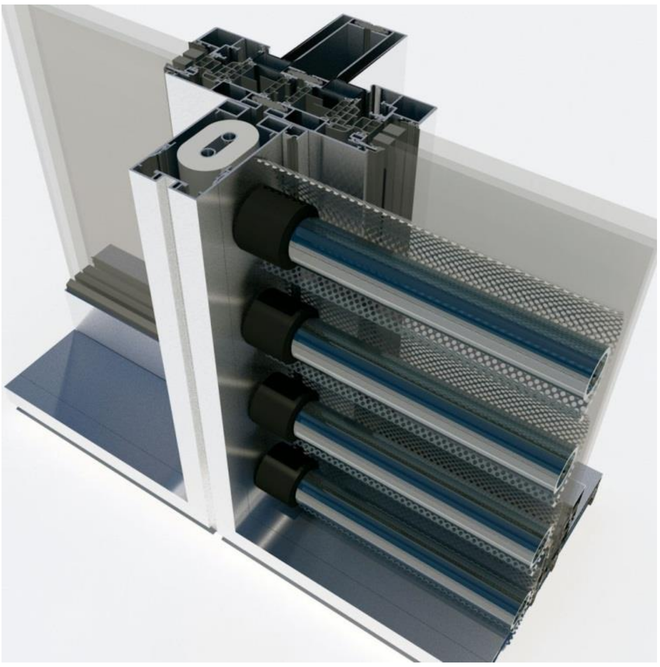


Figure 2.8 The BISTS using evacuated tubes and perforated parabolic mirrors developed by University of Stuttgart.

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

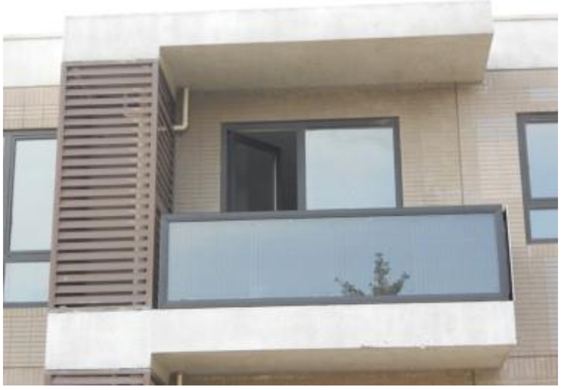


Figure 2.12 The all ceramic collector as a roof integrated system (left) and integrated as a balcony balustrade (right).

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.

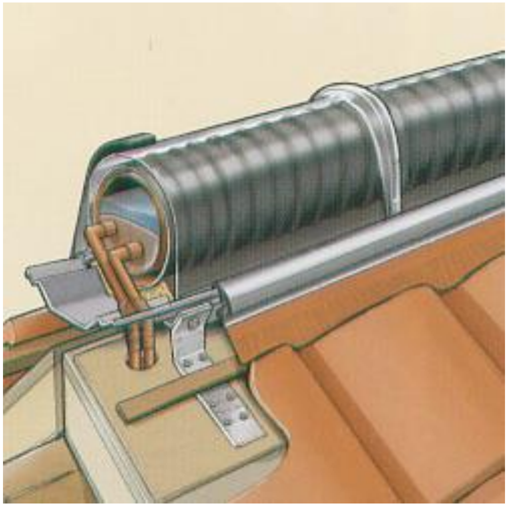


Figure 2.13 Eco-Nok ICS solar water heating collector.

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 d'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 d'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).

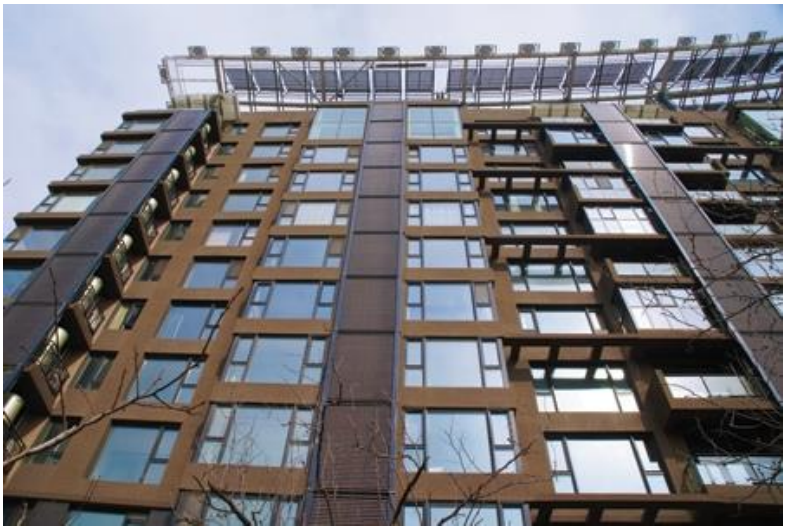


*Figure 2.19 E*vacuated tube solar thermal collectors horizontally integrated onto the façade of a building in the *Garden Utopia' Project in the Chinese city of Dezhou.*

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.

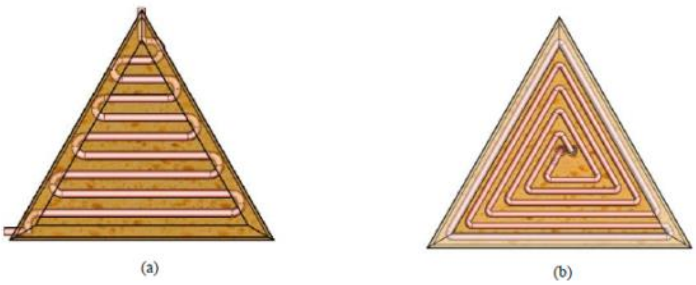


Figure 2.21 Tubes design for the triangle shape unit: a) inlet/outlet on the corners and b) inlet/outlet in the mass centre.

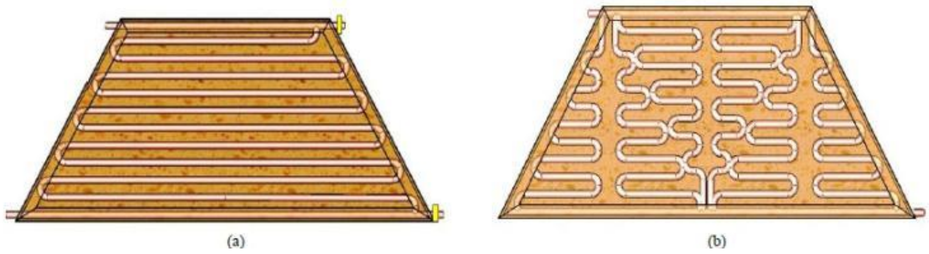


Figure 2.22 Design of the tubes in the trapeze unit shape a) serpentine b) novel design.

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.

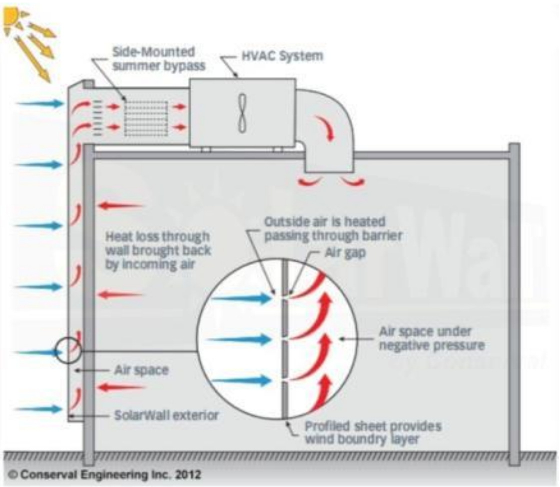

Figure 3.1 Single stage SolarWall® patented system with Rooftop HVAC.

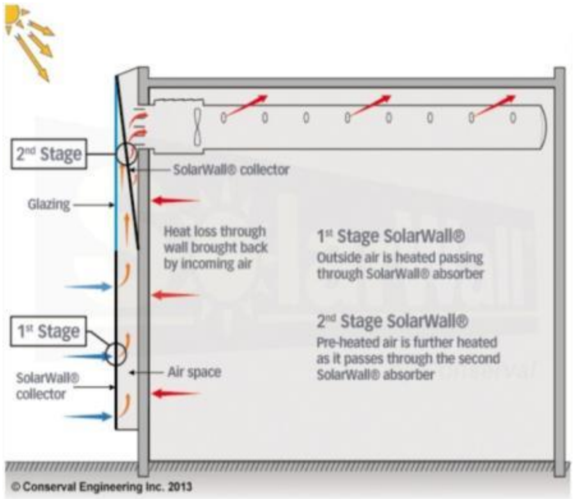

Figure 3.2 2-Stage SolarWall patented system ® with Interior Fan.

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.

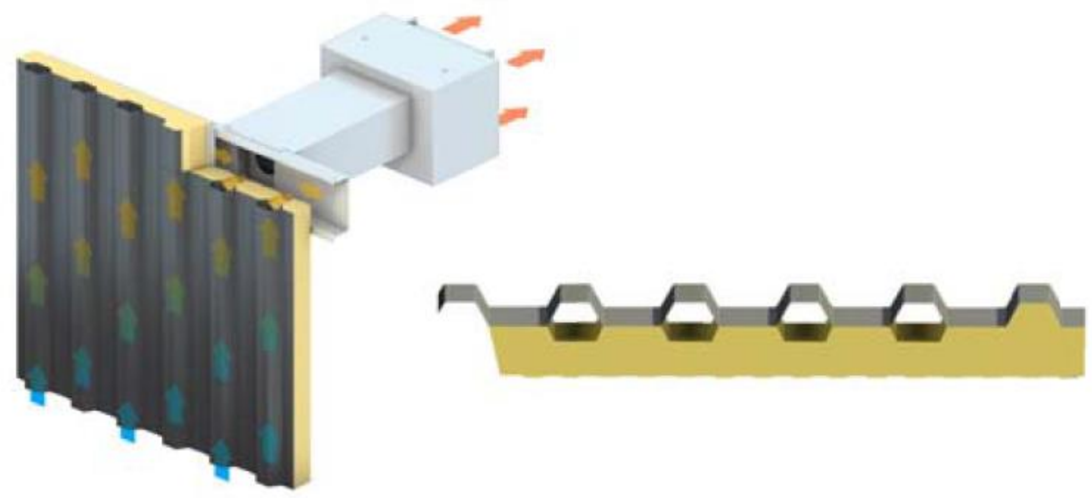

Figure 3.3 Schematic of the Kingspan Integrated Sol-Air Collector (ISAC).

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 technology 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.

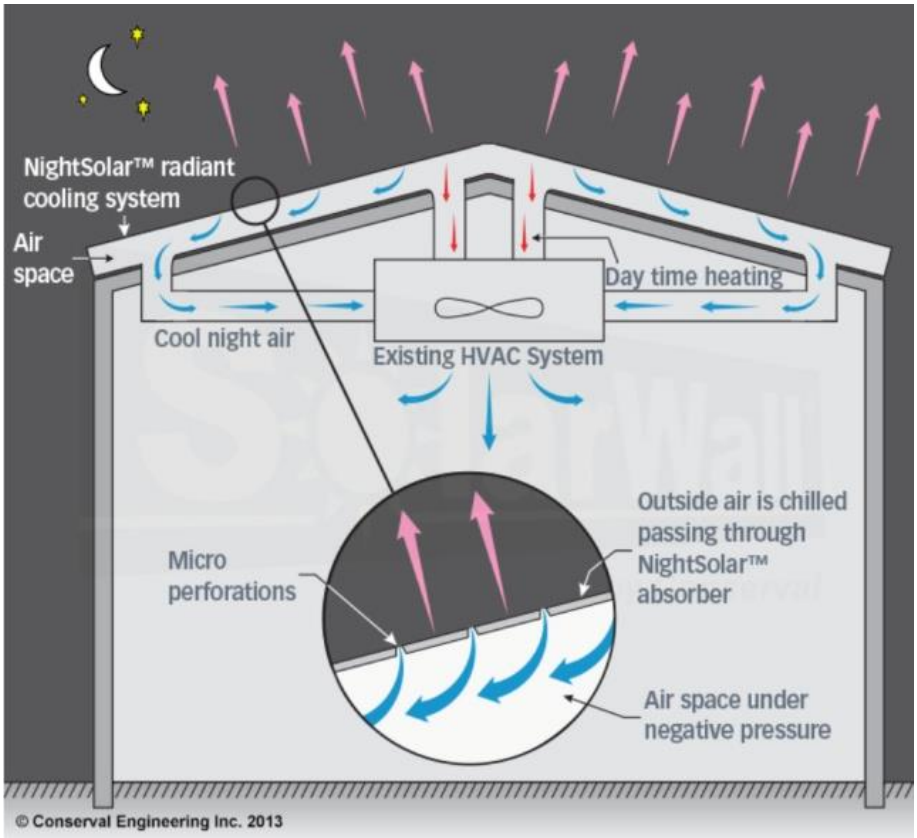

Figure 3.4 NightSolar® system showing the principle of operation.

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.

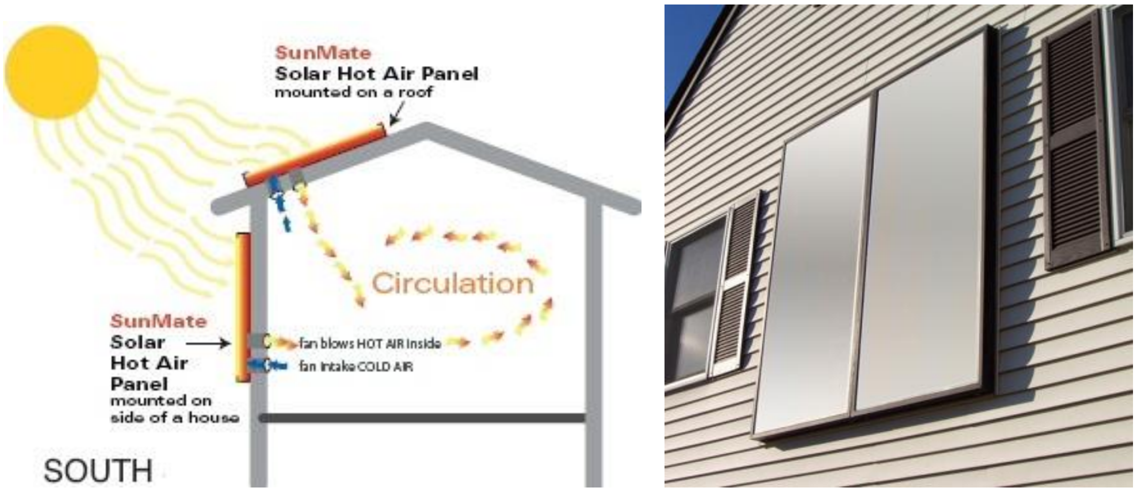

Figure 3.5 The SunMate™ Solar Air Heating Collector.

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.

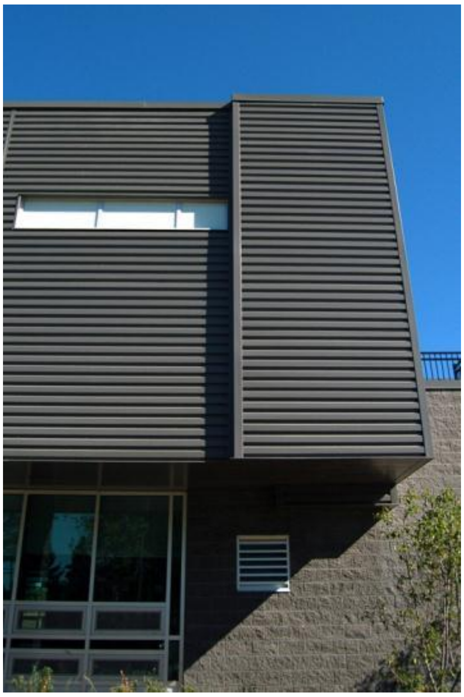

Figure 3.11 The SolarWall BIST in the Dr David Suzuki public school, Ontario, Canada

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 6^{th} and 14^{th} 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.

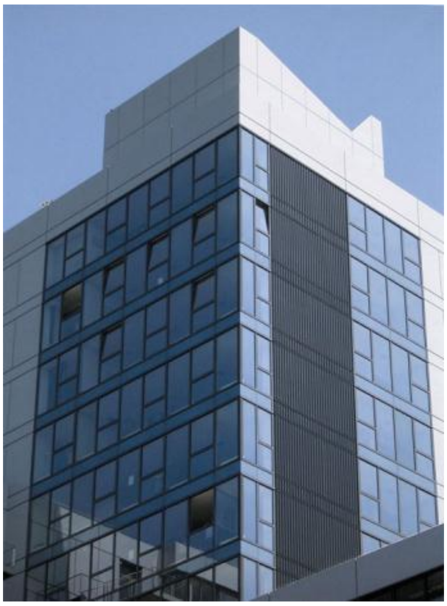

Figure 3.12 The SolarWall in the Erlangen City Hall, Germany.

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 2. 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).

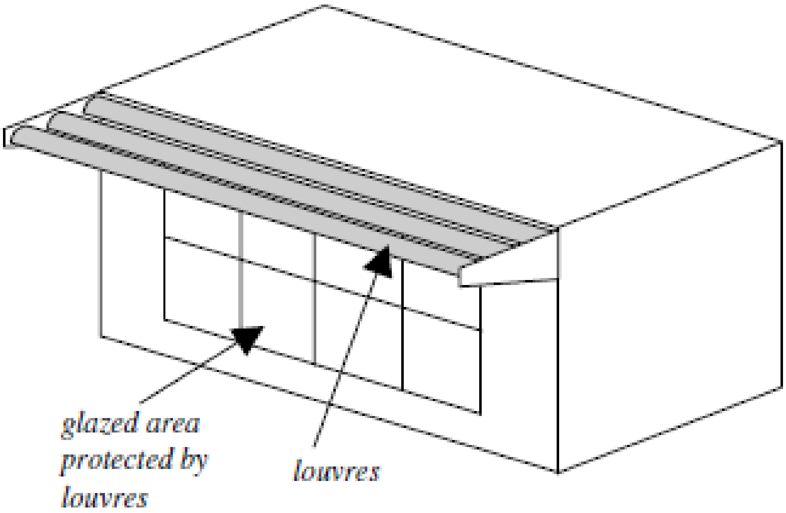

Figure 4.1 Use of a solar louvers collector to protect glazed surfaces (Palmero and Oliveira, 2006).

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.

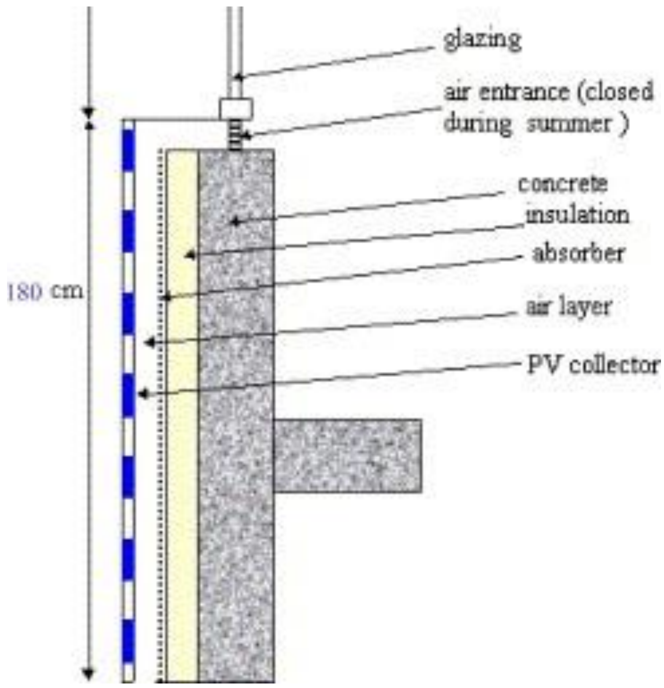

Figure 4.2 PV collector integrated in the facade, side view (semi-transparent PV collector preheating the ventilation air) (Guiavarch and Peiportier, 2006).

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 4.3). 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.

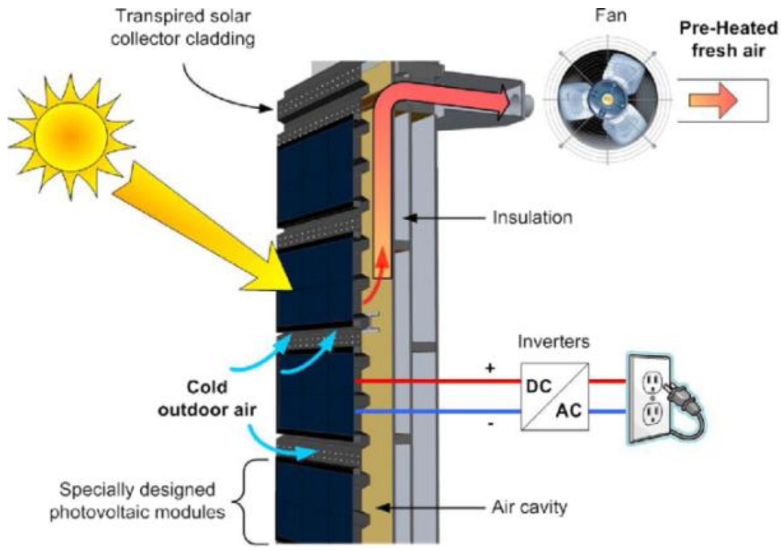

Figure 4.3. Concept schematic for BIPV/T system (top) and BIPV/T demonstration project (bottom) in a university building in Montreal (top floors) (Athienitis et al., 2010).

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 4.5), 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.

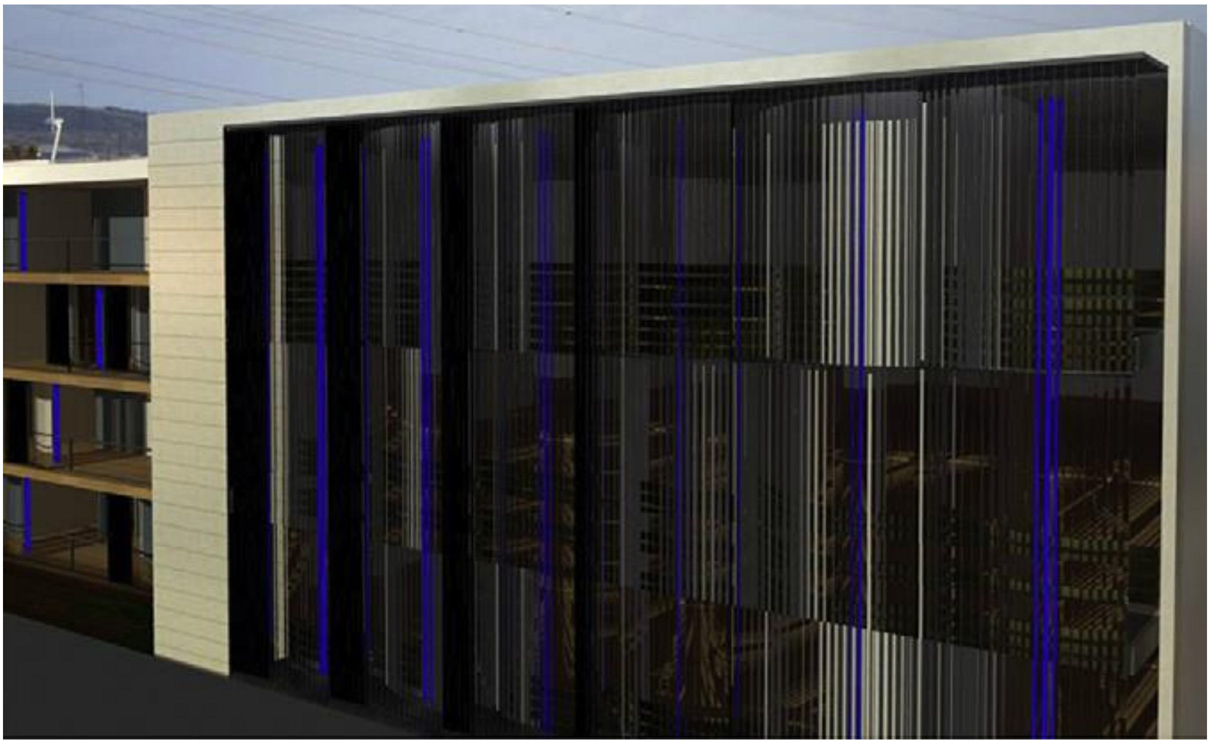

Figure 4.5 Architectural design of the building integrated concentrating system. The blue lines behind the Fresnel reflectors indicate the position of the receptors which are installed on the facade (Chemisana et al., 2013).

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).

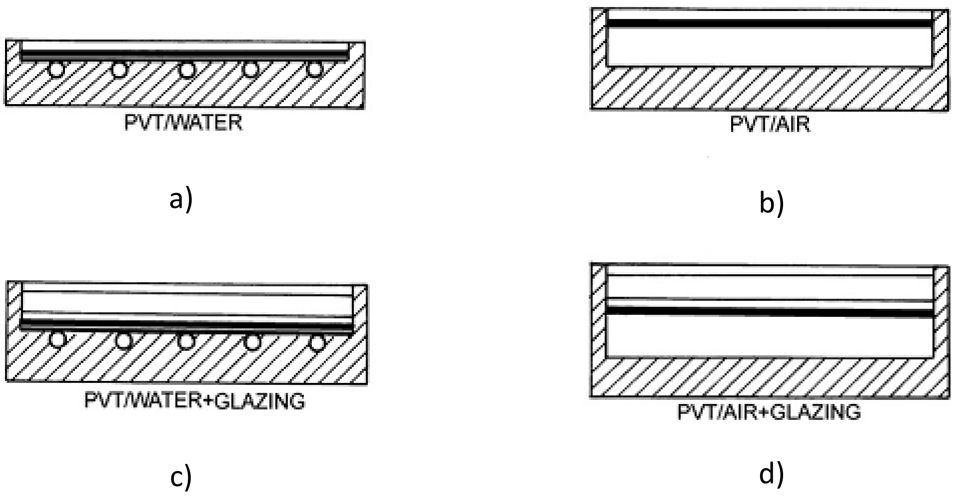


Figure 5.1 Cross section of the main PV/T geometries, a) PVT/water (unglazed) b) PVT/air (unglazed) c) PVT/water with glazing d) PVT/air with glazing.

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

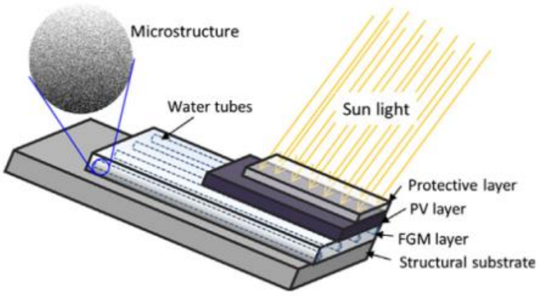
Yin et al. (2013) proposed energy system that seamlessly integrates novel hybrid solar panels into the building structure as a building integrated photovoltaic/thermal system (BIPV/T), and adaptively uses several operating modes to optimize panel and system performance as the environmental conditions 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.

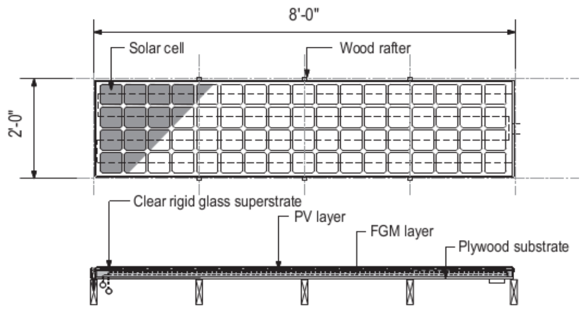
In Figure 5.2a, a novel hybrid solar roofing panel is proposed to perform the multiple functions of both a roof structural component and an energy harvesting device. The cross section of the residential system with the integrated hybrid solar panel is presented at Figure 5.2b. The innovations illustrated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



a)



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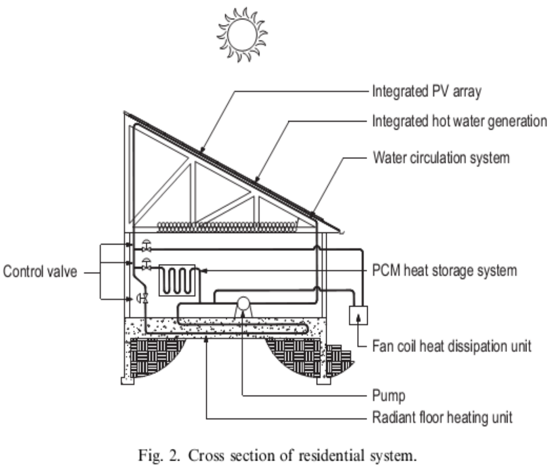

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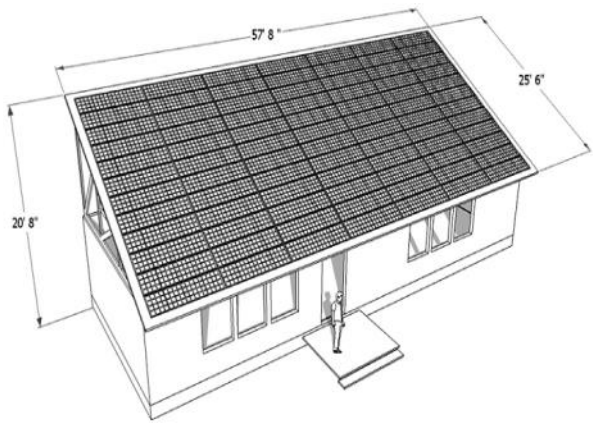


d)

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).

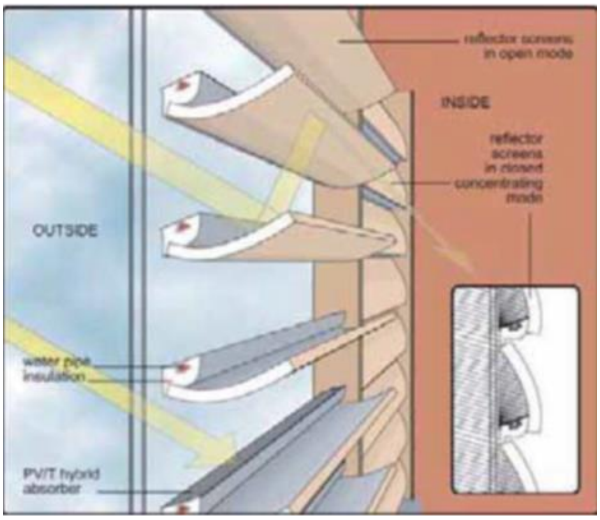
Based on the design philosophy, the benefits of this novel building integrated roofing system are:

- 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).

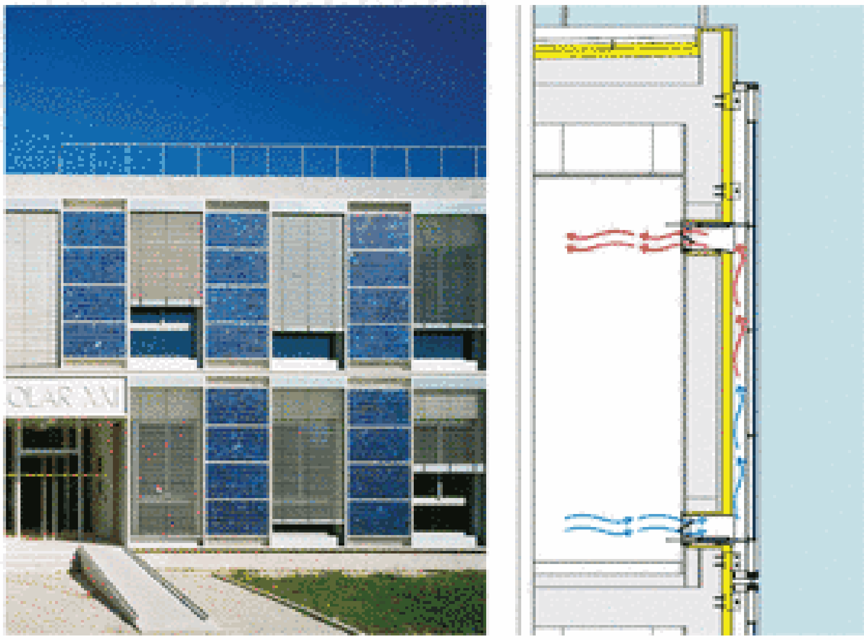


Figure 5.4 The building integrated solar PV/Thermal façade of the Solar XXI building in Lisbon, Protugal.

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).

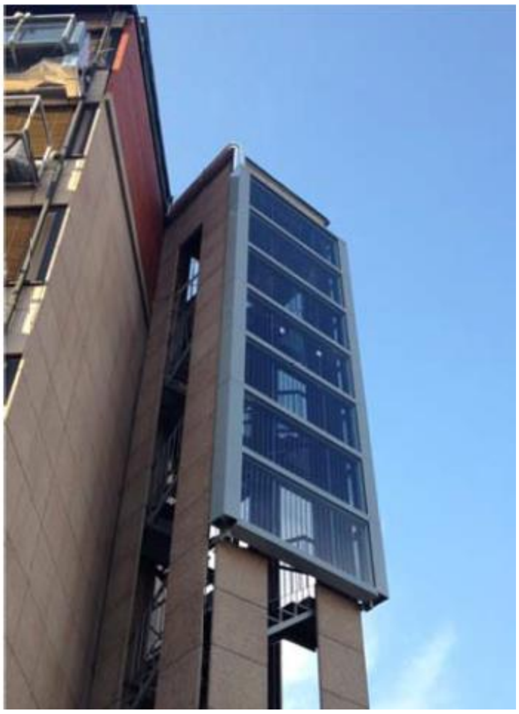

Figure 6.4 Integrated solar system in office building in Ljubijana.

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 5 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°.

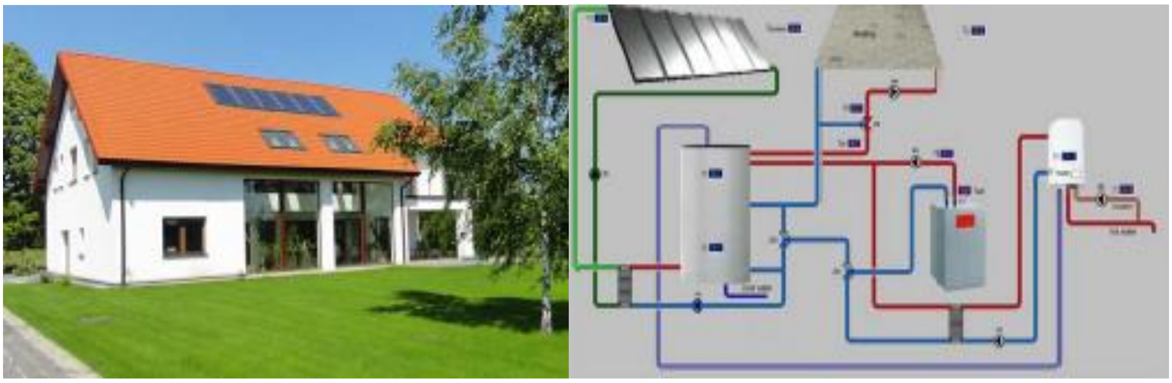

Figure 6.6 Combi BISTS in residential building in Warsaw, Poland.

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.

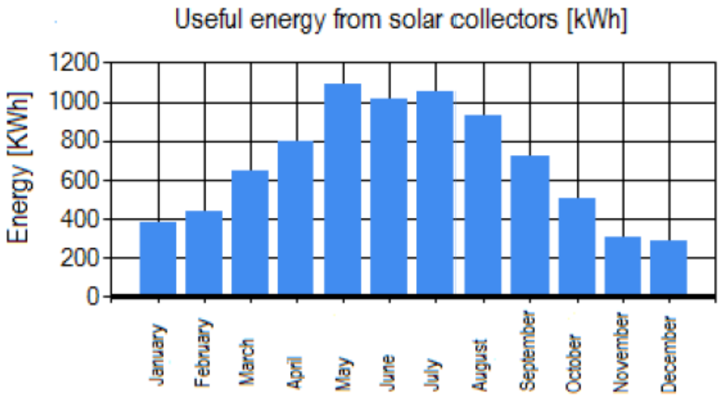

Figure 6 Useful energy from solar collectors – residential building, Warsaw, Poland.

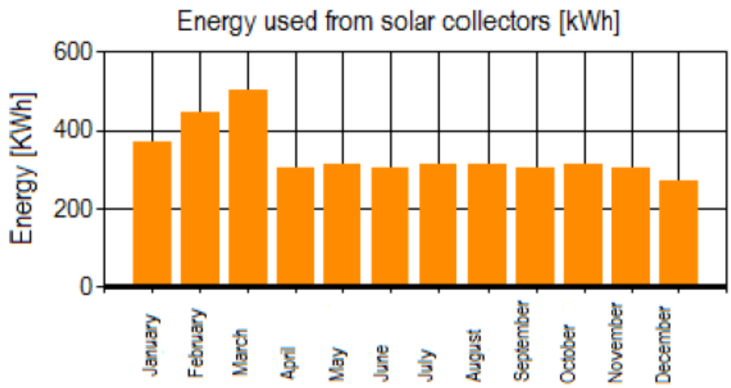

Figure 7 Energy used from solar collectors – residential building, Warsaw, Poland.

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).

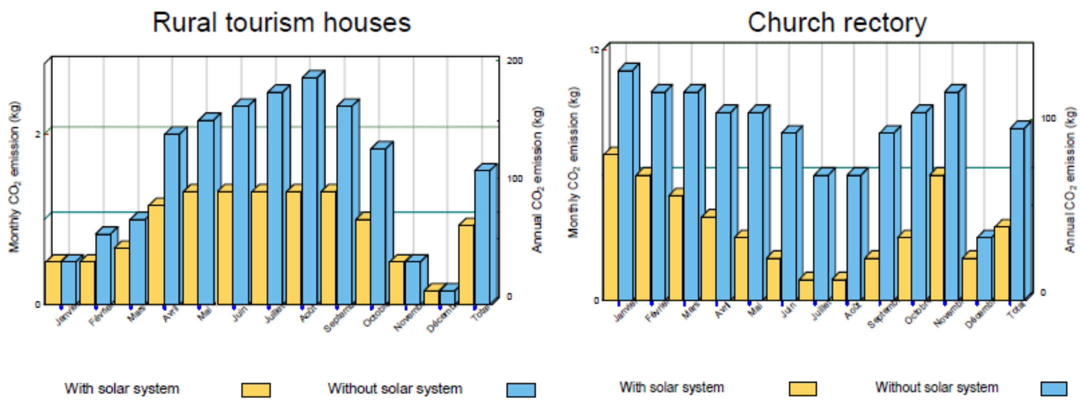

Figure 6.10 Avoided CO_2 emissions for the vacuum solar collector H20SS.

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.

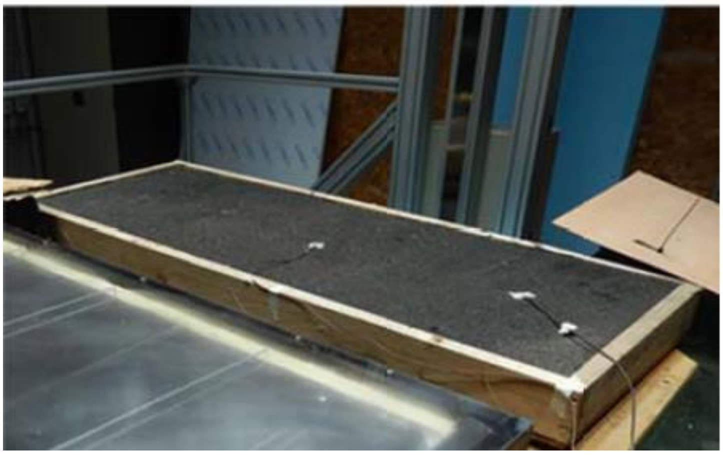

Figure 6.11 The asphalt in the wooden tray for the ACNT roof solar water heating collector.

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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.

7.2.1.1 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 7.8 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.

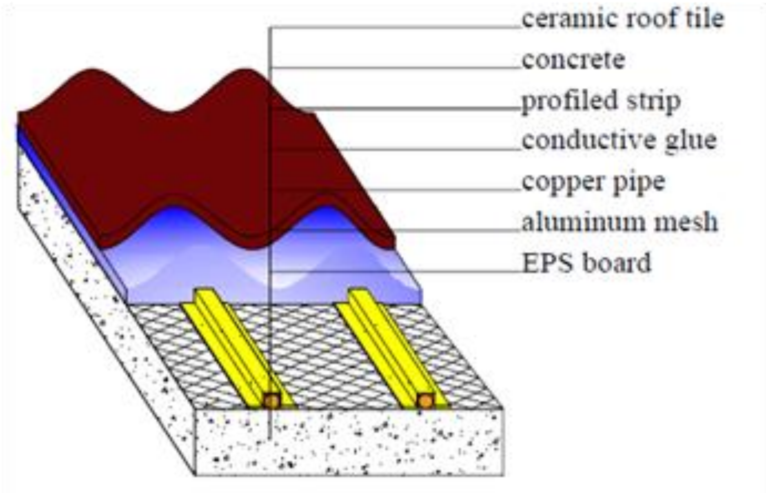

Figure 7.2 The arrangement of the solar collector.

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.

7.2.1.2 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 7.9 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 7.10 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.

7.2.2.1 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.

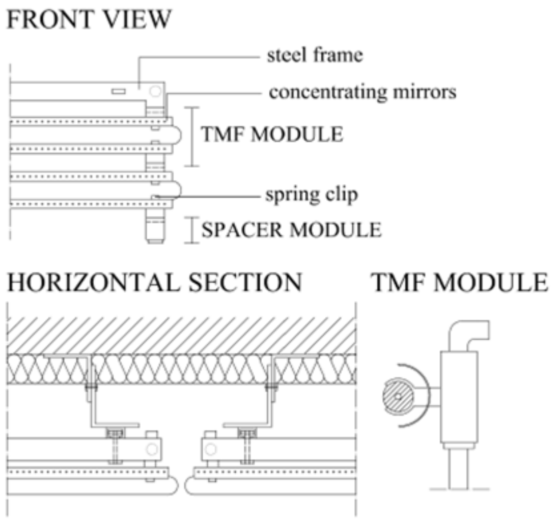

Figure 7.11 Design of a panel made by Tube mirror frame module.

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.

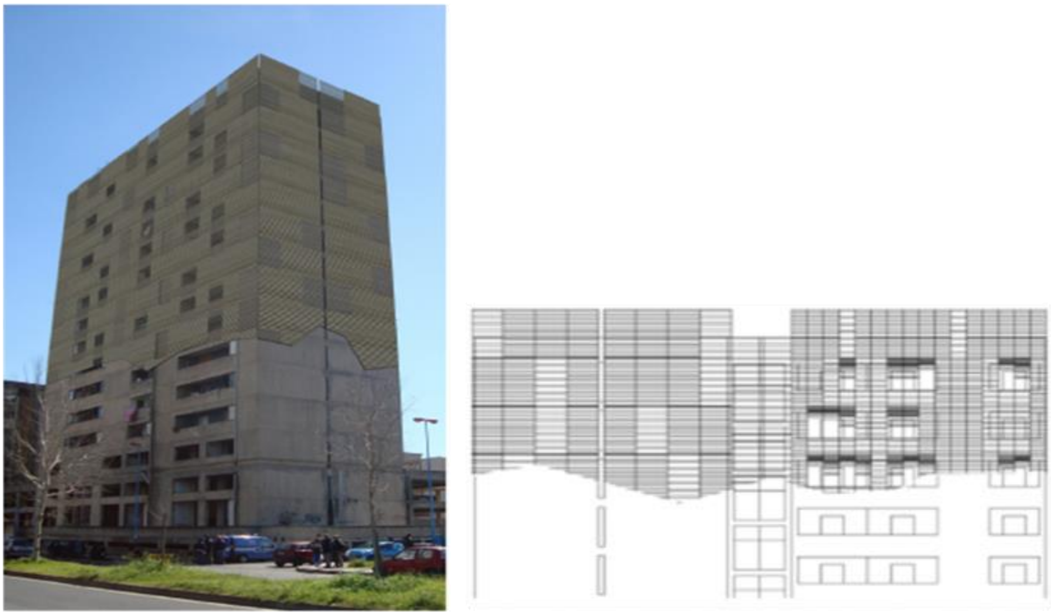

Figure 12.7 Proposed Building – Current façade and simulation of the new proposed solar thermal cover.

7.2.3 Other linked BISTS case studies

7.2.3.1 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 13 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.

7.2.3.2 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 14 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 (m²)
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.

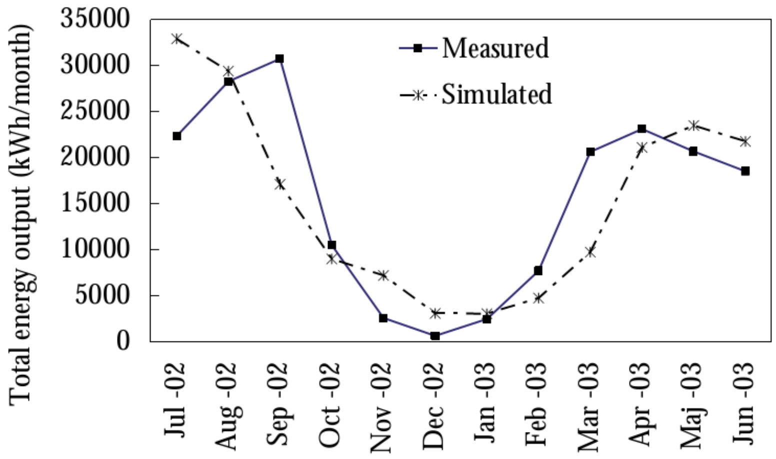

Figure 15 Measured and simulated results of the total monthly energy output from the solar thermal system.

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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:

8.1.1.1 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.

8.1.1.2 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).

8.1.1.3 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).

8.1.1.4 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).

8.1.1.5 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

8.1.2.1 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.

8.1.2.1.1 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.

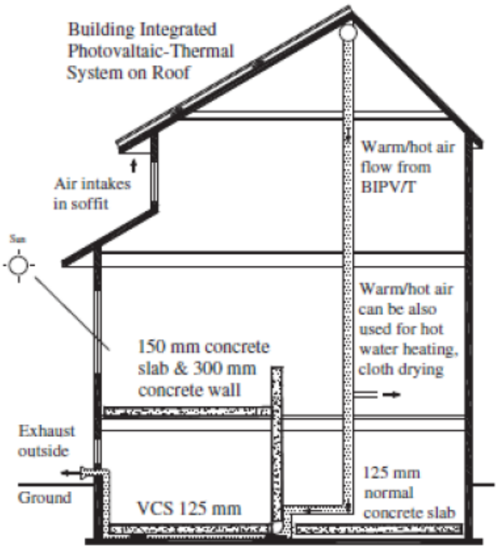

Figure 8.1 Scheme of the VCS linked with BIPV/T system.

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.

8.1.2.1.2 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.

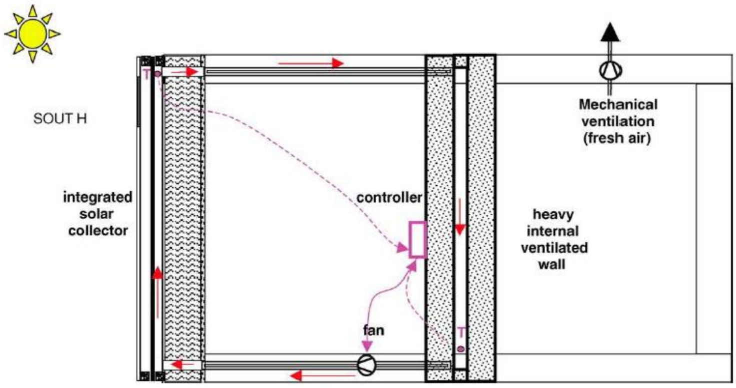

Figure 8.2 Diagram of a closed loop mode in winter.

8.1.2.2 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.

8.1.2.3 External solar façade

Double skin facades which act as an external storage component for heating or cooling purposes.

8.1.2.3.1 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.

8.1.2.3.2 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.

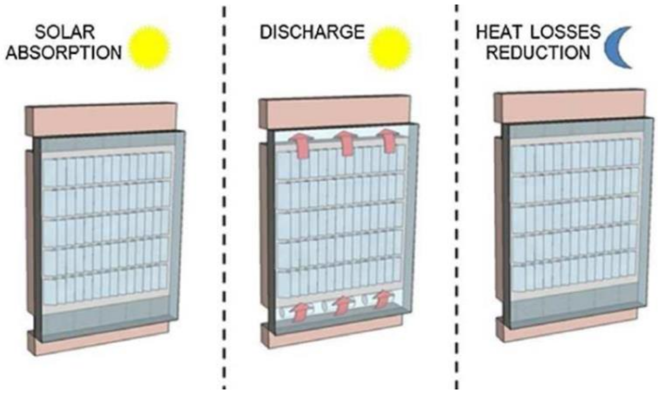

Figure 8.4 Operational mode for the system during winter.

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.

8.1.2.4 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.

8.1.2.4.1 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.

8.1.2.5 Examples of single dwelling Seasonal TES (STES)

8.1.2.5.1 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.

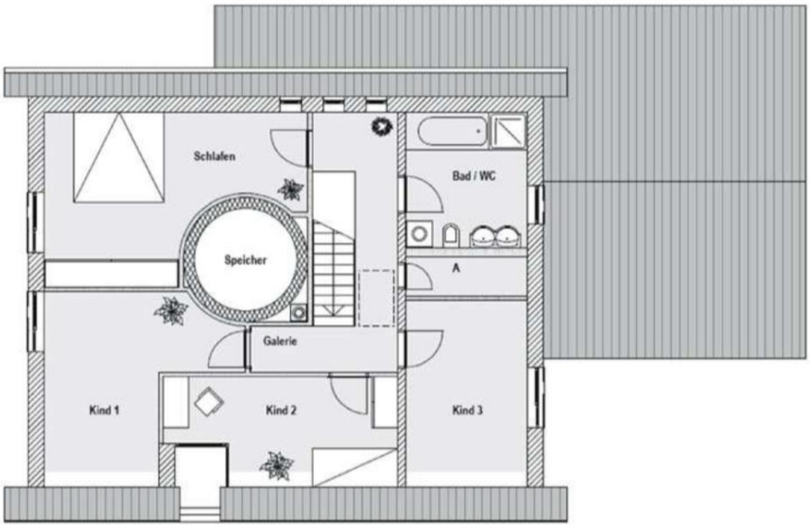

Figure 8.9 Location of tank 'Speicher' within Energetikhaus 100.

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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